AIR TRANSPORT AND OPERATIONS

Air Transport and Operations

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Preface

The focus of the Air Transport and Operations Symposium 2011 was about industry and academia considering how air transport should evolve in order to optimise its value in the 21st Century! Slowly but surely, countries are climbing out of the economic recession and growth rates are positive. The aerospace industry can now be very positive about recovery but in that pioneering spirit of the past, needs to focus more than ever on sustaining value in order to evolve faster in the right direction in this transition time of added opportunity; when we can emulate the pioneers of the past! The opportunity that lies in front of us includes other key aerospace performance challenges, such as the Single European Sky ATM Research (SESAR)'s aims in being able to handle a threefold increase in capacity, improving safety by a factor of 10, reducing environmental impact by 10% and reducing expenses by a half.

As we enter the 2nd decade of the 2nd century of aviation, and with the EU emissions trading scheme about to enter into force, ATOS 2012 aims to explore how we achieve sustainable progress for the industry. How do we identify, formalize, quantify, optimize and deliver sustained value within the current climate? Can we start to move towards a new Value Operations Methodology that raises the profile of operations research, and incorporates not only cost, but also the environment, safety and capacity into the equation? Indeed, ATOS 2012 aims to build on this aspiration of sustaining value in air transport and operations!

For this 2012 edition, it was fantastic that the true integrating spirit of ATOS was reflected in the American Institute of Aeronautics and Astronautics (AIAA), the International Meeting for Aviation Product Support Processes (IMAPP), SESAR's ComplexWorld and the Association for Scientific Development of Air Traffic Management in Europe (ASDA) joining to make ATOS 2012 the largest and most comprehensive edition yet, with over 200 attendees over the three conference days. The conference splits time equally between academic papers and more applied industry sessions, and it gives me great pleasure to see the majority of the academic papers collated into this 3rd ATOS Proceedings, published both online and in hard-copy format! A selection of the best papers will subsequently be invited for upgrade and submission to the Journal of Aerospace Operations. I hope you will enjoy the material herein and invite you to join us at ATOS in the future!

Prof. Ricky Curran

Original Words of Invite from IMAPP, ComplexWorld and ASDA

IMAPP

The International Meeting for Aviation Product Support Processes (IMAPP™), a conference-styled symposium, is sponsored by the American Institute of Aeronautics and Astronautics' (AIAA) Product Support Technical Committee (PSTC). IMAPP™ meetings have developed into an internationally acclaimed networking platform to collaboratively discuss Product Support and Aftermarket related Processes, Technologies, Trends, Best Practices, and Standards.

The IMAPP™ program includes panel discussions, presentations on selected subject matter with related technology demonstrations, harmonization, standardization in aviation-related compliance regulatory matters, as well as training, and high-tech business development discussions.

IMAPP™ 2012 will explore the field of Special Purpose Aircraft (SPA) Design and Operations as relevant for air travel, public transportation, equipment maintenance, and organizational adaptability. SPA incorporates Aerial Fire Tankers, Flying Hospitals, Exploration A/C, Civil Aerial Tankers, and all kind of flying platforms that have applications in addition to passenger/freight transportation. Abstracts exploring certification, qualification, and applicable airworthiness of SPA are encouraged and welcomed.

IMAPP™ 2012 will also take a comprehensive look at the primary and associated causes of No Fault Found (NFF) and Rogue Units and the development of cost-saving solutions in response to these causes. Since the reliability and cost of Aircraft Manufacturing & Operations are at all time highs the relevancy of this subject matter, which focuses on the use of improved reliability and repair systems based on technological and operational advances, cannot be understated. Abstracts in the areas of enhanced repair concepts leading to improved performance, cost, and safety aspects of air transport, development of integrated, 'safer', 'greener' and 'smarter' systems for the benefit of all airline operators and maintenance service organizations, and reduction of Aircraft-On-Ground (AOG) are encouraged and welcomed.

Lori Fischer

ComplexWorld

The first ComplexWorld event in 2012 is intended as a forum to bring together researchers from academia, research establishments and industry that share common interests and expertise in the field of Complexity Management that lies at the intersection of Complexity Science and Air Traffic Management.

ComplexWorld, one of the SESAR Work Package E research networks, will create an open partnership between universities, research centers and industry, aiming at lowering the barriers for the ATM community to have access to and benefit from Complex Systems science, attracting talented Complex Systems researchers towards ATM, and defining, developing and maintaining a clear roadmap for establishing and consolidating a research community at the intersection of Complexity and ATM of clear added value for the European Air Transport sector.

The Conference will focus on Complexity Paradigms for Smart, Green, and Integrated Transport, including new concepts and developments in areas that explore how Complexity Science can contribute to understand, model, and ultimately drive and optimise the behaviour and the evolution of the ATM system that emerges from the complex relationships between its different elements, in terms of safety, performance and sustainability.

The Conference will be open as well for presentations of specific air transport operation challenges of special complexity in terms of high number of stakeholders involved in the operation process, lack of a management paradigm of the information involved, decision-making processes in the context of high uncertainty, lack of data or information to support the decision-making processes. The challenges will be presented through a particular case study and the goal is to identify case studies with high potential of being analyzed through new paradigms by the research community.

David Pérez

ASDA

The goal of the Air Traffic Management is to achieve a safe and orderly flow of traffic. The economical benefit of an orderly (or high) flow is immediately clear, but who should pay for the safety? And how much should we spend to achieve an advancement in safety? Or on the environment? Are the goals set in Flight Path 2050 economically feasible?

On top of this, the Air Transport System is a distributed system with ground and airborne elements and many different stakeholders. This often means costs and benefits are also distributed. And not necessarily in the same way: very often the costs lie elsewhere in place and time compared to the benefits.

We all work on advancing the efficiency, sustainability and safety of air transport. What is the economical side of these developments? Do we take that into account sufficiently? How can we make a trade-off between the different aspects and interests? Are we currently on the right track or do we need to change the way we run ATM research? How do you make a trustworthy cost-benefit analysis of ATM research & development?

Do you have a topic related to this theme, which you would like to present and discuss with a broad audience of ATM experts, policy makers and industry at the ASDA seminar 2012? Send in an abstract of your paper/presentation and attend!

Jacco Hoekstra & Kurt Klein

Contents

Part I. ATOS

Part II. IMAPP

Part III. ComplexWorld

Part IV. ASDA

Part I

ATOS

Air Transport and Operations
R. Curran et al. (Eds.)
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Validating Value-Driven Design

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Value-Driven Design is a systems engineering process intended to improve the outcomes of large engineering systems development programs, which typically involve thousands of engineers, billions of euros of cost, and many years to complete. Does this, or does any comparable systems engineering methodology actually work? With such programs, it is impossible to conduct meaningful clinical trials. Also, the programs are sufficiently complex that it is impossible to observe much of what goes on. The Center for System Studies is developing a laboratory in simulation to examine systems engineering processes operating within simulated development programs. This paper reports on progress constructing multi-scaled simulations for this purpose. It also conveys the results of a prototype simulation project.

I. Introduction

DESIGNING large complex systems such as Boeing airplanes or NASA launch rockets is a social activity where thousands of engineers may work together through a hierarchical network of organizations. Such development programs, especially when they are publicly-funded, are notorious for cost overruns.[1] In the aerospace and defense industries, system engineering was developed sixty years ago as a way to combat overruns, and has been credited reducing overruns by 50%.[2] However, 50% does not seem good enough. Since the 1970's US government aerospace and defense programs that reach completion still overrun by about 50%,[3,4] and we can only assume that the one-third of programs that are cancelled before completion would fare even worse if they were permitted to proceed. Currently, the US Department of Defense (DoD) loses approximately 150 million per day to rising cost and declining value from delayed and cancelled production.[5] DoD is not being called out here as a particularly egregious example -- they are more likely typical. Rather, we cite DoD because they have a statistically useful number of very large system development programs, and the costs and schedules are regularly reported to the public.[6] In fact, NASA results are similar,[7] and private programs such as the Airbus A380 and the Boeing 787 typically incur multi-year delays and multi-billion euro or dollar overruns.

Perhaps systems engineering can once more ride to the rescue. Perhaps systems engineering processes can be improved to regularly yield elegant systems on time at a controllable cost.[8] However, a prerequisite to improving systems engineering is the capability to determine whether one method, process or tool, (such as value-driven design[9]) is better than another. The reader might be surprised that a comparison of two system engineering processes would not be simple and obvious. In fact, in a complex development program executed by thousands of engineers, little of what happens is simple or obvious. In the nineteenth century post-Napoleonic era, Carl von Clausewitz, writing about how to manage thousands of soldiers to effectively execute a battle, coined the expression "fog of war" to describe the inability to see inside two complex opposing armies performing differentiated tasks, and determine in a useful manner what is happening.[10] A similar problem presents in the development of a complex aerospace system. Thousands of people are executing different elements of a broad engineering program that is well beyond any single person's ability to comprehend. Like the seven blind

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men studying the elephant, each engineer understands only the region of the system within which they are working, some regions adjacent to their own, and hopefully some superficial aspects of the top level system purpose and organization.

There is some discussion as to whether an engineered aerospace system is complex in a technical sense, such that it exhibits emergent properties unintended by the reductionist designers. We do not take a position on this point. However, a large aerospace development program consisting of large engineering organizations and the (at least) complicated artifact which they are designing is a complex adaptive system.[11] Cost overruns are just one type of emergent property of these socio-technical systems.

A. The overall validation plan

Our research team at the Center for System Studies is confronting the challenge of how to study these systems, and specifically, how to assess the effectiveness of systems engineering technologies such as value-driven design. We have taken some direction form the National Science Foundation sponsored Engineered Systems Design Workshop (February, 2010), which recommended that this problem be studied in simulation.[12] A simulation can represent the inner workings of design teams and even the cognitive processes of engineers within the teams. In simulation, we can directly study the effects of a system engineering method by zeroing in on individual design decisions to see how the information and incentives drive the person or group making the decision, and to observe the consequences of that decision on the design of the product system.

Unfortunately, a simulation that represents the thoughts of every one of the thousands of engineers in a complex aerospace development program would be intractable. Therefore we are constructing a multi-scale simulation.

At the large scale, we will simulate an entire development program for a large aerospace system. This simulation will incorporate hundreds of design teams. The structure is essentially an agent-based simulation in which each team is represented by a single agent, and teams are connected through an organizational hierarchy (Figure 1). The large scale simulation will be a laboratory for investigating the impact of systems engineering methods and processes. Recursive guidance technologies (as discussed by Baldwin and Clark[11]) like requirements flowdown and allocation can be employed within this simulation, and their effect on the product of design, as well as relative effect on design cost and schedule, can be observed.

At the small scale, we will simulate only three teams from down inside the project organization hierarchy. However, we will model every engineer in every team as an agent. And instead of the classic "thin agent" model, in which the agent is instantiated by a set of rules that dictate its behavior, this simulation will employ "thick agents" with sufficient cognitive skills to make rational decisions, based on preferences, information, and anticipation of the future.[13]

We plan to use these simulations together to determine whether value-driven design[9] out-performs traditional systems engineering and whether there are other techniques, such as multi-disciplinary optimization methods (examples are Bi-Level Integrated System Synthesis[14] and Analytical Target Cascade[15]) that may work even better. The way we will use the simulation to validate systems engineering methods is as follows:

1) The large simulation will execute a simulated design process using the test methodology. The results will be analyzed to determine what micro-level behaviors in the simulation are chiefly responsible for the significant top-level results.

2) We will attempt to validate these critical micro-level behaviors using the small-scale simulation. Do the same behaviors appear in the more detailed simulation, and do they produce the same apparent effects? Are the behavioral phenomena in the small simulation similar enough to the large simulation to justify the conclusions with respect to the systems engineering methods? If so, we proceed to step 3. If not, we modify the rules governing design team behavior in the large simulation to better conform with the small simulation.

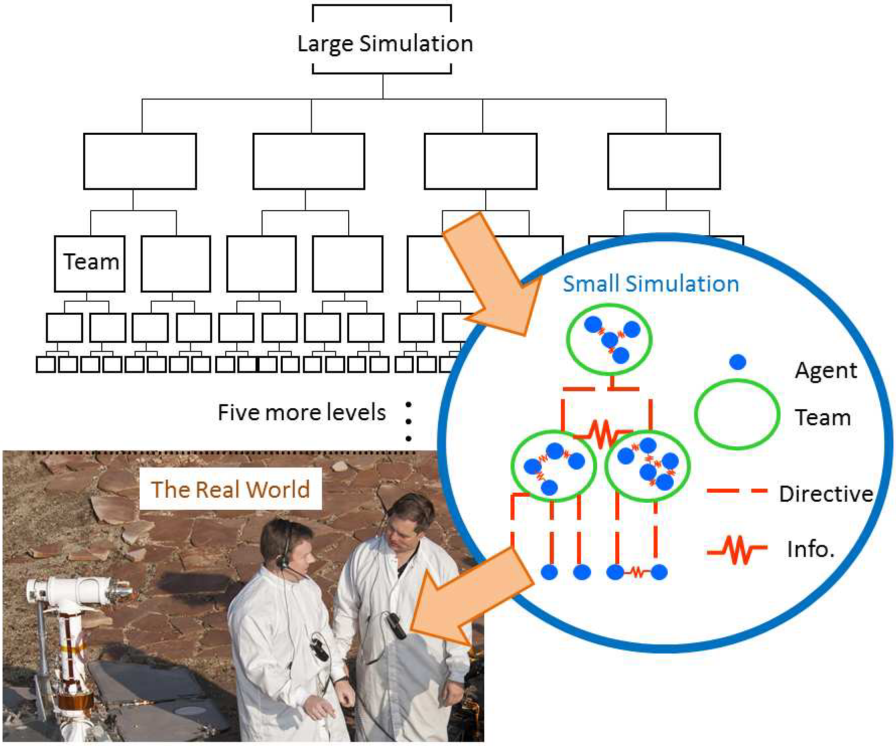

Figure 1. Multi-scale Simulation Verified in the Field.

The hierarchical map of rectangles indicates the large scale simulation, in which each rectangle represents a team that will be modeled as a thin agent. The blue circle is the small scale simulation, in which a thick agent will be used to model every engineer. The small scale simulation will be verified by comparison with practicing engineers in the field. (Photograph of engineers from Wikipedia Commons, courtesy of the Jet Propulsion Laboratory, Pasadena CA)

3) If the critical behaviors responsible for the large simulation analysis results are supported by the small simulation, we must ask what specific behaviors of individual engineers or what interpersonal or inter-team behaviors or phenomena are necessary to validate the large simulation.

4) Once we have identified the critical phenomena in the small simulation, we will study actual practicing design teams and verify that these phenomena correspond to behaviors in the real world. If so, the results of the large simulation will be accepted. If not, the small simulation will be modified to accord with the behaviors we have observed in real engineering organizations, and the large simulation will be updated for consistency with the small simulation. Then the validation process will be repeated.

Although we expect this overall process to be rather laborious the first few times it is exercised, we anticipate that, after several of these improvement cycles, the large simulation will become quite effective at reflecting the significant relevant behaviors of actual large design teams.

B. Overview of the paper

The paper is divided into three sections. The first will discuss the large simulation, the next addresses the small simulation, and the third describes our plans for verifying the performance of the small simulation with field work in actual design organizations. These are followed by a conclusion with a discussion of potential future work.

II. The Large Simulation

The Center for System Studies at the University of Alabama in Huntsville is working with Brian German at the Georgia Institute of Technology to construct a model of detailed design hierarchy for a moderately complex system and then use the model to assess several alternative methods for coordinating the design process. The model will represent a jet engine design organization in a seven level system / subsystem hierarchy, decomposing into about 500 parts at the lowest level. This hierarchy is represented notionally in Figure 2. Note that the organization hierarchy directly reflects the physical hierarchical decomposition of the engine into parts, with a design team assigned to work on each part, and additional teams to design each subsystem and component. The interrelationships between teams are largely driven by the interconnections between the parts and systems that the teams are designing. In contrast, during the preliminary design phase, the team is primarily divided along disciplinary lines (mechanical structures versus aerodynamics versus heat transfer, for example) and inter-disciplinary coordination is the primary organizational issue. We will study the detailed design phase where groups are divided along physical part boundaries, and disciplinary divisions occur within the boxes shown in Figure 4. Coordination of design teams is effectively the coordination of part designs and the interfaces among parts, sub-systems, and systems.

The design of a large-scale complex system such as a commercial airliner entails millions of parts and tens of thousands of engineers. We would like to replicate this degree of complexity, at least structurally, but we intend to begin with only one thousand design teams (representing perhaps five thousand engineers).

A. The detailed design project and its hierarchy

The subject of our simulated design activity will therefore not be an entire system (e.g., an entire commercial airliner), but only the propulsion subsystem. In particular, we intend to model the design of a large thrust class turbofan engine that would power a twin-aisle jet such as the Airbus A380. We have chosen a turbofan engine because it is a complex artifact with many design couplings between different components. For example, the work extracted from the gaspath by the high pressure turbine must be returned to the gaspath upstream by the high pressure compressor, and both components are constrained to turn at the same speed. A similar relationship binds the fan and the low pressure turbine. Additionally, the hot gas that turns the high pressure turbine must all flow through the low pressure turbine. Other constraints and couplings exist in the load paths that carry thrust from the engine to the aircraft and the heat transfer loads that cool parts which are sometimes immersed in flows of gas that are hotter than a part's own melting temperature. These complex interrelationships span to the deepest levels of the component hierarchy.

B. Interconnecting the hierarchy with design simulation models

Although will not attempt to model the engine with high accuracy, our simulation will include an aero-thermo-dynamic performance model, a structural model, and a heat transfer model that will represent couplings and constraints that interconnect parts. The hierarchy of design teams will also be connected by models of mass, reliability, manufacturing cost and maintenance cost. Thus, every design team will be concerned about several attributes of their design, and these attributes, in aggregate, will affect system level attributes (such as engine cost and mass), as well as the performance and constraints faced by other design teams.

This simulation may seem an overwhelmingly difficult task; however, we will pursue a modeling approach that will limit the scope while capturing key dependencies. The cost, reliability, and mass models are fundamentally additive and so do not present a great burden. The aero-thermo model will affect only gaspath components (about 60 part types) and will be simplified as much as possible while still retaining interactions and a correspondence to physics. At a system level, the model will predict thrust and specific fuel consumption at a high altitude maximum power condition (top of climb). The heat transfer model will address only components from the rear of the compressor to the core engine nozzle, about half of the engine parts, with simple physics representations. The structural model is expected to provide the most challenge in implementation. If inclusion of a large number of parts becomes too difficult, we may reduce the model to address only frames, cases, and major structural members; however, our initial plan is to include most parts in the structural model.

For tractability, we intend to ignore aeroelasticity, bearing dynamics, and most parasitic air flows. We will also ignore almost all part-specific design issues, such as damage tolerance of fan blades or corrosion of combustor fasteners, because these are unimportant to interactions between parts, other parts, and systems. Considerations of interactions are central to our study.

C. Atomic design team models

The representation of design teams, the interior of the boxes in Figure 2, will be very simple, but not so simple that the coordination strategy can directly optimize the design. Most teams will be represented by a choice-information-choice process, as was used in the design simulation in Collopy.[16] The choice-information-choice process works as follows:

1) A team's task is to pick a set of design variables (part dimensions, material, and so on) which determine a set of attributes (part mass, cost, and so on). In the simplest version, a pair of design variables determine all the attributes.
2) The team selects one design variable, based on a probabilistic prediction of the attributes.
3) Information is revealed (randomly generated from the distribution in step (2)) that fixes some of

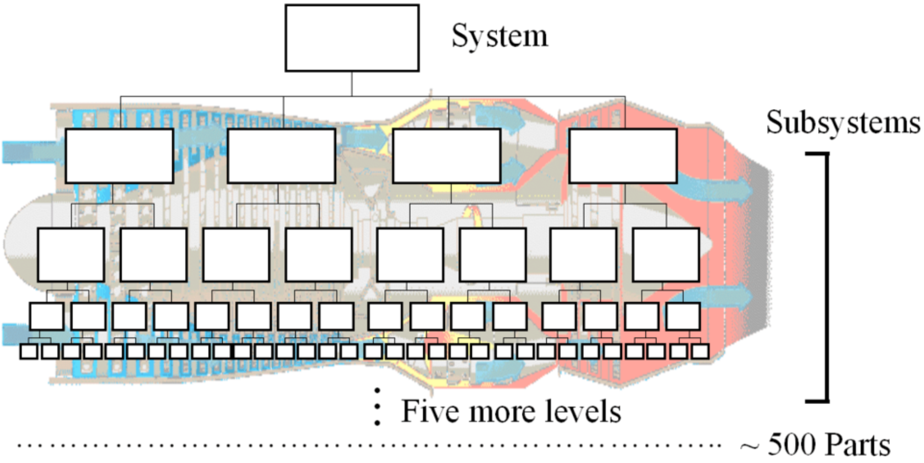

Figure 2. Large Scale Simulation.

In this simulation, each engineering team (represented by a rectangle) will be simulated as a single agent. The simulation will facilitate the study of systems engineering guidance technologies like requirements flowdown and allocation. (Jet engine drawing courtesy of Wikipedia Commons) the attributes.

4) The team selects the other design variable, based on the updated prediction of the remaining attributes.

5) The actual attributes are revealed (randomly generated from the updated distributions).

The choice-information-choice process will be coded as a parameterized subroutine and used to represent most of the design teams, for the sake of simplicity. Select design teams may be represented by more detailed models.

Note that the probabilistic prediction of attributes constitutes a local design model for the team. This is not the same as the engine design models discussed in the previous section. We use the engine design models to represent reality, but the local design models will represent each design team's perception of reality.

D. Coordination of design teams

In the simulation, two structures will interconnect design teams. The first is the design simulation described above (heat transfer models, mass models, and so on). The design simulation will aggregate part attributes into subsystem and system attributes, and impose unwanted interactions among different parts. The second structure is the process that coordinates design teams, through **measures** and **information**.

The coordination process provides each design team with a **measure** for comparing sets of attributes to decide whether one design is better than another. For example, in the traditional systems engineering process, each design team is provided a set of requirements that applies to their attributes. If the attributes meet the requirements (mass is less than required mass, reliability is greater than required reliability) the design is good, else it is bad. In another example, the coordination strategy could provide an objective function to each design team. The objective function converts the set of attributes into a score, where a better design has a higher score. The design team would try to choose the design with the highest score.

The coordination process can also provide each team with **information** about the design of the rest of the system. Recall that each design team makes decisions based on a local design model. This model can be updated only through information provided by the coordination process. Therefore, design teams can react to lateral couplings only if the coordination process conveys the coupling and stimulates the reaction.

E. Design rework

Collopy[16] developed simple models of design teams which will serve as a starting point for our team models. That study concluded that the use of one method (requirements flowdown) would cause design teams to redo design work much more often than an alternative approach (objective function flowdown).

Our study will monitor when coordination processes lead to design rework. In detailed design, all the activity at a particular level is presumed to take place simultaneously. Our simulation will generally follow this presumption, except when a precedence is clearly indicated prior to the start of design.

Design rework also tends to suffer many more constraints than first-pass design, because other components are now fixed. We will assess whether this is true in our model, and what the impact is.

III. The Small Scale Simulation

The small scale simulation will contain representations for individual engineers, designers, managers, design teams, design tasks, the design product, and design methodologies. The simulation will also support the study of interactions among these elements. We plan to perform this work with Daniel Shapiro and Arnav Jhala at the University of California at Santa Cruz. The plan is described in detail in Componation et al.[17]

Figure 3 presents the structure of the simulation. It will include at least two design teams and one systems engineering team modeled in detail, with one project manager responsible for leading the

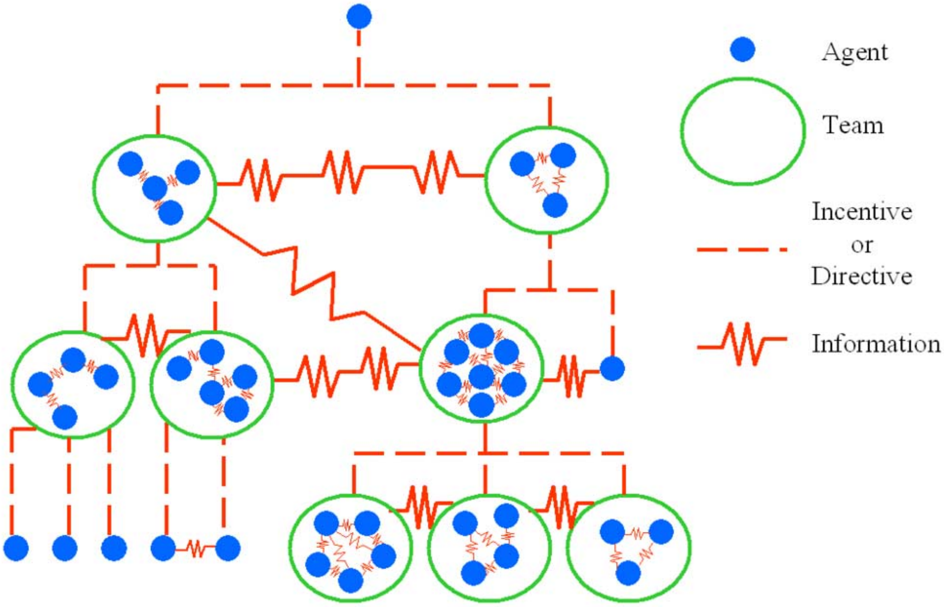

Figure 3. The small simulation.

Although we may only simulate three design teams (circles) in detail, this diagram shows additional lower fidelity agents that would contribute context.

project's overall direction. Regardless of his or her role, each engineer in these three teams will be modeled by an individual instantiation of a cognitive decision-making agent with individual preferences and a certain degree of variability.

As the simulation executes the flow of the design process, engineers on a team acquire information through test and analysis, make design decisions, and pass information to other engineers. Team managers are responsible for communicating directions and results to other teams' managers. Tasks completed by engineering teams will modify a representation of the product that is being designed.

We will model the cognitive process of design using the Function-Behavior-Structure ontology of John Gero.[18] In this ontology, a designer, in order to satisfy a **function**, creates a **structure** which has a **behavior**. **Function** represents at once the purpose of the artifact and any intentional effect resulting from the behavior of an object. **Behavior** is the set of attributes of a structure by which the artifact achieves the function. **Structure** is the physical embodiment of the artifact in terms of material, topology and geometry. For example, the function of an aircraft wing is to provide lift to the airplane. A possible structure can be represented by a solid model, indicating the planform area, aspect ratio, camber, and so on. Each particular structure has a behavior, which includes not only the amount of lift, but also weight, drag, manufacturing cost, and life. Design is a cognitive process which moves back and forth between possible structure and their expected behavior, regularly checking the behavior against the function.

The simulation will represent agents using Shapiro's value-driven agent framework.[13] Value-driven agents are embedded within the Icarus architecture, which provides a general theory of cognition and the strongest available model of decision analytic behavior for task specific agents. Icarus includes representations for probabilistic beliefs; current agent goals; the utility of current (or envisioned) beliefs; hierarchical skills composed of goals, sub goals, actions, and effects; and a feature-based model of the expected value of those strategies. It also provides mechanisms for perception, probabilistic inference to derive beliefs from perceptions, identification of situation driven and goal relevant courses of action, projection of future state, decision-making over those courses of action driven by an expected value calculation, and problem-solving to derive solutions for goals absent predefined skills. Lastly, Icarus provides a reinforcement learning mechanism for refining expectations based on observation. While these representations and mechanisms provide a fertile basis for conducting research on value-driven behavior in complex engineering tasks, we will need to extend the framework in several dimensions. For example, we will incorporate a more nuanced representation of utility than currently present, as value interactions and response to incentives are central aspects of this research. More broadly, we will need to approximate the impact of cognitive load on inference, projection of future state, and strategy/action selection, as bounded rational choice is central to the problem of modeling human behavior in complex engineering tasks.

We will employ these value-driven agents to model the knowledge and behavior of individual designers. As an illustration, an engineering design team for an aerospace project may have a lead design engineer, a mechanical engineer, a materials and manufacturing engineer, and a heat transfer analyst. These agents will have skills appropriate to their roles: the lead design engineer will develop the structure and features for the component being designed, and compare the behavior of the structure to the function; the mechanical engineer will predict aspects of the behavior such as strength and mass; the heat transfer engineer will predict the temperature distribution across the component at various design conditions; and the materials engineer will work with the mechanical engineer to produce mass and strength estimates, and will also predict manufacturing cost. Roles can be passed from one agent to another, but each agent will have a skill set, and therefore be much more proficient at some tasks than at others.

Every value-driven agent will carry a personal utility function which will govern its choices over disjunctive skills (computed after considering expected skill effects.) That function may or may not be perfectly aligned with the value proposition describing the design product, creating an opportunity to study the impact of bias and incentive incompatibilities on design.

Akin to a game of telephone, the accuracy to which a task is communicated throughout the chain will affect the end result that is passed to design engineers. This, in turn, affects how well the initial intended task is translated into positive, intended effects on the model of the product.

In our simulation, the design product (artifact) will be a low fidelity model of the object produced by an actual design process. It must provide all the information required to assess the artifact's value, and to enable simulated design actions that assemble components into a system.

IV. Results of Preliminary Work on the Small Scale Simulation

In 2010, the National Science Foundation provided a research grant to Paul Collopy, Daniel Shapiro, and Ray Levitt to develop a proof of concept agent-based model that successfully integrated value-driven cognitive agents into Levitt's Virtual Design Team agent-based information processing workflow simulation of design organizations. The purpose of this exercise to develop new capabilities for simulating design decision-making within teams and organizations and to pave the way for the small simulation in our current effort.

In this project, a team of researchers from Stanford University (led by Levitt), the Institute for the Study of Learning and Expertise (led by Shapiro), and the Value-Driven Design Institute (led by Collopy) integrated Levitt's agent-based simulation of design organizations, Virtual Design Team (VDT),[19,20] and Shapiro's Icarus cognitive value-driven agent architecture[13] to enable the development of a design organization simulation capable of studying the impacts of values, incentives, and organization hierarchy on the outcomes of the detailed design phase of system development programs.

VDT models a design project as an information processing system, where agents deliver information to other agents, and agents expend time converting the information they receive into information that they create and pass on. The structure of VDT served to represent the agent interrelationships we wished to simulate. The information passed between agents included

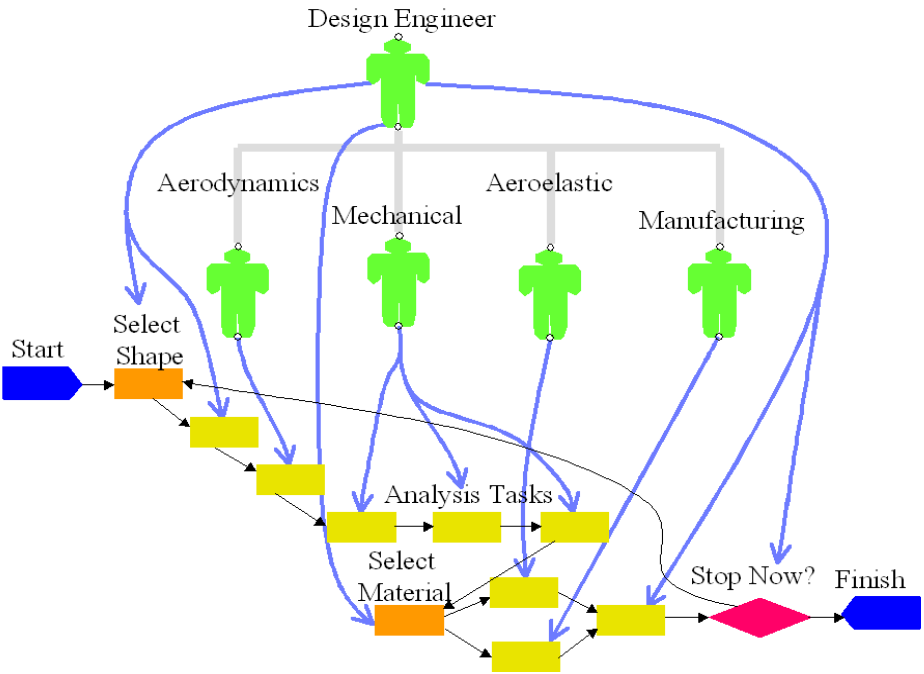

Figure 4. The compressor blade design team modeled in VDT.

The humanoid shapes denote members of the design team. The blocks are tasks, arranged in a directed graph, starting and ending at blue polygons. The orange rectangles (Select Shape and Select Material) are design decisions, and the magenta diamond is a work decision.

- directions from a supervisory group (the compressor systems team) to a lower level group (the compressor blade design team) denoting a design task and the evaluation criteria to use for a task.
- directions from a design engineer to an analysis engineer to conduct an analysis.
- analysis results from the analysis engineer back to the design engineer.
- design results returned from the compressor blade design team to the compressor systems group.

Cognitive capabilities were implemented in the design engineer, who made a preliminary try at a good design and iterated toward a better design using analyses of aerodynamic performance, weight, and cost from the analysis engineers (Figure 4).

A. Method

We used the POW-ER extension of VDT implemented in Python. Rather than interfacing to the existing cognitive agent expressed in the ICARUS language, the agent was recoded in Python to enable a deep integration with VDT.

The guidance communicated to the design engineer was a linear objective function of the following attributes: compressor power, efficiency, failure rate, mass, durability, and manufacturing cost. The design group was tasked to select the following set of design variables to maximize the objective function: compressor blade material, length, camber, chord, and thickness. Two analysis engineers are available. The aerodynamic analysis engineer can estimate power and efficiency from blade dimensions. The mechanical analysis engineer can estimate the remaining attributes from the full set of design variables. The design engineer chooses an initial set of design variables based on intuition and experience. The analysis engineers estimate the attributes based on the design variables, then the design engineer computes the objective function. She must decide whether to attempt to find a better design or settle for the design she has. If she chooses to try for a better design, she must select a new vector of design variables that she believes will improve the design, then repeat the previous steps.

Once the design engineer decides to settle on the current design and not make further attempts to improve, the design vector and the estimated attributes are conveyed to the supervisory group.

B. Procedure

The completed simulation was executed and generally produced good design results in three iterations. The convergence was almost certainly a result of the way the agent optimization behavior was modeled rather than a revealed characteristic of the phenomena we were modeling.

C. Findings

We found the following three results particularly enlightening:

1) Cognitive agents, capable of making design decisions based on maximizing expected utility, can be integrated into the Virtual Design Team agent-based simulation, producing a simulation that can examine networks of decision makers in an engineering design organization, while preserving the functionality of Virtual Design Team modeling inter-agent information flows and information processing in the organization.
2) For full scale development of the simulation of an engineering organization performing detailed design of a complex system, the cognitive design process should be represented in a more abstract manner. A great deal of knowledge that is very specific to the design of turbine engine compressor blades was encoded into the demonstration agent-based simulation. It will be impractical to collect the necessary knowledge to encode into each of the design engineers in a larger model.
3) While we had expected that most of the cognitive effort of the simulated design engineer would be devoted to producing the optimum design, in fact the area of highest cognitive demand was the decision whether to pursue another attempt at the design or accept the previous attempt as the best that can be done. This decision seems to draw on the number of iterations the design engineer expected a priori, the comparison between the current result and the best result so far, and the perceived convergence of the series of successive designs.

V. Conclusion

We are in the process of constructing an in-silicon simulation laboratory for rigorously examining systems engineering processes. The laboratory will consist of a large scale simulation of an entire organization executing the detailed design of a large system, and a small scale simulation of just a few design teams from that organization.

In this laboratory, we plan to validate (or invalidate) value-driven design and other systems engineering processes. We will implement the processes in the large simulation. Then, in a reductionist fashion, we will explain the critical local behaviors of the large organization by modeling them in the small simulation. Furthermore, although not detailed in this paper, we plan to validate the critical behaviors of the small simulation through ethnographic research in actual organizations.

As of the writing of this paper, we are ten months into a three-year project to build the large simulation. We have not begun work on the small simulation itself, but we have demonstrated the feasibility of the small simulation by building a successful prototype. From this prototype, we learned that we face a challenge formulating a sufficiently abstract representation of the design activity, and that the most intense cognitive effort by the design team leader was not invested in design decisions themselves, but instead in the choice to repeat the design or stay with current results.

Acknowledgments

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Value Driven Design in Automotive Transport Systems

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The main focus within value driven design in aerospace has been around the development of surplus value objective function for commercial aircraft application. However, it is still particularly new to the automobile industry. The surplus value function might also be applicable to wide range of commercial road transport industries, which have fundamental operations similar to commercial aircraft. Since the objective for every organization is to build a profitable environment to sustain their long term business. Therefore, it is important to identify the overall value of the fleet during acquisition phase, in order to eliminate future risk to the organization. In this paper, commercial buses have been used to represent the wide range of commercial road transports for this surplus value analysis. The influence of future fuel prices to overall value will be discussed. Moreover, how the use of advance materials influence overall value has also been included in the discussion.

Nomenclature

V_S = Surplus value
r_p = Multiplier based on the discount rate and program life for manufacturers
r_c = Multiplier based on the discount rate and program life for customers
N_{Bus} = Number of bus to be produced
N_{Trip} = Number of trips per day
$N_{Operate}$ = Number of days operate in a year
$C_{Revenue}$ = Potential revenue received from passengers per trip
$C_{Operate}$ = Operating costs per trip
C_{Tax} = Road tax cost
C_{MOT} = MOT cost
$C_{Insurance}$ = Insurance costs
C_{Main} = Maintenance costs
C_{Manu} = Manufacturing costs
$C_{Residual}$ = Residual costs
$C_{Develop}$ = Development costs

I. Introduction

The oil embargo in early 1970 in United States triggered the issue of energy security for a nation.[1] This issue will be critical to the countries, which are net crude importer. This shows the importance of the efficient use of energy, especially the use of fossil fuels within the road transport sector, since current industrialization activities are very much dependant on fossil energy. If we still rely on present technologies, it is expected that crude oil will still be highly in demand, as the world economy grows. This implies that the crude prices will grow in tandem with the world economy. In order to cope with soaring fuel prices, immediate action is required to improve the efficiency of current technologies.

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An improvement on vehicle efficiency will enhance the owners financial ability to cope with the soaring fuel prices. However, this burden was passed to the vehicle manufacturers, in order to deliver more efficient vehicles in the future. Although this will improve the vehicle fuel economy, the energy usage during its production phase is another questionable area. Normally, advanced technologies are much more energy intensive in fabrication. Effort on improving the vehicle efficiency will be pointless in the broader view, if the excessive energy use for fabrication cannot be traded off by the energy saved during its use phase. Moreover, the costs incurred for developing a new technology is one of the essential elements to be investigated. Since some of the existing technologies are not viable for current implementation, in term of its costs, present infrastructure, etc.

Therefore, the overall aim of this research is to build a computational modeling platform to illustrate the cost and energy consumed throughout the whole life for the automobile. However, the model must also be capable of application for various types of road vehicle by just altering significant parameters. Thus, this will provide a platform to aid decision making for future road vehicle design. This is to ensure the design for the upcoming road vehicle reaches the optimum between energy efficient and economic cost viable points of view.

Typically, the life cycle of an automobile consists of: raw material extraction; material production; vehicle fabrication; use phase; and end of life (recycle, reuse, energy recovery or disposal). However, the boundary for the concept of whole life is spread more widely than its life cycle alone. This may extended to the study on the fuel/energy cycle, vehicle maintenance services, transportation use throughout the vehicle whole life, etc.

As illustrated in Figure 1, generally, the whole system can be categorized into six distinct subsystems, there are: fuel/energy cycle; raw material extraction, material production and vehicle fabrication; use phase; vehicle maintenance services; end of life; road systems construction and maintenance services. The interrelationship between each system within the whole context is extremely complex. A little change within a subsystem might bring about change in other subsystems, and this will subsequently lead to the overall system change. For instance, the reduction on operating cost by using a vehicle fabricated from light weight material may increase the cost and energy use for material fabrication and this may subsequently increase the overall cost and energy required for the fuel/energy production.

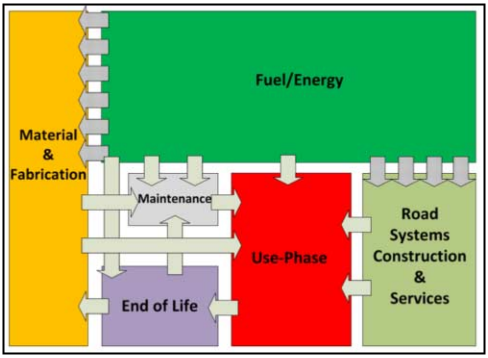

Figure 1. Whole life system for an automobile

II. The Problems

The current public transport network has played an important role for moving people around. Where people are unable to afford the cost of ownership due to high fuel costs, public transport is the only solution for them. If the future fuel prices continue to increase at today's trend, it is expected that numbers of people giving up owning a vehicle and shifting to use the public transport will increase. This implies that the public transport will be highly in demand, and more fleets will be acquired by operators to fulfill this demand.

Without the knowledge to identify the key driver of the implementation cost throughout the whole life operation of the fleets during the early acquisition phase, this will put an organization's future at risk. This will ensure that an operator acquires a fleet to suit their business operation based on more seeable parameters, such as acquisition cost; fleet capacity; range capability; etc. The risk will become even more critical, when fuel prices keep soaring. In this instance, fleet operating costs will dominate the overall value rather than the early acquisition cost. Subsequently, this will incur the reduction on organization profit. The only solution to maintain profit is to shift this excess cost to the public, and this may reduce the competitiveness of the organization within the industry.

A. Crude Prices

The internal combustion engine has been widely used in the vast majority of road vehicles. Thus crude oil is highly in demand. From the economic standpoint, the increases in demand will cause the prices of goods to soar. The market fuel prices are totally compliant with this notion. As can see from Figure 2, vehicle fuel costs have been rising considerably, along with the increases of road vehicle throughout last decade.

A sharply drop of fuel prices at the mid 2008 is mainly due to global economic recession. Basically, this sharp drop of fuel prices is driven by the market crude price. As the global economy entered recession, the demand for crude from the industry activities dropped substantially and this is the main reason for the sharp drop of fuel prices at mid-2008. However, it is expected that fuel prices will continuously increase for the next decade, unless a dramatic shift from current technologies. Therefore, it is crucial for organization to acquire the right product. This is particularly obvious to the organizations that fossil fuel usage is essential for their usual business. Therefore, without acquiring the right product in the first instance, this will bring a huge impact to long term profitability.

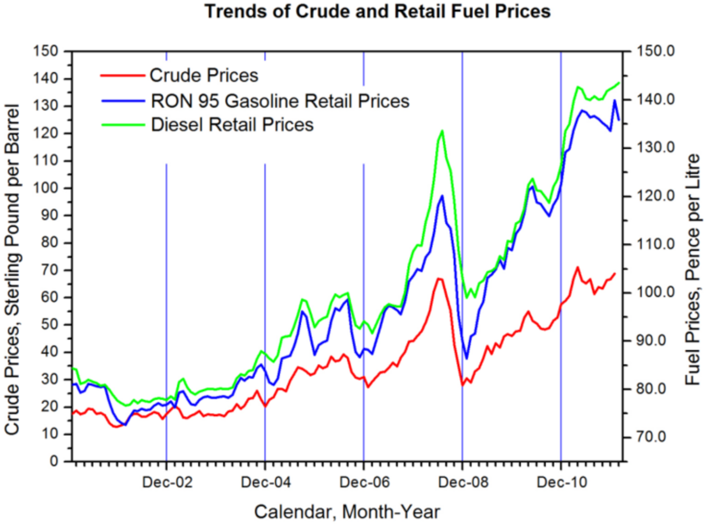

Figure 2. Trends of Crude and Retail Fuel Prices[2,3]

III. Value Driven Design

The value driven design methodology is an enhancement on the traditional Systems Engineering approach and can be defined as "an improved design process that uses requirements flexibility, formal optimization and a mathematical value model to balance performance, cost, schedule and other measures important to the stakeholders to produce the best possible outcome."[4]

Value driven design uses objective functions to access and optimize the designs in order to determine which design is the most valuable.[5] Various types of measures can be defined for these objective functions, it basically dependent on its project stakeholders. For the purpose of this study, surplus value has been selected with the stakeholders being the coach operator as well as the manufacturer. Surplus value was selected as the chosen objective function as it offers the potential to allow the operator to assess and investigate the overall value for a particular vehicle to its business, especially during early acquisition phase.

A. Surplus Value

Surplus value has been defined as the difference between reservation price and manufacturing cost where the reservation price is the maximum price customer willing to pay in the absence of competition.[6] Basically, it is a simple numerical expression, which uses factors such as potential revenue, operating costs, manufacturing costs, and development costs. Since the surplus value objective function has just been recently developed for the application within the aerospace industry. Therefore, the original objective function[5] needs to be modified to suit the automotive application and this gives the Eq. 1.

$$V_S = r_p.N_{Bus}[r_c.N_{Trip}.N_{Operate}\{C_{\mathrm{Re}venue} - C_{Operate}\} - \{C_{Tax} + C_{MOT} + C_{Insurance} + C_{Main}\} \\ - C_{Manu} \pm C_{\mathrm{Re}sidual}] - C_{Develop} \tag{1}$$

The surplus value objective function is adequate for assisting the early decision making process, especially during the early acquisition phase. Since the surplus value will be an indictor to overview the overall value for a particular product, and this will then subsequently provide guidelines for decision making. Moreover, the objective function has the ability to predict the maximum profit the product can achieve and also how the product can incur costs to its operator and its manufacturer.[5]

The expression in Eq. 1 is divided into subsystem calculations. Part of the subsystem calculations were using the methodologies derived by Roskam[7] which are empirical and based around. Whereas the fuel costs calculation is dedicated relying on the methodologies for obtaining the automobile fuel consumption within a driving cycle. Moreover, factors such as ticket price and fuel price were also included for this study.

IV. Surplus Value Studies

Coaches will be used in the following surplus value study. The coach services chosen for the analysis were on an assumed route operating in Ireland between Belfast and Dublin. The following Table 1 illustrates the schedule of coach services operate in between Belfast and Dublin.

Table 1. Schedule of coach service between Belfast – Dublin[8]

Belfast – Dublin (Depart – Arrive)		Dublin – Belfast (Depart – Arrive)	
AM	PM	AM	PM
01:00 – 03:25	12:00 – 14:25	01:00 – 03:25	12:00 – 14:25
03:00 – 05:25	13:00 – 15:25	03:00 – 05:25	13:00 – 15:25
05:00 – 07:25	14:00 – 16:25	05:00 – 07:25	14:00 – 16:25
07:00 – 08:25	15:00 – 17:25	07:00 – 08:25	15:00 – 17:25
08:00 – 10:25	16:00 – 18:25	08:00 – 10:25	16:00 – 18:25
09:00 – 11:25	17:00 – 19:25	09:00 – 11:25	17:00 – 19:25
10:00 – 12:25	18:00 – 20:25	10:00 – 12:25	18:00 – 20:25
11:00 – 13:25	19:00 – 21:25	11:00 – 13:25	19:00 – 21:25
-	20:00 – 22:25	-	20:00 – 22:25
-	21:00 – 23:25	-	21:00 – 23:25
-	23:00 – 01:25	-	23:00 – 01:25

The range distance for these services is about 200km for each trip. According to the schedule illustrated in Table 1, optimally, it can complete about four round trips in a day's service. The following Table 2 illustrates the basic design parameters for the coaches operate in these services. These parameters will be the main drivers to determine the fuel consumption on each trip travelled.

Table 2. Summary of the coach data used within the surplus value studies

Parameters	Symbol	Value	Unit
Gross weight[9]	M	19000	kg
Aero coefficient	C_d	0.8	
Frontal area[9]	A	8.65	m^2
Efficiency	η_D	0.34	
Maximum capacity[9]	N_{pax}	55	pax

Basically, there are several inherent resistances to overcome in order to cruise the vehicle at a desire speed. This implies that the vehicle propulsion should need to have the capability to overcome these inherent resistances during its operation. Otherwise the desire performance will not be able to achieve. The basic resistances incurred during the vehicle use phase are:[10]

i. Acceleration resistance (F_{Acc})
ii. Aero-dynamic resistance (F_{Aero})
iii. Rolling resistance (F_{Roll})
iv. Gradient resistance (F_{Grad})

Apart from that, there is an additional load subjected to vehicle use phase and extra fuel will be consumed. Auxiliary load incurred from powering the onboard electrical system for entertainment, lighting, climate control, etc, will contribute additional to its overall energy consumption. Moreover, for an engine propelled vehicle, part of the energy consumed within its operating lifetime is just for idling. Since vehicles are usually required to be stationary for a number of times during its normal operation, especially in traffic congestion, maneuvering, and loading and unloading. In these occasions, the vehicle engine is normally held under idle conditions. Although, the vehicle is stationary, its engine is still operating at idle speed, and hence still burning fuel. Since, once the engine is started, it will run continuously unless its systems breakdown, it run out of fuel, or someone terminates its operation. This being one of the disadvantages for combustion engines, because a portion of the converted energy is not being used for useful work.

Following Eq. 2 shows the summation of the resistance forces incurred during vehicle operation, and this will be the minimum force required from the propulsion system. The expression in Eq. 3 is expanded from Eq. 2, and it shows the key parameters that drive the resistances.[10]

$$F_{\mathrm{Re}q} = F_{Acc} + F_{Aero} + F_{Roll} + F_{Grad} \tag{2}$$

$$F_{\mathrm{Re}q} = M.\frac{dv}{dt} + \frac{\rho}{2} C_d.A.v^2 + M.g.f_R + M.g.\sin\alpha \tag{3}$$

By obtaining the total resistance force incurred during vehicle operation, the vehicle fuel economy can be computed by the following Eq. 4.[11] Thus the amount of fuel consumed by the vehicle can be obtained from the product of its fuel economy and mileage travelled.

$$B = \frac{\dfrac{C}{\rho_{Fuel}} \int b_e \left[\dfrac{F_{\mathrm{Re}q} v}{\eta_D} \right] dt}{\int v dt} \tag{4}$$

The notion of idle fuel consumption is normally defined as the amount of fuel consumed within a given timeframe, it is usually in term of liters per hour. This implies that the total fuel consumed under idling condition is just the product of time for idling and its fuel consumption, and this should be added to the overall operational consumption. However, this was just applicable to a specific condition. To fulfill this condition, the vehicle will need to be either stationary or traveling vehicle under not under load, ie, coasting or braking. Since there is a minimum threshold applied for engine speed during its operation. For simplification, it assuming that a few percent of fuel consumed to overcome the inherent resistances or idling is added to its overall consumption to represent the consumption on auxiliary load.

The coaches used for this study are assumed to follow the pattern of new European driving cycle (NEDC) as shows in Figure 3 iteratively, for each trip of services. It assumes to be operated in the flat terrain throughout its service lifetime. By this statement made, the gradient resistance incurred can be neglected. Thus the incurred resistance and fuel consumed at each second time step within the NEDC can be obtained by applying the methodologies stated in previous discussion. As can see from Eq. 3, vehicle mass is being a significant parameter to influence the overall resistance, especially to the resistance incurred from acceleration, rolling, and gradient. This will then influence the amount of fuel required to overcome those resistances. The fuel consumed at each second time step within the NEDC will considerably reduce the amount of fuel remaining in tank. This will then subsequently bring the reduction to its gross weight. The weight reduction caused by consumed fuel has taken into account for this use phase analysis. Since the amount of fuel remaining in tank has taken into consideration, therefore when the coaches will be refueled is crucial for this analysis. The coaches used for this study is assumes to be refueled, when the remaining fuel is not sufficient for completing a trip.

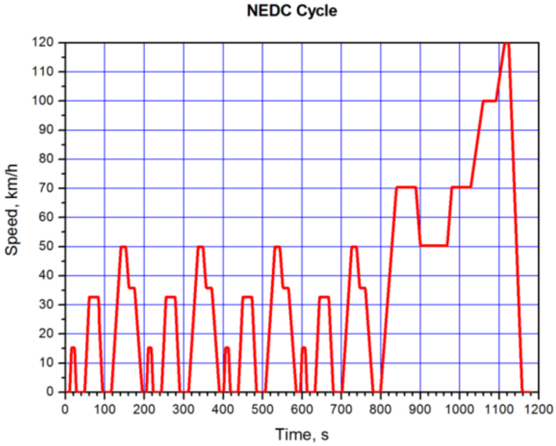

Figure 3. New European driving cycle[12]

The overall fuel consumption for completing a trip services is the cumulative of fuel consumed at each second time step within a numbers of complete NEDC. Since the coaches are assumed to follow the NEDC iteratively, until the cumulated distance travelled by the coaches is equal to the range distance for a trip services. The following Figure 4 depicts the cumulative fuel consumed for each incurred loads and resistances separately, within a complete NEDC.

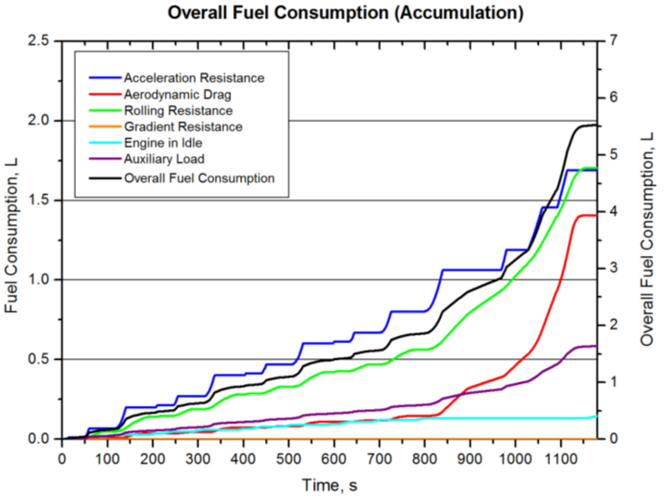

Figure 4. Fuel consumed for each incurred resistances and load

A. Influence of Fuel Prices to the Surplus Value

Fuel cost has substantially contributed to the coaches daily operating cost. This implies that the current fuel price is one of the important elements to drive its operating fuel cost. Nonetheless, it is difficult to project the exact operating fuel cost. Since the fuel prices are extremely uncertain and vary significantly throughout the time, as illustrated in Figure 2. Therefore, it is important to understand the elements that drive the current fuel prices. In the UK alone, the fuel prices that consumer paid consists several additional taxes, which implemented by government. Following Eq.5 shows the basic expression for retail fuel prices.[13] Clearly, the retail fuel prices are the summation of untaxed fuel prices, fuel duty, and value added tax (VAT) applied on fuel duty and untaxed fuel prices.

$$\text{Fuel Prices} = \text{Fuel Duty} + (\text{VAT} \times \text{Fuel Duty}) + (\text{VAT} \times \text{Untaxed Fuel Prices}) + \text{Untaxed Fuel Prices} \quad (5)$$

Generally, there are a few factors will bring the variation to the retail fuel prices. These include:

i. Market crude price
ii. VAT rate
iii. Rate of fuel duty
iv. Cost for refining, transportation, and retail

The market crude prices are extremely uncertain and vary significantly throughout the time, and this will bring a substantial impact to the retail fuel prices. Since the untaxed fuel price in Eq. 5 is mainly driven by crude price. There are wide ranges of factor constituent variation to market crude prices. Basically, these factors can be categorized into two groups, there are: market forces (inflation, seasonal demands) and global events (wars, gas shortages, security threats to oil supplies). For instance, the crude prices have dropped sharply at mid-2008, as the global economy recession. However, the rates of VAT and fuel duty are barely controlled by central government. Figure 5 depicts the contribution of fuel taxes to retail prices throughout the last decade. It about 50 to 80% of the retail fuel prices are contributed from government taxes. This implies that, apart than paying the fuel prices alone, consumers have to pay another 50 to 80% extra for every litre of fuel purchased.

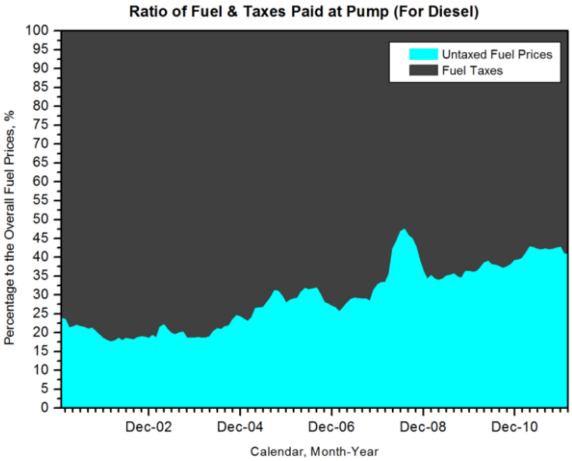

Figure 5. Ratio of fuel & taxes paid at pump

Figure 6 shows the influence of VAT and fuel duty rates to the retail prices. The variation of the induced VAT and fuel duty are not sufficient to change the trends induced by crude prices. However, it does significantly increase the retail fuel prices. Moreover, there is a gap lies between crude and untaxed fuel prices. Basically, these increments are mainly caused by the cost incurred from fuel production, transportation, and retails. For instance, the retail fuel prices at remote areas are much higher because of its delivery cost.

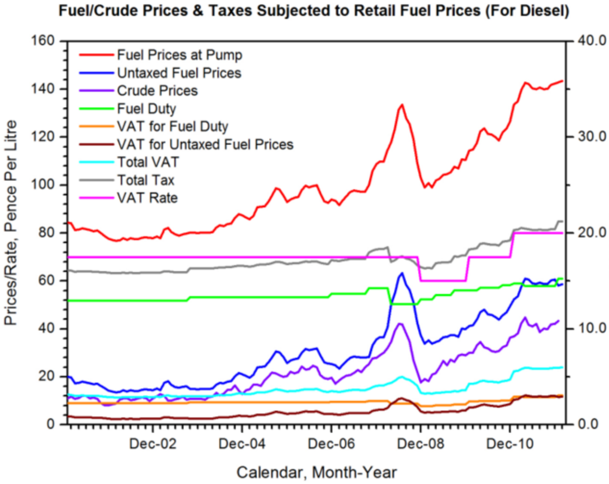

Figure 6. Fuel/crude prices & taxes subjected to retail fuel prices[14,15]

In this study, a brand new coach assumes to be started its services in early 2001. Without concerning its operating value, it expected that the average lifespan is more than 20 years. Conservatively estimate, a minimum 20 years fuel prices data is required to obtain its operating fuel cost throughout its service life time. Thus, the fuel prices projection for the following years are desperately required. Following Figure 7 shows the fuel prices projection beyond current available data, and it projected via crude prices slope in past 3 years. Moreover, Figure 7 also shows the fuel prices projection from both 50% increment and decrement of crude slope in past 3 years. This provides an additional opportunity to explore the influence of fuel prices to the surplus value.

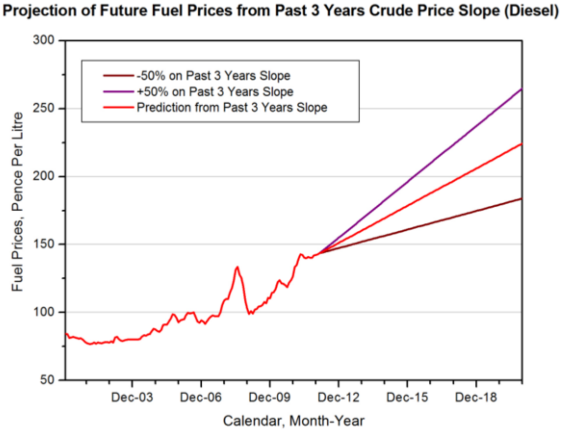

Figure 7. Fuel prices projection

In order to obtain the monthly fuel costs, the fuel data illustrated in Figure 7 will be used. In this case, the VAT and fuel duty rates for the projected fuel prices are assumed to stay at the current rate, which are 20% and 60.79 pence per liter respectively.[14,15] This is important because fuel costs have played a significant role to influence the operating cost, and this will vary according to the fuel prices. Moreover, the revenue received from each trip is typically relied on passenger occupancy rates. Typically, all seats will not be fully occupied at all time within its service lifetime. Therefore an average occupancy rates are assumed for this study, it about 27 seats are occupied for each trip. Furthermore, it also assumed that a single trip ticket will cost about £6.50, thus the revenue for each trip can be obtained. Table 3 illustrates the input data, which required for surplus value calculation. Those values are assumed to remain constant throughout its service lifetime. Therefore, the surplus value throughout its service life time can be obtained by Eq. 1.

Table 3. Data assumed to be identical throughout the time

Parameter	Value	Unit
Manufacturing costs (per coach)	645.67	GBP Thousands
Development costs (per coach)	15.49	GBP Thousands
Revenue (per trip)	175.50	GBP
Tax costs (per trip)	16.67	GBP
MOT costs (per trip)	2.50	GBP
Insurance costs (per trip)	166.67	GBP

The following Figure 8 depicts the influence of different fuel prices to the surplus value, which obtained by Eq. 1. Basically, these surplus value graphs are typically relied on the fuel prices illustrated in Figure 7. Initially, negative surplus value is presented due to its early acquisition costs, which mainly incurred from the manufacturing and development costs. At the beginning, the revenues received from its routine operation are beyond the operational expenses. Thus the surplus value will start to move towards the positive from the beginning of its operation, and it will reach the breakeven at about 3 to 4 years of its operation. Furthermore, the discontinuity at about mid 2008 is basically caused by sharp increases on fuel prices. This will then subsequently induced the sharp increases to its operating cost and bring the discontinuity to the surplus value graph. This implies that, the fuel prices are being one of the significant parameters to drive the surplus value. As illustrated in Figure 7, the fuel prices will keep increasing from current fuel price onward. It expected that the surplus value will reach the maximum by the end of year 2012. Because of the soaring fuel prices, the surplus value will start driven down by its operating fuel costs. If the coach is operate at the fuel prices, which projection from past 3 year crude slope. It expected that the coach will run out its entire value by the end of year 2019. However, for the case that the projection of fuel prices are from

50% increment on past 3 year crude slope, the coach is expected run out its entire value at least 1 year earlier than the coach operate at the fuel prices projected from past 3 year crude slope.

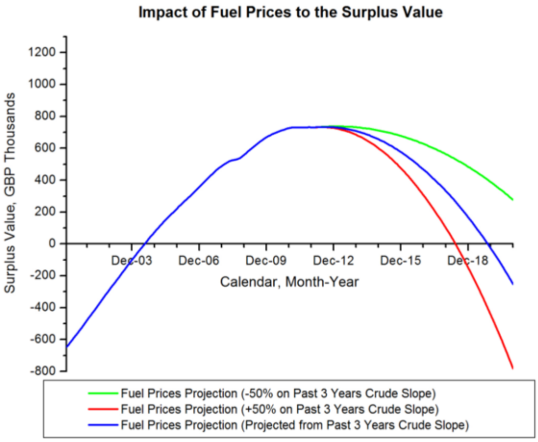

Figure 8. Impact of fuel prices to the surplus value

B. Influence of Lightweight Materials Used to the surplus value

As can see from Eq. 3 that the vehicle mass has played a significant role to influence the incurred resistances. The incurred resistances are being the minimum energy required from the vehicle propulsion. This implies that, the vehicle mass is a significant parameter to drive the vehicle fuel consumption. Since, the vehicle fuel is the main energy source to propel the vehicle. Therefore, a substantial reduction on vehicle gross weight will bring a significant reduction to its fuel usage. In order to improvement the vehicle fuel economy, vehicle designers are attempted to select the most suitable material to reduce its gross weight. The used of the lightweight materials being one of the solutions to reduce the vehicle gross weight.[16]

Similar notion is applied for study in order to reduce the gross weight of the coaches. In this case, it conventional steel body panels will be replaced by the lightweight aluminum. A lightweight aluminum with about 2825kg/m^3 in density will be used for this replacement.[17] It assumed that, same amount of material is required for this replacement, in term of its volume. Meanwhile the steel body panels account for about 15% of its gross weight, it weight about 1890kg. Thus it about 0.25m^3 of lightweight aluminum panels are required for this replacement, it about 680kg for its weight. By this replacement, a gross weight of the conventional has been reduced by about 1210kg.

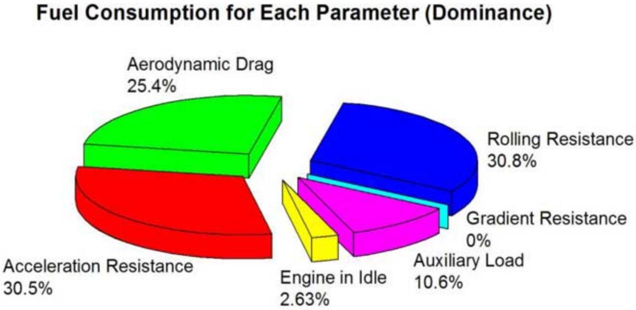

Figure 9. Percentage of fuel consumed for the incurred resistances and load (for conventional coaches)

This reduction will bring a significant gain to its overall fuel economy. The fuel consumed for the conventional and lightweight coaches for a 200km trip is about 99.4 liters and 94.3 liters respectively. The weight reduction has brought a few liter of fuel saving for every single trip. However, this can be a huge saving in the long run perspective. Figure 9 and 10 depict the fuel consumed for each resistances and load, which incurred from the operation of conventional and lightweight coaches. It can be seen that, there is a reduction for acceleration and rolling resistance. Generally, this reduction is basically induced by its weight reduction.

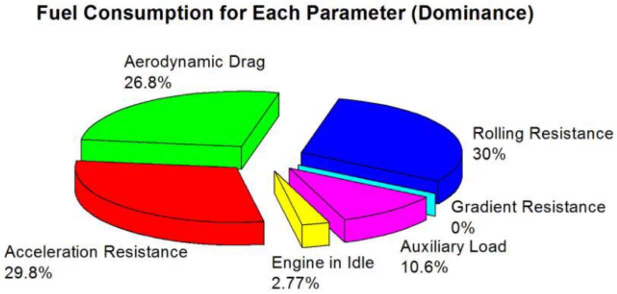

Figure 10. Percentage of fuel consumed for the incurred resistances and load (for light-weight coaches)

Since the lightweight aluminum is much energy intensive for its production, thus the cost of the lightweight aluminum is much higher than the conventional steel.[16] The unit price for the aluminum and steel is about £1.67/kg and £0.50/kg respectively.[17] Since the lightweight aluminum is much costly than the conventional steel, a 10% increases on manufacturing and development cost has been assumed for its production. These increases are mainly due to the materials costs as well as the need of new technologies for the production. Apart than that, all the remaining surplus value parameters are assumed to be identical to the previous study, except its operating fuel costs.

The following Figure 11 depicts the comparison of surplus value in between conventional and lightweight coach. Initially, the surplus value for the lightweight coach is much lower than the conventional because its manufacturing and development are cost much higher than the conventional. It will take about 3 to 4 years to reach the breakeven. At the beginning, the surplus value for the lightweight coach is lie under the conventional. Since the operating fuel cost for the lightweight coach is much lower than the conventional, therefore much profit will be received for each trip. Its surplus value will crossed over with the conventional at mid 2005, and it will reach the peak at year 2013. Since the lightweight coach is much fuel economy than the conventional, by compared to conventional, it will be less sensitive to the fuel prices. Thus the lightweight coach has much higher surplus value than the conventional, and it also having much longer value period.

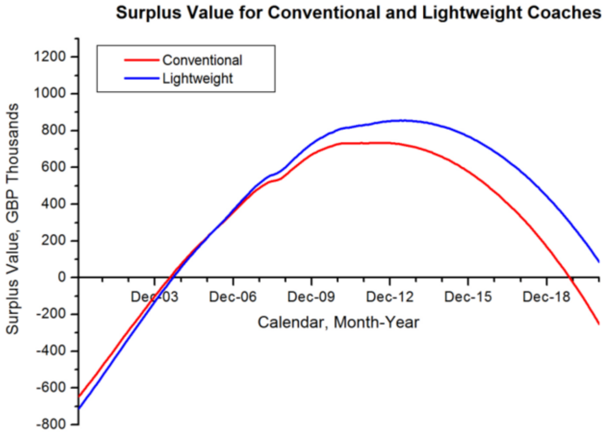

Figure 11. Surplus value for conventional and lightweight coaches

V. Conclusion

The main aims of this paper are to gain understanding whether the surplus value objective function is viable for automotive application. To achieve this, the original surplus value expression has been modified to suit for this application. Since the surplus value is trade off in between potential revenue and incurred costs, therefore commercial coach has been chosen for completing these studies. The best available data are gathered together for the use on these studies, in order to reflect its reality operation. Firstly, the influence of fuel prices to the surplus value has been analyzed. The methodologies to obtaining the vehicle fuel consumption have been used together with the surplus value equation to identify the overall value throughout its service lifetime. From that, we can conclude that soaring fuel prices will bring forward the time for the coach to run out its overall value. This conclusion is totally compliant with its real operations. Secondly, the study how the use of lightweight material influences its surplus value is conducted. The appropriate use of the lightweight material to its design will bring an improvement to its overall value. However, the excessive use of lightweight material to its design will substantially increase its initial acquisition cost. This will bring a huge initial cost differences in between the lightweight and conventional. If the fuel saved from this weight reduction is not obvious, the lightweight will require much longer period to reach the breakeven. Similarly, it will take much longer time to reach the crossover in between the surplus value of lightweight and conventional. This implies that, it requires a much longer timeframe then can see the advantage of lightweight over the conventional.

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How to improve operational availability and cost effectiveness using a pragmatic RAMS Value Driven Design effort

A Military Helicopter Case Study

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This paper gives insight into the development of a strategic value based decision model (SMARD) for the effective implementation of Reliability, Availability, Maintainability and Supportability (RAMS) in the design process of complex technical systems. This paper shows the application of this model to the military aircraft domain to improve operational availability and cost effectiveness. Two individual case studies performed in a military helicopter development program are described, emphasizing the lessons learned, best practices and improvement areas. These cases prove that the traditional Integrated Logistic Support approach towards the integration of RAMS in design and development of military systems has not been effective. Furthermore conclusions are drawn related to the further development and application of the RAMS Driven Design Approach in other industries.

I. Introduction

MAINTENANCE of modern large-scale complex technical systems, such as commercial aircraft, military weapons systems, rolling stock (trains), infrastructure (rail, water, road) and (chemical) process plants, etc. is becoming an increasingly important – yet under estimated - area of research attention.

Important, since these technical systems typically show high maintenance and support cost, to assure that these technical systems perform their functions in a safe manner over a life cycle of typically 30 or more years. Furthermore, effective maintenance assures the system performance and safety over the total life cycle, especially since these systems typically have a high risk of failure in terms of economical, operational and safety consequences. Finally, the changing business operating environment forces operators to significantly improve the performance of their technical systems, in terms of increased operational availability and reduced operational and maintenance cost.

Underestimated, since the RAMS characteristics, as key drivers for the long-term system availability and costs, and thereby the value of those systems, currently do not receive full and sufficient attention during design and development. Although various design concepts, methods, standards and references are available, the successful application hereof within industry is limited. This resulted in many technical systems in various industry branches, were the initial reliability and

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availability performance requirements were not met, the maintenance and support cost were underestimated, and significant rework and improvement was required.

A. Problem statement

As a result many questions are raised regarding how to address RAMS during design. Why is maintenance not considered as part of a closed loop, as shown in Figure 1? Why does the application of known methodologies not result in high available units, and why do the support costs continue to increase rather than reduce over time? Considering the huge amount of cost associated with maintenance and support, it is valid to ask ourselves do we do the right activities during design. Can we not significantly change the way we address maintenance and RAMS in design? Do we do the right things, and if so do we do them effectively? Is it possible to improve the operational availability and cost effectiveness using a pragmatic RAMS Value Driven Design effort?

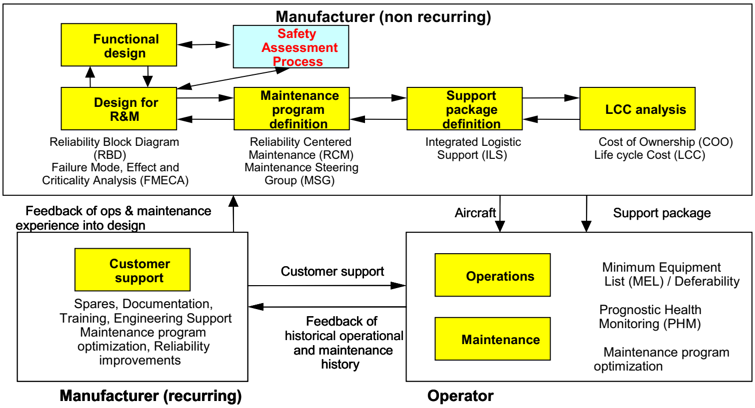


Figure 1. A closed loop approach towards maintenance

B. Content

This paper shows the application of the RAMS Driven Design model to the military aircraft domain to improve operational availability and cost effectiveness, by focusing on one of the most significant Military Helicopter Development programs in Europe of the past decades, the NH90 helicopter program. This paper describes at first briefly the NH90 program, the Helicopter, the project organization, and its design and development process. Secondly the traditional Integrated Logistic Support approach towards the integration of RAMS in design and development as used within the NH90 program is described. Section three gives an overview of the two case studies performed within the NH90 project. Since these case studies make use of the RAMS Driven Design Approach, section 4 elaborates upon the results of this research program. Finally the conclusions regarding the application of the RAMS Driven Design approach within the NH90 case studies are presented in section 5.

II. The NH90 Helicopter Program

The NH90 is a European medium sized, twin-engine, multi-role military helicopter designed and manufactured by NH Industries (NHI) against NATO requirements to meet a long term need. Two versions are available from the core air vehicle; Tactical Troop Transport (TTH) and NATO Frigate Helicopter (NFH). The first prototype had its maiden flight in December 1995. The NH90 entered service in 2006 and has been selected as a medium multi-role helicopter by 14 nations. As of March 2012 103 NH90s are delivered and in service out of a total order book of 529. NH Industries is the focal point for the NH90 program. Established in 1992, NHI has managed the design, development and entry to service of the NH90 for both NAHEMA (NATO Helicopter Management Agency) and export customers. NHI is a French SAS company wholly owned by Eurocopter, AgustaWestland and

Fokker Aerostructures. NHI is responsible for overall program management, quality assurance and airworthiness and the process of safety for its customers and the partner companies[1].

III. The Traditional ILS Approach

Besides managing the design, development and configuration process, NHI aims to ensure that the NH90 Helicopter can be supported in a cost-effective way throughout its life cycle. To achieve that goal, to improve the systems operational availability and reduce the cost associated with operations and maintenance, within the NH90 program the concept of Integrated Logistics Support (ILS) has been applied to all the phases of the program.

C. Origin of ILS

Developed and originated within the military forces of the United States, the application of integrated logistic support (ILS) and logistic support analysis (LSA) concepts and techniques during design and development of military systems aims to ensure that products and projects are fully supported through-life at minimum cost, acknowledging that support and operating costs are often far greater than the design and procurement costs.

D. Objective and goal

In general terms ILS can be defined as a disciplined unified, and iterative approach to the management and technical activities necessary to: 1) integrate support considerations into system and equipment design; 2) develop support requirements that are related consistently to readiness objectives, to design, and each other; 3) acquire the required support; 4) provide the required support during the operational phase at minimum cost[2.]

The main objective of the application of the concept of ILS within all phases of a program, is related to the integration of reliability, availability and maintainability and supportability (RAMS) in the design and development process, to ensure that RAMS is a design consideration and that logistic factors are used to achieve adequate and effective levels of supportability, and to provide effective logistic support. The principal logistics support elements are typically: maintenance planning; manpower and personnel; supply support; support and test equipment; training and training devices; technical documentation; computer resources; packaging, handling, storage and transportability; facilities; and reliability and maintainability.

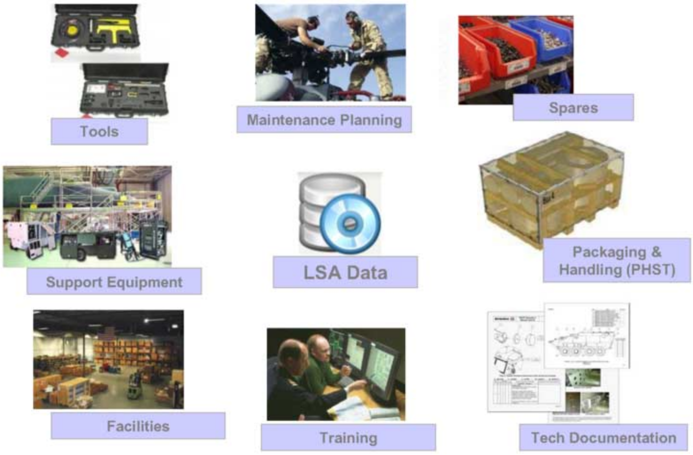


Figure 2. ILS Elements

E. ILS standards

The LSA process describes in detail the integrated and formalized processes activities required to achieve the ILS objectives. Standards like MIL-STD-1388-1A, Logistics Support Analysis[3], contain such formalized processes. Herein detailed descriptions can be found of the individual tasks that must be performed, the inputs required to perform a task and the outputs that performing a task are expected to generate, while MIL-STD-1388-2A, DoD Requirements for a Logistics Support Analysis Record[4], provides the requirements for creation and use of a single logistics database to record the results of the LSA process. Besides these standards many other sources can be found describing Integrated Logistic Support as a concept or management approach, and Logistic Support Analysis as the technical process and activities required. Examples hereof are Ref. 5, 6, and 7, but also company standards or even program defined standards (such as used within NHI) can be found.

F. Observations

Although these sources show some variations in content and approach, they all emphasize a strong focus on ILS planning and Management; ILS as integral part of system design, a strong relation between ILS and Design for RAMS, the importance of the right ILS activities and elements, and finally to aim at an integrated solution. However these processes and standards also require strong tailoring and adaptation of applicable processes and standards, logistic support elements, and logistic information and database requirements towards the specifics of the customer and it's program. Furthermore it can be concluded that current standards and processes are complex and exhaustive documents containing much detailed information, while associating ILS with a large complicated database. Both observations are main contributors to the fact that the true goal of this methodology has not been reached. Even though this methodology has been developed and detailed through a broad range of process descriptions, procedures, standards and handbooks on a variety of RAMS or ILS related topics, and this methodology has been applied within the whole NH90 industrial supply chain. Both case studies will illustrate this point.

Many industries face the same problems, since current industry practice shows RAMS/LCC, currently do not receive full, sufficient and timely attention, resulting in the ineffective application of limited engineering resources. A pragmatic and cost effective approach is needed. The NH90 project stands not on its own in terms of its need to more effectively incorporate RAM into design and development.

IV. RAMS Driven Design Approach

To address these problems a PhD research project was initiated at the Faculty of Aerospace Engineering, Delft University of Technology. It's aim was to develop and validate a generic *RAMS Driven Design methodology and model* which supports and enables all *stakeholders* – such as OEMs, designers, owners, operators, and maintainers – involved over the total life cycle in the design or redesign of *large scale complex technical systems* such as commercial aircraft, defence materiel and chemical process plants, to make strategic decisions to select and apply the required RAMS processes and activities which optimize Total Life Cycle Value, while taking into account all relevant business, organizational and contractual constraints.

G. RAMS Driven Design Model - SMARD

Using a cross-industry case-based research approach this project at first has led to the development of the SMARD Model for the incorporation of RAMS in the life cycle of large scale complex technical systems. This SMARD Model, which is generally applicable to a broad range of large-scale technical systems, addresses not only the technical processes and activities required to incorporate RAMS/LCC, it also emphasizes the organizational and information technology constraints and conditions which enable a successful integration of RAMS in design, as shown in Figure 3. Furthermore the SMARD model recognizes three dimensions: life cycle dimension; problem solving dimension; and domain dimension. The Technical process domain addresses both the functional as the RAMS/LCC design disciplines. Note furthermore that within this figure the problem solving domain is not elaborated upon. The systems engineering process is assumed to form an integral part of the design process and should therefore be included in the functional design discipline, one of the disciplines addressed in the technical process dimension.

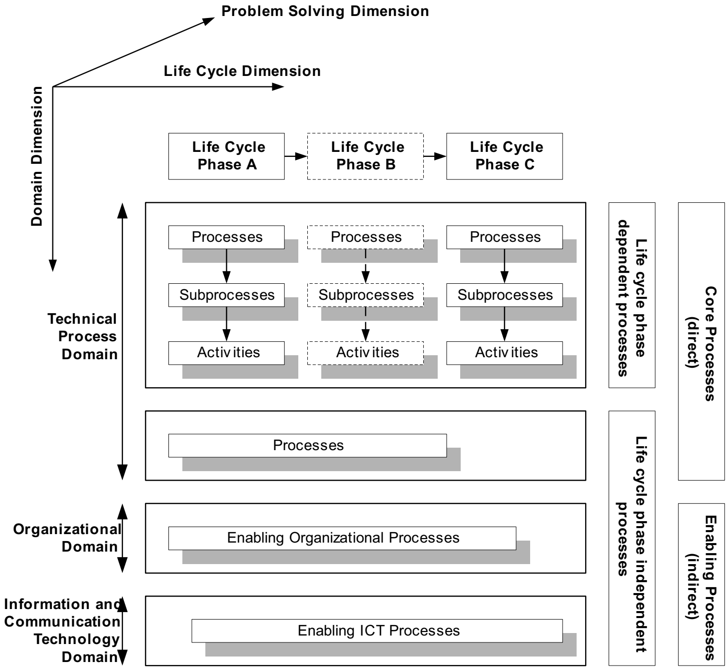


Figure 3. The SMARD Model Overview

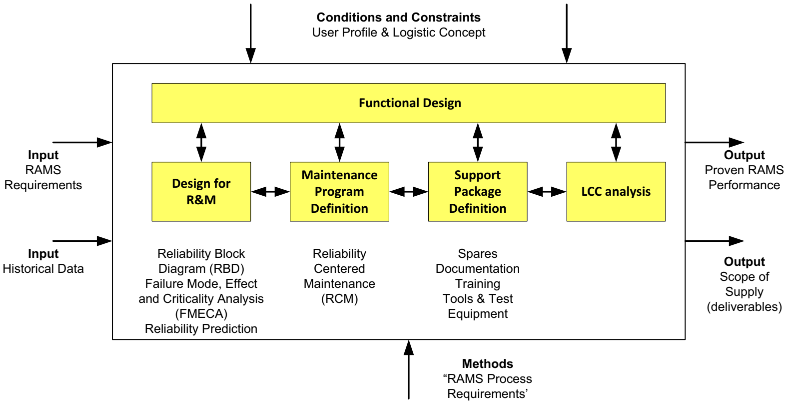


Figure 4. Conceptual overview of the integration of RAMS/LCC in the design and development process.

Figure 4 shows conceptually this iterative process as integral part of the functional design process. This allows for a concurrent design process in which continuously design trade-offs between RAMS/LCC, performance and cost are made to allow for the optimal design solution meeting all requirements. This Figure also shows the inputs for such a process, consisting at first of the (Top

Level) RAMS requirements to be achieved, and secondly the essential historical operational and maintenance data from already existing systems. The output of this process is also shown in this figure, consisting of proven compliance to the RAMS/LCC requirements, and secondly the required deliverables and substantiation. The constraints and conditions shown primarily consist of the user profile and logistic concept. Finally the methods to be applied are contained in RAMS/LCC process requirements. A detailed overview of the relationships and interfaces between the individual RAMS/LCC activities is provided in Figure 5.

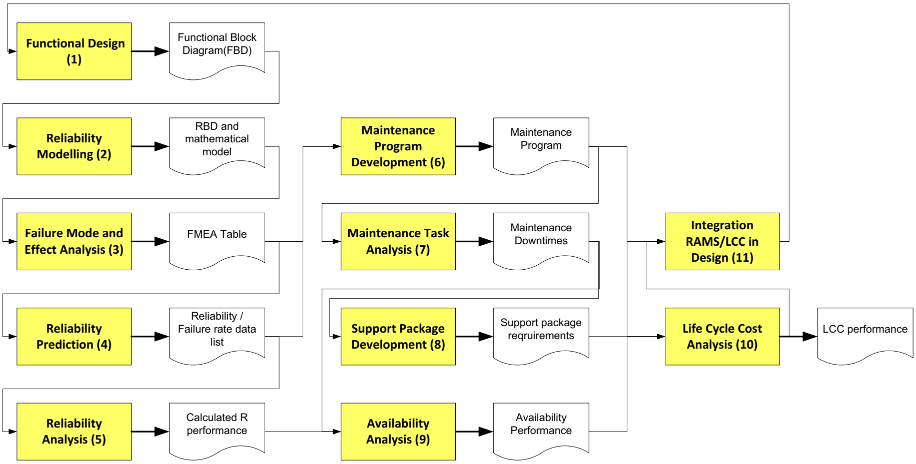


Figure 5. Detailed overview of the required RAMS activities

This process starts with the functional design process (1), during which the system architecture is defined using Functional Block Diagrams. Furthermore the functional performance is defined, including identification and definition of Functional Failures related to overall performance of the train sets. Based on this functional design, a Reliability & Maintainability (R&M) analysis is performed to identify which failures may occur, what the effect of those failures could be, and what the probability of occurrence of such failure is. To this end a Reliability Block Diagram (2) is developed including a Reliability Mathematical Model, to allow analysis of component failures on overall train set level. The FMEA analysis (3) provides an overview of all possible failure modes and effects related to the Functional Breakdown, while the Reliability Prediction activity (4) aims to determine the failure rate or probability of occurrence of each failure. During the Reliability Analysis (5), using the Mathematical model the reliability performance of the train set is determined to show compliance with the requirements. Based on these results, the next step defines an effective maintenance program (6) by determination of applicable and effective (preventive or corrective) maintenance tasks to mitigate the effect of failures or to reduce the probability of occurrence. In addition by performing a Maintenance Task Analysis (7) the maintenance downtimes are established. To support the execution of such a maintenance program the required Support Package (8) such as spares, training, documentation, tools, etc. needs to be defined. Combining the results of the reliability analysis and the maintenance task analysis the System Availability (9) can be determined. The costs associated with that solution can be determined from a life cycle cost perspective (10). Finally these activities have to be integrated in the functional design process (11).

H. SMARD Model Application

The SMARD model was applied in a wide range of case studies in various industries, including military and commercial aircraft industries. Implementation plans were developed guiding the successful and effective application of RAMS/LCC in the design and development process, depending on the specific type of technical systems and industry. Within the case studies the implementation plans were executed, evaluated, and continuously improved to suit best the projects need. In addition, cross-industry lessons learned were collected to develop a benchmarking tool to allow individual companies to compare their RAMS Driven Design performance against best-in-class performers.

I. Results of the research project

The project resulted in a Strategic Value Based Decision model to support designers and operators to make upfront the right decisions – based on a value function - for the most effective implementation of RAMS in the design process of complex technical systems, given their type of technical system, operations, and development project. Especially important since upfront resources are scarce as ever.

Based on the extensive case study application of the SMARD Model a value proposition was defined in which for each component (reliability, availability, maintainability, and supportability) key drivers were defined to identify and quantify the relationship between each component and its contribution to life cycle value. These key value drivers not only comprise the technical domain, but also address the organizational and information technology driven conditions required for effective implementation. The key drivers are furthermore differentiated towards different types of technical systems and development projects using scenario analysis. Metrics are defined showing the relationship between the RAMS investments and improvement in total life cycle value. Based on these metrics and key drivers the RAMS Driven Design strategic value based decision tool allows designers of complex technical systems to select upfront the most effective RAMS investment given their type of technical system, operations, and development project.

Finally the work has verified that a decision tool based on a value function which correlates RAMS investments in design to long-run availability and operational cost improvements can support all stakeholders in making effective decisions required for total life cycle cost optimization. It support designers to determine which RAMS activity really adds value for all stakeholders during all life cycle phases, and which approach towards maintenance provides maximum value, and under which conditions and constrains such an approach or methodology really is effective.

V. Case Studies

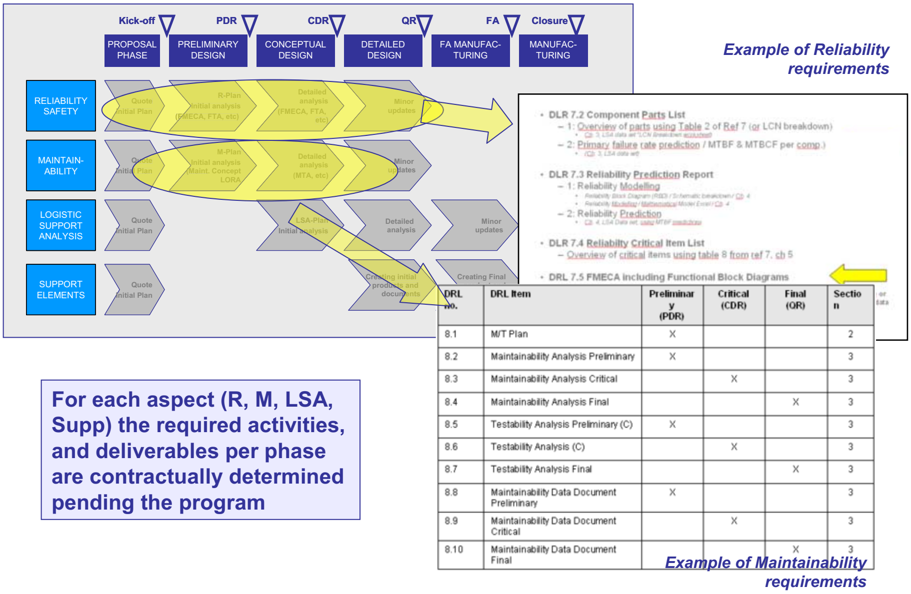
J. Overview

As part of the NH90 program two case studies were performed within the framework of the RAMS Driven Design research project. The first case study was performed in the 2001 -2002 timeframe, and involved the development of a primary aircraft system. The second case was performed in the 2009-2010 timeframe and involved the development of military mission equipment. Due to confidentiality the names of the suppliers and their systems are omitted.

In both cases an international aerospace and defence systems supplier was selected to supply an aircraft system to one of the partner companies of NHI. In close cooperation with NHI the supplier was responsible for the design, development, and manufacturing of the aircraft system according to NHI specifications, including all requirements related to ILS and RAMS, while applying and taken into account the NHI ILS methodology, processes, standards and databases. The RAMS Driven Design Model has been applied where possible to support the stakeholders to make strategic decisions to select and apply the required RAMS processes and activities which optimize Total Life Cycle Value, while taking into account all relevant business, organizational and contractual constraints.

K. Case study approach

Both cases show the same research approach. At first the ILS requirements were analyzed to develop a pragmatic ILS management plan aimed at achieving a cost effective realization of the ILS, R/A and M/T requirements within the NH90 program. This involved the translation and tailoring of the vast amount of NHI requirements, processes and methodologies to an effective and efficient RAMS Driven Design approach. As such the SMARD Model has been used to tailor the traditional ILS oriented approach used within the NH90 program. Figure 6 illustrates this pragmatic approach, which illustrates the relation between the design process, activities and deliverables for the most important ILS aspects.



For each aspect (R, M, LSA, Supp) the required activities, and deliverables per phase are contractually determined pending the program

- DLR 7.2 Component Parts List
  - 1: Overview of parts using Table 2 of Ref 7 (or LCN breakdown)
  - 2: Primary failure rate prediction / MTBF & MTBCF per comp.)
- DLR 7.3 Reliability Prediction Report
  - 1: Reliability Modelling
  - 2: Reliability Prediction
- DLR 7.4 Reliabilty Critical Item List
  - Overview of critical items using table 8 from ref 7, ch 5
- DRL 7.5 FMECA including Functional Block Diagrams

DRL no.	DRL Item	Preliminary (PDR)	Critical (CDR)	Final (QR)	Section
8.1	M/T Plan	X			2
8.2	Maintainability Analysis Preliminary	X			3
8.3	Maintainability Analysis Critical		X		3
8.4	Maintainability Analysis Final			X	3
8.5	Testability Analysis Preliminary (C)	X			3
8.6	Testability Analysis (C)		X		3
8.7	Testability Analysis Final			X	3
8.8	Maintainability Data Document Preliminary	X			3
8.9	Maintainability Data Document Critical		X		3
8.10	Maintainability Data Document Final			X	3

Figure 6. A pragmatic approach towards ILS – illustrative overview

Secondly, the ILS Management Plan has been developed to capture this approach, describing the organization, processes, activities, schedule, resources, etc. required to achieve the ILS goals as part of the overall project ambitions. The ILS Management Plan has been implemented to serve as the guideline for the supplier for the planning, control and execution of all ILS, R/A and M/T activities during the design and development phases. During the execution of these plans, in close cooperation with NHI and the NHI partner company this plan has been evaluated and improved based on the experiences gained with the application of the model within the NH90 program.

L. Case Study Results

This section highlights the conclusions regarding the application of the RAMS Driven Design approach within the NH90 case studies. It is not intended to discuss these results in detail, given the scope of this paper. Nevertheless, the following general remarks and conclusions can be made regarding improved operational availability and reduced maintenance costs.

1. Operational consequences:

Although supportability, life cycle cost, and operational availability are key performance indicators for the integrator and it's customers, these requirements are not transparently and unambiguously allocated downwards in the supply chain. As a result the supportability product and process requirements for suppliers have no visible relation towards the ultimate end goal, making it hardly impossible for suppliers to make a design trade-off regarding the impact of changes in their design on functional performance, availability and cost. Furthermore the design review process does not put equal weight to those requirements. Functional performance and schedule typically are more important than the execution of RAMS/ILS related activities and the results of these activities. As a result the traditional ILS process, or even the pragmatic RAMS Driven Design approach, is not performed as an integral part of the design and development process.

2. An integrated approach

From these case studies it can be concluded that no integrated systems (engineering) approach towards design for RAMS/LCC is applied. Prime systems engineering activities especially related to

RAMS/LCC are not / insufficiently performed, such as definition of user requirements, tradeoff between design concepts, configuration management, trade-off between engineering disciplines. Typically, a sequential design approach is followed in which in general the design for RAMS/LCC activities are performed after finalizing the functional design activities.

3. The traditional ILS approach

The case studies illustrated that the traditional ILS methodology does not result in an integrated design approach in which RAMS has been treated equal to performance requirements. The ILS methodology in itself does not assure that up to date design information is available and exchanged in real time between engineering and ILS departments, and between suppliers and integrated; design review include analysis of the impact of design changes on R/M/S aspects; verification of design includes all ILS, reliability and maintainability requirements, and guidelines; RAMS is considered a design variable, to allow trade-offs between functional performance and RAMS characteristics; and engineering, ILS, and project management work together to make it truly Integrated Logistics Support. The traditional ILS methodology focuses on the generation of contractually required documents and data elements, whereas the added value of some of these documents and data elements in total perspective can be questioned.

VI. Conclusions

In summary it can be concluded that the case studies showed that an integrated, life-cycle oriented, systems (engineering) approach is imperative for military aircraft development to really improve operational availability and cost effectiveness. The traditional ILS methodology in combination with the project organization and the design and development process do not facilitate such an integrated and value driven design process. However based on the application of the RAMS Driven Design approach valuable lessons were learned related to the further development of a strategic management value based decision model for the cost effective application of RAMS during design and development, especially related to the identification of the key value drivers and metrics in the organizational and information technology domain. These cases have contributed significantly towards the model validation and valorization of knowledge.

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Method-Driven Test Case Generation for Functional System Verification

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The test process of safety-critical systems underlies the challenges of growing complex systems and still limited means to satisfy the functionality of a system under test against its requirements. The whole test process has to fulfill the criteria of reliability, objectivity and traceability, because its results act as verification for the correct functionality of the safety-critical system to the public authority. The classification tree method is a common method to support the test process in a model based way. Unfortunately, the actual implemented variants of this method break either the reliability or the traceability. This article presents an extension to the classification tree method to satisfy both, the reliability in the classification tree results and the traceability in the estimation of the adequate test cases. The application of the implemented extension is shown as an example.

I. Introduction

Aircraft manufacturers try to strengthen their competitive position by incorporating new technologies into their products. The implementation of new technologies into innovative systems is essential to develop more powerful, economical and comfortable aircrafts. The use of innovative systems allows a lot of new product features, which in turn leads to increased product complexity.

Aircraft manufacturers take the responsibility for the functionality, reliability and operational safety of their products. In particular, improvements in safety-critical functions such as primary flight control, propulsion, or high-lift must meet the stringent requirements of aviation authorities. The proof of the correctness of these functions cannot be realized in a formal, analytical way. Consequently, new aircraft systems must be tested systematically and comprehensively in test campaigns.

Test campaigns include all tasks and activities which are required to guarantee the correct functionality of an integrated system. The effort of a test campaign rises depending on the complexity of the system. Nowadays, the verification effort for modern aircrafts has reached a threshold that aircraft manufacturers require new efficient approaches and methods handle test campaigns in a reasonable time. Because test execution has been largely automated by software and hardware-in-the-loop solutions, the challenge for an efficient test process moves to the test case creation. This task can be handled in a manual or in a method-driven process. A method-driven process achieves the objectivity and traceability and enables an efficient test case creation for the engineer by automating time consuming tasks and by removing redundant task.

The test case creation includes all steps to determine the adequate set of test cases and to implement the test cases. The determination of an adequate set of test cases is in the field of black box testing a complex challenge. It includes the identification of all test relevant aspects of a System under Test (SuT), the summarization of the test relevant aspects to test cases and finally, the selection of the adequate set of test cases. Nowadays, the engineer performs this important task on basis of a requirement catalogue and of his own engineering judgment. To satisfy the objectivity, reliability and the tractability, a method-driven process is required. In general, user experiences show that a method-driven test process is helpful in real-world test problems[1].

An industrial accepted method for the black-box partition testing[1] is the classification tree method (CTM). This method enables the modeling of all test relevant aspects regarding the relevant parameters and values of a SuT. Furthermore, the method can determine on basis of manual defined restrictions an adequate set of test cases. The manual defined restrictions describe both, test relevant aspects of the SuT and the test strategy. The weakness of the currently available CTM implementations is the missing determinism within the calculations and the weak possibilities to scale down the set of test cases by using the engineering judgment.

This paper presents an extension of the classification tree method. The objective is to extend the common CTM in such a way that it can be used in a safety critical environment. For this purpose, the extended CTM shall satisfy the required features of the objectivity and reliability. Furthermore, the extension offers some key functions to scale down the number of test cases to an adequate amount. The required knowledge, which is used for scaling down, can be modeled easily and the impact of the knowledge application (engineering judgment) is comprehensible.

In the following, the state of the art of the CTM is presented. Subsequently, the extension of the CTM method is motivated and our approach is presented. Finally, the application of the implemented CTM is shown at an example.

II. Classification Tree Method

The classification tree method (CTM)[2] involves two fields of application. First, the method is used to model the input domain of a SuT regarded under various aspects which are identified as relevant for a function test. Second, the method is used to define test cases. Within the first step, disjoint and complete classifications are formed for each test aspect. Classes resulting from these classifications may be further classified – even recursively. A class represents usually an equivalence class. In Figure 1 an example of a classification tree (CT) is given.

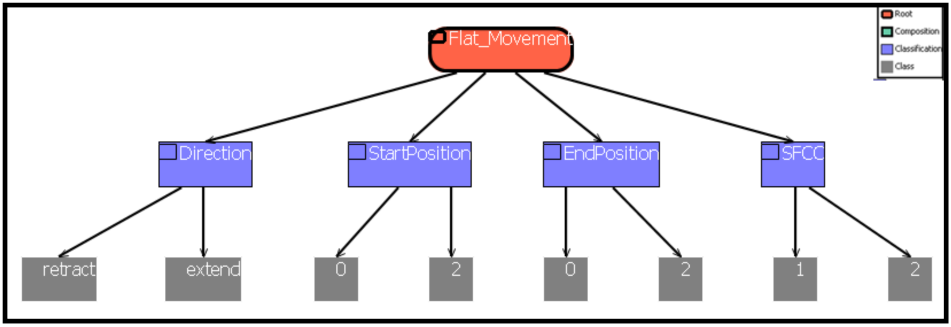


Figure 1. Example of a CTM

The classification tree in Figure 1 shows a function test to satisfy the Flat movement from a start position to an end position. Therefore, the start position, the end position, the direction and the used control computer are modeled as classification. Under the classification, the corresponding values are inserted whereby a value represents an equivalence class. For example, the flap can move in the direction *retract* or *extend*.

The CT is the basis of the calculation of test cases. In this paper a test case is defined as a set of classes of different classifications. For this purpose, the CT can be viewed as the head of a combination table. Thus, a test case is estimated by combining classes of different classifications. One possible test case could be on basis of Figure 1 (retract, 0, 0, 1). The number of test cases increases exponentially with the size of the classification tree. In consequence, CT for realistic areas of application results in millions and more of possible test cases. This circumstance demands to scale down the amount of test cases to achieve a test process in time and budget. The selection of adequate test cases is still a manual task of the engineer and requires his engineering judgment.

There are several methods, whereby an engineer is supported while he is selecting the relevant test cases. All established methods can be classified into two types. Methods of the first type use a subset of classifications to calculate the combinatory results. For this purpose, an engineer takes a manual selection/prioritization of the nodes of the CT and set it as input for the calculation. Bernhard & Mattner has developed a method in his software CTE XL in version 1.9.4[3] in which a user defines the subset of classification for the combinatory result. The test cases are calculated on basis of the marked classifications. Subsequently, the missing classes of the not marked classifications are inserted into the result. Unfortunately, the spawning method uses a random function and therefore, it calculates different results at different application times. In consequence, the whole test case generation method is not determinism and violates the criterion of the reliability.

Methods of the second type require two kinds of information. The first one describes how many test cases shall be calculated and the second is defined by a model, which determines the prioritization of the CT. On the basis of these two input sources, the number and the selection of the test cases are controlled. The selection process uses weights or probabilities within the trees to estimate the test cases. For this purpose, each node or edge of a classification tree needs a corresponding value. The required values are contained within the model. Such an approach is implemented by Bernhard & Mattner[4]. Their implementation uses as input model a usage model, an error model or a risk model to estimate the selection of the test cases. A model element represents an occurrence value to a class, whereby the sum of all classes composed within one classification is 1. An example of a simple annotated classification tree is given in Figure 2.

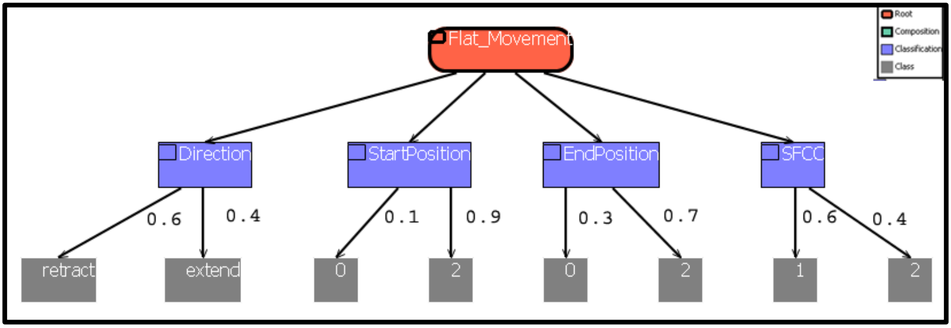


Figure 2. CT with Node Weights

The test case generation calculates on basis of the assigned weights the absolute frequency of the classes within the set of test cases. For example, the class retract is going to be assigned to 6 test cases if the engineer decides to generate 10 test cases. The engineer can pre-assess the number of test cases for a given class in such an easy example. Unfortunately, the depth and corresponding complexity of a CT can grow unpredictable in real world scenarios. An example of a CT, which has a higher dept, is shown in Figure 3

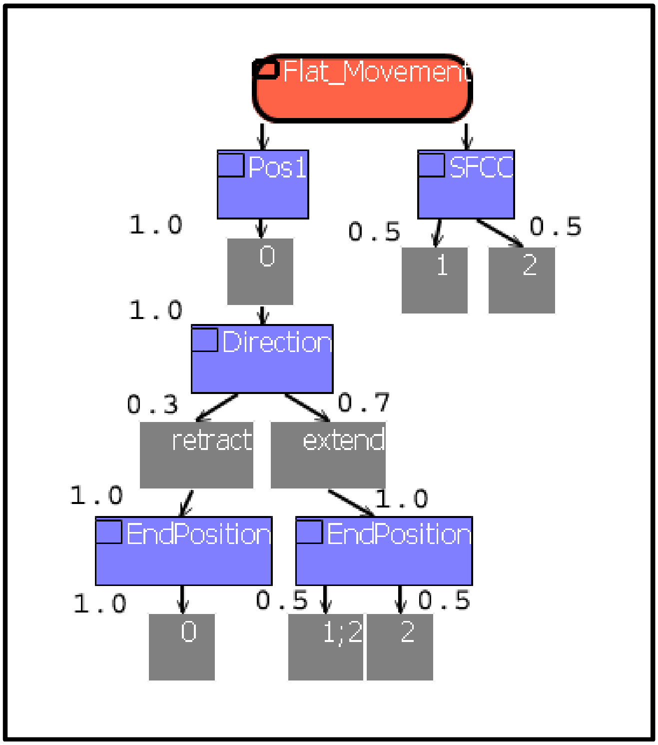


Figure 3. CT with a depth of 6 and Additional Node Weights

The skill to intuit the number of test cases, in which a specific class is assigned, decreases to the increased dept of a class within a tree. The absolute frequency of a class within a set of resulting test cases is calculated not only on basis of its weight but on basis of all weights of the path from the root to the specific class. This circumstance makes it difficult to get an intuitive overview about the resulting set of test cases. Furthermore, the step-by-step adaptation of the required weights is too complex to achieve a fast and a step-by-step approximation to the favored structure of the test cases. The adaption of the weights is a complex task, because the weights correlate to each other in the test case generation. In consequence, the creation and the adaption of the occurrence model satisfy all required criteria of a method-driven test case generation, but the application is not intuitive and not user-friendly.

In summary, the presented methods either satisfy the required criteria and are too complex or the do not satisfy the criteria and are applicable.

III. Extension of the CTM

The implemented extension of the classification tree achieves both, the objectivity, reliability and traceability. The extension specialize the node type class into two new node types: "free" and "non-free" class.

A *non-free* class is an important class of the classification tree and has no restriction. That means that a *non-free* class is combined with a *non-free* class of another classification during the calculation of the combinatory result. The result is a set of test cases which contains only *non-free* classes.

A *free* class is a not important class and has as restriction that it is not considered during the calculation of the combinatory result. A *free* class cannot influence the number of test cases. The task of a *free* class is to perfect a test case. For this purpose, all *free* classes are spawned into a given result of test cases. The absolute frequency of a *free* class, within the set of test cases, results from its weight. The weight represents the relative frequency of a class whereby the sum of all *free* classes has to be 10 rsp. 100% under one classification. An example of an extended CT, which includes both types of classes, is given in Figure 4.

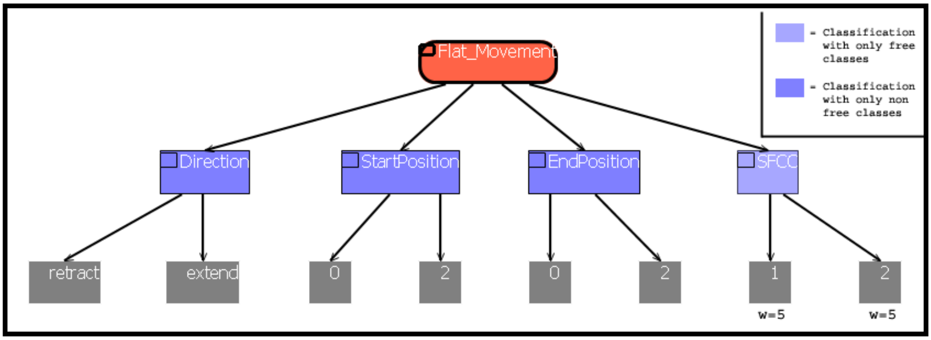


Figure 4. Example of an Extended CT

The generation of the test cases causes above two steps. In the first step, the set of test cases are calculated above the *non-free* classes. Therefore, the *non-free* classes are sorted by its identification code and a combinatory result is estimated over it. This step results in a set of test cases, whereby a test case contains disjoint *non-free* classes of all classifications. In the following step, the *free* classes are spawned into the result. The spawning method takes the set of *free* classes, order it by its identification code and calculate its absolute frequency. The absolute frequency of a class results from the number of test cases in the result and its relative frequency. Finally, the spawning method inserts the *free* classes regarding the order and the absolute frequencies of the classes. The consideration of the order identifications codes enables a determinism calculation method.

The whole test case generation is only influenced through the subtype of the node type class and through the assigned weights for the *free* classes. These two operators are the foundation to scale down the set of test cases to one set which is important to the regarded function test. The classification of classes to its subtype is an easy to use method to restrain the number of test cases. In a first step, the engineer has only to decide whether the class and its corresponding classification are important or not. In the second step the engineer prioritize the *free* classes with a value between 1 till 10, whereby the value 10 correlates to a relative frequency of 100%. This is also an easy to use way to assign the importance of the free classes. Both operators are so designed that the engineer can foresee the consequences of his changes to the classification tree. This circumstance enables an iterative process (step-by-step) to estimate the best set of test cases. The judgment of the calculated set of test cases is done by the engineer manually. For that reason it is important, that an engineer can follow his suggestions by application the both operators.

A. Application example

In the following an example is given, how a set of test cases can be generated by using the extended CTM. Furthermore, the iterative workflow to estimate the best test case selection is shown, whereby the classic CTM functions and the extended CTM functions are used in a holistic workflow.

The example scenario describes two desired test cases, in which a flat move from position 0 to 2 and another test case, in which a flat move from 2 to 0. The objective of both test cases is to satisfy that a flap can execute the requested movement.

In the first step of the method-driven test case generation, an engineer models a classification tree which defines all relevant parameters and values of the SuT. A corresponding classification tree is shown in Figure 5.

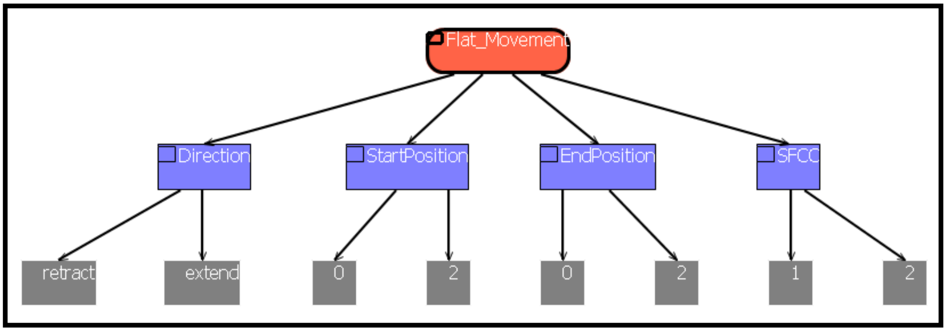
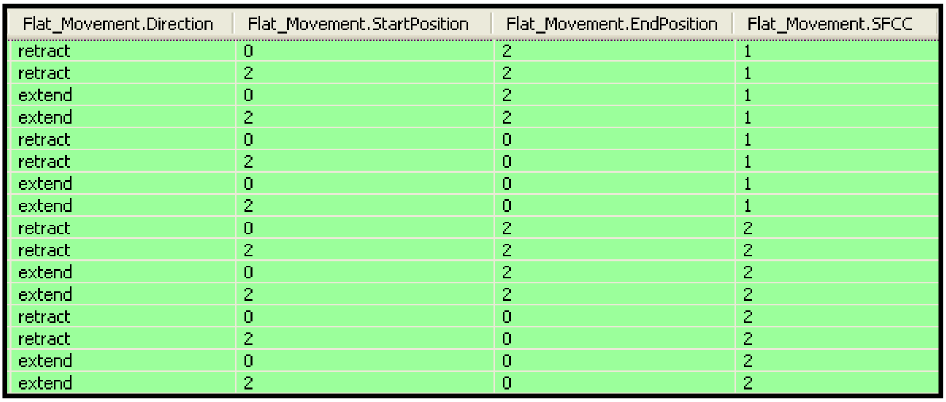


Figure 5. CT to model the Flap Movement

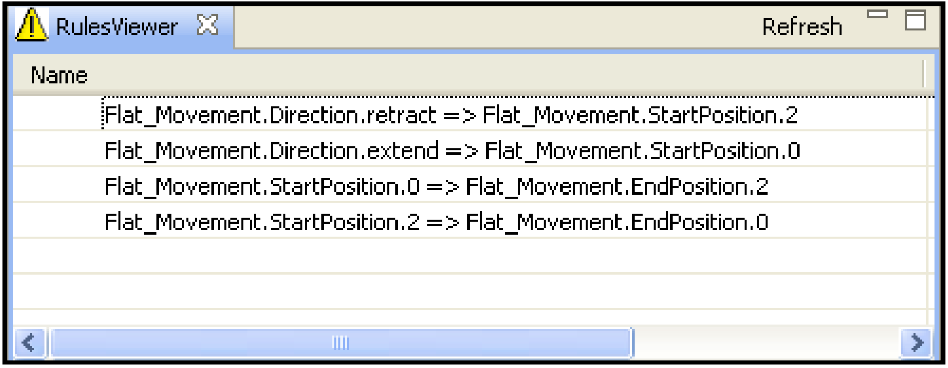
The test case generation calculates on basis of the CT in Figure 5, in which all classes are *non-free*, 16 test cases, which are listed in Figure 6



Flat_Movement.Direction	Flat_Movement.StartPosition	Flat_Movement.EndPosition	Flat_Movement.SFCC
retract	0	2	1
retract	2	2	1
extend	0	2	1
extend	2	2	1
retract	0	0	1
retract	2	0	1
extend	0	0	1
extend	2	0	1
retract	0	2	2
retract	2	2	2
extend	0	2	2
extend	2	2	2
retract	0	0	2
retract	2	0	2
extend	0	0	2
extend	2	0	2

Figure 6. Combinatory Result of Flap Movement CT

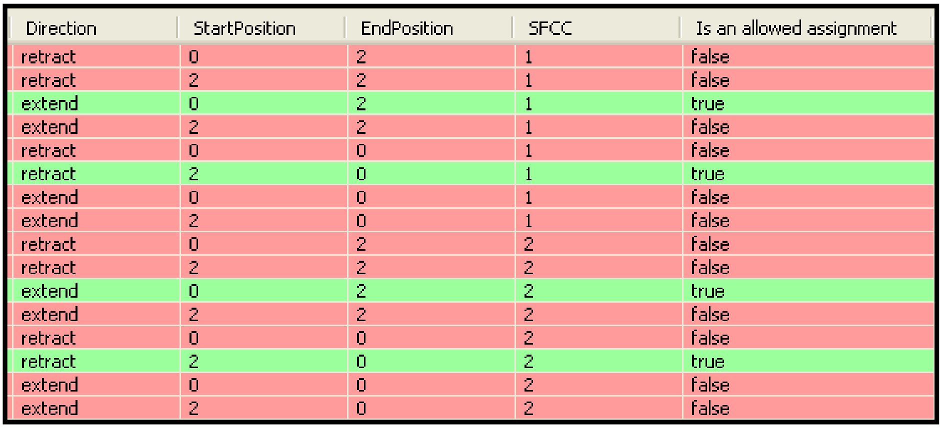
This set of test cases includes some ones which are irrelevant for the test scenario. For example, the set contains a test case, in which the flap shall move from position zero to position zero. This and other useless test cases can be eliminated by adding knowledge as rules to the CTM. The objective of a rule is to exclude particular permutations of the whole result. For example, the first rule in Figure 7 claims that every time where the class *retract* is assigned to one result, the class *2* have also to be assigned to this result as representation of the classification *StartPosition*. The application of



Flat_Movement.Direction.retract => Flat_Movement.StartPosition.2
Flat_Movement.Direction.extend => Flat_Movement.StartPosition.0
Flat_Movement.StartPosition.0 => Flat_Movement.EndPosition.2
Flat_Movement.StartPosition.2 => Flat_Movement.EndPosition.0

Figure 7. Example Set of Rules

the rules, which are shown in Figure 7, on the combinatory result in Figure 6 results in four test cases. The result of the calculation of the combinatory result and the application of the rules is given in Figure 8.

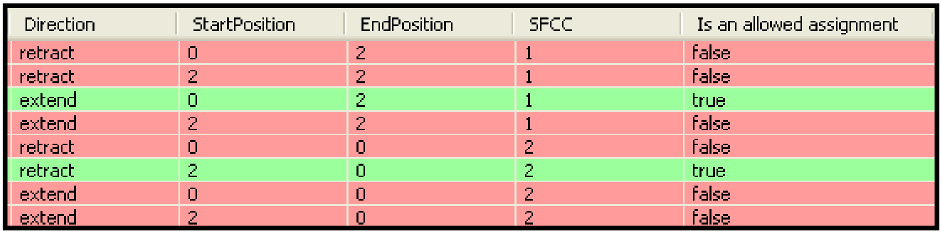


Direction	StartPosition	EndPosition	SFCC	Is an allowed assignment
retract	0	2	1	false
retract	2	2	1	false
extend	0	2	1	true
extend	2	2	1	false
retract	0	0	1	false
retract	2	0	1	true
extend	0	0	1	false
extend	2	0	1	false
retract	0	2	2	false
retract	2	2	2	false
extend	0	2	2	true
extend	2	2	2	false
retract	0	0	2	false
retract	2	0	2	true
extend	0	0	2	false
extend	2	0	2	false

Figure 8. Combinatory Result of the Rule Extended Flap Example

Figure 8 shows the combinatory result (the same result like in Figure 6) of the Flap example, whereby the red colored test cases are excluded through the application of the rules and the green colored test case are these one which are desired and would be implemented as test scripts in a subsequent step of the test process.

In our example, the engineer can either scale down the set of test cases through the application of additional rules or through the classification of the classes into *free* and *not free*. In our example we decide, that the classes under the classification *SFCC* are not so important for the test scenario. In consequence, the classes *1* and *2* of the classification *SFCC* are set as *free* classes. Now, the classification *SFCC* is not any more part of the calculation of the combinatory result. The classes 1 and 2 are spread out over the given combinatory result. Therefore, a relative frequency is assigned to each free class, whereby the sum must be 100%. In Figure 9, the result of the test case generation is given whereby all classes of *SFFC* has a relative frequency of 50%



Direction	StartPosition	EndPosition	SFCC	Is an allowed assignment
retract	0	2	1	false
retract	2	2	1	false
extend	0	2	1	true
extend	2	2	1	false
retract	0	0	2	false
retract	2	0	2	true
extend	0	0	2	false
extend	2	0	2	false

Figure 9. Combinatory Result of the Flap Example with added Rules and Free Classes

The engineer added in our example a set of rules and specified the classes into *free* and *non-free*. The application of these two operators scaled-down the set of test cases from 16 members to only 2. The same result can be achieved if an engineer chances the order of the operators. That means, that he first classifies all classes under the classification *Direction* and *SFCC* as *free* (weight of 5) and subsequently, he applies the last two rules of Figure 7.

IV. Implementation

The proposed extension of the CT was implemented within the research project BreTeCe[5] as a modeling tool. It offers the modeling of the extended CT and the calculation of the set of test cases. The user can scale down the set of test cases by the application of above presented methods.

The modeling tool was implemented as a rich client and can be used as standalone application. The tool has reached the stage of development that it is applicable.

V. Conclusion and future work

In this paper, the authors presented the research results in field of the classification tree. The weakness of this method, regarding the reliability and traceability resulted in an extension of the CTM. The implemented extension satisfies the requirements in a safety critical test process due to the objectivity, reliability and traceability. The calculation of the set of cases is determinism and therefore, the calculations generates every time the same results under the same conditions. This fact is a requirement to apply a method and its results as a certificate in a safety critical environment. The traceability is satisfied by the above mentioned operators which are both, independent of each other and easy to apply.

Furthermore, the given example shows how the engineer can use his knowledge of the SuT to scale down the number of test cases. The presented methods, the application of rules and the specification of the classes into *free* and *non-free*, enable an understandable and a reusable test case generation process. In the future work, the extended CTM will be evaluated on basis of a realistic function test within a test campaign.

The implemented classification tree is part of a method-driven approach to generate test scripts on basis of the extended classification tree and an extended activity diagram. In the near future, the extended activity diagram will be implemented and finally both diagrams are combined to a model based test case generation.

Acknowledgments

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Aviation Security in a Digital Age: can Security benefit from Wireless Communication Technologies in Passenger Air Transport?

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This paper highlights several aspects of introducing the integration of security relevant information from passenger air transport processes by utilizing Near Field Communication. Due to its inherent characteristics NFC can support new risk-based security strategies and likely prove to be accepted by passengers. Using mobile phones as the implementation form, perceived benefits and performance expectations could empirically be found in a passenger survey.

I. Introduction

Airport Security is a key element in the design of the seamless passenger air travel. From security checkpoints to immigration control it is often perceived as those processes that create the most tension among passengers and as a time consuming, occasionally misdirected obligation. With the current security practices in place all relevant stakeholders in air transportation, such as airlines, airports and authorities will face an increasing dilemma to cope with the regulations while trying to realize the projected growth rates and attain the aspired profitability levels while keeping the costs in reasonable boundaries. The methods currently in place are reaching the limits of operational practicability. The development of future aviation security practices and strategies need to address the uncertainty of attack methods by installing advanced sensor technology and simultaneously provide a guideline to free the burden for the vast majority of passengers. Furthermore there is the need to find and utilize supporting technologies for new aviation security strategies, such as risk-based differentiation between travelers. Policy formulation in aviation security needs to adapt to new technological trends such as smartphone usage by passengers to improve existing procedures in more interactive and efficient ways. The focus in the last decades has been mainly on the advancement of sensor technologies and imposing new regulations of information provision, leaving questions of security process facilitation unanswered. Currently there is a break between collected information and information that is needed for passenger analysis and identification purposes. Traditional methods are not reaching the potential of consistent information exchange, since data is generated and lost. Thus our research tries to find ways to overcome this dilemma by using wireless communication technologies to foster data integration, of which Near Field Communication NFC) shows most significant benefits.

In section II we will give a brief overview about the technological and strategic advances in aviation security and draw several key factors that have to be considered for a successful

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implementation of a new approach. Wireless communication technologies are discussed and trial applications of NFC that have been introduced in the aviation sector are presented in section III. The focus of the analysis lies on NFC, since this leads to the basis for our approach of using NFC in the aviation security context. In section IV we will describe the effects of introducing an NFC enabled mobile device as a digital key for the entire air travel and show the benefits of aligning commercial services, such as ticketing or payment, and security related processes with the objective of an overall benefit and a seamless aviation security process. Although it may be visionary to some extent, considerable implementations have occurred in other application fields of NFC technology especially in the mobile payment services with a similar data critical security obligation. A conceptual model of the modified passenger process is constructed, in which we are analyzing the introduction of security related factors to the IATA ideal process flow. Furthermore the development of a qualitative security process measure will be described and incorporated to the model. Section V is dedicated to the discussion of consequences to overcome regarding data privacy protection and acceptance by passengers. Several key figures from a passenger acceptance survey, which has been undertaken at the German airports Berlin/Tegel and Cologne/Bonn, will be highlighted to empirically analyze the importance of the passengers' viewpoint. The paper concludes in section VI with a reasoning summary and a brief outlook into further research tasks.

II. Advances in Aviation Security

A series of advancements and new regulations in the aviation security policies are almost constantly introduced worldwide. Terrorist attacks or attempts thereof have been the driving force in the aviation security agenda and lead to often impulsive reactive measures. Nevertheless, the efficient use of technology can prove to support new strategies in aviation security and be a proactive and sustainable solution. While some technologies failed to deliver the anticipated results and acceptance at the beginning, e.g. body scanners, other technologies still provide a great potential, e.g. automated boarding gates for immigration.

A. Technological

As a reactive measure to the threat situation in the late 1970s and 1980s, in which explosive materials were used in attacks on aircrafts, sensor technology to detect those materials has been introduced and improved constantly. Over the last decades explosive detection systems have been further refined and used to cover the 100% screening of checked baggage obligation. Advanced imaging technology came to publicity after the failed bombing of the *Northwest Airlines flight 253*, after which new sensor technology was asked for. However, media and public opinion discredited the sensor technology in some countries, leading to negative implications of "naked scanners" and the failure of acceptance. Whereas the principle of automation has been the driving force in most of the air transport process steps from check-in to boarding, the security checkpoint is still largely a manual process. It is arguable whether advanced imaging technology would lead to efficient automation and automatic detection of critical items is more effective than manual search. While automated processes might not be the most time efficient way for all passenger groups, for those, who are familiar with the once learned usage of an automated system, improved processing times with less waiting time and hassle factors can be realized. In 2009 automated gates were installed for the immigration at Frankfurt Airport's border control in a pilot program and have been successfully transferred to real operation since 2010. Key factors for successful implementation of new systems can be summarized as: focus on passenger centric design, communicating objective effectiveness, as well as proven usability by focusing on technology that is accepted or to some extent understood by the passenger.

B. Strategic and Systemic

Besides the introduction of new sensor technology in aviation security practices, the practices itself have been adapted over the years to changing threat scenarios and risk assessments by the authorities. The bombings of aircrafts in the 1980s, i.a. Air India 182 (1985) and Pan Am 103 (1988), have lead to new security practices such as the requirement of checked-baggage and the passenger-bag matching. In 1997 the *Computer Assisted Passenger Prescreening System (CAPPS),* in which passenger name record data was analyzed to determine a passenger's risk status, has been introduced and developed since then, leading eventually to the TSA's *Secure Flight* program. The attacks of September 11, 2001, have resulted in a series of tightened aviation security policies and comprehensive set of regulations, such as the *Aviation and Transportation Security Act* (2001) and the *Homeland Security Act* (2002). The attempted attacks of 2006, in which the explosive materials would have been assembled on board, led to the liquid, aerosols and gels prohibition. Furthermore the *Intelligence Reform and Terrorism Prevention Act* in 2004 has firstly transferred the pre-screening obligation from airlines to the federal Transportation Security Administration (TSA). The introduction of the *Advance Passenger Information System (APIS)* in 2005 marks the beginning of intensive data gathering and assessments of passenger records, the watch list checking procedure etc. Besides technical implementations in computer-based systems, the TSA started with a program to analyze passenger behavior called *Screening Passengers by Observation Techniques (SPOT),* whose results are seen critical. In recent years, a manifestation of the trend towards the implementation of an objective criteria based risk assessment and diversification among passengers can be seen within the overall security strategy. This follows a paradigm shift in searching for "bad people" instead of "bad objects", as sensor technology will reach its limits of practicability with high false rejection rates and increasing technology costs. Whether it is called profiling technique or in a more moderate term risk based grouping, aviation practitioners and leading industry associations[1] are increasingly favoring some kind of defined distinction between passengers. IATA's Checkpoint of the Future[2] serves as a thought-provoking impulse for further development in a sensitive area. It envisions a seamless walk-through control with no stopping, realized with advanced sensor technology. Nevertheless it is an insufficient example that does not acknowledge the perception of passengers among each other and cannot be aligned well with a trustful and open-minded security culture due to its obvious stigmatization of passengers' risk category. Leaving the security checkpoint at a single place, the control remains transparent and easy to study and test by possible attackers. Diverging concepts are evolving and addressing this critique by distributing sensor technology inside the terminal and adjusting sensor sensitivity based on risk assessments.[3] Whereas passenger profiling is practically a no go in current European politics and the societal thinking, perhaps the solution will come from a more technical oriented side. Maybe the objective should be to find the harmless passenger not the high-risk passenger. Trusted or registered traveler programs have been introduced in 2005 and tested in pilots since then. Basic principle of trusted traveler programs is to register a passenger in advance with certain information and biometrical data, e.g. fingerprint or iris scan, and if granted assign him with a lower risk status, dependent on his background information. This status will be valid for a defined time period and enable the passenger to access facilitated security control lines and automated border control gates. Currently though, none of the proposed tests and pilots for known traveler programs shows a clear record of practicability and a successful realization of the in fact beneficial concept is still needed. However it will eventually be a central element in future aviation security, since it provides a reasonable method to cope with rising passenger numbers and increasing efficiency losses at security and immigration checkpoints. All developments show that there is a clear need for substantial provision of security relevant information that determines how a passenger can be identified and checked throughout the process chain. Figure 1 highlights the development of the required data provisioning.[4]

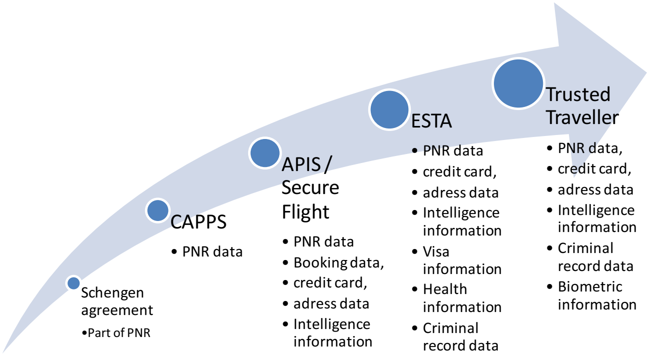

Figure 1. Development of data provisioning requirements in aviation security programs

The key factors for successful strategic changes in aviation security are: a focus on risk based passenger differentiation on objective criteria without discrimination, a focus on facilitating the security processes, building on technology/information that the passenger brings with him already, as well as communicating threat and risk perceptions and eventually develop a different security culture.

III. Wireless Communication Technologies in Passenger Air Transport

Wireless communication technologies encompass the whole range of RFID, NFC, WLAN or Bluetooth. Besides their different frequency, ranges and various characteristics of transmittal procedure all can be used in a mobile way, as required by seamless processes. Whereas WLAN and Bluetooth are primarily intended for the use in communication data transfer and require a configuration of connectivity, RFID and NFC are used in automatic identification procedures giving the flexibility of contactless data transfer. Figure 2 highlights some characteristics of those technologies.[5]

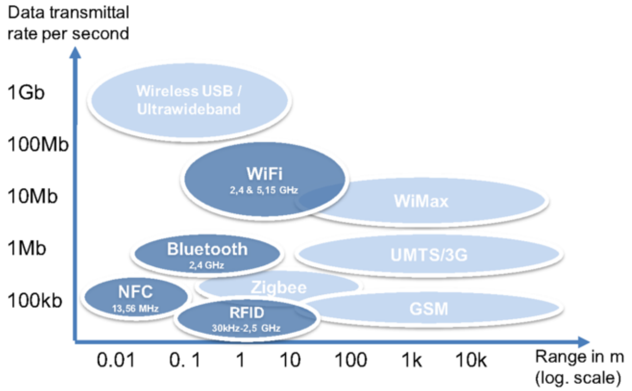

Figure 2. Key characteristics of wireless communication technologies.

Bluetooth and WLAN are fairly widespread for passenger applications between mobile devices or laptops. The provision of WLAN access points has been established on most international airports for passenger use, often with a limited time for free. Airports are addressing herewith the overall need for connectivity of passengers and are intending to increase the attractiveness of the airport. Operational aspects from the airline or airport view, e.g. by using Bluetooth or WLAN network signals of passengers' devices for flow and wait time analysis, have been implemented only recently.

Since the adaptation of RFID from the supply chain logistics to the air transport sector, RFID has been a particular case of overestimation and underutilization of its potentials. The first utilization field of RFID in air transport has been for baggage tagging to replace regular barcodes, which has been implemented in a first trial by British Airways in 1999[6] (although the roots of RFID are generally traced back to friend-or-foe systems during WWII to identify airplanes by broadcasting signals from a transponder). In 2005 the IATA has released the Recommended Practice (RP) 1740C document, in which the use of UHF tags and readers compliant with the ISO 18000-6C protocol for baggage tags is defined. The benefits and use of RFID has been explored by IATA in its *Simplifying the Business* program. According to IATA approx. 21% of baggage mishandling reasons, which are erroneous read rates (9.7%) and missing sorting information (10.9%), can be eliminated through the use of RFID tags and thus contribute to the estimated overall yearly savings for the airlines of 730 Mio. USD.[7] Several further pilot projects have been carried out by airlines and airports around the world, i.a. AirFrance/KLM at Paris CDG, Amsterdam Schiphol, and Beijing Airport[8], and been introduced in real operations, i.a. at McCarran Int. Airport Las Vegas or Hong Kong. The achieved read ranges averaged 99% and were a clear improvement to the 85-90% of barcode systems. Although IATA states that there should be an individual profitable business case for any airport and only selected large airports need to utilize RFID to reap 80% of handling improvements, RFID baggage tagging has not been implemented on a wider scale.[9] The FAA has studied the use of RFID with regard to aviation security matters focusing on controls over checked baggage handling and possible relation between high-risk passengers and their baggage.[10] After the 9/11 terrorist attacks the Department of Homeland Security has also focused on the use of RFID for baggage and people tracking and implementations of baggage tagging were realized at Las Vegas Airport with funding by the TSA. The expectations were to increase the security of baggage handling by enabling better tracking of screened baggage. However RFID systems in passenger air transport have never realized their expected potential and remain in isolated solutions without an integrative implementation among various infrastructures or services. This is mostly due to the difficulties in reaching a global agreement on the introduction as well as the fact that airports will bear considerable infrastructure investments whereas the airlines will reap the benefits of fewer mishandling baggage cases.

NFC is similar to Bluetooth, since it is a wireless data interface, and similar to RFID since it uses amplitude load modulation for the transmittal of data and allows to read and re-write RFID tags. NFC works by high-frequency (13.56 MHz) magnetic alternating fields and its communication range is limited to only a few centimeters. NFC interfaces can work in active mode, transferring data between two NFC devices, or in passive mode, in which one NFC device emulates a reader, the other a smartcard and vice versa. It is thus compatible to most smartcard systems (ISO14443). Besides short read ranges, NFC is more secure than RFID due to its capabilities of active-active mode in which considerable cryptographic measures can be run. Additionally, when implemented in a smartphone, the NFC is linked to the secure element, either a hardware embedded chip, the SIM card, or a MicroSD, and could incorporate biometric applications on the mobile phone.

Payment services in the retail and banking sector and ticketing in public transport[5] have been realized via NFC in mobile phones, yet the widely introduction of NFC in the aviation sector is still to come. Around the world, several airlines have piloted the introduction of NFC for the transmittal of boarding cards and frequent traveler authorization. In 2009 the qualification of NFC has been tested for the transmittal of the boarding card in the trial "Pass-and-Fly" by Air France, the airport Nice Côte d'Azur as well as the IT companies Amadeus and IER.[11] Within a six-month period members of the Club Airport Premier and frequent flyer had the possibility to test NFC on the Nice-Paris-Orly route. Processes of passenger identification, boarding and crediting of bonus points could be simplified and the trial results were positive. In a similar trial SAS Scandinavian Airlines has tested NFC in 2011 for their frequent flyer. By attaching an NFC sticker, traditional mobile phones could also be used as a SAS Smart Pass, to check-in, access fast track lanes at security control, and enter the lounge area. According to industry surveys approx. 80% of passengers are using self-service automation and 72% carry a smartphone.[12] NFC is facilitating self-service automation. When the smartphone usage within air travel processes is further increasing and once NFC enabled smartphones are used by a considerable percentage, it would be possible for the stakeholder to utilize this growing communication form without the need for investments on the passenger's side.

IV. NFC for Aviation Security

Besides the commercial applications of NFC that have been introduced in pilots, especially the application of NFC for aviation security matters has not yet been addressed in industry or scientific research. The analysis of possibilities for security relevant applications and their implications and effects for passengers is therefore addressed in our research work.

A. Conceptual model of the passenger process

The general concept of a digital process key for passengers is described by God et al.[13], in which the digitization of processes for a consistently harmonized security and service concept in air transportation is described. The implementation was outlined using NFC as the primary data transmittal method in process transactions. Aligning commercial services, such as ticketing or payment, and security related processes follows the objective of an overall benefit through seamless processes. There are three key benefits of the digital key based on NFC technology:

Firstly, it will improve the process, since the consistent digitization combines transactions (one-for-all approach) and simplifies the transaction itself (shorter processing time, usability in touch and go manner, facilitating automation). Furthermore, it creates frictionless linkages between transactions that are covered by the underlying technology, thus enabling the passenger to benefit from network effects in using the same device for multiple services without the need to learn the technological interaction.

Secondly, NFC enhances a secure data exchange. Using the secure element of the NFC device as the storage for the digital key, incorporating the boarding card, payment functionality, frequent flyer and loyalty member cards, the data trustworthiness and integrity of e-documents will be tremendously improved in contrast to existing paper documents. Since critical data can be linked to the secure element and paired with biometrical data for verification, the system makes it impossible e.g. to use counterfeit access documents to the security area or switch boarding cards between persons. Secure access to data can be incorporated using PIN and biometrical systems that are incorporated into smartphones such as facial or voice recognition, which is already implemented in devices available on the market. The inherent characteristics of NFC to only work over short ranges of a few centimeters contribute to the secure data transfer.

Thirdly, the NFC device collects and integrates process data in a seamless way without the need for passengers to configure connection details or even selecting application tasks in the menu, making new commercial services as well as new aviation security strategies possible. By collecting status data at each process step and transmit relevant data elements at a later process step, the system will contribute to a comprehensive provision of security and process related information at the authority or airport/airline level. On one hand this information can be used to allow for the optimization of passenger flows, the further automation of processes, and the efficient allocation of staff. For the airport or airline, handling process can be improved, knowing process locations and destinations of passengers in advance. On the other hand the interactive data exchange at each process step through real time collaboration and constant monitoring of the passenger status along the travel chain will be utilized by the authorities to improve awareness of critical situations and substantially improve the risk assessment methods. In turn the integrated information can be used to grant the passenger access to security fast lanes or modify procedures in the security control, e.g. in adjusting sensor sensitivity.

In 2006 IATA and the Simplifying Passenger Travel Interest Group have developed the Ideal Process Flow.[14] The outlined process scheme was developed to demonstrate process improvements in identification of passengers and the incorporation of technologies and further automation initiatives. Since then technology in general and with our focus specifically mobile technology has evolved tremendously. Starting with the introduction of the iPhone in 2007 smartphones have reached mass market appearance and application software became possible that could not be foreseen. The integration of these technological advancements has to be incorporated into the passenger process, to address the needs as well as be utilized for new ways of information exchange.

To integrate relevant security information an NFC device works as the ideal data storage and transmittal tool. At each process step, current status information is added and the passenger's attributes in terms of process advancement and security control are enriched. The fusion of related background information regarding flight and threat situation complete the actual risk assessment. Figure 3 shows the integration of exemplary security information that is added to the ideal process flow and transmitted over the NFC interface. In this approach it is not essential to register the passenger and still be gathering more information. Nevertheless, the system intends to facilitate the implementation of registered traveler programs and their automation principles, providing an easy method for secure automatic identification of passengers. Since it is not efficient to use the same measures for all passengers the focus is on facilitating the processes for those passengers, who pose the least amount of unknown risks, but in contrast are providing significant security relevant information. Besides the technical solution that NFC could provide, the systemic change depends on the collaborative exchange of information – a requirement that has not been achieved in the past. In this context the NFC device with its secure element could replace the need to set up an extensive database containing all information, instead passengers are keeping the necessary information in the palm of their hands and allowing access to relevant information by holding it to a reader.

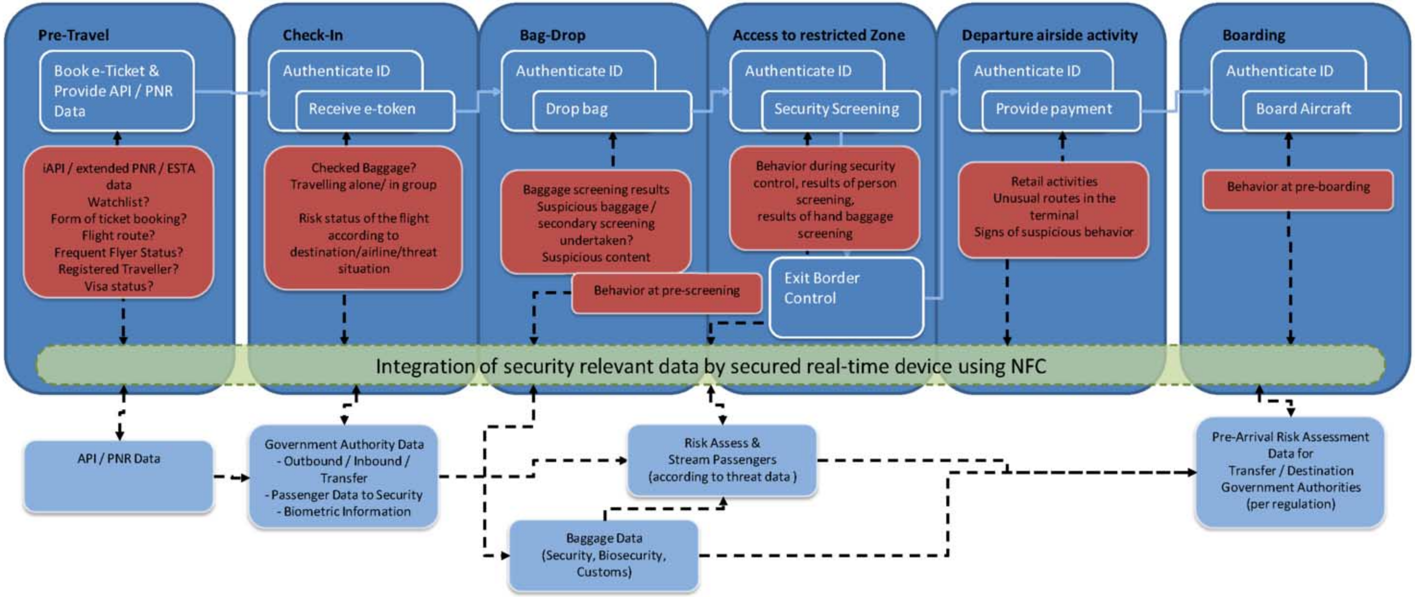

Figure 3. **Integration of selected security related factors to the IATA ideal process flow[14] (excerpt of departure process).**

B. Qualitative Security Measure

Using the system to gather and exchange security relevant data, a qualitative security process measure can be developed, which factors information and security level according to the related process status of a passenger. At each of the passenger process steps from booking to leaving the arrival airport, key information can be attributed to the passenger's risk status and thus lead to an overall ease and improvement of assessment methodology. Distinction in risk assessment between passengers could be supported due to the information status they provide: passengers with no information, normal information, e-docs, e-docs & biometrical, being a registered passenger and the like. The integrity of data varies between passengers, if more information of a certain kind is provided the assessment becomes more reliable. A quantitative security metric has been defined by Chawdhry as the permeability of combined procedures and technologies in aviation security processes.[15] In this context a qualitative measure based on the time period of availability of data and the integrity of the security relevant information is a necessary addition. The proposed NFC system delivers the suitable implementation form for such a qualitative measure.

V. Acceptance by Passengers

To be a successful solution, it is essential to consider a privacy-by-design approach in the development of the aforementioned system and take into account different use cases for heterogeneous passenger groups to analyze the acceptance by passengers. In the following sections the effects on data privacy protection as well as the acceptance is discussed, which has been empirically studied at two large German airports in a passenger questionnaire.

A. Data Privacy

Whereas the proposed integration of an NFC based digital key has the ability to improve the provision of the passengers' security relevant information for the authorities, it would be a large intrusion into privacy rights. Is there a substantial rights violation and can such data sharing be accepted or even be requested by the end-users? To some degree it depends on the legal context of the country, in which the system would be realized. While the legal requirements of current regulations have to be met, a change in security culture and the perception of security risks will affect the interpretation of and eventually lead to a change in regulations. Data privacy protection has to be recognized twofold. On one side data privacy is part of the passenger's overall acceptance of the system, which will be described in the following, on the other side it is an obligation of the entity that offers a technology or service, imposed by legal regulations, such as the German Data Protection Act (BDSG). Since the proposed system is designed towards a comprehensive data exchange, albeit defined and dependent on the access rights of a process owner, it is essential to realize the data transmittal in a responsible way. The inheriting advantages of NFC, such as transmittal only over short distance, data security by using the secure element, and proven methods in data critical applications from payment systems are key aspects in communicating and realizing a privacy sensitive approach. However, in the discussion regarding the e-Passport introduction RFID chips were perceived as being intrusive and easy to misuse, thus a negative influence on the perception of NFC could be induced in a similar way. Data privacy protection is a key factor in a passengers' overall determination of acceptance, as it can be linked to the estimated effort in use, as the release of personal information, which will be detailed in the following.

B. Acceptance

The potential of the system concept can only be successfully utilized, if a high usage rate will be achieved, which in turn is based on a high acceptance. It is essential to know about the factors determining a passenger's acceptance and incorporate them into the system development. The intention of using a technology can be fundamentally explained and described by cognitive reasoning theories. The study of acceptance among users of technology has been widely discussed in scientific literature. Based on the theory of reasoned action by Fishbein and Ajzen[16] and the theory of planned behavior by Ajzen[17], Davis has developed the *Technology Acceptance Model*[18] focusing of the adoption of technologies in services and products. Two key factors lead to the intentional use: the perceived ease of use, which is the subjective assessment of the effort to use or learn a technology, and the perceived usefulness, which represents the subjectively assessed probability of realizing a benefit by using the technology. This model has been further developed and applied in a series of research projects among them is the work by Venkatesh et al., who combined several aspects from acceptance models into a *Unified Theory of Acceptance and Use of Technology*[19], as can be seen in figure 4.

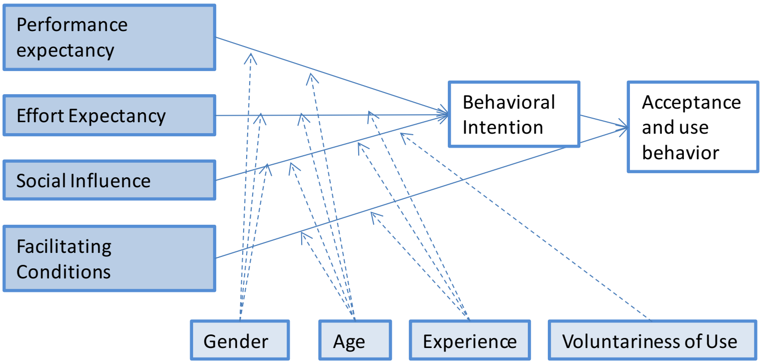

Figure 4. Schematic of the unified theory of acceptance and use of technology (Adapted from Venkatesh et al., 2003).[19]

Our survey was intended to represent this theoretical framework and incorporate the four major acceptance factors into the questionnaire. The results could then be used to specifically draw conclusions and reasoning towards the relevant acceptance factors and their influence on the system. Instead of presenting the interviewee with a model artifact that would require detailed explanations and the imaginary reasoning of the respondent, since the majority might not even be familiar with the NFC functionality, we focused on the implementation via a mobile phone respectively a smartphone that would supposedly contain an NFC chip. Several questions were designed to reflect the passengers' demographic and air travel behavior characteristics. The questionnaire was undertaken over two weeks each at the airports Cologne/Bonn and Berlin/Tegel in short interviews of approx. 6-8 minutes per passenger. In total we conducted 970 interviews with passengers, of whom the trip purpose was 45% business and 54% privately related with 1 % even, which is fairly representative of the passenger population of the selected airports. The survey statistics cover a sample of 39% female and 61% male passengers from all age groups. In our survey we could confirm the moderating factors of age, gender, and experience from the acceptance theory. Respondents from a younger age with more flights per year were more favorable of the usage of the mobile phone and valued the performance in usage as considerably higher than respondents from older age and with less experience. Additionally male respondents were more likely to have used a mobile phone in the passenger processes of identification at security checkpoint and the transmittal of relevant passenger data, as can be seen in figure 5 and were in general more favorable of other future services and applications. Since passenger characteristics differ, suitable customer groups have to be identified according to the needs in services and experience. If e.g. the flights per year are taken into account, the approval rates to use the mobile phone for identification, real-time information access or other commercial services are more precise, as can be seen in figure 6 for the example of identification

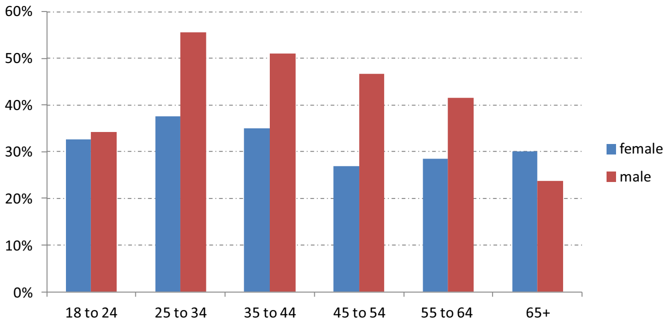

Figure 5. Percentages of passengers with positive view (yes/rather yes) regarding identification at security checkpoint and transmittal of passenger data via mobile phone in relation to gender and age group.

method. At least 55% of the frequent flyer with 6 or more flights p.a. are in favor of the use of mobile phones in security relevant identification procedures. Similarly, the approval rates to allow network communication, reveal actual location, and transmit personal data via mobile phones increase with annual frequency of flights.

All respondents furthermore have in majority seen a substantial performance enhancement by using the mobile technology. Therefore the proposed integration has a tremendous potential for improving the passenger transport processes. Nevertheless the effort expectancy in the form of data sharing and the allowance for access rights in the network communication was less optimistic. Together with a general skeptical view regarding data privacy protection, these obstacles need to be overcome for a successful implementation of the system. The key characteristics of NFC, such as the touch and go movement, are likely to be accepted, since transactions are initiated by a typical hand gesture and not in the passive method over long distances as in RFID systems.

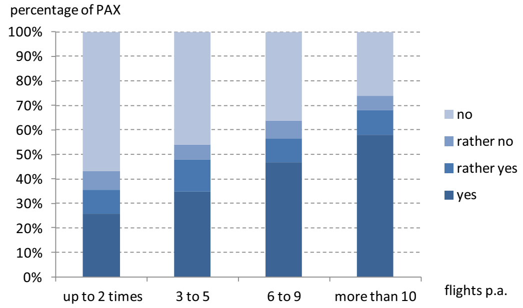

Figure 6. Distribution of passenger approval regarding identification at security checkpoint via mobile phone in relation to flights p.a.

Additionally, what is described in theory as facilitating conditions can be referred to in our application as the transferability and compatibility of the system regardless of the service provider or platform. There are considerable network effects towards the use of the NFC device in other services such as commercial payment. If it is learned once, the initial benefits will increase by using the NFC in secondary services along the travel process. Thus these facilitating conditions will play a decisive role in the acceptance rate. Therefore it can be reasoned, that the group to be targeted first for the implementation of the proposed NFC system are business related frequent flyer, who would benefit the most and are likely to have the highest network effects. Nevertheless, the inherent beneficial characteristics of NFC, e.g. the ease and security of transactions, have to be communicated appropriately, to counter the reservations and personal risk perceptions of possible first users.

Taking all acceptance factors aside, the proposed possibilities of NFC in passenger air transport depend on the market availability of mobile devices that feature this communication method. A decisive adoption rate will be achieved, when NFC is successfully used for mobile payment transactions on a wider scale. This seems to be the critical point for NFC to turn to mass market capabilities and be introduced in the passenger air transport. Air transport stakeholders should embrace for this moment by testing their individual applications and infrastructural requirements as well as giving their most valued customers the leading innovator role.

VI. Conclusion

The proposed approach to use an NFC enabled device to cover currently necessary information exchanges in the passenger process steps simplifies and eases the efforts for passengers. The inclusion into aviation security matters furthermore paves the way for NFC to be used in more comprehensive ways to establish the needed integration of security relevant information that would otherwise be lost along the process steps. NFC could support the role of data collection and still leave the control over the access to it in the hands of every passenger. Mobile phones are becoming increasingly accepted by passengers to be utilized as the digital boarding card. Since network effects are significant, it may be a short time until other commercial purposes, payment, and identification methods over mobile phone will become accepted by the majority of passengers. NFC then brings in the necessary data security and usability. Further research tasks that we will address are concerning the implementation policies, both operational and financial, and the legal implications. A simulation of the proposed system and qualitative security measure will serve as a validation tool of the concepts.

The changing threat situations determine the need for systematic changes as shown in previous examples of ever-more reactive technology introduction. Aviation security could well benefit from the possibilities of NFC, since it provides the needed characteristics of usability, data security and informational capabilities to support amongst others the strategy of passenger differentiation.

Acknowledgments

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Stall shield devices, an innovative approach to stall prevention?

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Stall has been an inherent hazard since the beginning of flying. Despite numerous efforts and a very succesfull stall mitigation strategy, stall as a phenomenon still exists and occasionally leads to accidents, mostly of a serious nature. This contribution explores the nature and dynamics of stall and the remedies that have been developed over time.

This contribution proposes an innovative approach, by introducing a stall shield device for prevention of stall in various segments of the fleet. A multi-actor collaborative approach is suggested for the development of such a device, including the technological, control and simulation and operational aspects of the design by involving designers, pilots and investigators in its development.

I. Introduction

From the early days of aviation, stall has been an inherent hazard. Otto Lilienthal crashed and perished in 1896 as a result of stall. Wilbur Wright encountered stall for the first time in 1901, flying his second glider. These experiences convinced the Wright brothers to design their aircraft in a ‘canard’ configuration, facilitating an easy and gentle recovery from stall. Over the following decades, stall has remained as a fundamental hazard in flying fixed wing aircraft. Stall is a condition in which the flow over the main wing separates at high angles of attack, hindering the aircraft to gain lift from the wings. Stalls depend only on angle of attack, not airspeed. Because a correlation with airspeed exists, however, a "stall speed" is usually used in practice. It is the speed below which the airplane cannot create enough lift to sustain its weight in 1g flight. The angle of attack cannot be increased to get more lift at this point and slowing below the stall speed will result in a descent. Airspeed is often used as an indirect indicator of approaching stall conditions. The stall speed will vary depending on the airplane's weight, altitude, and configuration. Fixed-wing aircraft can be equipped with devices to prevent or postpone a stall or to make it less (or in some cases more) severe, or to make recovery easier.

II. What is stall

A fixed-wing aircraft during a stall may experience buffeting or a change in attitude. Most aircraft are designed to have a gradual stall with characteristics that will warn the pilot. The critical angle of attack in steady straight and level flight can be attained only at low airspeed. Attempts to increase the angle of attack at higher airspeeds can cause a high-speed stall or may merely cause the aircraft to climb. Any yaw of the aircraft as it enters the stall regime can result in autorotation, which is also sometimes referred to as a 'spin'. Because air no longer flows smoothly over the wings during a stall, aileron control of roll becomes less effective, whilst simultaneously the tendency for the ailerons to generate adverse yaw increases. This increases the lift from the advancing wing and accentuates the probability of the aircraft to enter into a spin. In most light aircraft, as the stall is reached, the aircraft will start to descend and the nose will pitch down. Recovery from this stalled state involves the pilot's decreasing the angle of attack and increasing the air speed, until smooth air-flow over the wing is restored. The maneuver is normally quite safe and if correctly handled leads to only a small loss in altitude (50'-100'). During certification, a pilot is required to demonstrate competency to recognize, avoid, and recover from stalling the aircraft. The dangerous aspect of a stall is a lack of altitude for recovery.

A special form of asymmetric stall in which the aircraft also rotates about its yaw axis is called a spin. The net effect is that one wing is stalled before the other and the aircraft descends rapidly while rotating, Some aircraft cannot recover from this condition without correct pilot control inputs and loading. The most common stall-spin scenarios occur on takeoff (departure stall) and during landing (base to final turn) because of insufficient airspeed during these maneuvers. Stalls also occur during a go-around manoeuvre if the pilot does not properly respond to the out-of-trim situation resulting from the transition from low power setting to high power setting at low speed. Stall speed is increased when the wing surfaces are contaminated with ice or frost creating a rougher surface, and heavier airframe due to ice accumulation. A specific form of stall occurs while the aircraft is exposed to load factors higher than 1g. This stall is referred to as accelerated or turning flight stall and is typical for military aircraft which conduct their missions under extreme conditions. Modern civil commercial aircraft do not enter these flight regions by the protection of the flight envelope restrictions. Different aircraft configurations have different stalling characteristics. A benign stall is one where the nose drops gently and the wings remain level throughout. Slightly more demanding is a stall in which one wing stalls slightly before the other, causing that wing to drop sharply, with the possibility of entering a spin. A dangerous stall is one in which the nose rises, pushing the wing deeper into the stalled state and potentially leading to an unrecoverable *deep stall*. This can occur in some specific aircraft configurations wherein the turbulent airflow from the stalled wing can blanket the control surfaces at the tail.

III. Aircraft configuration

A. Swept wings

In particular swept wings are sensitive to flow disturbances by a phenomenon known as spanwise flow. This flow results from the sweepback of the wing where the thickening of the boundary layer near the tip of the wing causes a reduction of the maximum lift capability , compared with a two dimensional flow. At reaching the point of maximum lift coefficient, for straight wings with a constant airfoil section and without twist, initial stall would be expected to occur near the tip of the wing. For swept wings with the tip of the wing swept to the rear, the net lift distribution moves forward. Further increase of the angle of attack would inward progression of the stall, causing the plane to pitch up , leading to more stalling of the wing. Pitch up at stall is a highly undesirable flight characteristic, which is paid much attention to during the design and configuration arrangement in the development of a new aircraft. Such behavior is in contrast with straight wing aircraft that have inherent stability at stall and pitches down to a lower angle of attack back into an unstalled and fully controllable flight condition.

The solution to this stall problem took many forms, dealing with the aerodynamic design of the wings and stall avoiding or reducing devices, such as wing fences, notches to the leading edge. Modern solutions, driven by the need for shorter take off and landing than early large jets, have largely resolved the problem by the introduction of leading edge slats and compound trailing edge flaps.

Stall however, not only depends on the wing-alone stalling characteristics. Stalling and subsequent pitching characteristics depend on the aircraft configuration. The longitudinal and vertical position of the horizontal tail with respect tot the wing is particularly important.

B. T-tails

General aviation aircraft

In a T-tail configuration, the elevator is above most of the effect of downwash from the propeller, as well as the airflow around the fuselage and wings during normal flight conditions. Operating the elevators in this undisturbed airflow allows control movements that are consistent throughout most fly regimes. T-tails have become popular with light aircraft, because it removes the tail from the propeller wake or exhaust blast of the engines. Especially with sea planes and amphibians the horizontal surfaces are as far from the water as possible.

Small business aircraft

The configuration of small business aircraft favors an aft positioning of the engines mounted on either sides of the fuselage close to the tail. The size of this category of aircraft does not permit a mounting of the engines underneath the wing due to the restricted ground clearance and access comfort. In addition, during flight, passenger comfort is increased when the noise of the engine is at the aft, behind the passenger compartment. This positioning of the engines favors a T-tail configuration.

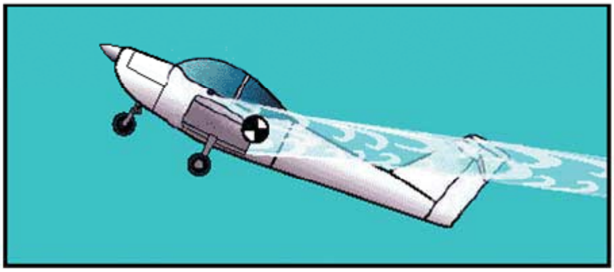

Fig 1. Stall conditions for general aviation aircraft

Large commercial aircraft

In the development of large commercial jet engine aircraft the T-tail has become a popular configuration. Its advantages included clean wing airflow without disruption by nacelles or pylons and decreased cabin noise. At the same time, placing heavy engines that far back created challenges with the location of the center of gravity in relation to the center of lift, which was at the wings. To make room for the engines, the tail planes had to be relocated to the tail fin, which had to be stronger and therefore heavier, further compounding the tail-heavy arrangement. T-tails also require additional design considerations to encounter the problem of flutter. The high load on the vertical stabilizer, caused by the positioning of the horizontal control surfaces at the top of the tail, creates additional momentum arms on the vertical tail. This must be compensated by an increased stiffness of the vertical tail fin and consequently, a weight increase.

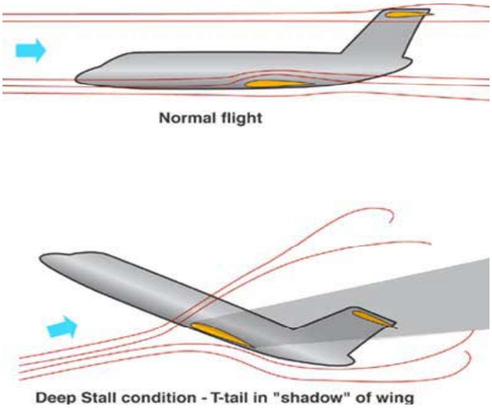

Fig 2. Stall conditions for T-tail configured commercial aircraft

In applying T-tails, during the majority of regular flight conditions, the horizontal tail planes are not influenced by the wake of the propellers. This exposure of the tail planes to the actual airspeed instead of the accelerated air flow of the wake causes a higher deflection of the rudder in order to achieve a similar pitch control force. Since the force on the elevators is proportional with the air speed, at high speeds a higher force has to be executed. Consequently, a T-tail configuration requires a higher control force on the rudders than another configuration. Alternatively, with an equal deflection of the rudder as in other configurations, a larger tail surface is required to achieve a similar pitch angle.

. In addition, in achieving an equal pitch momentum, the pitch forces required in a T-tail configuration are higher because the momentum arm is shorter. In addition, the positioning of heavy engines at the back of the aircraft creates an aft positioning of the center of gravity, reducing the momentum arm of the tail surfaces to the cg. Fluctuations in the cg must be compensated by a careful trim of the elevator, creating an induced drag penalty. While a T-tail configuration has considerable advantages regarding clean wing aerodynamics, passenger comfort and noise footprint, the configuration comes with a penalty of a heavier construction, additional weight and stall sensitivity as an inherent hazard.

In applying a swept wing configuration, at higher angles of attack closing in on the stall angle, the aerodynamic center of the main wing will travel forward, creating an additional negative momentum that has to be compensated by the elevator (Obert 2009).

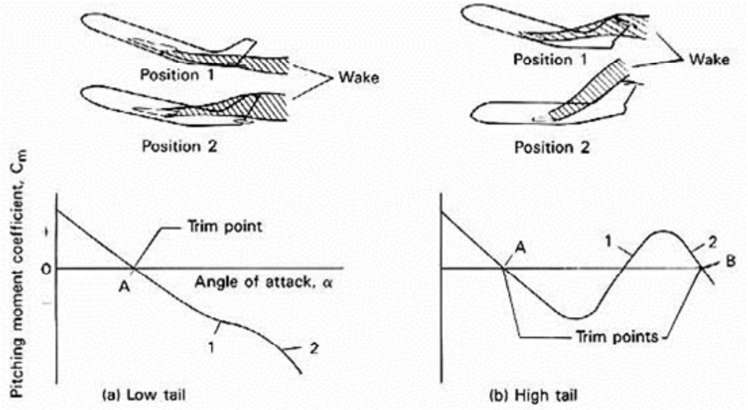

Fig 3. Cm alpha for large angles of attack

C. Cm-alpha diagram

The dynamic longitudinal behavior of an aircraft depends on the ability to recover from a stall and is expressed by the relation between the pitching moment and angle of attack.

In order to correct immanent stall at high angles of attack, a strong nose-down pitching moment is required. If such a moment is not produced, the angle of attack will increase until the tail plane becomes immersed in the wake of the separated flow of the wing (1). At such high angles of attack, the airplane will rotate further due to positive values of the moment coefficient (2). It will remain unstable and continue to pitch up until a new equilibrium is achieved at a very high angle of attack (b). Such equilibrium will be achieved at very high angles of attack because the pitching moment will become negative again. Due to the decreasing lift on the wings on these very high angles of attack, this maneuver may result in a ‘flat spin’ from which it is very hard to recover. The stability and controllability particularly of aircraft with T-tail configurations require very careful design to prevent the aircraft from entering such a ‘deep stall’ or ‘locked-in stall’ situation.

AERODYNAMIC DESIGN OF TRANSPORT AIRCRAFT

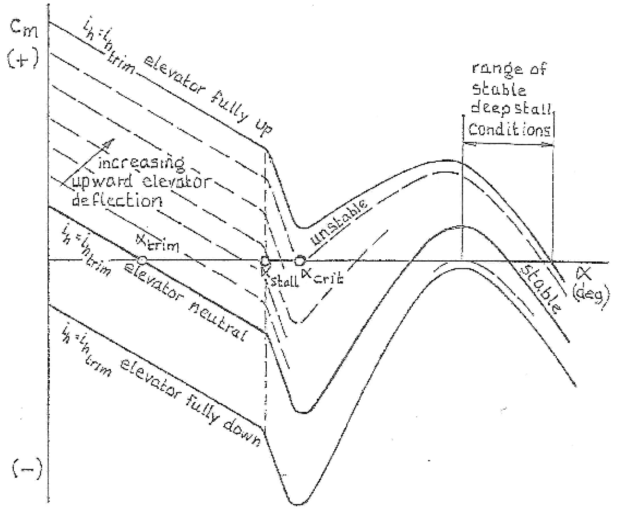

Figure 26.40 - Stability and controllability on an aircraft with a T-tail

Fig 4. Stability and controllability for T-tailed aircraft

IV. Stall devices.

A. Stall devices

Over the years, a wide range of devices has been developed to prevent, postpone or recover from a stall. Although a distinction is required between the various configurations, several generic aerodynamic, mechanical, warning and recovery devices have been applied:

Aerodynamic devices:

- aerodynamic twist will enable recovery because the downward twist at the tip will delay stall at the position of the ailerons, maintaining roll control when the stall begins
- stall strips, to trigger stall on certain positions of the wing to facilitate a controlled and gentle stall initiation and progressive stall development
- stall fences in the direction of the cord to stop progression of separated flow along the wing and dog tooth notches at the leading edge of the wing
- vortex generators to energize the flow, increasing the inertia of the boundary layer and delaying the separation of the boundary layer from the wing
- vortilons consist of flat plates near the wing leading edge. These vortex generators have a similar effect as the pylons of wing mounted jet engines and produce less drag than stall fences

Mechanical devices:

- stick pushers prevent a pilot to from entering stall because it pushes the elevator control forward, reducing the angle of attack while overriding the pilots input
- stick shakers are devices that warn the pilot for an oncoming stall by introducing artificial vibrations.

Warning devices:

- stall warning signals are applied to alert the crew audibly as the stall speed is approached
- angle of attack limiter is a flight computer that automatically prevents a pilot from a control input that rises the aircraft over its stall angle.
- angle of attack indicators are pressure differential instruments that integrate air speed and angle of attack in a continuous visual readout to the pilot as an indicator of available lift in the slow speed envelope.

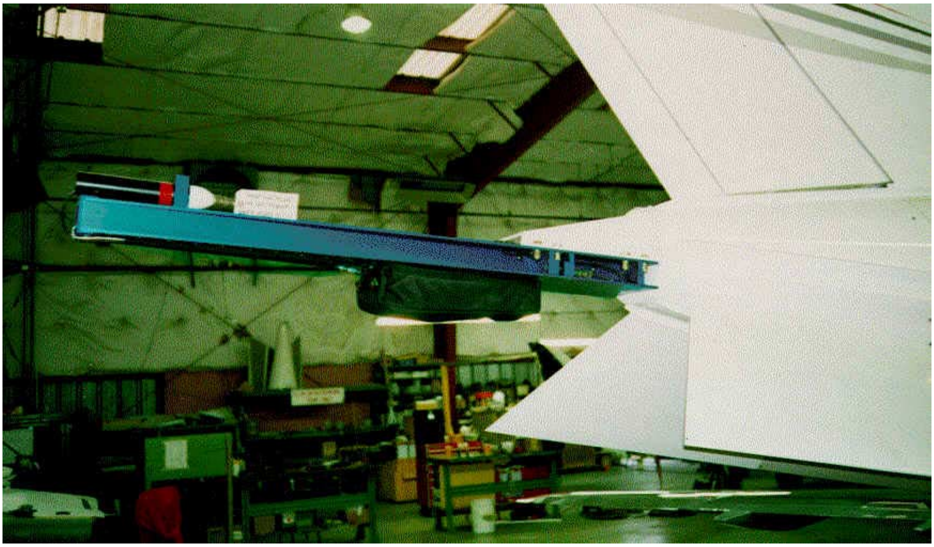

Fig 5. Tail mounted rocket and parachute stall recovery devices

A specific class of aerodynamic stall devices is created by the application of the canard configuration.
The canard is a control surface that functions as a horizontal stabilizer, located in front of the main wing. A canard actually creates lift to hold the nose up in contrast with a aft-tail design which creates a downward force to balance the aircraft preventing a nose down rotation. Canards can be designed either as the equivalent to an aft-tail control surface with similar size or as a tandem wing with the main wing. Canards advantages are in the area of stall characteristics because due to its design, the canard will stall before the main wing stalls, preventing a progressive nose-up rotation. Canards have several limitations. It is important that the canard stall before the main wing in order to prevent uncontrollable pitch up because the canard is positioned well before the centre of gravity. Because the canard stall first, some loss of maximum lift is incorporated because the main wing will never achieve its maximum angle of attack. Application of lift increasing devices on the main wing such as flaps, also require lift increase on the canard, putting strength and size demands to accommodate flap use. Finally, the downwash of the canard may interfere negatively with the flow on the main wing.
Canards have been applied on supersonic aircraft to improve the flight characteristics at low speed, such as with the Concorde and military fighters. A series of innovative designs has successfully applied canards to improve the overall aircraft flight characteristics, such as with the Piaggio P180, Beechcraft Starship and Rutan Long-EZ.

Fig 6. The Piaggio 180 canard configuration

B. Stall recovery

In order to recover from a stall, pilots have to be knowledgeable about the state of the aircraft and its dynamic behavior. Stall contributing factors should be familiar to pilots, such as the angle of attack, the air speed and the positioning of the center of gravity. A T-tail configuration as such is not principally different, but sensitizes the aircraft to a stall and deep stall behavior. In particular in landing configurations, the pilot must understand and follow proper landing procedures, in particular regarding the center of gravity position. Such information involves also aircraft loading, weight and balancers, trim, flap and power setting and meteorological issues, such as icing conditions. During the flight, the pilot depends on reliable air data information in order to interpret and monitor their flight performance. In modern fly by wire cockpits with flight envelope protection, impaired air data information may degrade normal protection systems. In many modern aircraft, an air data computer is applied to calculate airspeed, rate of climb, altitude, Mach number and rudder travel limits. Such a computer derives its information from the pitot static system, measuring the forces acting on the aircraft as a function of temperature, density, pressure and viscosity of the air. Errors in the pitot static system can be very dangerous because the information is critical to a successful flight performance. The pitot tube is sensitive to disturbances, such as clogging by water or ice, insects or other obstructions. Blocking the static port is a serious problem, because it affects all pitot static instruments. Such blocking will influence the horizontal and vertical airspeed indicator as the static tube is blocked at the altitude at which freezing occurred, misinforming the pilot about the actual horizontal and vertical airspeed. Erroneous data information will have its effect on the aircraft computer system by impairing the air data functions such as flight director, autopilot, auto throttle, rudder travel protection, speed calculations, wins shear protection and switches between Control Modes.

While recovery from a stall requires pilot skills that are considered basic to the aviator profession and are an integral part of flying skills, several dedicated mechanical devices for stall recovery have been developed:

- spoilers on either side of the wings can be deployed as asymmetric lift reducers to recover from an uncommanded roll towards the stalling wing by initiating a reversed roll due to lift loss on the non-stalling wing

- parachutes and rocket deployment underneath the tail end are developed as deep stall and spin recovery systems by providing a force pitching over the nose of the aircraft after entering a stall. Such systems are applicable on smaller aircraft only
- a specific design was developed with The Piaggio P180 and Learjet where a small forward wing combined with a main wing configuration. Although the front wings resemble a canard, a conventional tail providing stability. Aerodynamic stall recovery forces are provided by two 'delta fins' mounted on the bottom of the tail
- landing safely despite a deep stall or unrecoverable spin is optional due to the design and development of a ballistic recovery system, bringing down the entire aircraft to the ground by deploying a parachute in case of emergency. Such solutions however are restricted to smaller and light aircraft.


Learjet45

Fig **7. Delta fin configuration underneath the tail on a Learjet 45**

C. Beyond stall flight

Most military combat aircraft have angle of attack indicators indicating the pilot how close he is to the stall point. Modern commercial airlines collect information on the angle of attack, but do not directly display this information to the pilot. Instead, this information may drive a stall warning indicator system or provides performance information to the flight computer. In commercial aircraft, an immanent stall is indirectly communicated to the pilot through the Indicated Air Speed, depending on accurate and reliable air speed indicator equipment.

While the solutions to stall recovery took many and dedicated forms, modern commercial aircraft design takes stall into account in an integral design. The need for shorter takeoff and landing requirements have lead to the introduction of leading edge slats and large compound flaps, largely resolved the issue. In military aircraft, high maneuverability capability demands and beyond stall flight requirements have introduced the concept of vectored thrust. This engine thrust replaces the lift while maintaining alternative control over the aircraft replacing the loss of the ailerons and tail surfaces. Such post stall flights at very high angles of attack provides tactical advantages for military fighters and repeatedly have been demonstrated during air shows. Although such aircraft may be inherent unstable, their performance is kept under control by the 'fly by wire' system. Current fighters may perform in the deep stall region routinely using thrust vectoring.

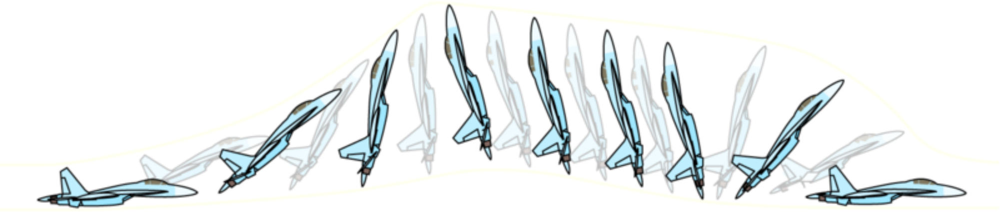

Fig 8. Sukhoi 27 performing a Cobra manoevre

V. Air accidents related to stall

Despite all efforst to reduce stall and deep stall to acceptable levels of occurrence, such events still happen occasionally in the commercial aviation community, raisng concern about their emerging complexity, dynamics and impact on public perception on safety of aviation. Such events have been subjected to major accident investigations are swerve as triggers for change throughout the industry.

A. Turkish Airlines TK1951

TK 1951 was a passenger flight which crashed on Wednesday 25 february 2009 in the vicinity of the Dutch Amsterdam Airport Schiphol. Nine out of the 135 occupants died.

The aircraft a Boeing 737-800 of Turkish Airlines, was heading from Istanbul Atatürk to Schiphol, but crashed at 10:26 hours, shortly before landing at the Polderbaan, and broke up into three parts.

The official investigation of the Dutch Safety Board (DSB) mentioned the behavior of the pilots as the main cause for the accident. Despite a defect radio altimeter and deficiënt instructions of ATC, the pilots couls have prevented the accident.

On March 4th, DSB gave a first press conference on the causes of the accident. The press was notified on a technical malfunctioning as the basis for the crash. As the plane flew at 1950 feet (approximately 600 meter) and had initiated the landing on autopilot,the left radio altimeter indicated an incorrect altitude of minus 8 foot. Thsi malfunctioning impacted the autopilot.The autopilot closed the autothrottle -which controls the engine power-, reducing the speed of the aircraft. The pilots,which earlier on notified the malfunctioning in the altimeter, did not respond to this change. Only when the aircraft was flying so slow that the stall speed warning was activated, the pilots directly intervened by giving full throttle. The aircraft had descended to an altitude of 150 meter and the respons came too late. Tha aircraft stalled and crashed shortly before the runway threshold. The problem with the radio altimeter had occurred 2 times before during the previous 8 flights in a similar situation before landing.

B. Colgan Air 3407

During the flight and continuing through the plane's landing approach, the crew had been flying on autopilot. During final approach, the pilots extended the aircraft's flaps and landing gear for landing. After the landing gear and flaps had been extended, the flight data recorder (FDR) indicated that the airspeed had decayed to 145 knots (269 km/h). The captain, who was the pilot flying, then called for the flaps to be set at the 15 degree position. As the flaps transitioned past the 10 degree mark, the FDR indicated that the airspeed had further slowed to 135 knots (250 km/h). Six seconds later, the aircraft's stick shaker, a device intended to provide aural and tactile awareness of a low speed condition, sounded.

After initial FDR and CVR analysis, it was determined that the aircraft went through severe pitch and roll oscillations after positioning its flaps and landing gear for landing. Until that time, the Dash 8 had been maneuvering normally. The de-icing system was reported to be turned on. During descent, the crew reported about 3 miles (4.8 km) of visibility with snow and mist. Preceding the crash, the aircraft's stall-protection systems had activated. Instead of the aircraft's diving straight into the house as was initially thought, it was found that the aircraft fell 800 feet (240 m) before crashing pointing northeast, away from the destination airport. The passengers were given no warning of any trouble by the pilots. Information from the aircraft's flight data recorder indicates that the plane pitched up at an angle of 31 degrees, then down at 45 degrees. The Dash 8 rolled to the left at 46 degrees, then snapped back to the right at 105 degrees, before crashing into the house.

The National Transportation Safety Board determines that the probable cause of this accident was the captain's inappropriate response to the activation of the stick shaker, which led to an aerodynamic stall from which the airplane did not recover. Contributing to the accident were (1) the flight crew's failure to monitor airspeed in relation to the rising position of the lowspeed cue, (2) the flight crew's failure to adhere to sterile cockpit procedures, (3) the captain's failure to effectively manage the flight, and (4) Colgan Air’s inadequate procedures for airspeed selection and management during approaches in icing conditions.

C. Air France AF 447

While the investigation is still awaiting formal conclusion, preliminary reports of the BEA stated that the aircraft crashed following an aerodynamic stall caused by inconsistent airspeed sensor readings, the disengagement of the autopilot, and the pilot making nose-up inputs despite stall warnings, causing a fatal loss of airspeed and a sharp descent. Additionally, reports indicated that the pilots had not received specific training in "manual airplane handling of approach to stall and stall recovery at high altitude", and that this was not a standard training requirement at the time of the accident.

The reason for the faulty readings is unknown, but it is assumed by the accident investigators to have been caused by the formation of ice inside the pitot tubes, depriving the airspeed sensors of forward-facing air pressure. Pitot tube icing has contributed to airliner crashes in the past – such as Northwest Airlines Flight 6231 in 1974.[

At 02:10:05 UTC the autopilot disengaged as did the engines' auto-thrust systems 3 seconds later. The pilot made a left nose-up input, as the plane began rolling to the right. The plane's stall warning sounded briefly twice due to the angle of attack tolerance being exceeded by short vertical accelerations due to turbulence. 10 seconds later, the plane's recorded airspeed dropped sharply from 275 knots to 60 knots. The plane's angle of attack increased, and the plane started to climb. The left-side instruments then recorded a sharp rise in airspeed to 215 knots. This change was not displayed by the Integrated Standby Instrument System (ISIS) until a minute later. The pilot continued making nose-up inputs. The trimmable horizontal stabilizer (THS) moved from 3 to 13 degrees nose-up in about 1 minute, and remained in that latter position until the end of the flight.

At around 02:11 UTC, the plane had climbed to its maximum altitude of around 38,000 feet. There, its angle of attack was 16 degrees, and the thrust levers were in the TO/GA detent (fully forward), and at 02:11:15 UTC the pitch attitude was slightly over 16 degrees and falling, but the angle of attack rapidly increased towards 30 degrees. The wings lost lift and the aircraft stalled. At 02:11:40 UTC, the captain re-entered the cockpit. The angle of attack had then reached 40 degrees, and the plane had descended to 35,000 feet with the engines running at almost 100%. The stall warnings stopped, as all airspeed indications were now considered invalid by the aircraft's computer due to the high angle of attack and/or the airspeed was less than 60 knots. In other words, the plane was oriented nose-up but descending steeply.

Roughly 20 seconds later, at 02:12 UTC, the pilot decreased the plane's pitch slightly, air speed indications became valid and the stall warning sounded again and sounded intermittently for the remaining duration of the flight, but stopped when the pilot increased the plane's nose-up pitch. From there until the end of the flight, the angle of attack never dropped below 35 degrees. During the last minutes, the thrust levers were in the "idle" detent position. The engines were always working, and responsive to commands. While the incorrect airspeed data was the apparent cause of the disengagement of the autopilot, the reason the pilots lost control of the aircraft remains something of a mystery, in particular because pilots would normally try to lower the nose in case of a stall. Multiple sensors provide the pitch (attitude) information and there was no indication that any of them were malfunctioning. One factor may be that since the A330 does not normally accept control inputs that would cause a stall, the pilots were unaware that a stall could happen when the aircraft switched to an alternate mode due to failure of the air speed indication.

In an article on High-Altitude Upset Recovery, captain C. B. "Sully" Sullenberger described it as a seminal accident. "We need to look at it from a systems approach, a human/technology system that has to work together. This involves aircraft design and certification, training and human factors. If you look at the human factors alone, then you're missing half or two-thirds of the total system failure..."

Sullenberger also believes that accurate airspeed indications alone aren't the best data the crew needs to recover from an upset. That requires knowing the wing's angle of attack (AoA). "We have to infer angle of attack indirectly by referencing speed. That makes stall recognition and recovery that much more difficult. For more than half a century, we've had the capability to display AoA (in the cockpits of most jet transports), one of the most critical parameters, yet we choose not to do it."

VI. Towards stall prevention?

A. Intermediate conclusions

Some intermediate conclusions on stall as an aerodynamic phenomenon can be drawn:

- Since the beginning of flying with fixed wing aircraft, stall has been an inherent hazard to flight safety.
- Various stall scenarios exist, discriminating between various flight conditions, aircraft configurations and flight envelope restrictions
- Stall does not derive from airspeed and can occur at any speed. Stall only occurs if the wings have too high an angle of attack.
- Stall is recognized as an inherent risk to aircraft with specific configurations, in particular aircraft with swept wings and T-tails
- A variety of dedicated solutions has been developed for stall recognition and recovery, covering aerodynamic, mechanical and behavioral issues.
- During the development of modern aircraft, a more generic approach has been developed, dealing with high lift wing design, flight envelope protection and pilot warning systems. This avoidance strategy of getting close to a stall region has reduced the occurrence of stall to an acceptable level of occurrance
- In the military, a different approach has been favored, with dedicated designs for thrust vectoring, taking over the loss of lift and controls by engine power vectoring the aircraft performance through the deep stall region.

Despite these solutions, stall and incidentally deep stall, still occurs. Flow separation on the wing may induce stall, while also the elevator will lose its effectiveness. A separated flow over the complete wing span will also eliminate most of the aileron effectiveness. A roll-off may result in a spin, which will most likely at these high angles of attack be a flat spin from which recovery is very difficult. Recent major accidents indicate the potential for stall, at a high altitude as well as low altitude. A timely recognition of stall is critical, but may be hampered by the ability of the crew to recognize and diagnose a stall in a timely manner and respond accordingly. The transparency of the automated flight management system for the crew is a safety critical factor in the ability to diagnose and recover from a stall. Under all flight circumstances a stable and controllable flight performance should be maintained.
Some recent air crashes indicate that due to operational circumstances beyond the aircraft design characteristics and performance, such a performance is jeopardized.

However, some more fundamental flight performance issues also emerge from this survey of the stall phenomenon:

- all stall recognizing and mitigating strategies have not eliminated the stall as a phenomenon; major stall related accident still occur. New form for old issue?
- airspeed indications are not redundant and only rely on the use of pitot tube technology. Applications of a new technology such as GPS might provide the necessary redundancy in air data information supply
- in contrast with roll and yaw control, pitch control of aircraft is not redundant. There are no substitute strategies for controlling the pitch of commercial aircraft, in contrast with the military where thrust vectoring is an option
- the angle of attack is only indicated as a secondary parameter, derived from the Indicated Air Speed. The commercial aviation has no direct alpha indicator, in contrast with the military
- civil aviation aircraft lack the ability to create a negative pitch moment throughout the flight performance envelope by having direct access to speed and attitude as safety critical flight parameters.

B. Towards innovative designs

While more pragmatic solutions have achieved a high level of sophistication in stall mitigation and recovery, a more fundamental approach to stall avoidance should be developed in order to deal with systemic deficiencies in stall avoidance.

An innovative solution to this more fundamental issue should comply with principles of dynamic flight control over the fundamental forces that are exercised on general aviation and commercial aircraft:

- introducing new aerodynamic forces instead of manipulating existing forces
- introduction of such aerodynamic forces in uncorrupted air flow
- generating high pitching moments by small forces combined with long arms
- introducing correcting forces only in case of emergency.

In dealing with stall, an innovative design is suggested, based on these principles of dynamic vehicle control (De Kroes 2012). Such a design is called a ‘stall shield device’ and consists of the following features:

- on the fuselage of the aircraft, several adjustable control surfaces are present, discriminating a neutral position in which the surfaces are incorporated in the fuselage structure and an operating position, extended into the free air flow around the fuselage
- these control surfaces are located at the nose and tail section of the aircraft in order to minimize the size of the aerofoil surfaces, providing the largest momentum arm to the center of gravity
- these stall shields are only deployed in case of near stall and emergent unstable flight under 1G conditions to eliminate aerodynamic drag in their neutral position
- to control the dynamic behavior of the aircraft in a near stall or stall these surfaces can adjust the required aerodynamic forces by manual or automated control over the surfaces by changing their size and/or angle of attack
- these surfaces can be operated by either select nose or tail or combine a nose and tail mode of operation to provide a stable flight performance, depending on the stall scenario, flight phase, aircraft configuration and operating conditions
- a stall shield control system is integrated in the flight management system, supported by dedicated computer software, depending on the level of sophistication of the aircraft control systems
- the stall shield device also incorporates a flight simulator program. Such a simulation program can be applied to train pilots in a flight simulator, or to assess stall characteristics in the early phases of a design by combining such a simulator with CFD applications. This may speed up the aircraft certification process, facilitating rapid safety critical design interventions before the phase of wind tunnel tests and flight tests and expensive adaptations are to be considered in the detailing phase.

Fig 9. Stall shields at the nose end of a T-tailed aircraft

Such stall shield devices and their control systems should benefit from developments in GPS systems for speed, altitude, positioning and flight attitude identification to provide redundancy over the pitot static data supply. In addition, a direct angle of attack indicator in the cockpit display is required to inform the pilot on the actual flight attitude of the aircraft while the stall shield device is operational.

Such an mobilization of rapid deployable control forces in dynamic vehicle control and recovery from unstable performance is not unique for the aviation sector. They also have found their application in the maritime sea going sector. The sea keeping behavior of fast ships in stern quartering and following waves should be improved. In particular the resistance against large combined yaw and roll motions in conditions with large waves is a known challenge. Hydromechanical research at DUT in cooperation with Damen Shipyards in the Netherlands has demonstrated the feasibility of a vertical controllable bow combined with a ‘magnus rotor’. In particular for fast vessels with a deeply submerged bow –the axel bow design- excellent test results have been demonstrated in preventing broaching conditions, never approaching seriously dangerous values (Keuning and Visch 2009)

Feasibility and market opportunities

Based on historical information on flight safety issues and accident investigations, the stall shield device has potential for several market segments:

- general aviation, in particular with less experience pilots, manual flight performance and VFR conditions. Stall shields at the tail end could improve stall performance of such aircraft
- small business aviation where stall sensitive configurations exist, combining jet engines with T-tails and swept wing designs. Automatically deploying stall shields on the nose could improve the stall performance of such aircraft
- commercial aircraft, in securing safety as a strategic public value in commercial aviation, balanced against other values such as economy, environment, dealing with performance optimization strategies. Automatically deployable stall shields at the nose and/or tail end could improve the stall performance of such aircraft
- innovations in aviation, based on strategic visions for future developments dealing with hyperbolic flight, smart wing technology, innovative power plants, composites, green and sustainable operations. Stall shields could be an integral part of the design of such aircraft, replacing conventional use of tail surfaces and controls.

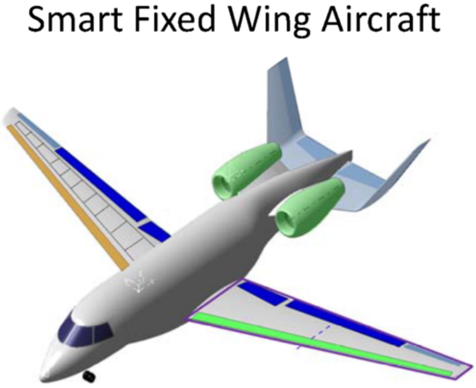

Fig 10. Aircraft development according to Flightpath 2050

VII. Conclusions

Assessment of the stall shield as a feasible and desirable innovation should be done in the early phases of conception. Discussing the issue of stall and remedies for stall related accidents are not restricted to the design community. Feedback from operationally experienced people such as pilots and accident investigators provide insights in the actual responses of the system under specific conditions that cannot be covered by an encompassing proactive survey during design and development. A multi-actor assessment should identify strengths and weaknesses, opportunities and threats of the stall shield, providing a safety impact assessment before the concept is released for practical use.

Eventually, if the concept contains inherent deficiencies and design flaws that have not been identified in the design, development and certification phase, they may emerge as accidents during the operational phase. In such a case, the cure could be worse than the cause.

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Flyover noise synthesis for the Virtual Community Noise Simulator

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Local effects of noise mitigation measures would best be researched with high-fidelity tools. It may be preferred to actually listen to the audible results from such a tool, which is possible by applying noise synthesis. Noise synthesis, based on separate modeling of airframe and engine noise components, is described for a virtual community noise simulator. The merits of individual atmospheric propagation models are qualified. The propagation results on synthesized aircraft noise, following the implementation of two different models, are presented to qualify the importance of atmospheric propagation modeling. The effects on common flyover noise metrics for single events are minimal for this particular flyover case. This is due to the fact that at a short distance, which defines the level of the noise metric, the atmospheric propagation is well modeled by traditional straight paths.

Nomenclature

c = Speed of sound
D = Directivity function
F = Frequency loading spectrum
l = Turbulent eddy length scale
M = Mach number
p = Acoustic pressure
P = Acoustic power loading function
r = Distance
V_{jet} = Jet velocity
θ = Observation angle

I. Introduction

As a result of the ongoing growth in air traffic, the impact of aircraft noise in communities near airports is or can become a limiting factor for expansion. Legislators are concerned with protecting the communities of adverse aircraft noise. Consequently, regulations were formed in the Netherlands that limit the noise at specific control points. At these control points, the accumulated noise over an entire year may not exceed a certain level. The metric used to accumulate and express the yearly noise is usually the L_{DEN} or a similar metric. Examining the effect of noise mitigation measures on the basis of a yearly averaged metric will exclusively allow determination of the average effects rather than local effects.

The local effect of a noise mitigation measure can be studied with more realism[1] by using a high-fidelity simulation model that predicts the actual sound signature, instead of a noise metric, at a particular position. Usually such a modeling approach implies a long calculation time and results in similar information, i.e. noise contour plots. One step further would be to listen to the difference rather than looking at a contour plot. Developments to that end, predicting the audible sound at a

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reasonable computational time, are ongoing at both the National Aeronautics and Space Administration (NASA) and the Dutch National Aerospace Laboratory (NLR).

The simulation environment at the NLR is called the Virtual Community Noise Simulator (VCNS). This paper describes recent progress of the work on the VCNS and future research directions.

II. Virtual Community Noise Simulator

In 2007, the NLR obtained the VCNS. The system originates at NASA where developments are ongoing since 2003. At NASA the idea to presents audible flyover results emerged. This ought to be combined with a virtual reality environment as to present the actual flyover results in a realistic setting. Developments to that end were presented[2-4] and the NLR started a cooperation with NASA to work together on this particular subject. As result, a test subject can be exposed to flyover noise in a virtual reality environment in the VCNS. The virtual reality is presented through a Helmet Mounted Display (HMD) whereas the sound is presented over headphones. The system is based on the basis of seperately modeling the source noise (prediction and synthesis), atmospheric propagation and listener effects. Each of these modelling steps is treated briefly.

A. Source noise prediction

An aircraft has different noise generating parts. The two most prominent ones are usually classified as engine noise and airframe noise. To model both, a notion of the aircraft flight mechanics and engine behaviour is necessary. The source is in this case simplified to be a compact source, i.e. all sound is assumed to be emitted from one position. This is a far-field assumption that is valid for the distances considered in flyover situations. As a consequence, all the acoustic pressures emanating from the source are assumed to be at one and the same position, usually the centre of gravity.

Airframe noise is generated by the turbulent wake coming from the gears or the wing. Fink[5] defined a relation that can be used to predict all airframe noise sources by applying empirical relations. The main equation describes the acoustic pressure and is, written as:

$$p^2 = \frac{P \cdot D \cdot F}{4\pi r^2 (1 - M\cos\theta)^4} \tag{1}$$

where, P is the acoustic power loading that depends on the geometry of the airframe component and airspeed, D is the directivity function and F contains the frequency spectrum loading of the airframe component. The denominator contains the spherical spreading loss and the convective amplification factor. If the denominator is unity, the acoustic pressure defined at a virtual sphere (1m. radius) around the airframe component source is found. Using the correct values for P, D and F for a particular aircraft leads to a Sound Pressure Level (SPL) prediction at the source. Figure 1 shows the result for a Boeing 747-400 flying at Mach 0.3 with the gear and high-lift devices fully extended, as a function of the (straight line) observation angle between the listener and the aircraft nose.

From Figure 1 it is observed that the flap and slats of this particular aircraft form the major overall contribution in this (landing) configuration of the airframe noise. The peak level (roughly 141 dB) of the overall airframe noise is radiated in the front arc of the aircraft. To the rear arc, the SPL drops gradually by more than 10 decibel. Also clear is that a clean configuration, i.e. no gears or flaps extended leaving only the dark blue entries in Figure 1, will lead to a significantly lower acoustic pressure at the source.

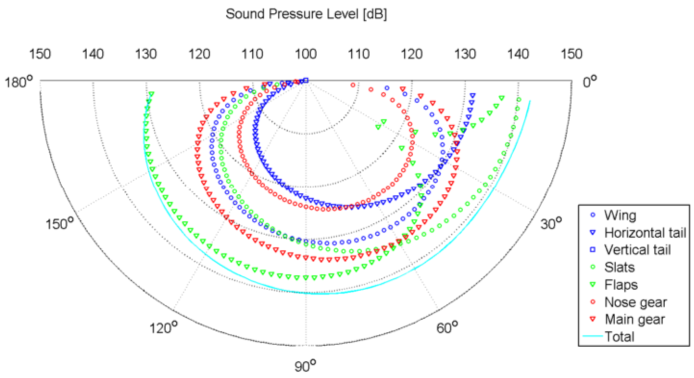

Figure 1 The airframe noise of a Boeing 747-400 from the individual airframe components.

The engine is modeled from two individual noise generating components, the jet mixing noise and the fan noise. Jet mixing noise is generated by the mixing turbulent airstreams that leave the gas turbine. Due to the velocity differences of the airstreams, turbulence is generated that emit acoustic waves. Lighthill[6] was the first to describe this complex phenomenon from a theoretical perspective. One of his breakthrough results was that a turbulent jet emits noise that scales proportional to the velocity difference of the jet and the ambient atmosphere. This equates to,

$$p \propto \frac{\rho V_{jet}^{8} l^{2}}{c^{5}} \qquad (2)$$

where, the acoustic power p is proportional to the density ρ, the jet velocity V_{jet}, the turbulent eddy length l and the speed of sound c. As the jet emitted from gas turbines is heated by the combustion, the exponent used for the jet velocity is usually lower.

Stone[7] developed an empirical scaling law based on this remarkable theoretical result. If it is applied to a regular by-pass engine, three turbulent areas are identified in his model that each produce jet noise. These areas are called the large scale, transitional scale and small scale mixing noise. The overall sound pressure levels of the jet mixing noises are illustrated in Figure 1.

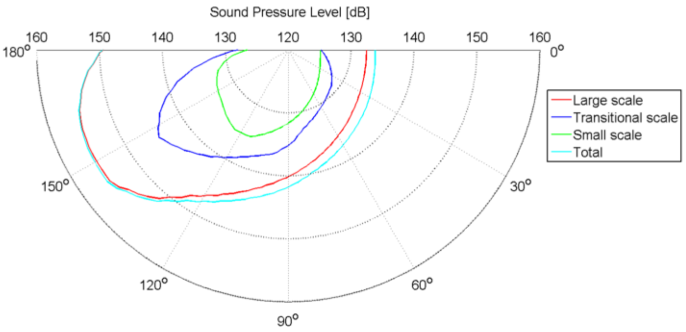

Figure 2 The jet mixing noise for a CF6-80C2 engine at 100 %N1.

The remaining engine noise source that is modeled is the fan. Whereas the jet mixing and airframe noise sources are generally of a broadband nature, the fan emits tonal components as well. The main tonal component is a function of the Blade Passage Frequency (BPF) and caused by fluctuating aerodynamic forces acting on the fan's rotor and stator vanes. These tones usually exhibit higher harmonics, i.e. tones at integer multiples of the BPF. Buzz-Saw is a second tonal component that can be generated by the fan. If the fan tip speed exceeds the sound speed, the shocks at the fan create a tonal noise. For this noise generating mechanism, the fan must be spinning at a high enough power setting and therefore this sound is usually only present in take-off conditions. The shocks emanating from each blade form a single shock system, i.e. a single tonal component, at a multiple of the engine rotational frequency which is lower than the BPF. The final (broadband) noise component that is emitted by the fan is due to the turbulent inflow of air passing the blades. These three components generate the fan associated noise. An empirical model is available[8] from which the individual noise contributions, for the same engine as for the jet mixing noise, is calculated. See Figure 2.

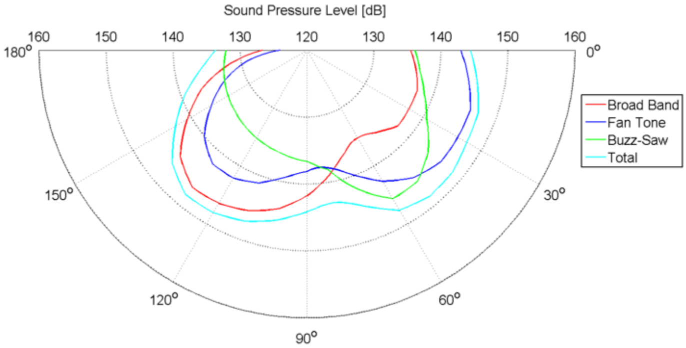

Figure 3 Fan noise components.

From Figures 1-3 we see that the directivity patterns are remarkably different for the individual components. Airframe noise is radiating more to the front than to the back. The fan shows a decrease in SPL when flying directly overhead, i.e. 90 degrees emission angle. The fan tones are more prominently audible to the forward arc than the rear arc and have a higher SPL than the airframe noise. The jet mixing noise is almost exclusively radiated to the rear of the engine. It is also, by far, the loudest source on the aircraft.

B. Source noise synthesis

Having a source noise prediction, demonstrated in II.A, is the start of the actual sound synthesis. Tonal components can be synthesized by applying the correct frequency and amplitude characteristics to a basic cosine wave form. Some of the particularities are recently described in[9]. Modulation in frequency and amplitude is necessary to improve the tonal synthesis. The details are not repeated here.

Two different synthesis methods are available at the NLR for broadband noise synthesis. First is the dynamic equalizer approach[10]. This equalizer modifies a pink noise source per third octave frequency band by equalizing/convolving the noise with the time varying calculated SPL. As a result the equalization applies effectively the directivity pattern as the calculated results vary with the emission angle.

More recent work[11], focusing on a new integrated framework for the noise synthesis in cooperation with NASA, uses a different approach. The difference is that the synthesis is executed in the frequency domain on a narrow band basis rather than a third-octave band level. Figure 3 shows the broadband synthesis steps graphically.

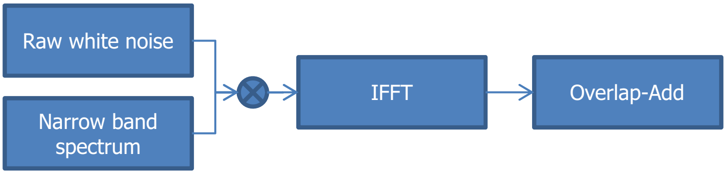

Figure 4 The synthesis method as applied in the new framework.

The synthesis starts with a white noise signal. At any given flyover time point, the results from the source noise prediction are used. If only third-octave band predictions are available, which is the case for the predictive models treated here, an interpolation is required. By multiplying both contributions, i.e. since this is carried out in the frequency domain it is equivalent to a convolution operation, the calculated spectrum is applied to the white noise. The succeeding intermediate result is transformed to the time domain by using an Inverse Fast Fourier Transform (IFFT). To build-up the entire signal from the IFFT results, an Overlap-Add technique is used. This technique ensures a smooth transition from one applied narrow band spectrum, i.e. directivity pattern, to the next as the aircraft is flying over. Any audible artifacts (clicks), due to changing directivity angles, power settings or changing airframe settings, are minimized by this Overlap-Add technique. The result is the broadband noise as emitted by the aircraft at the source.

C. Propagation

As the sound travels from the source towards the listener, the atmosphere influences the sound waves. Another propagation effect is due to the ground reflection of the sound which interferes at the listener's ears with the direct wave. The refractive and diffractive effects due to atmospheric propagation, predicted by a Fast Field Program (FFP)[12] and ray tracing, were shown to have an impact on the audible noise[12,13]. Atmospheric propagation effects are included in three methods: spherical spreading, ray tracing and an FFP.

Not every approach is equally capable to provide the required information for the noise synthesis. Spherical spreading ignores the effects of the wind and assumes that the propagation of the sound follows a straight line between the source and the listener. Both the FFP and ray tracing can calculate these effects but relevant information, like emission and receiver angles, is only accessible when adopting the ray tracing approach. Table 1 shows the different modeling options for atmospheric propagation.

Table 1 Phenomena that are possibly modeled (top three) and can potentially be extracted (bottom three) from the different atmospheric propagation models.

	Spherical spreading	Ray tracing	Fast Field Program
Absorption	x	x	x
Refraction		x	x
Diffraction			x
Emission angle	x	x	
Receiver angle	x	x	
Travel time	x	x	

Every propagation method has its merit. Spherical spreading is efficiently calculated and therefore attractive for real-time implementation in a virtual reality environment. As long as the wind effects are minute, spherical spreading provides a good indication of the propagation characteristics. If the wind conditions are more prominent, ray tracing or the FFP can be used. Ray tracing provides an accurate indication of the emission and receiver angle, necessary for the directivity at the source and the ground reflection at the receiver but lacks diffraction modeling. Diffraction is inherently included in the FFP, which solves the Helmholtz equation, but this comes at a computational penalty compared to ray tracing.

In the end, ray tracing is recommended. A correction method to incorporate diffraction is described[10] to augment the ray tracing solution. This result is a balance between all methods and includes all effects necessary for noise synthesis and is therefore selected.

The found propagation characteristics are calculated in the frequency domain and need to be applied to the synthesized sound at the source, which is in the time domain. The travel time is necessary to calculate at which time the sound will reach the listener and allows simulation of the Doppler shift [10]. The calculated absorption losses are transformed into a Finite Impulse Response (FIR) filter. By running the sound, containing the Doppler shifted frequencies, through the filter, the atmospheric absorption effects are applied. Propagation losses due to refraction and/or diffraction can be integrated in the absorption filter as an overall or frequency dependent filter gain. The ground reflection is added to the signal by taking the ground impedance into account and including the added travel time and phase shift due to the reflection. This digital signal processing effects apply the calculated propagation characteristics and return the sound at the listener position.

D. Listener effects

The listener is allowed to change his head orientation in the virtual reality environment in order to locate the aircraft and familiarize with the environment. During the altering head orientation, a sensor tracks the orientation and feeds it to the VCNS system. This is necessary because in order to locate the aircraft position during the flyover, inter-aural differences between the left and right ear must be modeled and applied over the headphones. To this effect, a Head Related Transfer Function (HRTF) is applied. Differences due to the orientation of a particular ear to the aircraft are applied by using HRTF filtering operations to the signal. The sound, as experienced in the simulator, is notably different for the left and right ear and often referred to as binaural modeling which allows localizing the aircraft.

III. Application

A full flyover simulation using the newly developed framework is demonstrated. The aircraft source was comprised of jet noise combined with tonal components of fan noise. The jet noise prediction was based upon a CF6-80C2 engine from a Boeing 747-400, whereas the fan noise prediction was based upon the Honeywell Tech977 engine. Because the simulation is prediction-based, alternative configurations are possible. Each noise component is synthesized independently and combined prior to propagation.

Researchers often apply a boundary layer model as input to atmospheric acoustic propagation problems. The most well-known of the boundary layer models are formed by the Businger-Dyer equations. These equations exclude the possibilities of wind speed inversions and changing wind directions. These limitations are circumvented by using measurements. The used atmosphere for the calculation of the propagation effects, during the flyover, is measured at Wallops field (Virginia, USA) on the 10th of October 2011. Figure depicts the atmosphere as used throughout this paper.

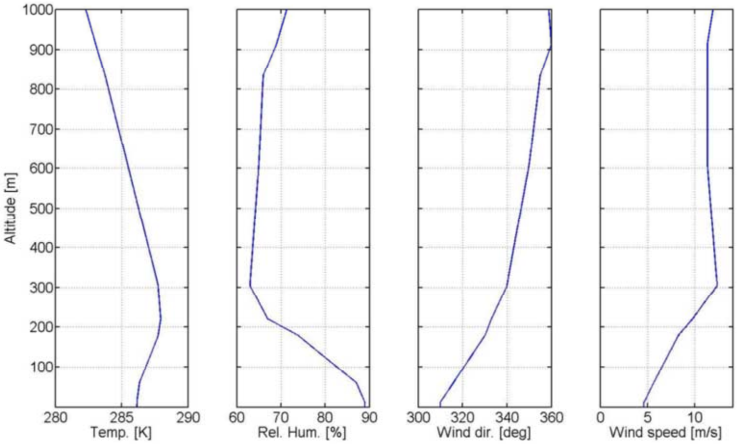

Figure 5 The used atmosphere for the calculation and application of the atmospheric effects.

The aircraft itself is flying a straight and level trajectory from x=6000 to -6000 m, at an altitude of 152.4 m (500 ft.), with a speed of 100 m/s. Both the engine fan and jet noise components are simulated at 87% N1. The listener is moving perpendicularly away from the ground track of the aircraft at a walking pace (5 km/h). Consequently, the aircraft does not fly directly over the listener.

Two different atmospheric propagation approaches are calculated and shown as spectrograms in Figure , this are illustrations depicting the frequency content and amplitude of the sound. The top illustration shows the results when using spherical spreading, i.e. a straight path approach, the bottom picture shows the result when taking the wind effects into account by using a ray tracing technique.

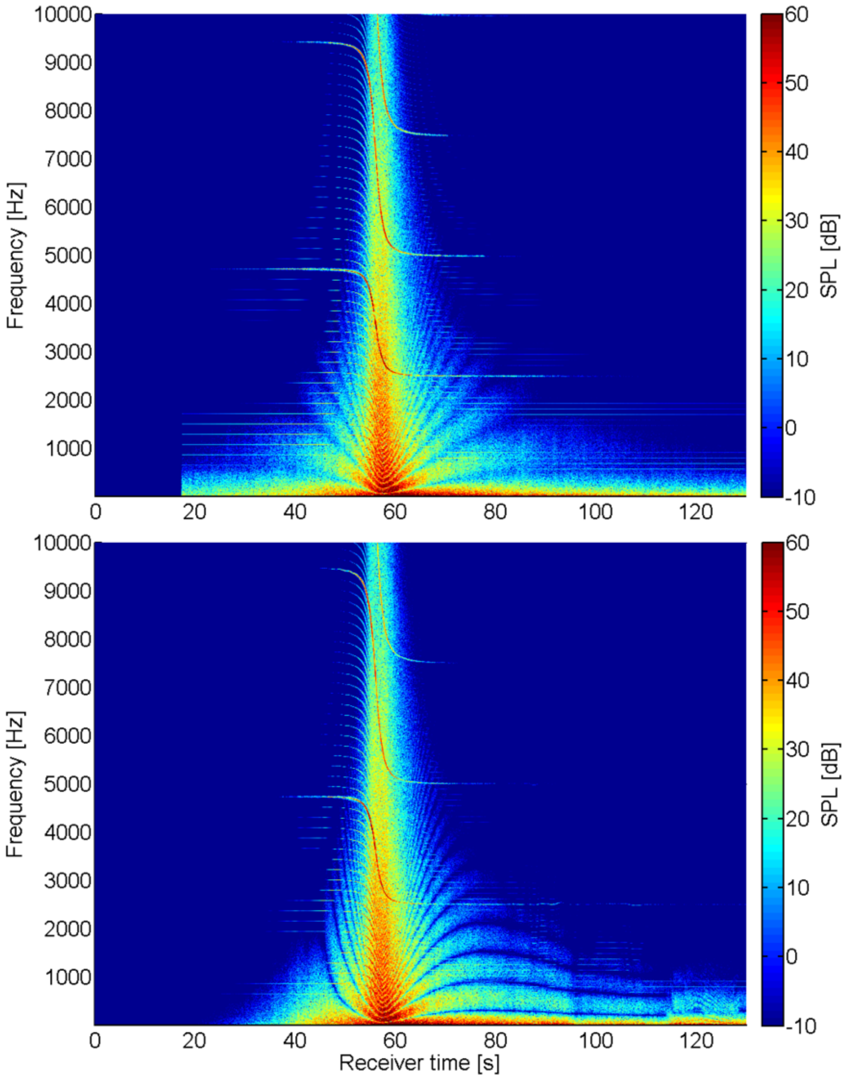

Figure 6 The straight path assumption result (top) and the curved path assumption result (bottom).

The differences between both assumptions become clear when looking to the spectrograms in Figure . First of all, the ground interference patterns, which are the indentations in the spectrogram, changed remarkably. Interference patterns are curved up and down due to the fact that the ray incidence angle is altered by the atmosphere. This causes the interference pattern to be asymmetric which, is not the case in case of a straight path assumption. The ray tracing algorithm predicts a shadow zone, i.e. an area without sound rays, in the first 35 seconds. This is why there is less sound compared to the straight path case. Around 95 seconds, the sound of the curved path assumption is damped more compared to the straight path assumption and, consequently, less sound is heard. However, around 117 seconds a second and third possible ray path is found that propagate sound towards the listener. This effect cannot be predicted by the straight path assumption. Note however that only the low frequency sound is audible as the atmosphere absorbed the high frequency part due to the long ray path length.

The impact on common noise metrics, like $L_{A,max}$ and SEL, is negligible for this case. These metrics are dominated by the received sound as the aircraft is at the closest distance. In this particular case, the aircraft is flying almost directly over the listener. At that point, the rays are not affected much by the atmospheric conditions compared to the straight path assumption. As a result, similar noise metrics are found.

IV. Conclusion

Flyover noise synthesis is a promising approach to explore future noise mitigation measures. Application is foreseen in a virtual reality environment and can encompass psychoacoustic research. By using synthesis, the atmospheric variables are fully controllable. A variety of effects can be studied with a relative high fidelity compared to standard INM alike models. The effects of wind, different engine conditions or varying flap settings are easily studied using this approach and present not only contour plots but include audible information.

Future research is foreseen to expand the modeling capabilities. For instance, different aircraft and engines are further explored. New research into the application of shadow zones as noise minimizing areas in communities can offer potential reductions in community noise exposure. This is a future study that can be adequately addressed by the modeling tools described here.

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Noise-minimal landing and take-off trajectories under procedural and safety regulations

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A framework is presented for the noise minimization of approach and take-off trajectories. Within this framework, population and terrain models are coupled with a dynamic trajectory optimization algorithm. By using a pseudospectral method to discretize the optimal control problem integrals can be handled very efficiently using matrix multiplication. Thus, a large number of noise stations can be included allowing an accurate calculation of the perceived noise on ground. The dynamic aircraft model included in the optimization framework is based on the BADA and ANP database of EUROCONTROL. Specific path constraints have been introduced to model regulations arising from various ICAO and FAA documents. Optimized trajectories for runway 08L of Munich airport are presented and compared.

Nomenclature

A = Aerodynamic Frame / Aerodynamic Motion / Aerodynamic Force (as index)
C_L = Lift coefficient
C_D = Drag coefficient
C_Q = Side force coefficient
D = Aerodynamic drag
$\mathbf{D}$ = Differentiation matrix
E = Earth-Centered Earth-Fixed Frame (ECEF)
$\vec{\mathbf{F}}$ = Force vector
G = Center of Gravity / Gravitational Force (as index)
H_G = Geopotential height
J = Cost function
K = Kinematic Flight Path Frame / Kinematic Motion
$\bar{K}$ = Kinematic Flight Path Frame K rotated around the x-axis by μ_K
L = Aerodynamic lift
$\mathbf{M}$ = Transformation matrix
N = Navigation Frame
O = North-East-Down Frame (NED)
P = Propulsive Force (as index)
Q = Aerodynamic side force
S = Reference area
SFC = Specific Fuel Consumption
T = Thrust / Time constant

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V = Velocity
g = Gravitational constant
h = Altitude above WGS84-ellipsoid
ℓ = Lagrange interpolation polynomials
m = Aircraft mass
n = Load factor
p = Roll rate
$\bar{q}$ = Dynamic pressure
t = Time
$\mathbf{u}$ = Control vector
w = Gauss quadrature weights
x = Northward position
$\mathbf{x}$ = State vector
y = Eastward position
z = Downward position
α = Angle of attack
α_1 = Engine dependent specific fuel consumption coefficient
β = Angle of sideslip
β_i = Engine dependent specific fuel consumption coefficient
γ = Flight-path climb angle
δ = Ratio of ambient pressure to sea level standard
δ_T = Thrust lever position
θ = Ratio of ambient temperature to sea level standard
μ = Flight-path bank angle
ρ = Air density
τ = Ratio of thrust to sea level maximum / Normalized time
χ = Flight-path course angle

Declaration: $\left(\vec{\mathbf{V}}^{\text{Reference Point}}_{\text{Type of Motion/Source of Force}}\right)^{\text{Reference Frame}}_{\text{Notation Frame}}$

I. Introduction

Air traffic has been continuously growing over the last decades and this trend is expected to last in the future. Nowadays, major airports are facing more than a thousand aircraft movements a day[1] leading to considerable annoyance of surrounding communities in terms of noise and air pollution. Plans for the extension and modification of approach and take-off routes are therefore strongly objected by the affected communities. Often countermeasures must be taken, e.g. banning night flights or providing nearby communities with better acoustic insulation. However, these measures are costly and can reduce the airport capacity. Due to the rise of new satellite based navigation systems it now becomes possible to define curved approach and departure routes instead of the conventional straight flight paths restricted by the use of ILS and VOR/NDB navaids. For this reason, considerable research has been dedicated to the design of approach and take-off procedures minimizing the noise impact on populated areas or other sensitive areas recently.

Visser and Wijnen published a series of papers concerning the optimization of noise abatement arrival and departure procedures[2,3]. They combined a noise model based on the FAA's Integrated Noise Model[4] (INM) and a geographic information system containing population data with a dynamic trajectory optimization algorithm. The cost function to be minimized is a weighted combination of the number of awakenings, a commonly used measure for noise nuisance, within the exposed community and the amount of fuel burned. Therein, the number of awakenings is calculated according to FICAN[5] as a function of the sound exposure level. To satisfy the need of the INM model for segmentation of the flight path, a collocation scheme is used for the optimization. An RNAV-extended version of this optimization framework was developed in Ref. 6, where a multi-phase formulation was used to model different RNAV path types like track-to-fix or radius-to-fix compliant with the use in current flight management systems. However, the structure of the considered route needs to be known a-priori and is obtained using the original framework.

A different noise nuisance model was proposed by Prats (2006), which is also based on the sound exposure level but takes into account the typical type of activity in a zone next to the number of people affected. A lexicographic method is identified most suitable for multi-objective optimization with respect to noise nuisance and fuel consumption[7]. Prats and Mora-Camino (2006) presented a framework for RNAV trajectory generation minimizing noise nuisance that is able to take into account trajectory constraints arising from RNAV operations[9]. They employ the noise model defined by Mora-Camino in Ref. 8 and solve the resulting optimization problem using the MATLAB software package DIDO, which uses a pseudospectral discretization method.

The use of pseudospectral methods for minimizing the environmental footprint of approach and take-off trajectories is also proposed in Ref. 10 by Houacine and Khardi (2010). In their study they use the well-known Stone model to calculate the overall sound pressure level at a receiver position due to the jet exhaust and present minimum fuel and minimum noise profiles for straight approach and departure routes. Another use of pseudospectral methods for minimizing the environmental impact of departure and arrival trajectories can be found in Ref. 11. Herein, a modified version of the INM methodology is used to estimate the noise impact of aircraft trajectories on the ground. To compute the number of awakenings due to a single event, a population database is included in the framework. To lower the computational cost, a set of virtual noise stations is defined from the population distribution using the k-means clustering method.

So far, most of the above mentioned literature uses optimal control theory and some kind of direct discretization method to obtain a parameter optimization problem. A different approach is described by Atkins and Xue [Ref. 12], who use a global optimization technique based on cell decomposition to optimize final approach trajectories for runway independent aircraft.

The paper at hand is organized as follows: In paragraph II the noise model used to calculate the nuisance to the population is described. To take into account the aircraft dynamics, a simulation model based on the base of aircraft data[18] (BADA) and the aircraft noise and performance[19] (ANP) database, both published by EUROCONTROL, is introduced in paragraph III. The path constraints and are described in paragraph IV, before the optimization problem is stated in paragraph V and discretized in paragraph VI. Results for runway 08L of Munich airport are presented in paragraph VII and finally conclusions are drawn in paragraph VIII.

II. Noise Model

In order to optimize flight trajectories with respect to noise nuisance, a model must be defined that summarizes the noise impact as a scalar function that is continuously differentiable with respect to the aircraft states and controls. Furthermore, a model describing the aircraft's noise emission and propagation is required. Both models are described in the following paragraph.

A. Noise cost function

The impact of perceived noise on the population is commonly described by dose-response relationships. Similar to previous research[2,3,6,11], the dose-response relationship proposed by the Federal Interagency Commission on Aviation Noise[5] (FICAN) is used in the paper at hand. It returns the percentage of persons awakened at a specific location as a function of the perceived indoor sound exposure level (SEL).

$$\%awak = 0.0087 \cdot \left(SEL_{indoor} - 30dB\right)^{1.79} \tag{1}$$

The equation was derived using a number of field studies and is supposed to represent the upper limit of the percentage of people likely to awake due to a single fly over at night time. The indoor SEL is estimated from the outdoor SEL by subtracting 20.5dB, a value representing the average loss due to the sound insulation of a typical house[2,3].

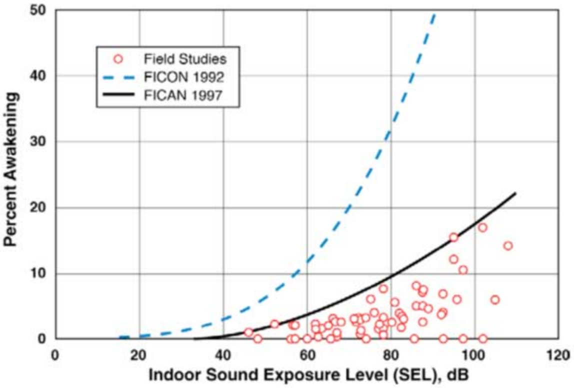

Figure 1: Sleep Disturbance Dose-Response Relationship, FICAN[5]

As seen from Eq. (1), the relationship is only valid for indoor SEL values greater than 30dB. For lower values the equation returns complex numbers, or, if only the real part is considered the percentage of awakenings is reaching a minimum for an indoor SEL value of 30dB and rising again for lower SEL values (see Figure 2). Therefore, the equation cannot be used immediately for trajectory optimization as it might be necessary to take into account receiver positions that are located far from the actual flight path resulting in low SEL values. In order to obtain a suitable cost function, the percentage of awakenings are set to zero for indoor SEL values below 30dB and the resulting curve is locally approximated using piecewise cubic hermite interpolating polynomials (MATLAB function *pchip*).

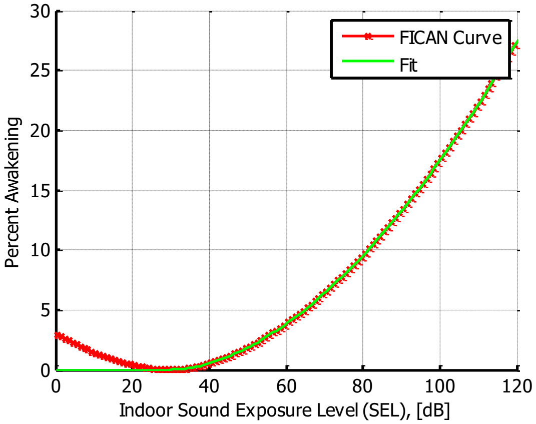

Figure 2: FICAN Curve showing the rise in percentage of awakenings for indoor sound exposure levels below 30dB and proposed fit to extend the definition range of the dose-response relationship.

The noise impact of a single flyover is then expressed by the total number of awakenings n_{awak} that results from the summation of the number of awakenings of each virtual noise station. Herein, the number of awakenings for a specific noise station is calculated by multiplying the percentage of awakenings of the station i with the population P_i assigned to that receiver.

$$n_{awak} = \sum_{i=1}^{N} \%awak_i \cdot P_i \tag{2}$$

B. Noise emission model

To calculate the number of awakenings for a specific receiver the sound exposure level of that receiver due to the approach or departure must be obtained. The SEL can be calculated by the time history of the A-weighted sound pressure level $L_A(t)$ using the following equation:

$$SEL = 10 \cdot \log_{10}\left(\int_{t_1}^{t_2} 10^{0.1 \cdot L_A(t)} dt\right) \tag{3}$$

To calculate the time history of the A-weighted sound pressure level $L_A(t)$ at a specific receiver position, the noise model proposed and validated by Figlar in Ref. 13 is used. It is based on INM and gives the time history of $L_A(t)$ as a continuously differentiable function of the distance between receiver and aircraft and the aircraft's corrected net thrust. In common with the INM, the model uses the Aircraft Noise and Performance (ANP) database published by EUROCONTROL, which is free and publicly available. The ANP database provides so called Noise-Power-Distance (NPD) data for flight path segments of infinite length, i.e. look-up tables are provided that can be used to determine either the maximum $L_{A,max}$ or the sound exposure level SEL for a whole flight segment. The model proposed by Figlar assumes that the $L_{A,max}$ data given in the ANP database is also valid for infinitesimal short flight segments. For such a segment the value of $L_{A,max}$ obtained from the NPD data represents the L_A value for a certain instance in time. Thus, by splitting the trajectory into infinitesimal short segments the time history of L_A can be obtained from the NPD data.

The NPD look-up tables provide $L_{A,max}$ data depending on an engine's corrected net thrust and the distance between the noise source and the receiver. To obtain a continuously differentiable function a fit via regression is derived from the tabulated data as described in Ref. 13.

It must be noted that the model does not contain any correction factors for lateral attenuation, engine installation or deviation from the reference speed. Furthermore, the NPD-data used here is very limited and does not allow to model changes in noise emission due to different aircraft configurations.

C. Population model

To assess the impact of a single flyover on the population a series of virtual noise stations must be defined which are characterized by their position and the number of people allocated to it. To this end, the population model of the European Environment Agency[14] is used. It provides the population density data in inhabitants/square kilometer for Europe with a resolution of 100mx100m using a Lambert Azimuthal Equal Area projection. In general, each of the grid points represents a virtual noise station that needs to be taken into account during the optimization. Thus, the horizontal position of the virtual noise stations is directly given by the grid points of the data set. The number of people associated with a virtual noise station is derived by multiplying the population density of the respective grid point with the area represented by a grid point. As each grid point represents an area of 1ha, the given population distribution must be divided by 100 to obtain the estimated population of that grid point. To lower the computational cost of the optimization problem it is advantageous to take only those virtual noise stations into account that exceed a certain population.

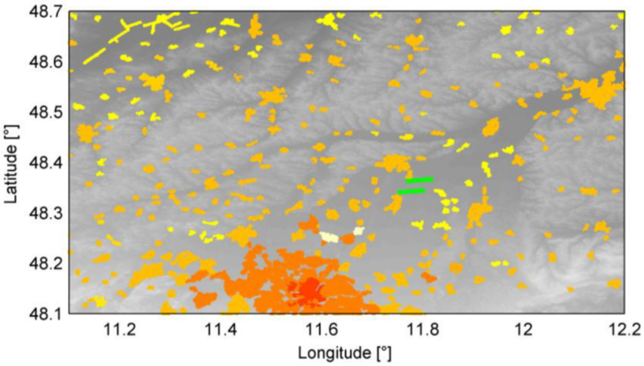

Figure 3: Population distribution around Munich airport together with terrain

D. Terrain model

As the population model only contains the horizontal position of the virtual noise stations, a terrain model must be included to determine the vertical position of the receivers. Furthermore, a terrain model is required for the inclusion of the minimum obstacle clearance constraint described in paragraph IV. In this paper, the Shuttle Radar Topography Mission (SRTM) data of NASA is used as terrain model. As the original data is erroneous and contains many voids where no data was received, the processed SRTM data provided by CGIAR-CSI[15] is used. It is freely available for non-commercial use with a resolution of three arc seconds, which is roughly 90m. To interpolate the terrain data between the grid points the quadratic Shepard method[16,17] is used. Figure 3 shows the terrain model together with the population distribution around the airport of Munich. For better orientation the two runways of the Munich airport, located to the north-west of the city, are plotted as green lines.

III. Aircraft Simulation Model

The aircraft dynamics are modeled using a point mass model with parameters taken from the base of aircraft data[18] (BADA) and the Aircraft Noise and Performance[19] (ANP) database, both published by EURONCONTROL. Together with the equations used to describe the motion of the point mass in space, the formulae to compute the aerodynamic and thrust forces as well as the fuel consumption are presented in the following paragraph. For simplification a non-rotating, flat earth is assumed.

A. Position Equations of Motion

The position equations of motion are formulated using the position vector in the local frame N that is derived from the NED-Reference frame with its origin fixed on the WGS84-ellipsoid. The x-axis of the local frame points northwards, the y-axis eastwards and the z-axis downwards. The flight altitude h is given as the negative of the downward position z.

$$\begin{pmatrix} \dot{x} \\ \dot{y} \\ \dot{z} \end{pmatrix}_N^E = \begin{pmatrix} V_K^G \cdot \cos \chi_K^G \cdot \cos \gamma_K^G \\ V_K^G \cdot \sin \chi_K^G \cdot \cos \gamma_K^G \\ -V_K^G \cdot \sin \gamma_K^G \end{pmatrix} \quad (4)$$

B. Translation Equations of Motion

The translation equations of motion are written with reference to the Kinematic Reference Frame *K* and given as a function of the total sum of forces in the Kinematic Reference Frame *K*. The according states are represented by the kinematic velocity V_K, the kinematic course angle χ_K and the kinematic flight path inclination angle γ_K. The first order time derivatives of those states are a function of the total sum of forces acting on the aircraft's center of gravity G:

$$\begin{pmatrix} \dot{V}_K^G \\ \dot{\chi}_K^G \\ \dot{\gamma}_K^G \end{pmatrix}_K^{EO} = \begin{pmatrix} 1 \\ 1/(V_K^G \cdot \cos \gamma_K^G) \\ -1/V_K^G \end{pmatrix} \cdot \left(\frac{1}{m} (\sum \vec{\mathbf{F}}^G)_K \right) \quad (5)$$

The total sum of forces comprises aerodynamic and propulsion forces as well as the gravitational force acting on the aircraft's center of gravity *G*.

$$\left(\sum \vec{\mathbf{F}}^G\right)_K = \left(\vec{\mathbf{F}}_A^G\right)_K + \left(\vec{\mathbf{F}}_P^G\right)_K + \left(\vec{\mathbf{F}}_G^G\right)_K \quad (6)$$

As no discrete jumps can occur for the flight-path bank angle μ_K it is added to the state vector of the simulation model. The first order time derivative of the kinematic flight-path bank-angle is set equal to the commanded roll rate $p_{K,CMD}$

$$\dot{\mu}_K = p_{K,CMD} \quad (7)$$

Similarly, as no discrete jumps can occur for the engine thrust either, the thrust lever position is added to the state vector of the simulation model and its dynamics are modeled using first order dynamics

$$\dot{\delta}_T = \frac{1}{T}\left(\delta_{T,CMD} - \delta_T\right) \tag{8}$$

C. Forces

The gravitational force is assumed to be constant over the regarded altitude interval and is given in the NED-Reference Frame O. It can be transformed to the Kinematic Reference Frame K by the transformation matrix $\boldsymbol{M}_{KO}$ between the Kinematic Reference Frame K and the NED-Reference Frame O.

$$\left(\vec{\mathbf{F}}_G^G\right)_K = \mathbf{M}_{KO} \cdot \left(\vec{\mathbf{F}}_G^G\right)_O \tag{9}$$

The aerodynamic forces acting on the aircraft are the lift L, drag D and side force Q that result from the relative motion of the aircraft to the airflow surrounding the aircraft given by the aerodynamic velocity V_A. While the lift force vector is perpendicular to the aerodynamic velocity, the drag force acts parallel to the aerodynamic velocity. Therefore, the aerodynamic forces are calculated in the Aerodynamic Reference Frame A, whose x-axis coincides with the aerodynamic velocity vector. The drag force is modeled according to BADA using a quadratic polar.

$$D = \bar{q} \cdot S \cdot C_D = \bar{q} \cdot S \cdot \left(C_{DO} + C_{D2} \cdot C_L^2\right) \tag{10}$$

It is assumed that the aerodynamic angle of sideslip is negligible at all times. Therefore, the side force Q is set equal to zero.

$$Q = \bar{q} \cdot S \cdot C_{Q\beta} \cdot \beta_A = 0 \tag{11}$$

The lift is assumed to be linear in the angle of attack α_A.

$$L = \bar{q} \cdot S \cdot C_L = \bar{q} \cdot S \cdot \left(C_{L0} + C_{L\alpha} \cdot \alpha\right) \tag{12}$$

The dynamic pressure used in the equations above is given by:

$$\bar{q} = \frac{\rho}{2} \cdot V_A^2 \tag{13}$$

The aerodynamic force vector in the Aerodynamic Reference Frame A is then given by:

$$\left(\vec{\mathbf{F}}_A^G\right)_A = \begin{pmatrix} -D \\ 0 \\ -L \end{pmatrix} \tag{14}$$

The propulsion force is modeled according to the ANP data, where the maximum available take-off thrust is given as a function of the calibrated airspeed V_{CAS} and the aircraft altitude h. The following equation holds for one engine of a jet powered aircraft with the calibrated velocity given in knots and the altitude in feet.

$$T_{\max} = \delta \cdot \left(E + F \cdot V_{CAS} + G_a \cdot h + G_b \cdot h^2\right) \tag{15}$$

The constants E, F, G_a and G_b are given in the ANP database for a wide variety of engines, δ is the ratio between ambient air pressure and the reference air pressure at MSL. The calibrated airspeed used to compute the maximum available thrust can be estimated by[19]:

$$V_{CAS} = \sqrt{\frac{\rho}{\rho_0}} \cdot V_A \tag{16}$$

To compute the actual population force acting on the aircraft's center of gravity, a the maximum available thrust of one engine is multiplied with the number of engines installed n_{eng}. Furthermore, a linear model is used between the thrust T and the thrust lever position δ_T.

$$T = T_{\max} \cdot \delta_T \cdot n_{eng} \tag{17}$$

For the sake of simplicity, it is assumed that the thrust always acts in direction of the aerodynamic velocity. The propulsion force vector in the Aerodynamic Reference Frame A then results as:

$$\left(\vec{\mathbf{F}}_P^G\right)_A = \begin{pmatrix} T \\ 0 \\ 0 \end{pmatrix} \tag{18}$$

The force vectors of aerodynamic and propulsion forces given in the Aerodynamic Reference Frame A can then be transformed to the Kinematic Reference Frame K by the appropriate transformation matrix $\boldsymbol{M}_{KA}$ taking into account the influence of wind.

$$\left(\vec{\mathbf{F}}^G\right)_K = \mathbf{M}_{KA}\left(\vec{\mathbf{F}}^G\right)_A \tag{19}$$

D. Fuel Consumption

To assess the total environmental impact of an approach or departure route, the fuel consumption is modeled using the following model involving the specific fuel consumption SFC and the aircraft thrust T:

$$\dot{m}_{fuel} = SFC \cdot T \tag{20}$$

The specific fuel consumption is calculated using the following equation derived by Yoder[20].

$$\frac{SFC}{\sqrt{\theta}} = \alpha_1 + \beta_1 Ma + \beta_2 \exp\left(-\beta_3 \cdot \left(\frac{\tau}{\delta^{0.3}}\right)^{0.3}\right) \tag{21}$$

where θ is the ratio of ambient temperature to sea level standard, δ is the ratio of ambient pressure to sea level standard, τ is the ratio of thrust to sea level maximum, Ma is the Mach number and $\alpha_1, \beta_1, \beta_2, \beta_3$ are engine dependent parameters.

E. Static Atmosphere

The static pressure, the static temperature and the density for a specific altitude are computed based on the International Standard Atmosphere DIN ISO 2533. First, the geopotential height is computed from the earth radius r_E and the geodetic height h:

$$H_G = \frac{r_E \cdot h}{r_E + h} \tag{22}$$

If the geopotential height is smaller than or equal to the maximum geopotential height for the troposphere layer, that is 11000m, the density ρ and the static pressure p are computed as follows:

$$\rho = \rho_S\left[1 + \frac{\gamma_{Tr}}{T_S} \cdot H_G\right]^{\left(-\frac{g_S}{R \cdot \gamma_{Tr}} - 1\right)} \tag{23}$$

$$p = p_S\left[1 + \frac{\gamma_{Tr}}{T_S} \cdot H_G\right]^{\left(-\frac{g_S}{R \cdot \gamma_{Tr}}\right)} \tag{24}$$

Here, γ_{Tr} is the temperature gradient of the polytropic troposphere layer and R the specific gas constant. g_s, T_s, ρ_s and p_s indicate the gravitational acceleration, the temperature, the density and the pressure at mean sea level (MSL), respectively.

IV. Path Constraints

Aircraft approach and departure routes are subject to various regulations to ensure safe landing and take-off of aircraft. As the results of the optimization shall be considered as a first guess to help trajectory planners, it is mandatory to take into account procedural and safety regulations during the optimization process. The regulations arise from various documents published by ICAO or FAA as well as from physical considerations. The following paragraph summarizes the path constraints used during the optimization of approach and take-off trajectories.

A. General

This section summarizes all constraints that are used for the optimization of approach as well as departure trajectories. First, the commanded controls are restricted to be within the following limits

$$0 \le \alpha_{A,CDMD} \le \alpha_{\max} \tag{25}$$

$$-15°/s \le p_{K,CMD} \le 15°/s \tag{26}$$

$$0 \le \delta_{T,CMD} \le 1 \tag{27}$$

These constraints arise from the physical limitations of the aircraft, where the maximum aerodynamic angle of attack can be calculated from the stall speed given in the BADA data. The minimum aerodynamic angle of attack is set to zero. Furthermore, the calibrated airspeed is limited to:

$$K \cdot V_{stall} \le V_{CAS} \le 250kt \tag{28}$$

where $K = 1.3$ for an approach and $K = 1.2$ for a departure. As the maximum velocity of 250 knots is well below the speed of sound no additional constraint concerning the maximum Mach number is taken into account here.

To generate realistic altitude and velocity profiles it is required that altitude and calibrated airspeed decrease monotonically during an approach flight and increase monotonically during a take-off. The equations given below represent the constraints for an approach. For a take-off path the signs of the functions change accordingly.

$$\dot{V}_{CAS} \le 0 \tag{29}$$

$$\dot{h} \le 0 \tag{30}$$

For some of the optimized trajectories the aircraft is required to follow a given reference trajectory using the spline constraint function described in Ref. 21. To this end, the given approach or take-off trajectory is approximated using cubic splines and the horizontal and vertical deviation of the aircraft from the reference spline are restricted.

Furthermore, a constraint concerning the load factor acting on the aircraft was introduced to ensure acceptable passenger comfort:

$$0.85 \le n_z \le 1.15 \tag{31}$$

B. Approach

For the optimization of approach trajectories the following two constraints concerning the kinematic bank angle and the kinematic flight path angle are imposed. The first constraint follows from ICAO Doc 9905[22], where a maximum bank angle of 20° is proposed. In the same document a minimum flight path angle of $\gamma_K = -3.6°$ is given. However, for the given optimization problem a minimum flight path angle of $\gamma_K = -5°$ is used.

$$-20° \leq \mu_K \leq 20° \tag{32}$$

$$-5° \leq \gamma_K \leq 0° \tag{33}$$

Next, as required by the Advisory Circular (AC) 120-71A[23] of the FAA the aircraft has to be in a stabilized state not later than 1000ft above runway elevation. In the AC a stabilized approach is characterized by an aircraft velocity within the target range, the aircraft being on the correct track, fully configured and having established the desired descent angle. The aircraft may use so called "bracketing maneuvers" to maintain the correct track and desired vertical profile. These "bracketing maneuvers" generally include bank angles not in excess of 30° or as specified in the appropriate airplane manual. The stabilized approach is therefore modeled in two steps, where below 1000ft AFE the following two equality constraints are imposed:

$$\gamma_K = -3° \tag{34}$$

$$V_{CAS} = V_{TARGET} \tag{35}$$

Below 500ft AFE it is furthermore required that the aircraft is in level flight, which is equal to:

$$\mu_K = 0° \tag{36}$$

Furthermore, ICAO Doc 9905 requires the aircraft to maintain a specific minimum obstacle clearance depending on the approach segment (initial, intermediate, final, etc.). However, the SRTM data used here only represents the terrain but does not contain any obstacle data. Thus, the minimum obstacle clearance reduces to a minimum terrain clearance, which is enforced by restricting the distance between a set of evaluation points extending up to 2x the required navigational performance (RNP) of the specific segment to the side of the aircraft as shown in Figure 4 and the surrounding terrain. Table 1 gives the minimum obstacle/terrain clearance for each segment together with the required navigational performance. It may be noted that appropriate models containing obstacle data can be integrated easily into the optimization framework.

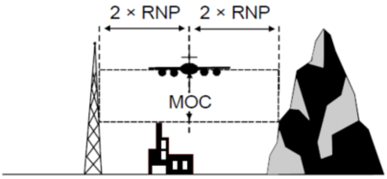

Figure 4: RNP segment widths and Minimum Obstacle Clearance[21]

Table 1: Minimum obstacle clearance and RNP values for approach segments

Segment	Minimum Obstacle Clearance [m]	RNP Values [nm]	
		Standard	Minimum
Initial	300	1	1
Intermediate	150	1	0.1
Final	50	0.3	0.1

The obstacle clearance constraint was turned off for altitudes below 500ft AFE as the aircraft is then on the nominal approach track.

C. Take-Off

For the optimization of take-off trajectories the following constraints concerning the bank angle arise from ICAO Doc 8168[24].

$$\begin{array}{ll} \text{Below 400ft:} & 0° \le \mu_K \le 0° \\ \text{400ft - 1000ft:} & -15° \le \mu_K \le 15° \\ \text{1000ft - 3000ft:} & -20° \le \mu_K \le 20° \\ \text{Above 3000ft:} & -25° \le \mu_K \le 25° \end{array} \tag{37}$$

Next, two additional constraints follow from AC 91-53A[25], where the FAA describes two noise abatement procedures. Within the document it is stated that no thrust cut back shall be initiated below 800ft above field elevation.

$$\text{Below 800ft:} \qquad \delta_T = 1 \tag{38}$$

Furthermore, the thrust level remaining after thrust reduction must ensure a minimum flight path of 1.2% in the event of an engine failure. From Eq. (5), the minimum thrust level necessary can be calculated by:

$$\begin{aligned} \left(\dot{V}_K^G\right)_K^E &= \frac{T_{\min} - D}{m} - \sin\gamma_{\min} \equiv 0 \\ T_{\min} &= \left(m \cdot \sin\gamma_{\min} + D\right) \end{aligned} \tag{39}$$

For a twin engine airplane, the thrust provided by one engine must equal the minimum thrust level.

$$T_{\min} - \mathrm{T}/2 \le 0 \tag{40}$$

V. Optimal Control Problem

After the definition of an appropriate cost function to assess the noise impact, the definition of the dynamic system and the path constraints, the following optimal control problem can be stated:

Determine the optimal control histories

$$\mathbf{u}^*(t) \in \mathbf{U}^m \tag{41}$$

and the corresponding optimal state trajectories

$$\mathbf{x}^*(t) \in \mathbf{X}^n \tag{42}$$

that minimize the number of awakenings for a given population distribution

$$J = n_{awak} = \sum_{i=1}^{N} \%awak_i \cdot P_i \tag{43}$$

subject to the state dynamics

$$\dot{\mathbf{x}}(t) = \mathbf{f}(\mathbf{x}(t), \mathbf{u}(t)) \tag{44}$$

the initial and final boundary conditions

$$\mathbf{\Psi}_0\left(\mathbf{x}(t_0), t_0\right) = \mathbf{0} \qquad \mathbf{\Psi}_0 \in IR^p \qquad p \le n \tag{45}$$

$$\mathbf{\Psi}_f\left(\mathbf{x}(t_f), t_f\right) = \mathbf{0} \qquad \mathbf{\Psi}_f \in IR^q \qquad q \le n \tag{46}$$

and the appropriate equality and inequality constraints as described in paragraph IV

$$\mathbf{C}(\mathbf{x}(t), \mathbf{u}(t), t) \le \mathbf{0} \qquad \mathbf{C} \in IR^r \tag{47}$$

Herein, the control and state vector of the simulation model described in paragraph III are given as

$$\mathbf{x} = \left[x, y, z, V_K, \chi_K, \gamma_K, \mu_K, \delta_T, m\right]^T \tag{48}$$

$$\mathbf{u} = \left[\alpha_{A,CMD}, p_{K,CMD}, \delta_{T,CMD}\right]^T \tag{49}$$

VI. Gauss Pseudospectral Method

The Gauss Pseudospectral Method[26,27] is used to transcribe the infinite dimensional optimal control problem stated above into a finite dimensional optimization problem with algebraic constraints, also known as Non-Linear Programming Problem (NLP). The resulting NLP is then solved using the commercial SQP-Package SNOPT[28]. The Gauss Pseudospectral Method uses a set of Lagrange interpolation polynomials that are defined using the Gauss points, which lie on the interior of the interval $\tau \in (-1,1)$, plus the initial point $\tau_0 = -1$. Note, that each interval $t \in [t_0, t_f]$ with t_0, t_f free or fixed can be mapped to the general interval $\tau \in [-1,1]$ using the affine transformation $\tau = 2t/(t_f - t_0) - (t_f + t_0)/(t_f - t_0)$. The states are then approximated by:

$$\mathbf{x}(\tau) \approx \mathbf{X}(\tau) = \sum_{i=0}^{K} \ell_i(\tau) \cdot \mathbf{x}(\tau_i) \tag{50}$$

where

$$\ell_i = \prod_{j=0, j\neq i}^{K} \frac{\tau - \tau_j}{\tau_i - \tau_j} \tag{51}$$

As the final state is not part of the approximation, an additional constraint is added that relates the final state to the initial state and the state dynamics:

$$\mathbf{x}(\tau_f) = \mathbf{x}(\tau_0) + \int_{-1}^{1} \mathbf{f}(\mathbf{x}(\tau), \mathbf{u}(\tau), \tau) d\tau \tag{52}$$

Using Gauss quadrature this equation can be discretized and approximated by

$$\mathbf{X}(\tau_f) - \mathbf{X}(\tau_0) - \frac{t_f - t_0}{2} \sum_{k=1}^{K} w_k \cdot \mathbf{f}(\mathbf{X}(\tau_k), \mathbf{U}(\tau_k), \tau_k) = \mathbf{0} \tag{53}$$

where w_k are the Gauss weights. Next, to ensure that the discrete states satisfy the dynamic equations orthogonal collocation is used, which requires the derivatives of the state interpolation to equal the dynamic equations at a specific set of collocation points, which are in this case the aforementioned Gauss points. The derivative of the state approximation is given by:

$$\dot{\mathbf{x}}(\tau_k) \approx \dot{\mathbf{X}}(\tau_k) = \sum_{i=0}^{K} \dot{\ell}(\tau_k) \cdot \mathbf{X}(\tau_i) = \sum_{i=0}^{K} \mathbf{D}_{ki} \cdot \mathbf{X}(\tau_i) \tag{54}$$

where $\boldsymbol{D} \in \mathbb{R}^{K\times(K+1)}$ is the differentiation matrix of the Lagrange polynomials. Thus, at the collocation points the following equality constraints are enforced

$$\sum_{i=0}^{K} \mathbf{D}_{ki} \cdot \mathbf{X}(\tau_i) - \frac{t_f - t_0}{2} \mathbf{f}(\mathbf{X}(\tau_k), \mathbf{U}(\tau_k), \tau_k) = \mathbf{0}, \quad (k = 1, \ldots, K) \tag{55}$$

For the discretization of the control any approximation that has the property $\boldsymbol{u}(\tau_k) = \boldsymbol{U}_k, (k = 1, \ldots, K)$ can be used.

Finally, integral terms occurring in the cost function can be approximated using Gauss quadrature as before.

$$\int_{t_0}^{t_f} g(\mathbf{x}(t), \mathbf{u}(t), t) dt \approx \frac{t_f - t_0}{2} \sum_{k=1}^{K} w_k \cdot g(\mathbf{X}_k, \mathbf{U}_k, \tau_k) \tag{56}$$

The Gauss quadrature can be implemented in MATLAB very efficiently as a pure matrix multiplication. Thus, the use of the Gauss Pseudospectral Method allows for the inclusion of large numbers of virtual noise stations during the optimization process.

VII. Results

In the following paragraph optimized approach and take-off routes for runway 08L of Munich airport are presented. As stated above, the use of the Gauss Pseudospectral Method allows the inclusion of a large number of virtual noise stations while keeping the computational cost in acceptable limits. However, as many virtual noise stations represent only a very small number of inhabitants and have nearly no effect on the total number of awakenings, it has been decided to take into account only those stations that represent at least a population of two persons. With the area-of-interest specified by the lower left corner $N48.1°, E11.1°$ and the upper right corner $N48.7°, E12.2°$, a total of 44674 virtual noise stations with a population of about 2 million people result (see Fig. 3).

A. Approach EDDM 08L

For the optimization of approach trajectories the RNAV (GPS) approach to runway 08L was chosen as reference and approximated using cubic splines. The approach starts at NDB MIQ north of the runway and leads westward before turning left to intersect the extended runway center line. The horizontal profile of the approach route is depicted together with the horizontal profile of the reference departure trajectory in Fig. 5. The vertical profile of the reference trajectory is a standard 3° glide path profile with a minimum initial altitude of 5000ft.

A total of four noise optimal trajectories were calculated, which differ in the allowed deviation from the reference track.

- **APP I**: horizontal and vertical profiles are prescribed by imposing the spline constraint mentioned at the end of paragraph IV.A. Thus, only the speed profile and the timing of configuration changes are varied to minimize noise impact
- **APP II**: only the horizontal profile is prescribed, the vertical profile is subject to optimization, the initial altitude is fixed to 5000ft
- **APP III**: both the horizontal and the vertical profile are subject to optimization, the initial altitude is fixed to 5000ft
- **APP IV**: both the horizontal and vertical profile are subject to optimization, the initial altitude is free but required to be below 10000ft

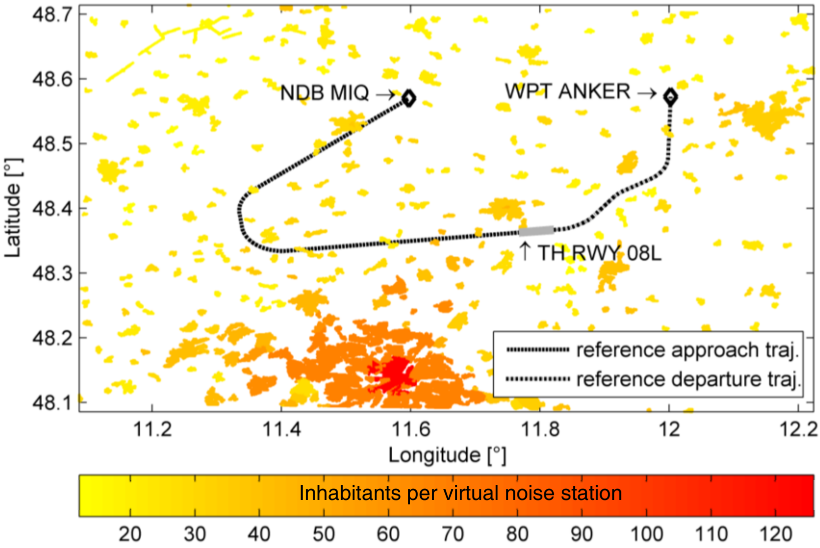

Figure 5: Reference approach and departure trajectory EDDM RWY 08L with population distribution

Table 2 summarizes the initial and final boundary conditions imposed on the aircraft states.

Table 2: Initial and final boundary conditions for approach optimization

State	Initial	Final
x	fixed	fixed
y	fixed	fixed
h	5000ft AFE / below 10000ft	50ft AFE
V_K	free	$1.3 \cdot V_{stall}$
χ_K	228°	82°
γ_K	0°	-3°
μ_K	0°	0°
m	free	MLW, 66t

For the optimization of the route with free horizontal and vertical profile an additional penalty term is added to the cost function regarding the final time to generate more realistic and smooth trajectories.

$$J = n_{awak} + 0.1 \cdot t_{final} \tag{57}$$

Table 3 summarizes the environmental impact of the four routes. The reduction of flight time and fuel burned for the fully optimized paths is mostly due to a shorter path length. It must be noted that the shorter approach trajectory is an attribute specific to the u-shaped reference track. For other reference trajectories the optimized trajectories might be significantly longer leading to longer flight times and higher fuel consumption.

Concerning the reduction of noise impact it can be observed that the number of awakenings is reduced by 2% APP II with free vertical profile compared to APP I. A much greater reduction of about 45% is achieved if both the horizontal and vertical profiles are left for optimization (APP III). As expected, the maximum reduction in number of awakenings (60%) is realized for the fourth case, where both profiles are optimized and the initial altitude was left free. Furthermore, the fuel consumption is reduced considerably for the fourth case due to the higher initial total energy of the aircraft.

Table 3: Environmental impact of optimized approaches

	Unit	APP I	APP II	APP III	APP IV
Number of Awakenings	[-]	449	440	247	180
Flight Time	[s]	603.8	619.9	481.6	408.3
Fuel Burned	[kg]	310.9	298.2	225.6	120.8

Figure 6 shows the sound exposure level of the reference trajectory (APP I) with a maximum SEL of about 86dB occurring at the end of the trajectory. The black dots shown here and in the subsequent figures represent the virtual noise stations close to the track. Figure 7 to Figure 9 show the difference in the SEL between the optimized flights (APP II – APP IV) and the reference flight (APP I). For APP II, where only the vertical profile is optimized, only a small reduction in SEL value and therefore in number of awakenings is achieved. However, the SEL for nearly all virtual noise stations is reduced or at least maintained, i.e. none of the virtual noise stations exhibits a higher number of awakenings. In contrast, for the two other cases a higher reduction in number of awakenings is achieved by avoiding higher populated areas. However, this comes at the price of increasing the number of awakenings in other, lower populated areas.

The "bubbles" seen in Figure 7 result from small changes of the difference in SEL values around 0dB, i.e. the "bubbles" represent a change from slightly negative values to slightly positive values.

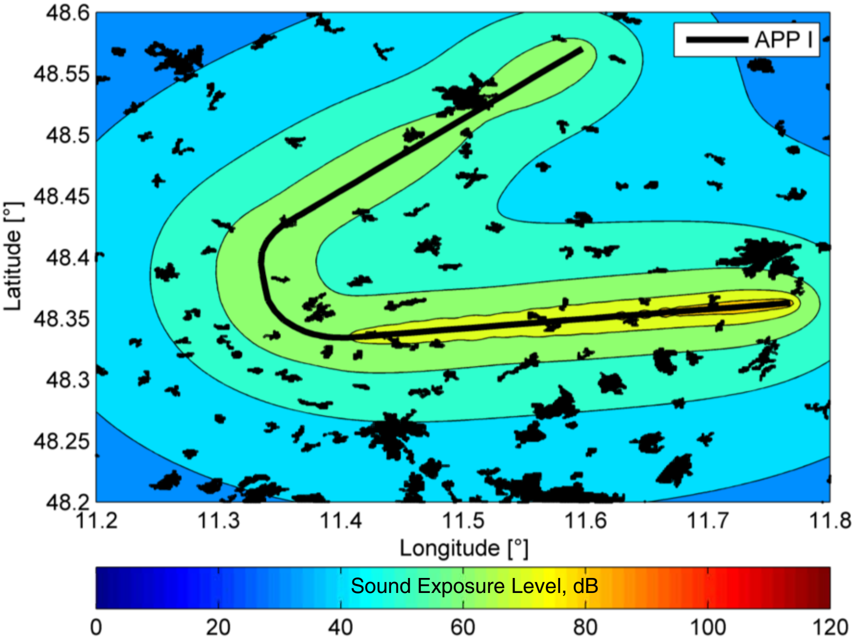

Figure 6: Sound exposure level for reference trajectory (APP I)

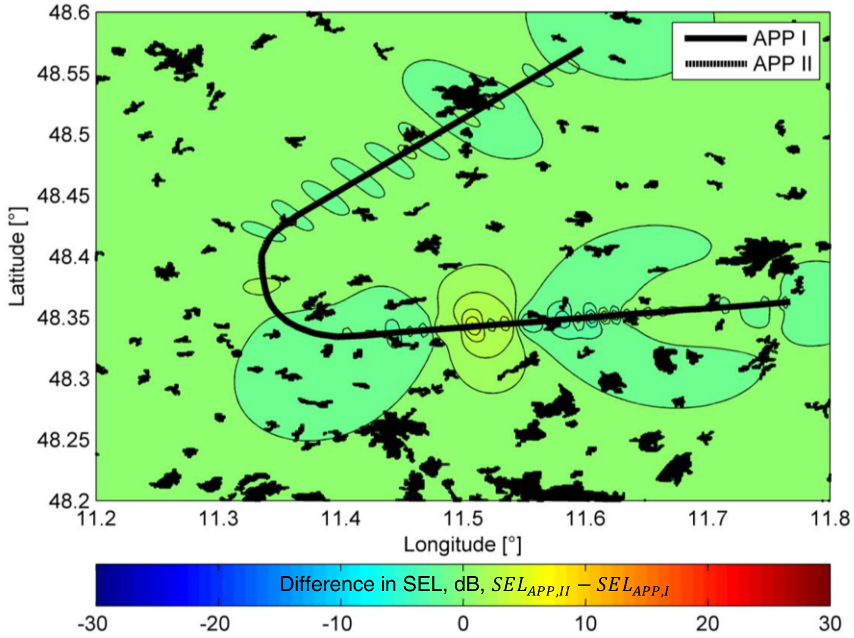

Figure 7: Difference in SEL between APP I and APP II

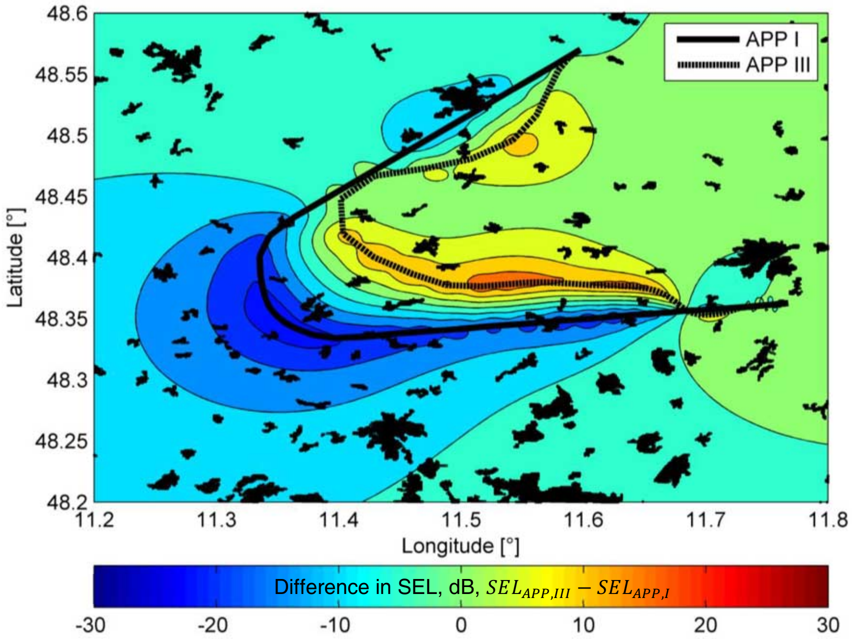

Figure 8: Difference in SEL between APP I and APP III

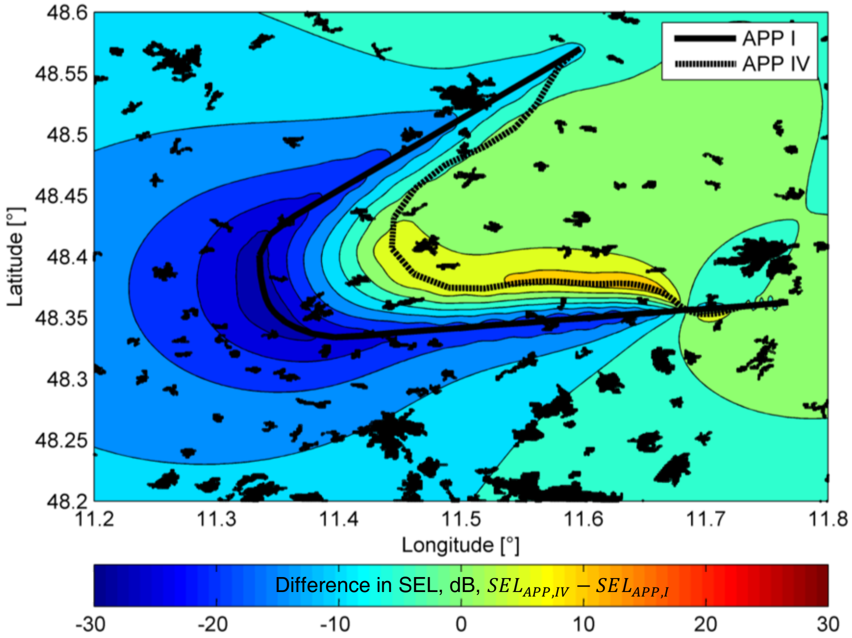

Figure 9: Difference in SEL between APP I and APP IV

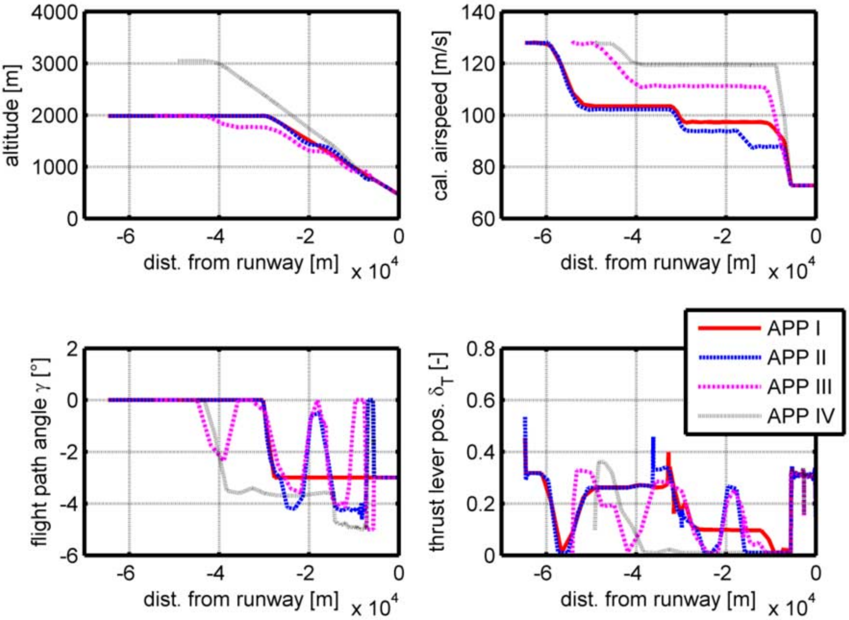

Figure 10: Selected states for noise optimal approaches

B. Take-Off EDDM 08L

For the optimization of take-off routes the RNAV (GPS) SID ANKER SEVEN QUEBEC departure from runway 08L was chosen as reference trajectory. As seen in Fig. 5, the published take-off trajectory already represents a noise abatement procedure, which avoids overflying populated areas at low altitude. Only two noise optimized routes were calculated as the vertical profile depends strongly on the aircraft weight and the installed engines. Hence, the vertical profile was left for optimization in both cases, which start 50ft above the runway threshold with a calibrated airspeed of $1.2 \cdot V_{stall}$. The departures end at the waypoint ANKER with a course angle of $\chi = 1°$ but free final altitude. Table 4 summarizes the initial and final boundary conditions imposed during the optimization of the departure tracks.

- **DEP I**: only the horizontal profile is prescribed, the vertical profile is left free
- **DEP II**: both the horizontal and the vertical profile are subject to optimization

Table 4: Initial and final boundary conditions for approach optimization

State	Initial	Final
$\boldsymbol{x}$	fixed	fixed
$\boldsymbol{y}$	fixed	fixed
$\boldsymbol{h}$	50ft AFE	free
$\boldsymbol{V_K}$	$1.2 \cdot V_{stall}$	free
$\boldsymbol{\chi_K}$	82°	1°
$\boldsymbol{\gamma_K}$	free	free
$\boldsymbol{\mu_K}$	0°	0°
$\boldsymbol{m}$	MTOW, 78t	free

The sound exposure level of the departure DEP I is shown in Fig. 11. As can be seen in Fig. 13, the horizontal profiles of the optimized and the reference trajectory are nearly identical. The vertical profiles (see Fig. 12) differ at the beginning of the departure but are very similar for the rest of the flight. In contrast to DEP I, where altitude is gained immediately, DEP II has a short acceleration segment with nearly constant altitude just at the beginning. Both profiles show another acceleration segment with constant altitude just above 700m, where the aircraft reaches nearly the maximum velocity of 250kts (128m/s). After the acceleration segment the aircraft is climbing again until reaching a final altitude of nearly 2500m. As the horizontal and the vertical profile as well as the profiles of the other states are quite similar, the environmental impact of both departures is nearly equal (see Table 5).

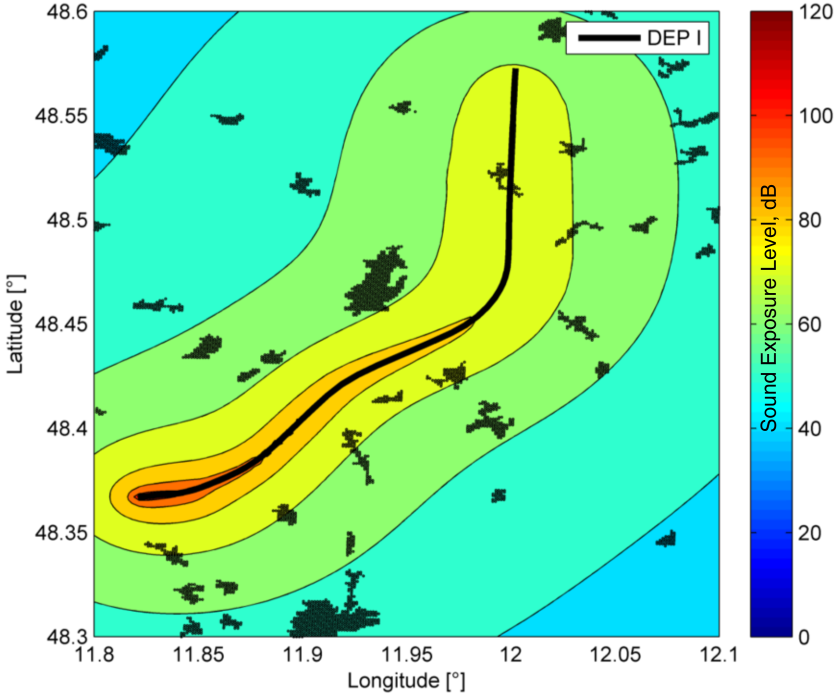

Figure 11: Sound exposure level in dB for reference departure

Table 5: Environmental impact of optimized departures

	Unit	DEP I	DEP II
Number of Awakenings	[-]	661	642
Flight Time	[s]	240.9	235.5
Fuel Burned	[kg]	446.1	437.1

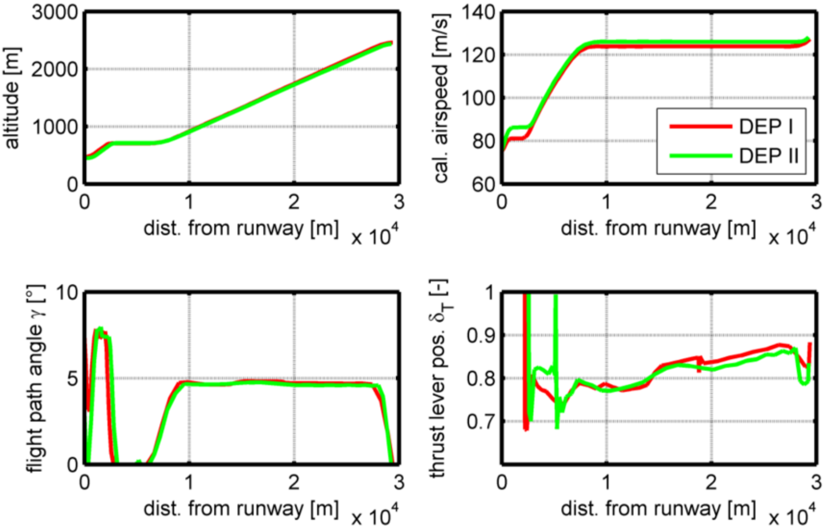

Figure 12: Selected states for noise optimal departures

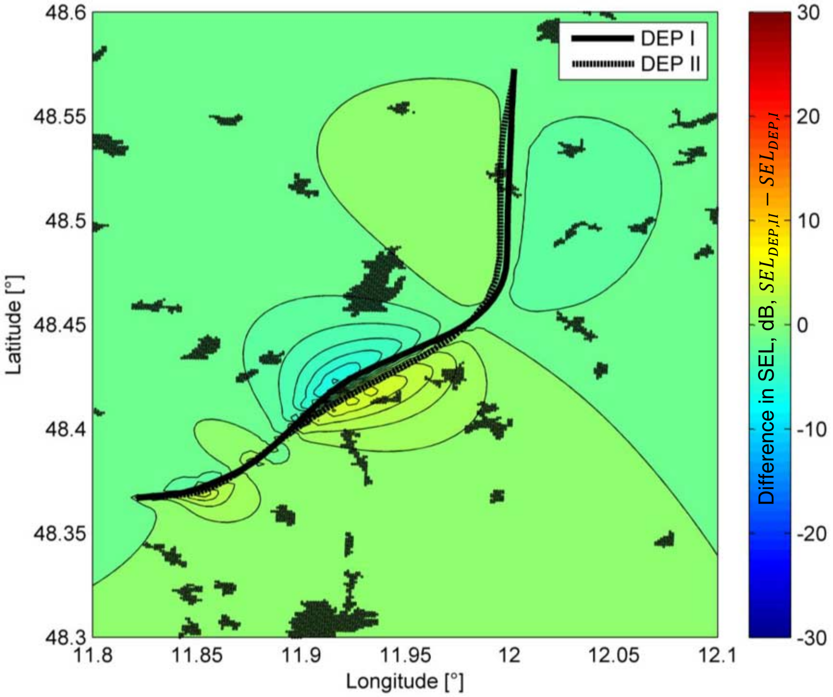

Figure 13: Difference in SEL between DEP I and DEP II

C. Validation

The optimized trajectories were validated using the Integrated Noise Model (INM) of the FAA. Exemplarily, Fig. 14 shows the sound exposure levels calculated with INM for the reference approach on EDDM RWY08L. The highest SEL values occurring are about 86db with the SEL rapidly decreasing away from the reference track. Figure 15 shows the difference in SEL values between the INM results and the results obtained with the method used within this paper (Figlar's method). It can be clearly seen that the difference between both methods is quite high (up to 16db) and that the noise model proposed by Figlar gives in general higher values, thus, potentially overestimating the perceived noise. However, the main differences between INM and Figlar occur far away from the track where SEL values are in general quite low resulting in very little or no nuisance to the population. Close to the track, both methods are in good agreement with a difference of only a few decibels. The difference in SEL values lateral to the track is most likely due to the fact that lateral attenuation is not taken into account by Figlar's Model so far.

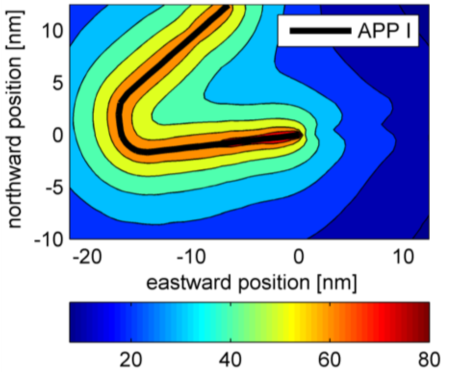

Figure 14: Sound exposure level from INM for reference trajectory (APP I)

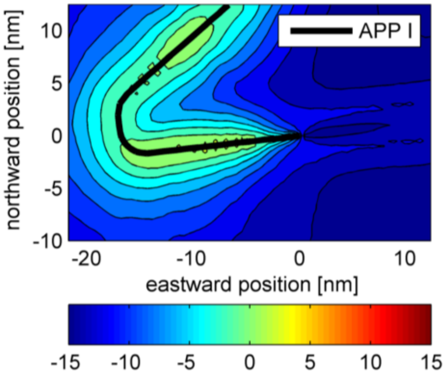

Figure 15: Differences in sound exposure level between INM and Figlar's method

VIII. Conclusions

By the proposed optimization framework, noise minimal approach and departure routes around airports can be defined taking into account important safety and procedural constraints arising from ICAO and FAA documents. Due to the use of the Gauss Pseudospectral Method it is possible to consider a large number of virtual noise stations leading to an accurate representation of the perceived noise on ground. In the numerical examples it was shown that the environmental footprint of aviation can be lowered significantly by varying both the horizontal and vertical profile of the trajectories. The resulting noise minimal routes may be seen as a valuable starting point helping trajectory developers defining new or modifying existing trajectories. This is all the more necessary as effective noise abatement procedures depend strongly on the population distribution around an airport. Hence, the benefit of standard procedures such as those proposed by the FAA in AC 91-53A is limited. Worth noting is the fact that the optimized horizontal profile for the considered departure is nearly identical to the reference track. This indicates that the optimized tracks exhibit a reasonable degree of realism and may be used for practical applications.

However, the proposed framework so far has many shortcomings, mostly due to the lack of accurate data. The SRTM data used to model the terrain has a coarse resolution and does not include any obstacles like cranes, etc., which are necessary to model the minimum obstacle constraint. Likewise, the publicly available NPD data used for noise emission calculation is very limited and does not allow modeling the noise influence of configuration changes. Thus, in the model used a flight with an extracted landing gear emits the same amount of noise as a flight with retracted landing gear, except for the additional thrust required by the increase in aerodynamic drag.

Therefore, it is mandatory for future research to obtain more accurate data that are publicly available. Next, the noise model used within the optimization must be enhanced to take into account different correction terms like lateral attenuation and deviations from the reference speed. Another concern is limitations imposed by air traffic control. Information is given from the air traffic controller to the pilot in discrete form, e.g. a clearance is given for a specific velocity or a specific heading. Thus, it might be useful to introduce discrete ATC commands into the dynamic formulation.

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Traveler expectation and airport service improvement: Kaohsiung International Airport, Taiwan

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This paper aims to explore traveler expectations and service improvements for a regional airport. Using Kaohsiung International Airport (Taiwan) as an example, it is illustrated how a simple integration of three-factor theory and SERVQUAL into QFD can help planners to identify feasible strategies that can increase passenger numbers. Among the 29 identified service attributes, travelers identify four attributes having great potential to increase overall traveler satisfaction if they are improved. These attributes are: design of special category lounge, travel information service, baggage claim wait time, and clarity of airport entry sign. The traveler perception of attribute importance is then translated into designing 20 quality improvement strategies, which are weighted for feasibility by airport managers. The researching findings suggest the following feasible strategies: increase variety of food options, improve wayfinding and airport terminal design, improve airline services, minimize baggage claim wait times, and redevelop and extend departure lounge facilities.

Nomenclature

ACI = Airports Council International
APM = Automated People Mover
ASQ = Airport Service Quality
KHH = Kaohsiung International Airport
HOQ = House of Quality
LOS = Level of Service
QFD = Quality Function Deployment
SERVQUAL = Service Quality Framework

I. Introduction

KAOHSIUNG International Airport (IATA: KHH), locating in southern Taiwan, is an airport that services passengers with travel mainly originating in the Asian region. The agreement which was reached in 2008 to allow flights between Chinese mainland and Taiwan island to become regularly scheduled and direct non-stop services (without having to go through Hong Kong or Macau) has successfully increased the cross-strait travel demand. The number of passengers at KHH has steadily grown despite the reduction in travelling from other Asian countries due to global recession. Over the course of the past 4 years (from 2008 to 2011) passenger numbers had grown from 8,483 to 469,163, its compound annual growth rate is 172.71%. Whereas the year-over-year growth rates of both domestic and international passenger numbers are -4.43% and -3.86%, respectively. Since the decline in domestic air travel is believed to be an inevitable result of short travel distance and competition from high speed rail, it is therefore important for KHH to provide better services in order to attract more travelers (particularly cross-strait tourists), and service quality can only be effectively improved when the most important needs and expectations of travelers are satisfied (Gilbert and Wong, 2003).

Accordingly, this paper explores traveler expectations and airport services improvements. Specifically, the paper integrates both three factor theory and SERVQUAL into the Quality Function Deployment (QFD) method in order to translate traveler desires into designing quality improvement strategies. The paper first reviews

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relevant literature on general service quality and airport services in section II. The way in which how the three factor theory and SERVQUAL work and their links to QFD can be used as a simple yet practical planning tool and its benefits are described in section III. The paper continues with illustrating how such an approach could focus and align together both traveler desires and airport resources to follow quality improvement strategies. Finally, the paper concludes with some implications for planning.

II. Theoretical Framework

A. Service quality

Studies have explored determinants that significantly impact on consumers' behavioral intentions. Of these, service quality is the single most researched determinant in services marketing (Zeithaml, Bitner, and Gremler, 2006). It is the four major characteristics of services—i.e., intangibility, heterogeneity, inseparability, and perishability—that make the quality of service difficult to define and measure (Parasuraman, Zeithaml, and Berry, 1985). After the successive endeavors of several researchers (e.g., Cronin and Taylor, 1994; Parasuraman, et al., 1985; Teas, 1993), the most widely used definition of service quality is defined as the result of the consumer's comparison of expected service level with perceived service performance (Zeithaml et al., 2006). Further, although there is a lengthy debate regarding the inclusion of consumers' expectations into the measurement of service quality (Carman, 1990; Cronin and Taylor, 1994; Parasuraman et al., 1994; Teas, 1993), if the primary purpose of measuring service quality is to explain the variance on dependent variables, the use of performance-based determinants is an appropriate one (Parasuraman et al., 1994). Performance-based determinants thus become growingly accepted by services marketing researchers (Cronin et al., 2000; Tam, 2004).

Performance-base determinants, as argued by researchers (e.g., Schneider and Bowen, 1995), are not only the result of seemingly tangential cues experienced by consumers during the service delivery process but also those procedures that were in place to facilitate the delivery of excellent service. Accordingly, models have been proposed to examine dimensions of service quality. Parasuraman, Zeithaml, and Berry 's (1988) SERVQUAL model explores five dimensions of service quality—reliability, responsiveness, empathy, assurances, and tangibles—in order to assess the gap between consumers' expectations and their perceptions of actual performance. Whereas Grönroos (1982) suggests two dimensions, Dabholkar et al. (1996) propose five: the reliability, corporate policy, personal interaction, problem solving, and physical characteristics of the service experience. Modified from both Parasuraman, Zeithaml, and Berry's (1988) SERVQUAL model and Grönroos's (1982) two-factor Nordic conceptualization, Rust and Oliver (1994) offer a three-component model including the service product, service delivery, and service environment. The authors argue that service quality is defined by either or all of a consumer's perception regarding (1) an organization's technical and functional quality; (2) the service product, service delivery, and service environment; or (3) the reliability, responsiveness, empathy, assurances, and tangibles associated with a service experience. Also, Brady and Cronin (2001) tie service quality perceptions to distinct and actionable dimensions: outcome, interaction, and environmental quality. In turn, each dimension is divided into three sub-dimensions that define the basis of service quality perceptions. That is, consumer perceptions of service quality reflect (1) the service outcome quality in terms of wait time, tangibles, and valence; (2) the service interaction quality in terms of employee attitude, behavior, and expertise; and (3) the physical or "built" service surroundings in terms of ambient conditions, design of facilities, and social factor. Brady and Cronin further suggest that for each of these sub-dimensions to contribute to improved service quality perceptions, the quality received by consumers must be perceived to be reliable, responsive, and empathetic.

Furthermore, a number of studies have reported that consumer satisfaction is positively correlated with service quality and is a significant mediator of service quality and behavioral consequences (e.g., Cronin et al., 2000; Yu et al., 2006; Tam, 2004). By definition, satisfaction is the consumer's assessment of a service in terms of whether that service has met his/her needs and expectations (Zeithaml et al., 2006). Therefore it is viewed as a complex determinant with both cognitive and affective components (Oliver, 1993). Building on this understanding, three primary dimensions and six sub-dimensions were used to measure traveler satisfaction with service quality at KHH: (1) service interaction quality: employee attitude and employee behavior, (2) service environment quality: ambient conditions and design of facilities, and (3) service outcome quality: wait time and tangibles.

B. Airport service quality

International travelers' impressions of a particular country are frequently affected by their first and last encounters at the airport. Their overall perceived and recollected experience may have a considerable impact on tourism development and economic growth in the corresponding country. Thus passenger satisfaction levels on airport services is considered as a key performance indicator for the operation of an airport. Yeh and Kuo (2003) apply fuzzy logic to obtain an overall service performance index for each of Asia-Pacific's 14 major international airports based on six passenger service attributes: comfort, processing time, convenience, courtesy of staff, information visibility, and security. Expanding from the Airports Council International (ACI) airport service quality (ASQ) passenger survey, Correia et al. (2008) then develop a global index for the evaluation of the level of service (LOS) of the operational components at an airport. In their study, an overall LOS evaluation is presented as a function of the following components: enplaning curbside, ticket counter and baggage deposit, security screening, departure lounge, circulation areas (corridors, stairs, elevators, etc.), and concessions. The authors further measure the overall LOS for airport passenger terminals based on nine passenger service attributes: wait time, processing time, walking time, walking distance, level changes, orientation/information, and space availability for passengers. Zhang and Xie (2005) address passengers' choice behavior in selecting between a local small community airport and a more distant major commercial airport. Zhang and Xie propose six determinants in choosing an airport: ticket price, flight frequencies, time of flights, airline preference, type of aircraft, and distance to airport. Recently, Fernandes and Pacheco (2010) comprehensively examine service quality between two different dimensions related to airport service procedure. The authors examine four passenger service attributes, i.e., access/parking, airport/terminal, departure lounge, and essential commercial activities, under the physical equality dimension. While it is information services, check-in, and security check under the service quality dimension.

The airport service quality literature also often examine specific passenger service attributes for further service excellence. Lam et al. (2003) believe that passenger wayfinding is an important aspect in airport terminal layout design and planning. The authors propose a visibility index model and prove that the success of the passenger's ability to locate a facility can be based on their model. Churchill et al. (2008) reinforce this evidence by studying several different visibility index models that are introduced in the literature. Tam and Lam (2004) find that the existing wayfinding aids are inadequate in Hong Kong International Airport and improvements are needed in six facilities: the automated people mover (APM), the lost and found office, trolleys, the airline information counters, seats in the public area, and the auto teller machines. Also, the characteristics of departure lounges (e.g., space available per passenger and number of seats per passenger) is also an important aspect of airport passenger terminal layout design and planning. Correria and Wirasinghe (2008) apply regression analysis to analyze the LOS at departure lounges in airport passenger terminals. In their study of Sao Paulo International Airport, it is found that the airport has to provide more seats than passengers to obtain a good LOS evaluation. This is due to some passengers occupy more than one seat. It is also due to groups of passengers will want to sit together. In addition, the authors find that wait time is only more associated with LOS related to departure reliability. Many passengers arrive at the departure lounge before the requested check-in time; therefore, a long wait time could not be associated with a poor LOS. Similarly, a short wait time would not necessarily represent a high LOS, but that the passenger probably arrived late at the lounge.

Perng et al. (2010) applies grey relational analysis to establish the priority relations of product categories for shopping purposes and satisfaction. In their study, the satisfaction survey shows higher rankings for brand-name, utility, and low-cost products, and low satisfaction levels on quality and price of cafe products. Torres et al. (2005) demonstrate that the more time spent in the airport, the greater consumption by passengers. And, business travelers tend to consume more than do vacation travelers if the length of stay prior to boarding is less than 45 minutes. Both Gilbert and Wong (2003) and Parker (2007) compare differences in passengers' expectations of the desired airline service quality in terms of the dimensions of in-flight service, reservation-related service, perceived price, perceived value, reliability, assurance, facilities, employees, and flight patterns. The authors find that there are significant differences among passengers of different ethnic groups/nationalities as well as among passengers who travel for different purposes. They also find that passenger perceptions are significantly different across airlines, seat classes, and usage frequencies. Moreover, there are cases when passengers are willing to pay a premium to reduce the travel time, in particular when the trip has to be made. Tsamboulas and Nikoleris (2008) find two important attributes: ground access time to the airport and mode used to arrive at the airport, the latter being important for comfort considerations (especially for baggage carrying passengers). Further, airport screening procedures in the US (and many other countries) have undergone significant changes to ensure passenger safety since the events of September 11, 2001. These changes have important implications in several aspects of air travel business. One important implication is to strike a balance between security and customer service (i.e. minimizing wait times). In the study of Gkritza et al. (2006), it is found that, while wait times at security screening points are significant determinants of passenger satisfaction, many other factors come into play. The study results also show that the determinants of customer satisfaction are not stable over time. These findings suggest that airport managers should not exclusively focus on minimizing wait time at passenger screening points.

Overall, the studies described explored passenger service attributes to satisfaction experience based on airport passenger service flow. Accordingly, 29 service attributes identified from the seven aspects of service flow at KHH—(1) access/parking, (2) entry vestibule, (3) commercial activity, (4) airport/terminal layout, (5) airline service, (6) security checkpoint, and (7) departure lounge (for convenience and comfort conditions)—

were used in this study to explore the potential satisfaction for airport service. These 29 attributes are listed in Table 1.

III. Methodology

This paper integrates both three factor theory and SERVQUAL into QFD in order to further service excellence. As shown in Figure 1, the proposed approach comprises three phases. In phase I, a total of 29 service attributes corresponding to the above mentioned three primary dimensions, six sub-dimensions, and seven aspects of airport passenger service flow are first identified. These attributes are then grouped into three categories with a different impact on the formation of traveler satisfaction. According to Matzler et al. (2004), these three categories are defined as follows:

- Basic factors are defined as having low implicit but high explicit importance. Thus, the fulfillment of basic requirements is a necessary but not sufficient condition for satisfaction.
- Performance factors are low in both implicit and explicit importance. These factors lead to satisfaction if fulfilled or exceeded and lead to dissatisfaction if not fulfilled.
- Excitement factors are of low explicit but high implicit importance. These are the factors that increase traveler satisfaction if delivered but do not cause dissatisfaction if they are missing.

In addition, parameter values which are used to categorize factors (or attributes) can be obtained by regressing the following equation:

$$CS_{tot} = \beta_o + \beta_{1fact\text{-}1} dummy_{1fact\text{-}1} + \beta_{2fact\text{-}1} + \cdots + \beta_{1n} dummy_{1fact\text{-}n} + \beta_{2fact\text{-}n} \quad (1)$$

Therefore, based on the five-point overall satisfaction ratings, attribute satisfaction ratings are recorded. "Satisfied and very satisfied" ratings were used to form the dummy variables to quantify excitement factors (value of "0"), while "somewhat dissatisfied" and "very unsatisfied" ratings were used to form the dummy variables expressing basic factors (value of "1"). "neither satisfied nor unsatisfied" were defined as expressing indifference (expectations were met). Indifferent passengers comprise a reference group. Based on this recoding, a multiple regression analysis is conducted to quantify the basic and excitement factors using as dependent variable and dummy variables for rewards and penalties as independent variables. The constant in formula (1) is the average of all the reference groups on overall satisfaction. "Penalties" are expressed as an incremental decrease (i.e. amount subtracted from the constant) associated with low satisfaction, while "rewards" are expressed as an incremental increase (i.e. amount added to the constant) associated with high satisfaction on a certain attribute. If the penalty exceeds the reward, the attribute in question is a basic factor. If the reward outweighs the penalty, the attribute is considered as an excitement factor. If reward and penalty are equal, the attribute leads to satisfaction when performance is high as well as to dissatisfaction when performance is low. Hence, it is a performance factor.

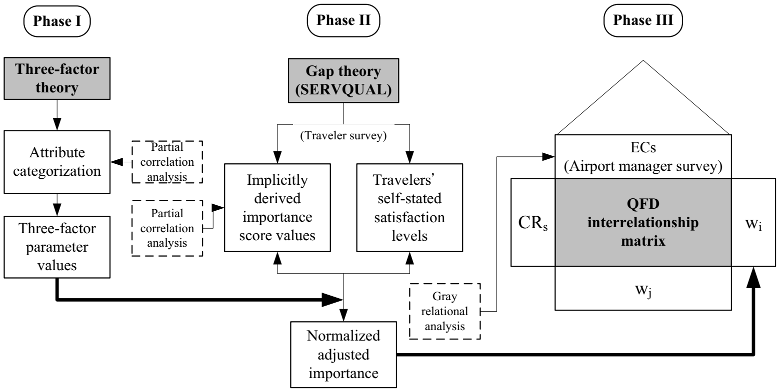

Figure 1. Proposed approach.

Moreover, as argued by Tan and Pawitra (2001), KHH needs to know its performance on satisfying each and every traveler needs if the airport wants to achieve a high degree of traveler satisfaction. Accordingly, in phase

II of proposed approach, service attributes are rated in terms of performance and satisfaction levels by the traveler. Likert scale ranging from 1 (very dissatisfied/unimportant) to 5 (very satisfied/important) in the traveler survey. Next the implicitly derived attribute importance is measured according to the procedure proposed by Deng et al. (2008), and they are as follows:

Step 1. Transform all attributes performance (AP) into natural logarithmic form

$$AP_i \rightarrow \ln(AP_i), \quad i = 1, 2, \cdots, n \tag{2}$$

, where n is the total number of attributes.

Step 2. Set natural logarithmic AP (1n(AP$_i$)) and overall travel satisfaction (OTS) as variables in a multivariate correlation model.

Step 3. Execute partial correlation analysis for each attribute performance with OTS. The partial correlation coefficient is the implicitly derived attribute importance. For example, suppose that X_1, X_2, X_3, X_4, ..., X_n are included in a multivariate correlation model. The coefficient of partial correlation between X_1 and X_2 when X_3, X_4, ..., X_n are fixed is given by Neter, Wasserman and Kutner (1985):

$$\rho_{12\bullet34\cdots n} = \frac{\sigma_{12\bullet34\cdots n}}{\sigma_{1\bullet34\cdots n}\,\sigma_{2\bullet34\cdots n}}, \tag{3}$$

Therefore, let OTS be X_1, $\ln(AP_1)$ be X_2 and the rest of $1n(AP_1)$ are X_3 to X_n, the partial correlation coefficient of No. 1 attribute can be obtained by formula (2).

The last part of phase II, as shown in Figure 1, is then to derive and rank the adjusted importance weights of attributes based on the following procedure introduced by Winterfeldt and Edward (1986):

Step 1. Identify service gaps between implicitly derived importance *and perceived satisfaction level (Qvoc$_i$) of attributes and rank these attributes accordingly.*

$$Qvoc_i = I_i - S_i \tag{4}$$

, where I_i is the level of importance score and S_i is the perceived service score. These values are also called as SERVQUAL's predicted service scores.

Step 2. Calculate unadjusted attribute importance weight (Wvoc$_i$) by

$$Wvoc_i = n + 1 - R_i \tag{5}$$

, where n is the total number of attributes and R_i is the ranking of attributes in step 1. *The higher traveler's ranks, the lower the traveler satisfaction.*

Step 3. Derive adjusted attribute importance weight (W$_{adj}$) by incorporating three-factor parameter values obtained in phase I of proposed approach.

$$W_{adj} = (Wvoc_i) \times (three\ factor\ parameter\ values), \tag{6}$$

Therefore, multiplier values of "1", "2", and "4" are assigned to the basic, performance, and excitement categories, respectively. The idea is to magnify the importance of higher-return attributes in increasing overall consumer satisfaction. These values are the so-called "three-factor parameter values" in the formula.

Step 4. Normalize adjusted attribute importance weight (W' voc$_i$) by

$$W'voc_i = \frac{W_{adj}}{\sum_{i=1}^{n} W_{adj}} \tag{7}$$

Finally, in phase III of proposed approach, a House of Quality (HOQ) matrix is utilized to relate what the traveler wants to how the KHH manager is going to meet those wants. HOQ matrix forms the central tool of QFD and is its most recognized form (Bossert, 1991). Specifically, the study first identifies quality improvement strategies that correspond to meet the specified traveler requirements. The study then calculate the importance degrees of strategies by incorporating both the normalized adjusted attribute importance weights and the scores of quality improvement strategies given by the airport managers in the QFD process. And, it has been shown that the gray relational analysis can be used to solve a number of inexact problems containing multiple criteria and objectives which are involved in the typical QFD process (Mu and Zhang, 2007). Grey relational analysis is designed to handle the uncertain systematic problem under the status of only partially known information. A procedure proposed by Wu (2007) for the grey relational analysis, which is appropriate for Likert scale data analysis, consists of the following seven steps:

Step 1. Generate reference data series x_0

$$X_0 = (d_{01}, d_{02}, d_{0m}) \tag{8}$$

, where m is the number of respondents. In general, the x_0 reference data series consists of m values representing the most favored responses.

Step 2. Generate comparison data series x_i

$$X_i = (d_{i1}, d_{i2}, \cdots, d_{im}) \tag{9}$$

, where $i = 1, \ldots, k$. k is the number of scale items. So, there will be k comparison data series and each comparison data series contains m values.

Step 3. Compute the difference data series Δ_i

$$\Delta_i = (|d_{01} - d_{i1}|; |d_{02} - d_{i2}|; \cdots, |d_{0m} - d_{im}|) \tag{10}$$

Step 4. Find the global maximum value $\Delta_{\max}$ and minimum value $\Delta_{\min}$ in the difference data series.

$$\Delta_{\max} = \forall_i^{\max} (\max \Delta_i) \tag{11}$$

Step 5. Transform each data point in each difference data series to grey relational coefficients. Let $\gamma_i(j)$ represents the grey relational coefficient of the j^{th} data point in the i^{th} difference data series, then

$$r_i(j) = \frac{\Delta_{\min} + \varsigma \Delta_{\max}}{\Delta_i(j) + \varsigma \Delta_{\max}} \tag{12}$$

, where $\Delta_i(j)$ is the j^{th} value in Δ_i difference data series. ς is a value between 0 and 1. The coefficient ς is used to compensate the effect of $\Delta_{\max}$ should $\Delta_{\max}$ be an extreme value in the data series. In general the value of ς can be set to 0.5.

Step 6. Compute grey relational grade for each difference data series. Let Γ_i represent the grey relational grade for the i^{th} scale item and assume that data points in the series are of the same weights, then

$$\Gamma_i = \frac{1}{m} \sum_{n=1}^{m} r_i(n) \tag{13}$$

, where the magnitude of Γ_i reflects the overall degree of standardized deviance of the i^{th} original data series from the reference data series. In general, a scale item with a high value of Γ indicates that the respondents, as a whole, have a high degree of favored consensus on the particular item.

Step 7. Sort Γ values into either descending or ascending order to facilitate the managerial interpretation of the results. The higher the value of Γ , the more important it is for the quality improvement strategy.

IV. Empirical Results

A. Descriptive analysis

The proposed approach described in section III will be applied for each individual service dimensions and attributes adopted. Data have been obtained by observation and interviews of 447 departing passengers at Kaohsiung International Airport in Taiwan during September 2009. Table 1 provides a profile of surveyed passengers. A majority of passengers are college educated males with a monthly income either less than NTD 25,000 or ranging from NTD 40,001 to NTD 60,000. Moreover, the individual age distribution for passengers is concentrated in the age span of 27-45. And, over 80% of passengers travel either for business or on a personal vacation. These findings suggest that passengers are typically middle-aged vacationing or business travelers.

Similar to the dichotomous outcome observed for the survey question on monthly income, passengers report that they travel abroad either less than two times or more than seven times per year. Also, approximately 82% of passengers are Taiwan citizens and, therefore, they are either simply dropped-off by their friends or relatives at the airport or take public transportation to the airport.

Table 1. Respondent profile.

			N	%
Gender	Male		296	66.22%
	Female		151	33.78%
		TOTAL	*447*	*100.00%*
Age	Less than 20 years		38	8.50%
	21 to 26 years		62	13.87%
	27 to 35 years		136	30.43%
	36 to 45 years		121	27.07%
	46 to 60 years		80	17.90%
	60 years or above		10	2.24%
		TOTAL	*447*	*100.00%*
Education	Less than high school		85	19.02%
	Bachelor degree (include some college)		268	59.96%
	Master's degree		67	14.99%
	Ph.D. diploma		27	6.04%
		TOTAL	*447*	*100.00%*
Monthly income (New Taiwan Dollar, NTD)	Less than 25,000		89	19.91%
	25,001-40,000		73	16.33%
	40,001-60,000		110	24.61%
	60,001-80,000		54	12.08%
	80,001 or above		81	18.12%
		TOTAL	*407*	*91.05*
Nationality	Taiwan		369	82.55%
	Foreign		69	15.44%
		TOTAL	*438*	*97.99*
Times of traveling abroad annually	Less than 2 times		167	37.36%
	3 to 4 times		97	21.70%
	5 to 6 times		64	14.32%
	7 times or above		119	26.62%
		TOTAL	*447*	*100.00%*
Purpose of travel	Business		175	39.15%
	Vacationing		209	46.76%
	Visit people		24	5.37%
	Other		39	8.72%
		TOTAL	*447*	*100.00%*
Destinations	China (exclude Hong Kong)		148	33.11%
	Other Asian countries		293	65.55%
		TOTAL	441	98.66%
Ground transportation drop-off	High speed rail		20	4.47%
	Subway or charter buses		96	21.48%
	Driving		66	14.77%
	Friend/relative		130	29.08%
	Taxi/rental car		98	21.92%
	Hotel shuttle		11	2.46%
	other		26	5.82%
		TOTAL	*447*	*100.00%*

Note: Some passengers refused to disclose their nationality or monthly income due to either less willingness to participate or a greater tendency to regard this question as sensitive.

B. The QFD result

1. Phase I: Three-factor parameter values

Table 2 presents passenger-perceived satisfaction score and three categories of the attributes. This information indicates where resources should or should not be targeted. Taking airport parking pricing (SQ6) as an example. This attribute registered as the lowest score (-0.078) among passengers with low levels of satisfaction. However, reduce parking fees would probably not ensure traveler satisfaction. This is because, as shown in Table 1, a majority of passengers are either dropped-off by their friends or relatives at the airport or take public transportation to the airport. Hence, changing in parking fees would not felt strongly by the surveyed passengers. Another example, airport tax level (SQ8) registered as the highest level of low satisfaction score (-0.001). However, reduce or even eliminate the tax would probably not be a wise strategy because it is included in the airline ticket price and is likely insufficient to lead to a positive satisfaction experience.

Efforts, however, should be directed at the performance and excitement attributes with low scores among passengers reported low satisfaction levels (i.e., "accuracy of flight information display system", the score is -0.104; "travel information services", score is -0.050). Many travelers would inquire departures flight information at the airport. Therefore, providing better access to the displays or improved accuracy of real-time departures flight information would greatly help passengers to check flight information around the airport and improve satisfaction. In addition, if the airport provides more travel information to passengers about their destinations, passengers would greatly appreciate such services and improve satisfaction. Efforts should also be directed at the performance attributes with low scores among passengers reported high satisfaction levels because these services would probably lead to dissatisfaction if they are not maintained. For example, shops pricing (SQ12) registered as the lowest level of high satisfaction score (0.018). Passengers are more likely to buy gifts for their families and friends at the airport. Therefore, increasing the cost of buying gifts is more likely to reduce satisfaction. Passengers are also more likely to get a meal or drink at the airport and, hence, variety of food service options (SQ9) should be maintained to prevent any dissatisfaction.

Table 2. Passenger satisfaction score and three-factor category

Aspects of KHH service flow	Service attribute	Passenger satisfaction score		Three category*	Multiplier value
		Low	High		
Access/parking	Accessibility of real-time flight information (SQ1)	-0.072	0.045	P	2
	Types and availability of ground transport (SQ2)	-0.072	-0.038	B	1
	Vegetative screen (SQ3)	-0.072	0.110	P	2
	Clarity of entry sign (SQ4)	0.032	0.052	E	4
Entry vestibule	Ease of parking (SQ5)	-0.062	-0.027	B	1
	Parking pricing (SQ6)	-0.078	-0.028	B	1
	Easy handling of airside baggage cart (SQ7)	0.014	0.021	E	4
Commercial activity	Airport tax level (SQ8)	-0.001	-0.003	B	1
	Variety of food service options (SQ9)	-0.035	0.021	P	2
	Food pricing (SQ10)	0.006	0.026	E	4
	Shop options and services (SQ11)	-0.069	0.024	B	1
	Shops pricing (SQ12)	-0.009	0.018	P	2
	Design of special category lounge (SQ13)	0.061	0.088	E	4
	Wireless internet services (SQ14)	-0.061	-0.012	B	1
Airport/terminal layout	Design of passenger terminal wayfinding (SQ15)	-0.016	0.165	E	4
	Accessibility and accuracy of FIDS (SQ16)♣	-0.104	0.106	P	2
Airline service	Flight check-in services (SQ17)	0.016	0.063	E	4
	Employee attitude (SQ18)	-0.077	0.084	P	2
	Overall performance of employee services (SQ19)	-0.017	-0.007	B	1
Security checkpoint	Security screening and ID verification (SQ20)	-0.129	-0.110	B	1
	Baggage check (SQ21)	-0.054	0.053	P	2
	Baggage claim wait times (SQ22)	0.045	0.110	E	4
	Quarantine and inspection services (SQ23)	-0.053	0.044	P	2
Departure lounge	Walking distance from passenger terminals (SQ24)	-0.041	0.016	B	1
	Comfort conditioning maintenance (SQ25)	-0.102	-0.012	B	1
	Cleanliness (SQ26)	0.088	0.267	E	4
	Accessibility of toilet facilities (SQ27)	-0.054	-0.023	B	1
	Design of departure gate areas (SQ28)	-0.044	0.084	P	2
	Travel information services (SQ29)	-0.050	0.169	E	4

Note: *B = basic factor, P = performance factor, E = excitement factor.
♣FIDS represents flight information display system.

2. Phase II: Normalized adjusted attribute importance

Table 3 shows the averaged satisfaction and importance scores given by the surveyed passengers based on the five-point ratings. Passengers are very satisfied with three attributes—airline employee attitude (SQ18), overall performance of airline employee services (SQ19), and cleanliness of departure lounge (SQ26). They also consider these attributes are highly important leading to a positive satisfaction experience. While, all the identified passenger service attributes within the commercial activity dimension along with vegetative screen (SQ3) and airport parking pricing (SQ6) are perceived as not so important. In addition, accessibility of toilet facilities within the departure lounge (SQ27) is perceived to have low satisfaction scores but high importance levels.

The averaged satisfaction and importance scores are then incorporated with the multiplier values of three categories to form adjusted importance weights. These adjusted attribute importance weights are then transformed to be in the range of 0 and 1. Interestingly, the attribute ranking has somewhat altered after the transformation. More importantly, a set of four attributes—design of special category lounge (SQ13), travel information services (SQ29), baggage claim wait times (SQ22), and clarity of airport entry sign (SQ4)—have great potential to increase overall consumer satisfaction if they are improved. On the other hand, resources should not be devoted into the following attributes because they have low potential to improve satisfaction: accessibility of toilet facilities within the departure lounge (SQ27), overall performance of employee services (SQ19), accessibility and accuracy of flight information display system (SQ16), and walking distance from passenger terminals (SQ24).

Table 3. Normalized passenger satisfaction score and adjusted attribute importance weight

Service attribute	Perceived satisfaction score	Normalized satisfaction score	Perceived importance Level	Normalized adjusted importance weight
Access/Parking				
Accessibility of real-time flight information (SQ1)	3.714	0.955	4.074	0.038
Types and availability of ground transport (SQ2)	3.760	0.961	4.132	0.012
Vegetative screen (SQ3)	3.300	0.898	3.550	0.033
Clarity of entry sign (SQ4)	3.611	0.942	4.235	0.092
Entry Vestibule				
Ease of parking (SQ5)	3.609	0.942	3.993	0.011
Parking pricing (SQ6)	3.191	0.883	3.711	0.021
Easy handling of airside baggage cart (SQ7)	3.687	0.952	3.962	0.031
Commercial Activity				
Airport tax level (SQ8)	3.184	0.882	3.367	0.026
Variety of food service options (SQ9)	2.510	0.774	3.736	0.027
Food pricing (SQ10)	2.549	0.780	3.743	0.088
Shop options and services (SQ11)	3.533	0.931	3.644	0.020
Shops pricing (SQ12)	3.274	0.895	3.711	0.031
Design of special category lounge (SQ13)	3.345	0.905	3.521	0.111
Wireless internet services (SQ14)	3.487	0.925	3.964	0.025
Airport/Terminal Layout				
Design of passenger terminal wayfinding (SQ15)	3.802	0.967	4.257	0.073
Accessibility and accuracy of FIDS (SQ16)♣	3.799	0.993	4.128	0.008
Airline Service				
Flight check-in services (SQ17)	4.009	1.000	4.302	0.011
Employee attitude (SQ18)	4.068	0.986	4.367	0.010
Overall performance of employee services (SQ19)	3.950	0.986	4.347	0.002
Security Checkpoint				
Security screening and ID verification (SQ20)	3.955	0.978	4.293	0.011
Baggage check (SQ21)	3.893	0.923	4.313	0.029
Baggage claim wait times (SQ22)	3.472	0.964	4.163	0.096
Quarantine and inspection services (SQ23)	3.782	0.959	4.188	0.034
Departure Lounge				
Walking distance from passenger terminals (SQ24)	3.744	0.979	3.796	0.009
Comfort conditioning maintenance (SQ25)	3.895	0.994	4.380	0.010
Cleanliness (SQ26)	4.020	0.977	4.380	0.023
Accessibility of toilet facilities (SQ27)	3.883	0.966	4.409	0.001
Design of departure gate areas (SQ28)	3.794	0.945	4.040	0.013
Travel information services (SQ29)	3.612	0.955	3.953	0.107

Note: ♣FIDS represents flight information display system.

3. Phase III: Prioritize quality improvement strategies

Based on the traveler satisfaction survey results reported in sections I and II as well as the discussions with airport operators and researchers, we prepared a list of 20 quality improvement strategies from the 29 service attributes (Table 4). Due to physical constraints, we did not find a corresponding strategies to further improve comfort conditions (SQ25), walking distance from passenger terminals to departure gates (SQ24), and some tangibles (SQ1, SQ16, SQ2, SQ5, SQ20, SQ23, SQ12, SQ17, and SQ13).

Table 4. Quality improvement strategies

Primary dimension	Sub-dimension	Service attribute	Strategy
Service interaction quality	Employee attitude	SQ18	(1) Provide training and development opportunities for airline employees regularly (2) Incorporate customer relations management into airport employee training and development program
	Employee behavior	SQ19	(3) Increase the efficiency of bottleneck step in airline check-in process flows (4) Establish a customer-oriented interaction mechanism (5) Establish standard operating procedure for the check-in process flow and emergency response
Service environment quality	Ambient conditions	SQ3	(6) Develop new airport marketing programs regularly, and provide landscaping and vegetative screen to soften edges of buildings (7) build airport city
		SQ26 SQ27	(8) Adopt a single point of responsibility design-build contract to outsource the job of cleanliness and maintenance (9) Check the cleanliness of departure lounge regularly
		SQ25	n.a.
	Design of facilities	SQ28	(10) Provide wireless internet access in gate areas
		SQ15	(11) Check and replace the existing airport wayfinding aids
		SQ4	(12) Provide the airport wayfinding guide at information counters within the arrival/departure area
		SQ24	n.a.
Service outcome quality	Wait time	SQ22	(13) Develop key performance indicators based on baggage arrival times (14) Shorten baggage claim wait times
	Tangibles	SQ7	(15) Greatly improve availability and ease of finding baggage cart
		SQ29	(16) Provide travel information in the departure gate areas
		SQ9	(17) Increase options among restaurants according to traveler preference
		SQ11	(18) Add new features and shopping options
		SQ14	(19) Test internet access speed regularly
		SQ1 SQ16 SQ2 SQ5 SQ20 SQ23 SQ21 SQ17 SQ13	n.a.
		SQ6 SQ8 SQ12 SQ10	(20) Execute food and shops pricing review mechanism

In order to properly allocate airport resources, we surveyed the perception of airport managers regarding the relationship between service attributes and the corresponding quality improvement strategies. Weightings are given depending on the following three values : 1, 3, and 9 points, where 1 = weak relationship and 9 = strong relationship. We then incorporate the results of both traveler satisfaction survey and airport manager survey into the QFD matrix (The sizes of matrix tables preclude including them here). Based on the perceived feasibility by airport managers, 10 quality improvement strategies are proposed to KHH managers. The resultant collective strategies are listed in Table 5.

Table 5. Proposed quality improvement strategies

- Establish a customer-oriented interaction mechanism	- Establish standard operating procedure for the check-in process flow and emergency response
- Check and replace the existing airport wayfinding aids	- Shorten baggage claim wait times
- Provide wireless internet access in gate areas	- Increase the efficiency of bottleneck step in airline check-in process flows
- Increase options among restaurants according to traveler preference	- Develop key performance indicators based on baggage arrival times
- Provide travel information in the departure gate areas	- Check the cleanliness of departure lounge regularly

V. Conclusions

This article provides a real application of translating traveler desires into designing quality improvement strategies in order to further service excellence. The article has two key objectives. First it demonstrates that an integration of both three factor theory and SERVQUAL into QFD method pinpoints strategies that are feasible to implement. Second, it highlights a critical importance of both traveler and manager perceptions in addressing strategic issues and as well as highlighting immediate concerns. Using Kaohsiung International Airport (Taiwan) as an example, the findings suggest the following feasible collective strategies: increase variety of food options, improve wayfinding and airport terminal design, improve airline services, minimize baggage claim wait times, and redevelop and extend departure lounge facilities. These strategies are aimed at attracting more travelers to use a regional airport.

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Air Traffic Control Complexity, Fatigue & Service Expectation: Results from a Preliminary Study

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Air transport is an innovative industry that drives economic and social progress. Beyond the 32 million jobs annually that it maintains, air transportation is a major facilitator of global trade, with some estimates placing the total value of goods transported representing 35% of all international trade. Safety represents a cornerstone of the industry with billions being invested every year in new technologies aimed at making air transportation safer. While the utility of such technologies cannot be questioned, the issue how increasing complexity may impact the various services air traffic controllers are called to provide must be addressed. The present paper explores how the services of safety and efficiency may be impacted by changes in reported traffic complexity. Based on a preliminary study conducted at a busy terminal facility, we examine tradeoffs in the provision of safety and routing efficiency as a result of performance unpredictability that is linked to sustained and complexity and momentary traffic demands. The implications of our findings are discussed.

I. Introduction

Facing the continued growth of civil aviation and thus the increased demand for Air Traffic Control (ATC) services, there is a need for increasing the capacity of the airspace through adaptation of the existing airspace design, traffic flow, and control tools and procedures (Athenes, Averty, Puechmorel, Delahaye & Collet, 2002). A key concern of increasing throughput in the global ATC system is how such increases will affect the safety of the flying public. Even beyond commercial air travel, are concerns over how the flow of goods using air transportation will be impacted as a result of projected demand. With 35% of global trade occurring through aviation, there is understandably increased scrutiny over the provision of safety, which represents a defining trademark of the industry. This scrutiny is the result not only of projected demand for air transportation, but greater flexibility requests from air carriers, who are all vying to use the same region of airspace, at the same time, employing aircraft of varying capability and performance specifications. The consequence of this reality, is that researchers are confronted with addressing how the resulting ‘complexity’ of the air traffic situation impacts service provision, of which safety is a component.

A. Considering complexity

Complexity is a variable of interest, presumably only to the extent that it has a measurable impact on the provision of services to the stakeholders. The idea of **services** is one that is often overlooked by researchers but has tangible meaning to those who have a vested interest in the ATM system. For example, there is common tendency to assume that safety is the only ‘service’ of interest to airlines. This tendency is not without merit. Customers are only inclined to procure transportation services from an airline if they believe they are assured safe passage from origin to destination. However, the safest airline in the world is one, which does not fly at all. If an airline doesn’t fly, it is not profitable. Hence, a tradeoff exists between financial viability of an air carrier and the safety associated with increased transportation frequency. The same may be said of tradeoffs that exist between safety and efficiency. For example, an aircraft dispatcher actively monitoring flight progress affords diminishing returns in terms of his/her cognitive efficiency to impact flight routing as the volume of traffic he/she must manage increases. Consequently, there is a decrease in efficiency-based cost associated with

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increasing safety (and vice versa). Hence, in examining the impact of complexity, it is worthwhile considering it's impact on a) a singular service of interest to the stakeholder, and b) how disruption to this singular service propagates across other services of interest.

Naturally, this raises the question of what a 'service' is. Our definition of the term is drawn directly from Appendix D of the Global Air Traffic Management Operational Concept, Doc 9854). This document provides an overview of a variety of expectations that stakeholders of the air traffic system may have. Some of these services are described below (adapted from Nunes & Hendrick, 2010).

i. Safety: The foremost role of an air navigation service provider (ANSP) is to ensure safety of the users that utilize the airspace system. Safety, most often refers to the appropriate level of physical separation that must exist between vehicles within a prescribed region. In implementing elements of the global aviation system, safety needs to be assessed against appropriate criteria and in accordance with appropriate and globally standardized safety management processes.
ii. Efficiency: Generally, the term efficiency refers to the operational and economic cost-effectiveness of gate-to-gate operations. However, given that financial efficiency may be conceptualized in terms of cost-effectiveness, for the current proposal we use the term efficiency to refer to operations alone. That is, operational efficiency may be conceptualized primarily along the temporal dimension (e.g., how much fuel is burnt for distance travelled, or how long does it take to traverse a specified distance per unit time).
iii. Environment: Procedures and policies in an ATC system should facilitate the protection of the environment by minimizing the release gaseous emissions, noise and other hazardous products.
iv. Flexibility: An ATC system must be capable of affording to users the ability to dynamically adjust flight trajectories and estimated departure/arrival times. Doing so offers the user the ability to exploit the operational efficiencies/capabilities that exist in the system.
v. Predictability: A user must be able to expect the same aggregated level of service from an ATC system over a specified timeframe. Predictability is essential to users of the airspace as well as managers as schedules and operational procedures are conceptualized and implemented.
vi. Access: An ATC system should be capable of affording users an environment where the resources of the system and access to their resources are fully available in order to ensure that the user's operational requirements are met.
vii. Capacity: an ATC system that is global in nature should be capable of utilizing the inherent capacity that exists to ensure that the demands of users are met with minimal restrictions on traffic flow.
viii. Cost-effectiveness: Cost to the user must always be an important consideration when evaluating any proposal/concept that seeks to change ATC service performance/standards. This may in some instances prove to the challenging as the various interests of the aviation community are considered.
ix. Security: Users of the ATC system must be protected from threats associated with intentional (e.g., terrorism) and unintentional (e.g., natural disasters) acts, that may have a direct impact on users of the ATC system, the entities that transport them as well as the facilities used to support those entities.

B. Complexity, Fatigue & Service Expectation

Having discussed services of potential interest to the stakeholder, the next step is to determine how services are impacted by changes in complexity. This determination is largely empirical and is subject to variations based on attributes of the environment (e.g. airspace characteristics), task (e.g., vectoring), and individual differences (e.g., experience). However, for the purposes of this paper, we first describe what the term 'complexity' means to us. Much of the research on complexity has been focused on expression in mathematical terms, which based on specific factors, correspond to the degree of inferred influence. A number of studies have identified these factors and found significant relationships between them and controller workload (for a review, see Majumdar and Ochieng (2002) and Mogford, Guttman, Morrow, & Kopardekar (1995). Some of these factors include (but are not limited to), aircraft count, aircraft density, aircraft type mix, % of climbing/descending aircraft, etc. While such studies (Mogford et al, 1995; Guttmann 1995; Laudeman, Shelden, Branstrom, & Brasil, 1998), highlight the importance of complexity as being a performance factor worthy of consideration, they for the most part demonstrate two shortcomings, which we contend limit generalizability of results to the stakeholder.

Firstly, a review of much of the research demonstrates that the emphasis in terms of complexity impact is on workload. That is, the question often posited is, how do variations in traffic complexity impact the workload of the controller? The manner in which the question is asked also dictates the 'weighting' factors that are assigned to complexity contributors. Using a variety of statistical techniques (the most common being multiple regression), complexity factors (represented by scaled numerical figures) are used to predict workload. Workload values are usually the result of subjective assessments, which are particularly common in the ATC domain (see Becker & Milke, 1998; Cobb, 1968; Trites, 1961). Even in instances where more objective workload measures are employed (such as secondary task response time), researchers fail to draw an adequate link between workload and on-the-job performance. The resting hypothesis is all to often that increases in workload result in performance impairments (and hence it makes intuitive sense to isolate workload as the dependent variable). While there is some truth to such a statement, the reality is more complicated as demonstrated by Sperandio (1971, 1978). In much of his earlier works, Sperandio examined the relationship between changes in traffic load and the cognitive processes employed by controllers. He found that controllers could mitigate the impact of specific variables, using cognitive strategies, thereby ensuring that performance was kept at an optimal level independent of workload. More broadly, he also found that behavioral changes in strategies employed ensured the maintenance of optimal performance, in light of profound effects of the impacting variables on the resource capacity of the operator. Similar findings have been found in more recent years (e.g., see Nunes & Kramer, 2009). Collectively, this suggests that workload may not be an optimal dependent measure when examining the impact of complexity.

A more appropriate dependent measure we contend is fatigue. Although a recognized problem in the transportation industry (Williamson & Friswell, 2011), the usage of this term as a result of complexity may seem unusual. Certainly over the last few decades, the term has been most commonly associated with incidents that arise from inadequate sleep opportunity, suboptimal sleep quality and disruptions to the normal circadian rhythm (European Transportation Council, 2001). Hence, if adoption of a definition of fatigue is performance impairment that is the direct result of circadian factors, then the application of the term here is inappropriate. However, one must consider many of the documented manifestations of fatigue, such as a reduction in optimal reaction times (Dinges, 1995) and increased periods of nonresponding or delayed responding (Haraldsson et al., 1990; Kribbs, Dinges, 1994). Processing and integrating information takes longer, the accuracy of short-term memory decreases (Dinges, 1995). Such evidence suggests that a consequence of fatigue, is performance unpredictability (Davis, 1946), rather than a performance decrease. Such unpredictability is precisely the type of measure that is of interest to stakeholders because it affects every facet of operational planning. The level of agitation passengers feel regarding a delayed flight is lower when they are informed of how long the delay is going to be. Unpredictability directly impacts one's ability to make such an assessment. Hence we contend that an accurate description of fatigue is an increase in the level of performance unpredictability that is the direct result of momentary or sustained exposure to specific set of variables, experienced in isolation or synchrony. An example of one such variable is complexity.

A second shortcoming of existing research, is the emphasis on safety as being the sole performance metric that is relevant to the aviation community. An examination of a plethora of human performance research associated with complexity reveals the near uniform link that is drawn between input parameters and safety (usually conceptualized as operational errors or proximity events). While such linkages are important, as previously noted, safety is not the only 'service' of interest to stakeholders. There are a range of other services that must be considered, as they are by air carriers for example when scheduling and operating flights. For example, an airline may schedule flights from multiple hubs to arrive at a destination at approximately the same time as competing carriers. In doing so, the airline accepts the increased *safety* risk associated with the operation of a greater volume of traffic in the same region of space, as well as the decreased *efficiency* of movement that may be the result of limited routes to enter and depart from the airport. However, such tradeoffs may be bearable, if there is sufficient demand amongst passengers for *access* to the destination. The point here is that, if the impact of complexity (and any input parameter for that matter) is to be taken seriously by stakeholders in the ATM system, its effect must be expressed across multiple versus a singular service expectation.

II. Current Study

Having identified shortcomings of past empirical efforts, the goal of the present research thrust was to a) determine how variations in traffic complexity impact performance predictability (subsequently referred to as fatigue in this paper), and b) how specific services afforded by the controllers are subsequently impacted. In light of the limitations of previous research described above, the present study was aimed at examining the role that reported complexity on performance. The pilot study (the results of which are described in the present paper) had two main objectives. First, to assess how changes in reported traffic complexity impact controller fatigue, as measured by a basic psychomotor task. Second, to examine the extent to which complexity impacts service expectation (the specific services of interest in the present study being safety and efficiency). Given the exploratory nature of the initial study, a total of six controllers from a busy ATC facility were recruited. In addition to the administration of a psychomotor test before and after targeted shifts, radar track information associated with every aircraft managed by the selected controllers was collected. We expected subjectively reported complexity (tied to specific variables described below) to directly impact a) performance on the psychomotor test, and b) to manifest itself as tradeoffs in the provision of service expectations by controllers.

C. Method

Participants

Six professional air traffic controllers were recruited for the study, with a projected negligible attrition rate. All controllers were fully licensed at the facility from which they were recruited and were in good standing with the ATC regulator.

Design

A within-subject quasi-experimental design was employed. That is, all six were tracked across their entire six-day working cycle, which included two consecutive morning, afternoon, and night shifts.

Variables

Specific independent variables of interest, included reported complexity, traffic count during a given shift and sleep duration prior to coming on shift.

- Reported complexity was defined as being a controller's perception of the relative difficult of a given shift based on parameters that included traffic density, converging traffic volume, number of climbing/descending aircraft, average aircraft proximity and speed variations.
- Traffic count was defined as being the total number of aircraft that transitioned through the airspace sector being monitored. We note that aircraft count was confounded with reported complexity due to the nature of operations at the facility being tested.
- Sleep duration prior to shift was defined as being the total volume of sleep accumulation that occurred within the 12 hours preceding the shift start time.

Specific dependent variables of interest, included fatigue, safety and routing efficiency.

- Fatigue was defined as being the level of response time unpredictability on the psychomotor vigilance task. The PVT is well-characterized unprepared simple reaction time test that is sensitive to both sleep loss and time on task (Wilkinson & Houghton, 1982; Dinges & Powell, 1985; Thorne et al., 2005; Wesensten et al., 2004). The PVT yields asymptotic performance in a few sessions (i.e., is not subject to lingering practice effects), and thus is suitable for repeated measures designs (Thorne et al., 2005).

- Safety was defined as being the ability of the controller to ensure safe separation between aircraft over the course of their assigned shift. Safe separation parameters were 3 miles longitudinally and 1000 feet vertically (standard terminal area requirements). Expression of this measure was categorical (i.e., frequency-based)

- Routing efficiency was defined as being the average distance an aircraft being controlled had to traverse from its point of entry to its exit point in the sector (regardless of whether or not it had a departure, arrival or en route flight plan with the controller). This metric was expressed in nautical miles.

Procedure

The study was conducted by tracking controllers managing live traffic at a major ATC terminal//approach facility across a six-day work cycle. During this cycle, controllers worked two morning (0600 – 1400), two afternoon (1400 – 2200) and two night (2200 – 0600) shifts. Participants were selected prior to tracking on the first day in order to acquire demographical information and obtain informed consent. Following this, controllers were assigned subject numbers in order to preserve participant confidentiality. The same procedure was employed during each of the six days that the controllers being tracked worked. Prior to and at the end of each shift, the PVT was administered to obtain relevant response latency/unpredictability data. During the shift, all radar data associated with the controllers being tracked was collected and stored for subsequent analysis. This data contained the flight profiles (momentary position and altitude information) for all the aircraft managed by the controller during the specified shift. At the conclusion of the study (last night shift), participants were thanked for their participation and the data was subsequently analyzed.

D. Results

The results presented in this section pertain to measures of fatigue (using response latency/unpredictability), safety and routing efficiency. Given the exploratory nature of the study, a small sample size was used. Consequently, the authors were limited in their ability to apply standard statistical techniques for data analysis. This limitation is addressed in the discussion section.

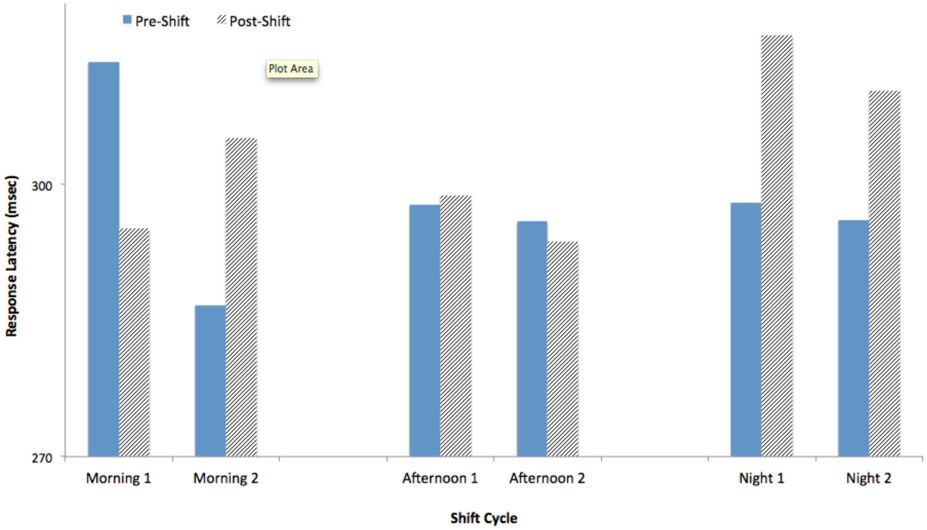

Figure 1: Fatigue Latency by shift/reported complexity

In the present paper, we discuss fatigue metrics strictly from the perspective of response latency. We note that subsequent work presents this data in the form of predictability variance discussed above. Initial analysis shows that notwithstanding the first morning shift worked by controllers during which inadequate sleep was obtained prior (a normal consequence of trying to fall asleep earlier), response consistency was largely driven by traffic complexity and load. Performance on the PVT during the night shift, which was rated as being the most complex and demanding shift, was highly sensitive to this fact. Conversely, virtually no pre-post effect was observed during the afternoon shift, which was rated as being the least complex/demanding.

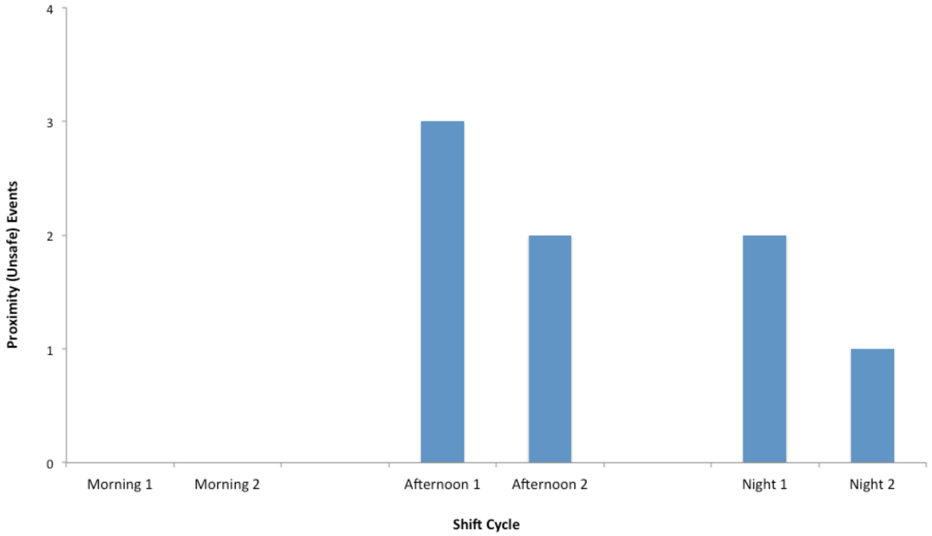

Figure 2: Safety (proximity events) by shift/reported complexity

Radar data was analyzed using ISA Software's RAMS Plus^{TM} software, to assess the presence of proximity events. RAMS Plus^{TM} is a complete turn-key, high-fidelity, cost-effective easy-to-use gate-to-gate ATM simulation tool, which can be adapted to assess the presence of proximity events using pre-specified separation criterion. The analysis of data using rams revealed the presence eight proximity events that were unevenly distributed across the six-day work cycle. Surprisingly, the highest concentration of errors occurred during the afternoon shift, which was rated as being the least complex/demanding. This was followed by the night cycle (most complex/demand) and finally the morning shift during which no events were recorded.

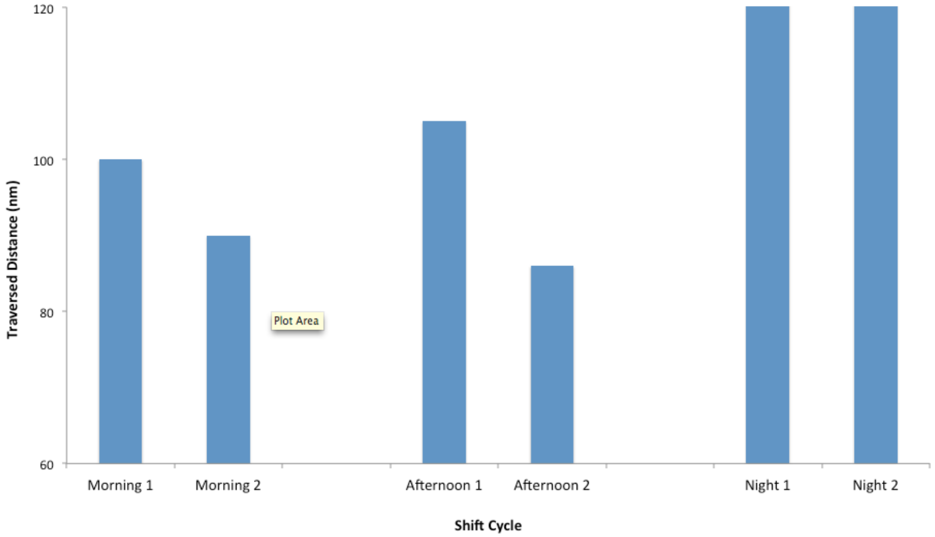

Figure 3: Routing efficiency by shift/reported complexity

A similar analysis was applied to radar data using RAMS Plus^{TM} to calculate the average distance traversed by each aircraft based on the shift worked. This analysis revealed that while routing instructions across morning and afternoon shifts resulted in near uniformity in terms of distance traversed, this was not the case during the night shifts. In these instances, aircraft traversed an average of approximately 20 nautical miles more when transitioning through the relevant sector's airspace.

E. Discussion

The results provide a complex perspective of how variations in traffic complexity, traffic load and shift cycle can interact to produce variations in the quantitative aspects of service afforded by ATC to its stakeholders. Analysis of fatigue latency data (Fig. 1) suggests that while circadian factors can influence controller responses, complexity and traffic count, may be just as influential (if not more so) in impacting operator responsiveness. Increases in response latency and unpredictability (discussed in more detail in Nunes et al, 2012), may be representative of a decreased ability of the operator to cope with unexpected events and effectively problem-solve when the situation dictates. What is noteworthy about the results is how variations in the type of fatigue experienced based on complexity/traffic demands, manifest themselves in terms of the provision of service expectations by operators to aircraft being controlled. Specifically, in instances where the overall complexity of the traffic situation is extremely low, and the volume of aircraft being managed is reduced (the afternoon shift), the impact of increased response latency and unpredictability appears to manifest itself in the form of safety events. That is, the service expectation of safety is negatively impacted (Fig. 2). This effect is noteworthy because historically, many incidents/accidents have occurred between midnight and 6am, during which there is little-to-no activity taking place in the domain of interest. Researchers have found this to be the case as early as the 1970's (Harris, 1977). It has hence been postulated the occurrence of such events is due primarily to disruptions to the circadian rhythm, as a result of having to work through the night, and to a lesser degree the inactivity/monotony associated with the task itself. The present results suggest otherwise, as the highest number (on average) of proximity events (representative of compromised safety service provision), are observed during the afternoon shift during which the same level of sleep disruption and circadian lulls are not usually experienced. This highlights the potentially more prominent role of task activity as being a driver of fatigue and subsequently, safety service provision.

The other noteworthy effect is the impact that high levels of complexity appear to have on the efficient routing of aircraft. As seen in Figure 3, decreases in routing efficiency appear to be related with increasing traffic complexity/load, which is most evident during consecutive night shifts. This may largely be the result of air carriers scheduling flights to arrive and depart from a facility at the same time based on customer demands for access. Whether or not such demands sufficiently offset the decreased routing efficiency (which on a daily basis may result in additional fuel costs and more long term may serve as a precursor to a proximity event given controller fatigue), is a decision only the carrier in question can make.

While the preliminary study was motivated by shortcomings of past research, there exist a number of limitations of our work, which must be acknowledged. Firstly, the extremely low number of participants inhibits the application of sound tests to examine statistical significance. This issue is being currently addressed by considerably increasing subject size during on-going work. Another major limitation is the fact that complexity/task activity/traffic level was confounded with shift. That is, the highest reported complexity was always experienced during the night shift, largely based on scheduled traffic flows into and out of the facility, whereas the lowest reported complexity always occurred during the afternoon shift. At the same time, reported complexity also corresponded to traffic volume. Isolating these variables individually would go a long way in ascertaining their relevant contribution to service provision. However, given the quasi-experimental nature of the study, this was not possible. The authors are working to address this issue in on-going work. Finally, the services examined here only pertained to safety and efficiency. As described earlier in the paper, there exist a range of other services, which must considered when examining the impact of changing traffic complexity. To address this issue, the authors have developed specific metrics for a range of these services and are using them as dependent variables during on-going research efforts.

III. Conclusion

The goal of the present research thrust was to a) determine how variations in traffic complexity impact performance predictability (subsequently referred to as fatigue in this paper), and b) how specific services afforded by the controllers are subsequently impacted. Our results suggest that whereas performance unpredictability associated with low traffic complexity may impact the provision of safety, performance unpredictability associated with high traffic complexity can impact the routing efficiency. While the results are preliminary and limited in their generalizability due to design constraints/confounds, they highlight the importance of adopting a multi-dimensional approach towards performance measurement, versus historical approaches, which have focused solely on safety. After all, an ATC system can be safe and highly efficient as a system, but its users will not think so if the service it provides is not the service they need (Hopkins, 1995).

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A Value Operations-based methodology for airport concept development for the year 2050

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One of the core bottlenecks with respect to the continued growth of aviation in the coming 40 years is the airport itself. The 2050+ Airport project investigates the step change innovation needed for the airport to enter the second half of this century. Three concepts are being researched: a time-efficient, cost-effective and ultra-green airport. To support the development of future concepts, the Concept Development Methodology is created. It builds upon the Value Operations Methodology to develop each airport concept and assess the expected benefits for the different users in 2050. The main contribution of this paper is to highlight the development of the Concept Development Methodology and to outline its individual steps. It is shown that the methodology is fit for application in the draft development stage, but further work is required to support detailed concept evaluation. Particularly the Change-Impact sub-method is promising and as such requires more research.

Keywords: Value Operations Methodology, airport, concept design, framework

Nomenclature

2050AP	=	2050+ airport project	v_n	=	Value contribution of value lever n
CAD	=	Context and Architecture Description	x_q	=	attribute score of attribute q
C-I	=	Change-Impact	x_{max}	=	upper limit of attribute
F.R.	=	Feasible Range	x_{min}	=	lower limit of attribute
IDEF	=	Integration Definition	ΔV	=	delta Value
VOM	=	Value Operations Methodology	λ_j	=	weight factor of value lever j
			ω_p	=	weight factor of attribute p

I. Introduction

The Advisory Council for Aeronautics Research in Europe (ACARE) has written "A Vision for 2020" [1]. It provides, together with the Strategic Research Agenda (SRA) 1 and 2[2,3], the vision of Europe on the future Air Transport System (ATS). One of the core bottlenecks that was foreseen with respect to the continued growth of aviation in the coming 40 years is the airport as element of the aviation system. However, up to now the programs in the 7th framework, like the level 3 project SESAR and the level 1 projects ASSET and TITAN, do not investigate the step change innovation

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needed for the airport to enter the second half of the century [4]. "The 2050+ airport" project (2050AP), also within the 7th Framework, develops airport concepts that address these gaps [5]. It will build upon the ideas from the "Out of the Box" project [6], detail them, enhance them with new solutions and will provide a first indication of the performance to be expected. Concretely, the project aims to produce three distinct concepts, namely the *time-efficient airport*, *cost-effective airport* and the *climate neutral airport*. By allowing the development to focus on one particular key aspect at a time, it will be possible to create truly innovative solutions within this larger time horizon up to 2050 .

As the airport is a complex environment where a large variety of different processes take place and where many different knowledge areas are needed for development of advanced operations, the 2050AP project has defined a clear scope for its activities knowing that it cannot address the entire airport into sufficient detail. More precisely, the project looks at aircraft-ground interface, airport layout and intermodal connections. Additionally it is assumed that the airport concepts will be land-based, civil-use with mixed fleet (possibly including VTOL aircraft) and oriented towards expected future aircraft capabilities.

The current paper develops a novel methodology to systematically approach future airport concept development. It describes why and how the method was developed, what it consists of, its intended use and expected benefits, as well as limitations that merit more detailed research. It is structured as follows. Following the introduction, the current chapter 1 outlines the need for this methodology and the theoretical background it is based on. Chapter 2 then describes the Methodology in detail, its different sub-methods and how it is to be applied. Chapter 3 summarizes the main results and benefits that are expected from applying the methodology, while chapter 4 describes future steps in the research. Finally chapter 5 offers a conclusion.

A. The need for a methodology

Work Package 2 of the 2050AP project aims to develop a methodology and framework in order to enable the systematic development, analysis and evaluation of the three concepts. Particularly, this framework takes a Value Operations viewpoint to the development of airports, which focusses on the actual *value* creation to be expected from the concept solutions. In this sense, value is interpreted in the broadest sense by accounting not only for economic performance, but also aspects like environment, efficiency, capacity et cetera. In order to do this, three steps are taken:

- The evaluation of current airports in light of goals and requirements set for the specific concept in 2050.
- Analysis of the core challenges and bottlenecks that exist (now or in the future) to reach these goals and to derive focused solution directions to overcome these.
- Evaluation of the impact on operational value creation, expected from these proposed solutions, so as to show their potential for each concept for 2050.

By approaching a complex problem from this perspective, it is ensured that there is clear focus on those aspects of the design that add real value to stakeholders at the end, as opposed to directly developing ideas in many directions, just because they are implicitly 'perceived' to have some contribution (e.g. from isolated brainstorm sessions). It is intended that all three concepts, although quite different in focus, are developed in a comparable fashion under similar assumptions, and can eventually be compared side-by-side on their potential to add value for stakeholders, such as travellers, operators, ANSP's, communities et cetera in the year 2050.

By interlinking each of the development aspects and letting each step follow logically from the previous, each concept (Time-efficient, Ultra-Green, Cost-Effective) will offer a comprehensive overview of why it was developed, with what focus, what challenges were addressed in detail and why, and what the final gains are expected to be. Especially with regard to this last point, the quantitative value assessment (via the a Value Operations focus) adds to the comprehension of the concepts, because it offers a more tangible and more readily 'comparable' evaluation of their net contributions. Taking such a step is paramount if it is intended to elevate the outputs of this project to a higher level of validation, as opposed to the conceptual brainstorm level of initiatives such as "Out of the Box" [6]. In short, the methodology is needed for:

- Obtaining a clear understanding of goals and attributes that need to be, respectively, satisfied and measured when developing a future airport concept.
- Analysis of current airport operations and identification of specific bottlenecks that prevent achieving the concept's goals.
- A systematically derived set of solutions that target current shortcomings and achieve the stated goals for 2050.
- Analysis of the expected operational impacts of these solutions.
- Calculation of the added value of these solutions, in order to trade-off those with the greatest potential.

The subsequent sections will outline how the methodology addresses these needs.

B. Theoretical background

The Concept Development Methodology makes use of a number of existing tools and methodologies to facilitate the process of operations analysis and creative solution finding. Among these are IDEF0 and IDEF3 to visualize processes[7,8], as well as Morphological grids[9] and design option trees[10,11] to facilitate systematic finding of new operational solutions. As these tools are well-established, and only used in support of the main framework, their workings will not be further detailed here. Instead, this section will discuss the Value Operations Methodology that is at the center of the Concept Development Method.

The Value Operations Methodology (VOM) was developed by Curran et al.[12] and applied in a number of case studies[13,14,15] as a way to estimate the added value in the aerospace design projects and operations. It is based on the concept of "value focused thinking" as developed by Keeney[16,17,18]. 'Value' (either through a design, decision, strategy etc.) for stakeholders is created by the fulfilling of *objectives* of these stakeholders: the better a certain goal is achieved, the more value is created for that stakeholder. In complex decision situations where there are many objectives, stakeholders are questioned in detail to derive a complete set of *fundamental objectives,* which are the key objectives that they intend to satisfy. For example, an objective such as "to have sustainable production" is a fundamental objective, where a goal such as "use recyclable production materials" would be a so-called *means objective* as it implies a boundary condition of how the higher objective should be satisfied.

The advantage of breaking down a decision situation into a clear set of higher- and lower-level objectives is that much information about the context of the problem is obtained beforehand. Moreover, conflicting objectives can be detected early, which forces stakeholders to rethink their specific aims. Having such a context beforehand enables one to eliminate many unclarities and ambiguities beforehand, and developing highly focused solutions as a result.

The fulfilment of objectives can be quantified by means of appropriate attributes (or KPIs as used in business). However, in the Value Operations Methodology it is argued[12] that striving for an 'absolute' number of value is not preferable and not even needed. Instead, it is better to define a so-called *delta Value* (ΔV), which is a relative measure. The reasoning behind this is that it is much more logical to relate the value of one instance with another, as any comparison without a baseline has no purpose. As long as the alternative under consideration has more value points than a certain reference, the alternative is preferable over the reference case. Obviously the reference needs to be chosen carefully in order to make the most appropriate comparison. Combining the attributes with appropriate weighting factors to account for the objectives' relative importance and the use of a differential, additive value function leads to the following expression of value:

$$\Delta V(v_1, v_2, v_3 \ldots v_n) = \left\{ \sum_{j=1}^{n} \lambda_j \frac{v_{j1}}{v_{j0}} (x_1, x_2 \ldots x_q) \right\} - 1 \tag{1}$$

The value function uses the ratio of the value-elements of instance 1 (the analysis case) to instance 0 (the reference). Additionally, the ΔV is now a function of the separate value-elements v_1 to v_n , with relative weights λ_j , while these themselves are a function of the attributes x_1 to x_q.. The second level of the value function (that of the individual elements) is modelled by summing the value contributions of the different attributes, with appropriate weights ω, like:

$$\frac{v_{j1}}{v_{j0}}(x_1....x_q)=\sum_{p=1}^{q}\omega_p\frac{\left(x_{j,p}\right)_1}{\left(x_{j,p}\right)_0} \tag{2}$$

Finally, he concept of the *feasible range*[14,15] of an attribute recognises the fact that attributes cannot physically change infinitely, but are bounded by an upper (x_{max}) and lower (x_{min}) limit. The attribute values within the feasible range (F.R.) can be calculated using the following two equations, for attributes with an upwards (meaning 'more is better) and a downwards (meaning 'less is better) direction of preference respectively:

$$(x_{j,p})^{F.R.}=\frac{(x_{j,p})-x_{\min}}{x_{\max}-x_{\min}} \tag{3}$$

$$(x_{j,p})^{F.R.}=1-\frac{(x_{j,p})-x_{\min}}{x_{\max}-x_{\min}}=\frac{x_{\max}-(x_{j,p})}{x_{\max}-x_{\min}} \tag{4}$$

Converting attribute scores to a number within the feasible range ensures that the ΔV will never increase to an infinite level, but always has a maximum value of 1 (when $x = x_{max}$). Conveniently, these equations also makes it easy to handle attributes which have a downwards direction of preference. Instead of inverting the ratio in (2) for such attributes to x_0/x_1 (which is intuitive to ensure that low numbers are assigned high value), one can simply use equation (4) to convert the attribute values to values within the feasible range, and then the normal ratio x_1/x_0 can be used in (2).

II. Overview of the Concept Development Methodology

The methodology is shown graphically in Figure 1 and consists of three sub-methods that each address a key step in the airport concept development process:

- The Value Operations framework
- The Concept Context and Architecture Description method
- The change-impact method

In the subsequent sections these different parts of the methodology will be further outlined.

A. General overview

The Concept Development Methodology's framework encompasses the two phases of the 2050AP concept development: a draft phase and a detailed phase. Furthermore, the framework presupposes that information with respect to stakeholder influences and goals is available (either in detail, or at a draft level to be developed further), and that any 'external' constraints (regulations, specific requirements) to the design are given. In the current project, this information is available by way of a pre-existing "Vision 2050" document[19].

In the draft phase, the airport concepts are developed in their initial form. The aim in this phase is to develop a clear understanding of what each concept should entail, which main bottlenecks in current airport operations prevent the achievement of these goals, and to derive, in a structured way, potential solution directions. The analysis can be detailed to a small (S), medium (M) or large (L) airport, or a selection of these depending on scope and resources. The draft phase is concluded with an initial value calculation to assess which solutions have most potential. At that moment also an initial validation exercise can be carried out to assess the *feasibility* of the solutions.

In the detailed phase, the concepts' best initial solutions are developed in depth. In addition, the knowledge that was obtained with respect to goals, attributes, operational context etc. in the separate concepts is now combined in a broader design framework. Developers can use this combined knowledge to analyse their concept from a broader viewpoint than just their own (e.g.

time-efficient, cost-effective or ultra-green), without having to develop those frameworks themselves. More specifically: the combined framework provides possibilities for broader analysis, without enforcing it. It allows developers to only focus on their concept's viewpoint in the draft phase, without taking all aspects of operations / value into account, which is highly practical given 2050AP's limited (time) resources.

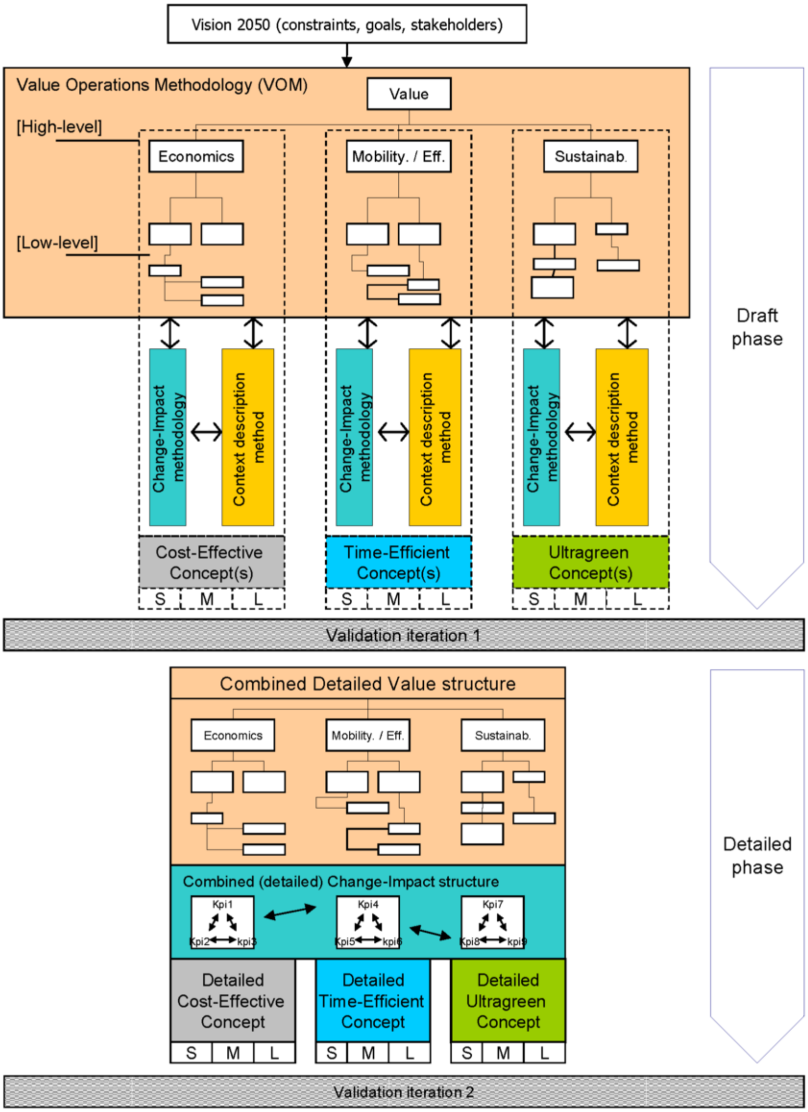


Figure 1. AP2050 Concept development methodology.

B. Value-Operations framework

The Value Operations framework is at the heart of the Concept Development Methodology. In line with both value-focused thinking and engineering practice, the first aim of any concept design should be to establish a clear set of goals and requirements that the design has to fulfil in order to be considered valuable. Using the Value Operations Methodology, first a high-level structure of objectives and attributes is established for all three airport concepts, and combined into a high-level Value Function. These goals and attributes are purposely kept broad so as to be applicable for mostly any 'generic' airport, regardless of operational focus. This enables comparability between the concepts, when using the broad goals to establish a value metric (ΔV).

The key value components for an airport are in this case considered to be *economics, mobility/efficiency and sustainability.* These three levers are selected to match with the three concepts' foci and will thus each get primary importance in one of the airports developed. The aspect of safety has not been given a specific lever, because it was believed to be of equal importance for all concepts, as it is an inherent component for all types of airport operations. Therefore, safety will be captured and fulfilled by all concepts by taking it as a boundary conditions to their development. The high-level value therefore becomes:

$$\Delta V(AP_{2011}^{2050}) = \left\{ \lambda_{mob} \left(\frac{Mobility_{2050}}{Mobility_{2011}} \right) + \lambda_{ec} \left(\frac{Economics_{2050}}{Economics_{2011}} \right) + \lambda_{sust} \left(\frac{Sustainable_{2050}}{Sustainable_{2011}} \right) \right\} - 1 \qquad (5)$$

The obvious difference between the three concepts is that the *relative* importance of each of the high-level goals is not similar. The Cost-Effective concept will e.g. attribute much more weight to the economics goals, while the Time-Efficient concept will gain more value from efficiency goals. This difference will be captured by assigning appropriate weight factors to the different value levers, as described in the VOM. No specific methods to derive these weight factors are prescribed, but the Analytical Hierarchy Process (AHP[20]) has proven[13,15] to be a worthwhile alternative to ensuring consistent weights are derived.

While the high level value structure is similar for all three concepts, more focus is given to each facet by breaking down these generic goals in a lower-level analysis. For example, a goal to "reduce costs" can be broken down to "reducing airside cost" and "reducing landside cost" (or even further) for the Cost-Effective concept, where this more detailed view gives better understanding of its value drivers and can also be accounted for by more specific weight divisions. Conversely, it can be imagined that this detailed division is of less importance to an Ultra-Green concept, where the focus would be on understanding in high detail the different environmental value drivers. Allowing for this concept-specific detailing enables developers to focus their efforts first and foremost on their specific concepts, and use the detailed knowledge obtained by the other concepts in the detailed development phase. The following sources are used to derive more detailed goals:

- Concept-specific details obtained from the "Vision 2050"[19]
- Expert knowledge from within the development team
- External expert knowledge obtained from an industry workshop[21]

C. CAD method

The purpose of the Context and Architecture Description method (CAD) is to enable analysis of current and future challenges or bottlenecks that (will) exist within airport operations, with respect to the goals of each specific concept. First, this is necessary to develop understanding of baseline airport performance with respect to cost-effectiveness, time-efficiency or environmental performance. With this information, the baseline airport can be used as the reference situation for the calculation of value (ΔV) of final concept solutions. Secondly, analysing current and expected bottlenecks in operations in a systematic way a) focusses on the key challenges in operations and b) helps derive insightful ideas to possible solution directions that could help overcome these challenges. An overview of the CAD is given in Figure 2, applied to the Time-efficient concept as an example.

In the *analysis step* a current airport's operations are analysed in light of the previously-established goals for either cost/time-efficiency/environment to establish what they look like and where bottlenecks to the concept goals exist, or can be expected to occur if no changes are made. To account for the different focus of the three concepts, three so-called *views* can be taken in the analysis:

- *Process-oriented view*. This view is most appropriate for the Time-efficient airport and focusses on the organisation, performance and interdependencies of all airport processes. In this view, standard methods such as IDEF[8] are used for analysis.
- *Service-oriented view.* This view if intended for the Cost-Effective concept and focusses on the airport's function as a provider of services and how these can be economically optimized (such as ground handling, ATM, shopping etc.) In this view, standard analysis methods from business economics are used, such as cost pies or NPV analysis.
- *Infrastructure-oriented view.* This view if intended for the UltraGreen concept and focusses on the existing infrastructure of the airport and its environmental impact (terminal buildings, energy provision, ground vehicles). In this view, e.g. breakdown structures of energy needs/sources, or Life Cycle Assessment (LCA) can be used for analysis.

The output of the first step is a clear overview of a baseline airport, its operations in terms of either economics, time-efficiency or sustainability and what bottlenecks pose challenges to the goals established for each concept with the Value Operations framework.

The second step in the CAD method is the *solution finding step*. Using the obtained results on airport operations and bottlenecks, the aim is to find solution ideas for the key challenges. As this is the most creative step in concept development, developers are left free as much as possible to explore new ideas. To maintain uniformity and comparability, the methods of Morphological grids[9] and Design Option trees[10] are used next to more general brainstorm approaches. The advantage of embedding these two methods within the second step of the CAD is that they enable a very systematic analysis of all possible options for making changes to the existing *architecture* of processes/services/infrastructure, so that, theoretically, an exhaustive set of possible solutions is obtained.

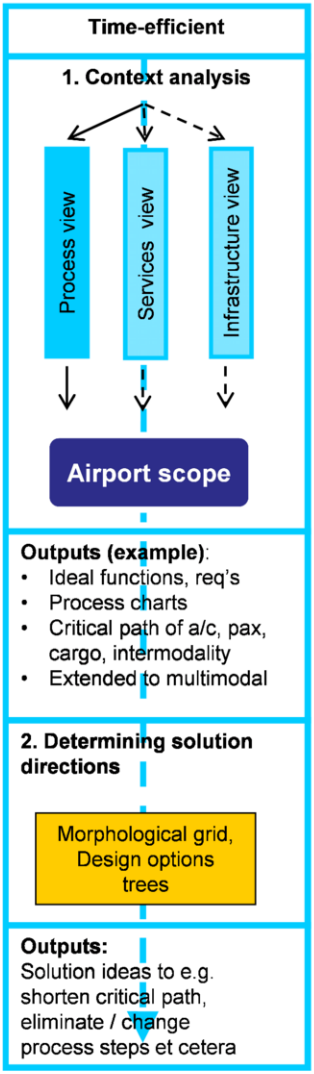


Figure 2. CAD method (Time-efficient airport example)

D. C-I method

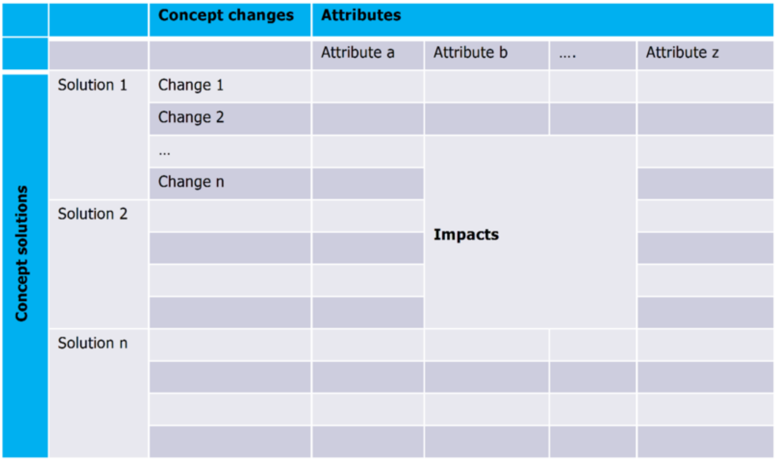
The purpose of the Change-Impact (C-I) method is to map and quantify the performance impacts that the proposed solutions for the 2050 concepts will have on the Value levers. This information can then be fed back into the Value Operations framework, to calculate the ΔV score. The C-I method consists of three main steps, with a fourth being the calculation of the ΔV:

- *Description*: outlining the proposed operational (sub)concept and listing the airport's operational areas that will be impacted by this (e.g. landside, airside or both)
- *Categorisation*: listing the specific operational aspects that will be affected by the solutions (e.g. specific turnaround processes, check-in infrastructure etc.) If possible and applicable, any significant secondary impacts (resulting from the first) should also be listed during this step. This depends highly on the operational expertise of the analyst(s), as the current method is still qualitative and detailed relationships may not yet be inferred.
- *Quantification*: consists of two phases: a *broad quantification* of the impacts on a qualitative scale or a *detailed quantification* of the impacts using actual performance numbers, to be

derived via e.g. simulation or expert opinion. The second type is applicable during the detailed phase of development.

- *Calculation*: First with a *broad calculation* of ΔV scores, using the simple scale, to rank and select concept solutions that are expected to have the strongest positive impact. This can then be followed by *detailed ΔV calculation*, using information obtained in the detailed design phase, to quantify the actual value-adding performance of key solutions

The tool for capturing the change and impact information is the *Change-Impact matrix*. This is a matrix that lists, for each individual change contained in a solution, the impacts this will have on the value attributes that were selected with the VOM. Impacts can be Negative (-) -meaning that the impact drives the attribute downwards, or Positive (+) -meaning that the impact drives and attribute upwards. For each direction, the impact can be Small, Medium or Large. An empty C-I matrix is given in Figure 3 as an example.



		Concept changes	**Attributes**			
			Attribute a	Attribute b	....	Attribute z
Concept solutions	Solution 1	Change 1				
		Change 2				
		...		**Impacts**		
		Change n				
	Solution 2					
	Solution n					

Figure 3. Example Change-Impact matrix

To enable input into the Value function, a numeric conversion of the impact levels is used. Additionally, three conversion types are selected to easily incorporate sensitivity analyses on the ΔV calculation. These are shown in Table 2.

Conversion type	Impact score						
	- - -	- -	-	0	+	+ +	+ + +
1. Constant impact	-1	-1	-1	0	1	1	1
2. Linear impact	-3	-2	-1	0	1	2	3
3. Exponential impact	-9	-3	-1	0	1	3	9

Table 2. C-I conversion scale

Since there are 3 different scaling methods proposed, there are also three feasible range limits for each conversion. As derived and applied in earlier work[15] with the same C-I scoring mechanism, these are shown in Table 1.

Conversion type	xmin	xmax
1. Constant impact	≤-1	≥1
2. Linear impact	≤-3	≥3
3. Exponential impact	≤-9	≥9

Table 1. Feasible range conversion limits for each impact score

When the impact scores are converted to the feasible range, the total impact on each attribute is used in equation (2) and (5) to calculate the ΔV. The upper and lower limits of the feasible range are set in such a way that they are always higher or lower than the attribute value for the reference (x_0). This in order to prevent dividing by 0 in the calculation of x_1/x_0, which could occur when $x_0 = x_{min}$ or $x_0 = x_{max}$. Consequently, in case of values beyond those given in Table 1, the x_{min} and x_{max} are scaled accordingly.

For the first development cycle (draft phase) the impacts are determined according to a broad scale, complemented by expert assessment to give a rough estimate of the change to be expected in the value attributes. For the detailed development cycle, the process can be improved by data gained from the first validation cycles to provide more accurate impact estimates.

III. Expected results and benefits of the methodology

The Concept Development Methodology is expected to produce the following results when applied to airport concept development for the year 2050:

- A comprehensive and argued derivation of goals and attributes that need to be respectively satisfied and measured when developing either a Time-Efficient, Cost-Effective, or Ultra-green airport.
- A clear analysis of current airport operations in terms of services, processes or infrastructure and identification of specific bottlenecks that prevent achieving the concept's goals.
- A systematically derived, exhaustive set of potential solutions that target current operational shortcomings in order achieve the stated goals for the 2050 airport.
- A comprehensive and argued analysis of the expected operational impacts of these solutions.
- A calculation of the potential added value of each of these solutions, with respect to the concept's goals, which makes it possible to select those with the greatest potential for detailed design.

Furthermore, there are a number of benefits expected from the use of this methodology:

- The common and uniform approach and terminology ensure comparability between the three airport concepts, despite their distinctly different focus.
- By approaching the complex concept design problem from a value-focused perspective, and also developing a value function in the same line, it is ensured that there is always a clear focus on those aspects of the design that are most likely to add real value to stakeholders at the end. This as opposed to directly developing ideas in many directions in a pure brainstorm-like fashion, just because they are implicitly 'perceived' to have some contribution. The Value Operations Methodology offers coherent and structured guidance to this end and has proven itself in previous applications.
- The method clearly interlinks all important aspects from the analysis of airport challenges/bottlenecks, the generation of solution (ideas) and the assessment of these solutions' operational impacts. By letting each step follow logically from the previous, each concept will offer a comprehensive overview of why it was developed, with what focus, what challenges were addressed in detail and why, and what the final gains are expected to be.
- The quantitative value assessment (ΔV) adds to the comprehension of the concepts, because it offers a more tangible and more readily 'comparable' evaluation of their net contributions than purely descriptive statements.

IV. Next steps in the research

Currently, the Concept Development methodology is in its first phase of application, where the scope, goals and requirements of the airport concepts are analysed. As outlined in Figure 1, this entails a further breakdown of each value lever into more detailed objectives and associated performance attributes. Similarly, the fields of cost, processes and environment are analysed with the CAD method, after which the solution directions that are found can be preliminary quantified on their value-adding potential with the Change-Impact method.

Before the start of the draft design phase, the Concept Development methodology was presented to industry experts at a project workshop[21]. The response to the method was positive; the only comment questioned how the different views of stakeholders are to be incorporated with the VOM, as different priorities (and thus goals and associated weight factors) could lead to vastly different concepts or value-estimates. Currently, the preferences and weightings of the airport operator are taken into account first, as it is the airport operator that finally has to make the ultimate decision on his future development strategy. However, it is easily possible to account for all stakeholders separately by doing the value calculations using their specific weighting preferences, which also gives insight as to where value is created/destroyed and for whom. Methods for better unifying the various stakeholder priorities will be explored as the Methodology is developed further.

In addition to the comment above, there are a number of aspects that merit future research. Specifically the Change-Impact method should be further improved. First, the different relationships that exists between operations and performance attributes, and how different change and impact types that influence these should be formally captured. Additionally, the compound impacts of multiple changes on attributes and the propagation of secondary impacts should be further investigated and embedded in the method. Finally, more detailed studies with actual operational data should be conducted to test the methodology and substantiate the different change-impact relationships. Doing so will make the C-I methodology a robust tool for forecasting the effects of operational (design) changes in airports.

V. Conclusion

One of the core bottlenecks that is foreseen with respect to the continued growth of aviation in the coming 40 years is the airport itself. The 2050+ Airport project investigates the step change innovation needed for the airport to enter the second half of the century and to this end develops three separate concepts: time-efficient, cost-effective and ultra-green.

To support the development of future concepts, the Concept Development method is created. It builds upon the Value Operations Methodology to assess the expected benefits of each concept for the different users in 2050 and consists of three sub-methods: the Value Operations framework, the Context and Architecture Description and the Change-Impact method. By applying each of these in a step-wise fashion the goals, needs and solutions, and finally the impacts of new airport operations can be evaluated for each of the three future concepts. This consistent approach with a common terminology allows for comparison between the three concepts despite their different focus.

Currently, the methodology is in its first steps of application and as such no final statements about its validity can be made. However, most of the sub-methods and tools contained within it are either well-established or proven successful in earlier case studies. Moreover, discussions with industry experts during a project workshop revealed no major shortcomings. The method is therefore deemed suitable to help the development of the first draft airport concepts. Future research will improve the method using lessons learned during this phase, especially with respect to the Change-Impact method, which is still quite experimental.

Finally, it can be said that the main contribution of the current work is that it offers a consistent framework and step-wise approach to future airport concept development, coupled with initial quantification of benefits, and thereby progresses beyond more traditional brainstorming and "out-of-the-box" approaches.

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Simulation of Taxiway System Maintenance to Optimize Airport Operational Value

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This paper sets out to investigate the impact of the taxiways' status on airport operations. The main objective is to create a quantifiable method to measure the research project's consequences e.g. a modeling tool. The main findings will be the measurable impact/consequences of maintenance activities on different stakeholders. A simulation is developed and used to test and optimize certain scenarios with a validation carried out at Schiphol airport, Amsterdam. It will show that the simulation tool is an effective way of optimizing taxiway system maintenance so that impact on airport operations is minimized in terms of performance and ideally, the total value to the airport operator. In general, the full paper will aim to explore the possible financial benefit for operators, the optimization between work-costs en fuel-costs, and the optimization between costs and capacity; in order to explore the potential the tool has as an analysis and decision making tool.

I. Introduction

An airport often undergoes all sorts of maintenance works in progress. Those include maintenance and projects (for taxiway fillets, lighting systems, signage, etc) on the runways system, taxiways system, aprons and many other sub-systems. This project will focus on the taxiways system.

Maintenance activities are carried out periodically to keep the taxiways at optimum operational and safety levels. There are two kinds of maintenance: planned and ad-hoc. The planned maintenance have been on the schedule well before the maintenance work take place, while ad-hoc maintenance are implemented when there is a spontaneous need for it. Obviously, any maintenance work will disturb operations of other air transport operators including the airport operator, airlines and air traffic controller. While the reasons to carry out maintenance work are justifiable, the consequences of maintenance work on each concerned parties are not known. There has not been a quantifiable method to measure these consequences in hard numbers. This research involves creating a simulation tool to calculate those consequences so that by forecasting the consequences, the managers will be able to make informed decision in the futures.

II. Methodology

The leading research question addressed is: 'is it possible to design a discrete-event simulation tool to assess the impacts of various categories of maintenance activities on airport operations?' The airport process composes of several stakeholders. There are the airport operators, the airport authority, the air traffic provider, the airlines, the aircraft ground handlers, the regulatory authorizes and the local community. Since this project focuses on the taxiway maintenance, only the concerned stakeholders at the airside will be taken into consideration. They are the airport operator, the air traffic provider and the airlines. The particular parties are Schiphol airport, ATC the Netherlands LVNL and KLM airline as the home carrier. The research environment is the department of Construction & Maintenance Control (a section of the department Airside Operations) at Amsterdam Schiphol Airport. Historical data will come from database of concerned parties in the project, namely Schiphol, KLM and LVNL. The availability and reliability of these data will determine the accuracy of the model.

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The modeling phase will simulate the consequences of the taxiway maintenance upon different parties. The optimization phase will be to find the optimal solution with respect to a certain objectives. A sensitivity analysis will be conducted and different airport maintenance scenarios will be evaluated. Interviews with experts are critical to get realistic working practices at the airside. The interviews are conducted in two rounds. The first round commences the beginning of the project. They are to gain a sound understanding of the airside operations and airside problems at Schiphol. These interviews partly contribute to the Kick-off report. The second round contains of in-depth interviews: obtaining the historical data and answering extensive questions. The information from the second round determines the accuracy of the model.

From the airport perspective, we look at the airside conditions of Schiphol. Based on the airport layout, the taxiway system will be prioritized into the global taxiway sub-system and the local taxiway sub-system. Furthermore, the taxiway system will also be divided into normal taxi paths and important taxi paths – hotspots. Should an equivalent maintenance work occur, the hotspots are the taxi paths that cause much more consequences than the normal taxi paths. Therefore, the research will be carried out firstly on the global taxiways and the hotspots. Later on the local taxiways and the normal taxi paths will be studied.

From the airline perspective, the project will focus on KLM, since Schiphol is the main partner of this KLM and vice versa. In the final phase of the project, if time permits, other members of Skyteam alliance will also be taken into consideration. The project will go through 3 phases: Model, Optimization and Sensitivity analysis. The work breakdown structure can be seen in the Figure 1

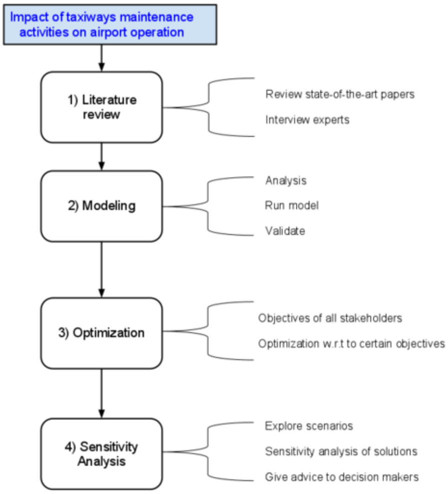

Figure 1 Work breakdown structure

III. Taxiway maintenance operations

Firstly, for practical purposes, the authors interviewed all the concerned stakeholders at Schiphol airport. The purpose of these interviews was to have a good understanding of the objectives of each stakeholder and how they related among one another. The preliminary mapping of the stakeholder objectives are illustrated in Figure 1

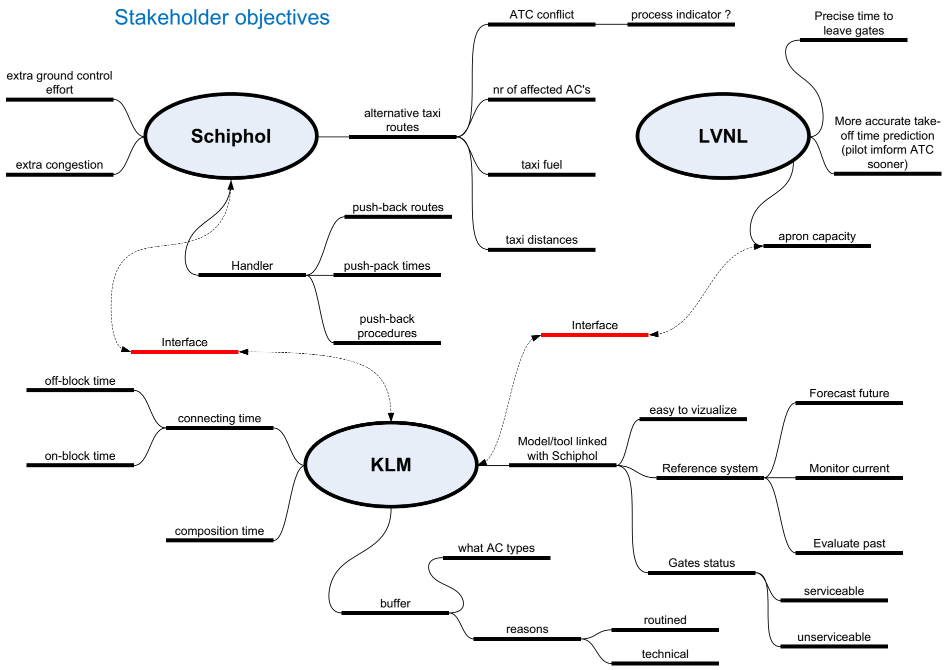

Figure 2 Mapping of objectives of the stakeholders (where LVNL is the ATC provider)

Table 1 Relative importance of objectives from the stakeholder

Importance	Objectives	Stakeholders
1st	Time • Extra taxi time • Taxi distance due to alternative routes • Holding time • Minimum connecting time (block time, arriving at gates, off-block time)	 AAS, KLM AAS, KLM KLM
2nd	Congestion • Buffer handling (fair-share policy) • How many aircraft take alternative routes • Fuel consumption/cost	 KLM AAS AAS, KLM
3rd	• Apron Capacity • Gates u/s Congestion • Extra mental workload • Extra ground control effort • Extra team to tow/clean aircraft • Push-back way variation	KLM, LVNL KLM LVNL LVNL AAS, handlers AAS, LVNL

The objectives can be prioritized based on how often a certain objective is mentioned in the interviews. If an objective is mentioned more often than others, it means this objective is of interest of many stakeholders. As a consequence, the model will try to solve such objective at the first place. However, there are objectives that are mentioned more than once, but they are not considered the most important objectives e.g. apron capacity (mentioned by the experts of KLM and LVNL). The objectives can be categorized into three levels of importance; they are listed in Table 1.

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IV. Literature Review

Literature was used to review the building blocks that constitute the main topic: impact of taxiway system maintenance .These building blocks are Airport layout, Taxiway system, Airport maintenance, Airport operations and Taxiway maintenance. They are illustrated in Figure 3

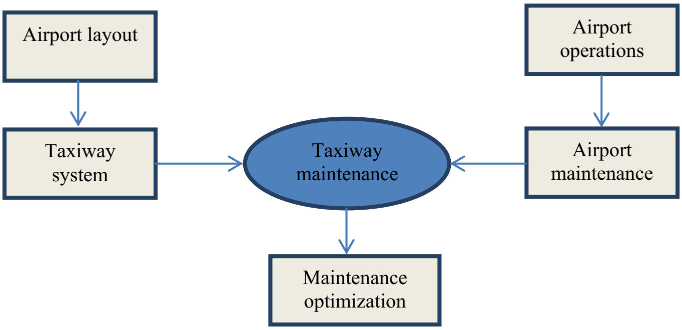

Figure 3 Building blocks of taxiway system maintenance

The main topic will be approached from two perspectives: layout and operations. From the layout planning perspective, the airport environment starts with the airport layout. The airport layout includes all the contributing sub-systems of an airport: taxiway, runway, hangars, viaducts, landside, etc. Among those, the taxiway system will be considered in this report. On the other hand, from the operational planning perspective, airport operation is the most important function. Airport operations comprise many activities: pavement management, aircraft rescue and firefighting, snow and ice control, ground handling, airport maintenance, ground handling, bird control, etc (*Well et al., 2004*). Airport maintenance has many types, for instance runway maintenance, taxiway maintenance, lighting maintenance, etc. By combining these two perspectives, it is observed that the taxiway maintenance is yielded from direct cooperation between taxiway system layout and airport maintenance activities. Finally, optimization of the taxiway maintenance will be achievable once the taxiway maintenance is fully understood.
In the next sections, literature of each of the five building blocks will be reviewed.

Airport layout

To cope with increasing competition, many airports are adopting the concept of Airport City in their strategy. Airports can be considered the platform for two-sided market (*Appold and Kasarda 2011*), the business model which has become an important area of business strategy of the airport managers. Case studies from airport cities such as Amsterdam airport area, Alliance Texas, Panama City, The North Carolina Global TransPark (*Appold and Kasarda 2011*) shows that non-aeronautical revenues (*Graham ,2009*), real estate development (*Golaszewski*), monopoly and locational rents (*Forsyth, 2004*) have enabled leapfrog development in the surrounding area and captured a greater growth than otherwise might have been the case. Another similar concept proposed by de Neufville (2003) is called Airport Systems. This concept pointed out the activities that now concern managers in the periods where aeronautical revenues are declining. The activities include cleaning and maintenance, environmental management, management of concession, parking services, real estate development, transport service of employees and passengers. These two new concepts certainly will affect the future airport layout, comparing to the aeronautical-revenue -focused airport in the past.

Traditional airport geometric layouts are designed according to best experience. Nowadays with the advent of affordable and powerful computers, airport layout can be automatically optimized. Normally the optimization process can occur the project goes on. Or the layout can already be integrated into design framework from the beginning of the project (*Osman et al., 2003, Yeh et al., 1995 and Mawdesley et al., 2003*). One of the most recent developments in optimization method is the genetic algorithm. Both *Mawdesley and Al-Jibouri (2003)* and *Osman et al (2003)* used genetic algorithms to optimize the construction planning layout issues. However, automatic computation does not necessarily lead to optimal design (*Osman et al (2003)*). Secondary objectives should be taken into account to increase the accuracy of solutions. Furthermore, safety and environmental aspects should be included into the design to balance the finances of the projects (*Mawdesley et al., 2003)*.

The inputs needed to simulate an airport can be varied depending on the purposes of the users. One can use nodes and links (*Vaddi et al., 2011*) to create the taxiway/runway network. Or nodes and links can be combined with polygons (*Theunissen et al., 2003*). While the airport layout is static, the airport configuration can change dynamically (*Vaddi et al., 2011*). This idea is complemented by the study of *Theunissen et al (2003*) where the author emphasis on the importance of using up-to-date information from the database.

There are various ways to build a simulation package to model an airport. Depending on methodology, an airport model can cover the landside, the airside or the airspace around the airport. With the increasing complexity of airports, it is very hard to design a simulation package that can anticipate all future developments of an airport. One approach is to utilize modular-based design (*Adelantado et al., 2004*). Modular-based design allows the simulation package to be adapted, reused and computed in parallel without extensive recoding. This method is complemented by agent-based framework (*Scerri et al., 2010*), which supports distributed simulation and incremental development.

Airport operations

While the airport operates both the airside and the landside, only the airside operations will be considered. An overview of flight movement phases at the airside is given by *Kageyama and Fukuda (2008)*. Once the airside phases are known, an overall picture of classical airside operations simulation is presented in *de Neufville (2003)*. After that, *Adelantado et al (2003)* describes a recent attempt to have a better coordination among all parties involved in airside operations.

According to *ICAO Common Taxonomy Team (CICTT)*, an aircraft flight consists of many phases in sequential order. They are Standing (STD), Pushback/Towing (PBT), Taxi (TXI), Takeoff (TOF), Initial climb (ICL), En route (ENR), Maneuvering (MNV), Approach (APR), Landing (LDG), Emergency descent (EMG), Uncontrolled descent (UND), Post-impact (PIM). Taking a different view by focusing on airport related activities, *Kageyama and Fukuda (2008)* suggests that a flight operation can be divided into four distinct phases: Pre-Departure, Departure-Taxing, flight and arrival-taxing. In this model, the authors also take into account the delays and placed them in the context of each phase. This model is depicted in Figure 4.

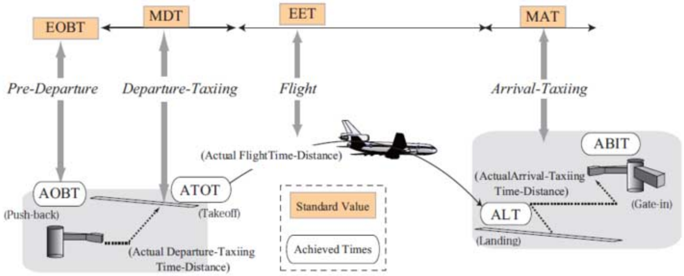

Figure 4 Airside Operations (*Kageyama and Fukuda 2008*)

The level of detail can determine the accuracy of the model (*de Neufville., 2003*). The level of detail can be low (macroscopic model) or high (microscopic). Macroscopic models are designed to give approximate answers on planning and some design issues, while microscopic models aim to representing the airport processes in great accuracy. Non up-to-date information sharing among airport operators reduces the efficiency of the whole system. Advanced Surface Monitoring Ground Control Surface (A-SMGCS) and Airport Collaborative Decision Making (A-CDM) promise to solve this issue. *Adelantado et al (2003)* mentioned the importance of A-SMGCS as a concept "expecting to provide adequate capacity and safety in relation to the specific weather conditions, traffic density and aerodrome layout by use of modern technologies and high level of integration between various functionalities".

Taxiway system

The taxiway system at an aerodrome facilitates the processes of taxi-in for arriving aircraft and taxi-out for departing aircraft. The taxiway network includes the taxi routes, holding bays, taxi lanes at aprons. This section will look at a number of aspects that influence the taxiway system simulation. Firstly, the software's level of details is looked at (*Theunissen et al., 2003)*. Secondly, programming algorithms are to be considered (*Roling and Visser 2008, Lee and Balakrishnan 2010, de Neufville 2003, Balakrishna et al., 2010, Gupta et al., 2010)*.

The simulation speed of is largely determined by the level of details of a model. One often has to choose one of two options: low-detailed models are fast to simulate, high-detailed models are slow but offer more accurate results. There was another approach by *Theunissen et al., 2003* that used two levels of detail in their model. The authors found out that using two levels of details may serve the users better, depending on different circumstances. Low level-of-detail network can be simulated very quickly in order to compute the start-point, end-point and intersections. Later on, the founded nodes and routings are inputted to rendering the map in high level of detail. This approach could significantly speed up the whole process, in contrast to using high level of detail in every step. Furthermore, a pictorial representation of the taxi routes on the computer display of the air traffic controllers (*Koeners and Kerstens 2001*) proves very useful in reducing misinterpretation in airport communication.

The programming algorithm is the essential part of any simulation tools. There are a number of available algorithms: mixed integer linear programming, Monte Carlo stochastic simulation, A* Algorithm and database utilization. The mixed integer linear programming (*Roling and Visser 2008, Lee and Balakrishnan 2010, Gupta et al., 2010)* is able to optimize the objective function which is the weighted combination of the total taxi time and the total holding time. It is desirable that the tool will offer a graphical user interface in which the user can freely choose and adjust the criteria to meet his/her specified needs (*Roling and Visser 2008)*.

Depending on the inputs, the models can be deterministic or stochastic (*de Neufville 2003*). If the model accepts probabilistic quantities (random variables), the model is stochastic, so called Monte Carlo simulations as treated in the research of *Pitfield et al., 1998*. If the model has constant parameters over time, deterministic model can be built.

Genetic algorithms combined with A* Algorithm can find an optimal surface routing, including the use of dynamically varying costs to model resource utilization (*Brinton at al., 2002*). Dijkstra's algorithm proves to be able to find the shortest routes for operation on a network of runways and taxiways (*Gupta et al., 2010*). Another programming approach is to use the existing database of the airport to build the simulation tool (*Balakrishna et al., 2010*).

Airport maintenance

Airport maintenance is one of the main activities of airport operations. Maintenance activities can be divided into two subgroups: preventive maintenance and corrective maintenance. Preventive maintenance includes planned maintenance and conditioned based maintenance (CBM). Planned maintenance can sometimes be called planned predictive maintenance (PPM), scheduled maintenance, or statistical based predictive maintenance (*Canero 2005*), which includes a set of activities to improve the overall reliability and availability of a system (*Moghaddam and Usher 2011*). CBM occurs when needs arise. Corrective maintenance on the other hand, deals with existing or imminent failures. These failures may be found during preventive maintenance or unexpected failures (*Vanderlande Industries*). A more qualitative comparison among different kinds of maintenance strategies are depicted in Figure 5 by *Umiliacchi et al (2011)*

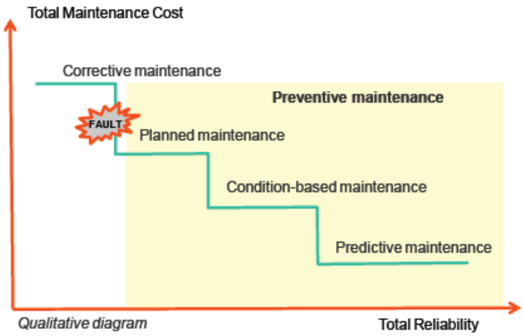

Figure 5 Possible maintenance strategies (*Umiliacchi et al., 2011)*

Since specific literature about airport maintenance is not freely available, studies about maintenance works of other branches of engineering will be given. Nevertheless, maintenance practices from other branches can certainly help to improve the maintenance processes at the airport airside.

It is widely accepted that the most important criteria considered are cost and reliability (*Arunraj and Maiti 2009*) or cost, risk and losses (*Hadavi 2009*). When risk is considered the first priority, CBM is preferred over time-based maintenance (TBM) because CBM has better risk reduction capability than TBM (*Arunraj and Maiti 2009*). On the other hand, corrective maintenance is better suited when cost is the criteria (*Arunraj and Maiti 2009*). Another criterion often neglected in many maintenance optimization models is loss. There can be production loss (*Sortrakul et al., 2005*), revenue loss (*Chen et al., 2003*), profit loss and penalty due to missing delivery of service (*Busacca et al., 2001*).

Maintenance schedule is often subjected to multi criteria decision making. When multi-criteria selection is required, for instance both cost and risk are of equal importance, one would rather choose CBM for high-risk equipment and CM for low risk equipment. (*Arunraj and Maiti 2009*)

Maintenance optimization

There is a variety of maintenance optimization algorithms. *Hadavi (1998), Podofillini et al (2006), Busacca et al (2001), Colorni et al (1991), Hiller and Lieberman (1967),* used GA while *Mattfeld (1995) combine GA and job shop algorithm*. Analytic hierarchy process (AHP) and goal programming (GP) were used by *Arunraj and Maiti (2009*) to optimize maintenance, heuristic algorithms in electrical railways (Chen et al., 2011), spreadsheet modeling (premium solver) and Weibull distribution to find optimum maintenance scheduling of wear out components (*Artana and Ishida 2002*), questionnaire surveys and historical performance plots are used to describe the performance threshold, performance jump and performance trend of the equipment (*Lamptey et al., 2008*). Optimization problems can be divided into single-objective and multi-objective ones. The multi-objective problems in general are more complex and require more computational power than single-objective problem.

Linear and non-linear programming techniques often have difficulty in optimizing problems dealing with global optima and multi-objective analysis. Nature-inspired optimization computation, on the other hand, has achieved great popularity in tackling those obstacles, thanks to its intelligence, global search and parallelism capabilities. This family of techniques emulates the principles of biological evolution to solve optimization problems. There are many nature-inspired optimization algorithms available, for instance Extremal Optimization (EO), Simulated Annealing (SA), Evolutionary Algorithm (EA), Differential Evolution (DE), Particle Swarm Optimization (PSO), Ant Colony Optimization (ACO), Estimation of Distribution Algorithm (EDA) etc. as listed in *Weise (2011).* Depending on the input data types and complexity of the problem, one can choose a suitable algorithm among many options. Conveniently, the Matlab environment offers two built-in toolboxes to solve optimization problems: Optimization Toolbox and Global Optimization Toolbox. Their differences can be seen in Table 1 which was extracted from *Kozola 2011.*

Table 2 Comparing Optimization and Global Optimization Toolboxes (*Kozola 2011)*

	Optimization Toolbox	Global Optimization Toolbox
Faster/fewer function evaluation	√	
Larger problems/higher dimensions	√	
Find local minimum/maximum	√	
Find global minimum/maximum		√
Better on		√
• Non-smooth		√
• Stochastic		√
• Discontinuous		√
• Undefined gradients		√
Custom data types (in GA and SA solvers)		

After computing an optimized maintenance process, the information needs to be shared adequately among stakeholders. There have been several initiatives to maintain a better information flow among all stakeholders. *Nucciarelli and Gastaldi (2009)* did a study on The Travel Information-based Exchange (TIE). This collaboration platform manages cooperation among airports, local and national stakeholders. This effort aims at creating a common strategy, a competitive advantage and value added for companies and passengers. TIE was validated by a case study in central Italy. Another platform initiated by Eurocontrol is called Airport - Collaborative Decision Making (A-CDM). *Adelantado et al (2003)* emphasized that CDM would provide a complementary promising concept (alongside A-SMGCS), based on a framework of information exchange and data sharing between all ATM actors.

V. Intended Results and Conclusions in Full Paper

In this case study, the Inbound Peak for runways 18R and 18C at Schiphol airport were considered. Under normal situation, aircraft lands on runways 18R and 18C wanting to park at the Southern side of the airport e.g. B platform or C-pier, can taxi via taxiway Quebec to reach their destination. In November and December 2011, Quebec was closed for traffic for several days. During these times, the traffic had to be diverted via the north of the airport to finally arrive at the gates. Thus, impact on taxi times (Δt) were inevitable and recorded by the airlines. This data will be used to validate the simulation developed to predict delay times for improved taxiway maintenance management. The taxiway Quebec was closed in Saturday 26th November 2011 and data from this day will be used as disturbed situation. The undisturbed situation is chosen at Thursday 24th November 2011, as the traffic distribution on runways 18R and 18C was similar to those in 26th November.

1) Recorded impact on taxi time from actual data

1.1 Inbound taxi time from 18R to gates

Figures 6 and 7 shows the distributions of taxi times, in minutes, from runway 18R to the Southern gates in the undisturbed and disturbed states respectively. It can be seen that in undisturbed case, taxi time varies from 10 minutes to 16 minutes, and most taxi-in movements need 11-12 minutes. In the disturbed case, the majority of aircraft need 13-15 minutes to taxi in. There were several instances where aircraft need 17-19 minutes to taxi to the gates (higher than maximum taxi time in undisturbed case).

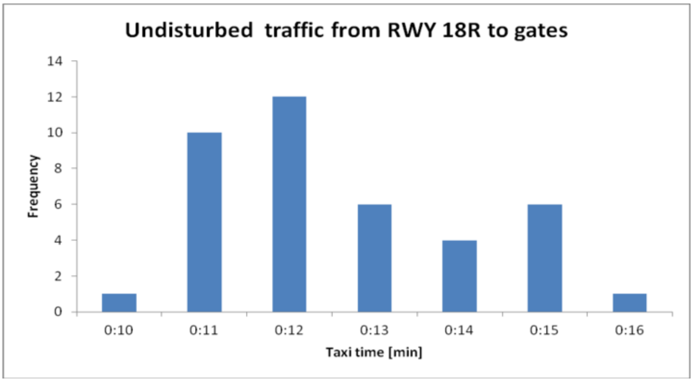

Figure 6 Frequencies of taxi times from RWY 18R to gates in undisturbed case

The airport and airlines divide a working day into many time brackets employing different runway combinations. Each time bracket lasts from 20 minutes to 1 hour. Consequently, the delay data can be analyzed in terms of the average difference in taxi times during each time bracket for the disturbed and undisturbed cases. Consequently, the difference is calculated by subtracting the average taxi time in disturbed situation by the average taxi time in undisturbed situation. However because of different daily schedules, not all time brackets are used in every day and therefore, only the comparable time brackets that aircraft were arriving on from runway 18R on both days (24th and 26th) were used in the analysis, as presented in Figure 8.

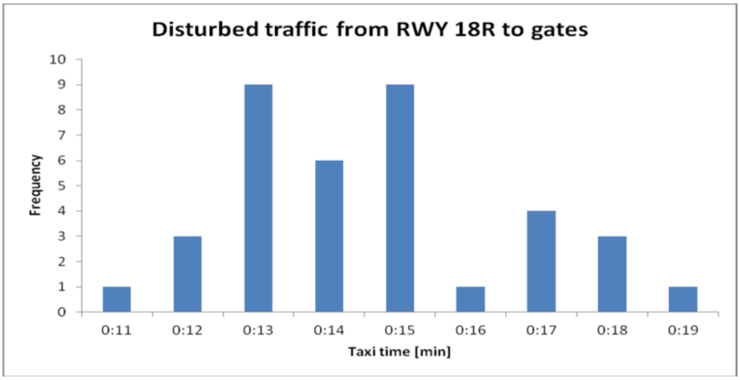

Figure 7 Frequencies of taxi times from RWY 18R to gates in disturbed case

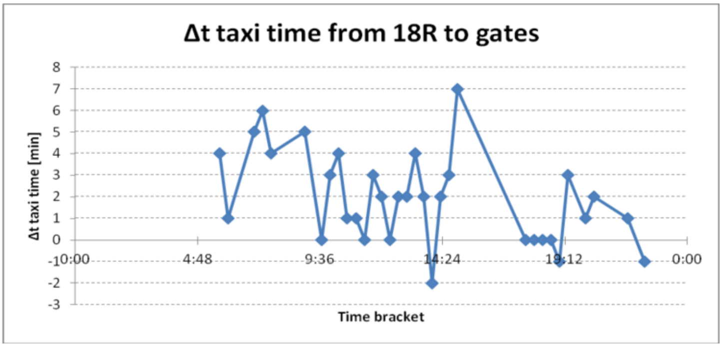

Figure 8 Average Δt of undisturbed & disturbed cases for different time brackets from RWY 18R to gates

It can be seen from Figure 8 that Δt for each time bracket varies considerably, from 0 minutes to 7 minutes. There were even 3 instances where Δt is negative; meaning taxiing in the disturbed situation was faster than that of he undisturbed situation. This may be explained by the fact that there are time brackets with less traffic in the disturbed case to that of the undisturbed day, leading to a slightly lower number of movements for the disturbed case.

1.2 Inbound taxi time from 18C to gates

A similar statistical analysis was carried out for runway 18C to the gates and the results are shown in Figures 9 through to 11. Since there were fewer aircraft landing on runway 18C than landing on runway 18R, there were fewer samples to be used in these histograms. The majority of taxi time in undisturbed case last less than 7 minutes; while in disturbed case most aircraft need 8 minutes or more to taxi in.

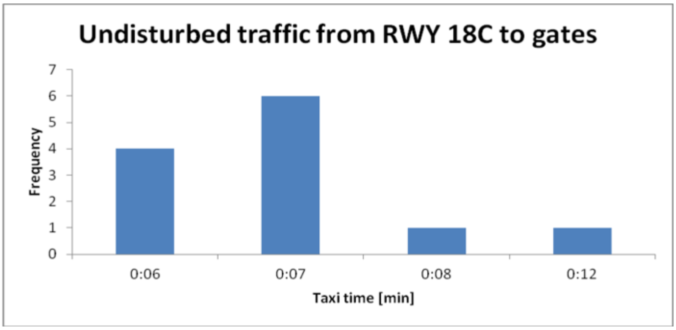

Figure 9 Frequencies of taxi times from RWY 18C to gates in undisturbed case

The estimates of delay from the airlines relative to the taxiway Quebec construction were found to be on average an extra Δ3-4 minutes to taxi from runway 18R to B-platform and Δ2-6 minutes to taxi from runway 18C to B-platform, while taxiing to C-pier, aircraft had to spend Δ1-5 minutes from runway 18R or 18C.

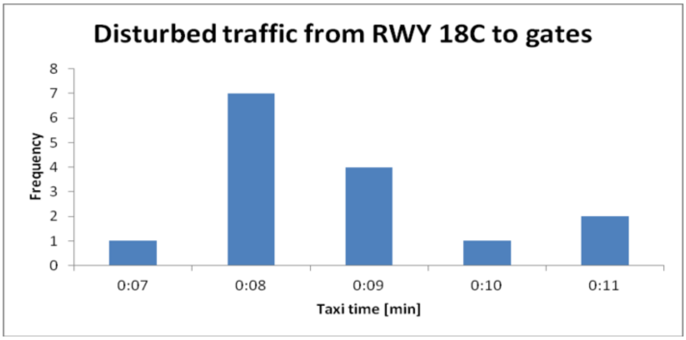

Figure 10 Frequencies of taxi times from RWY 18C to gates in disturbed case

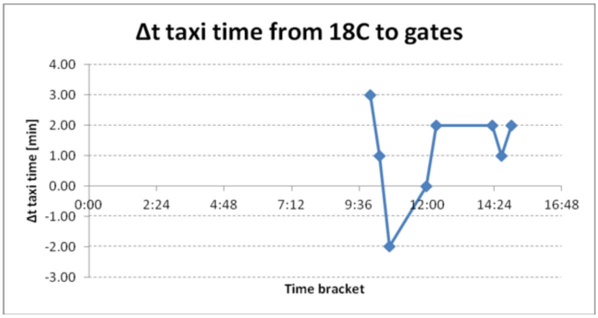

Figure 11 Average Δt of undisturbed & disturbed cases for different time brackets from RUNWAYS 18C to gates

2) Estimated impact on taxi time from the simulation

2.1 Inbound taxi time from runway 18R to B-platform

The B-platform consists of approx. 50 gates, populated in south west – north east direction, as can be seen in Figure 12. The further to the south west part of the platform, value of Δt becomes larger because the nominal taxi distance to this part of the platform is shorter while the nominal taxi distance to the north east part of the platform longer. Gate B63 was chosen because it is located in the middle of B-platform, which consequently has the average Δt of all the gates. Aircraft have 2 options in taxiing to B-platform, via W5 or via Zulu (Z), where W5 is preferable as the most direct and shortest taxi route to most gates. However, W5 is only available for traffic when runway 18C is not in use and otherwise aircraft have to travel via Z to avoid disturbance with aircraft landing from the north on runway 18C. In Figure 12 and Figure 13, the purple lines illustrate the nominal taxi routes from runway 18R to B-platform via W5 and Z respectively, while the blue lines indicate the alternative routes via the north side of the airport.

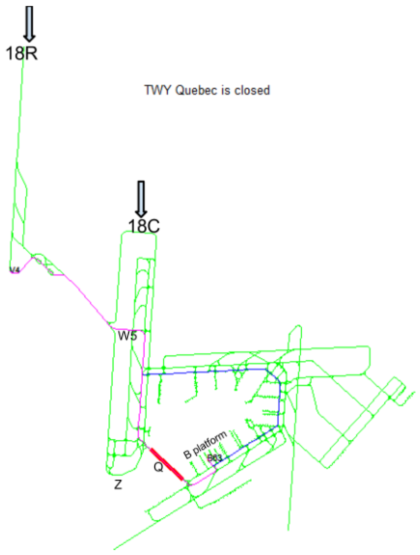

Figure 12 Taxi routes from RWY 18R to gate B63 via W5

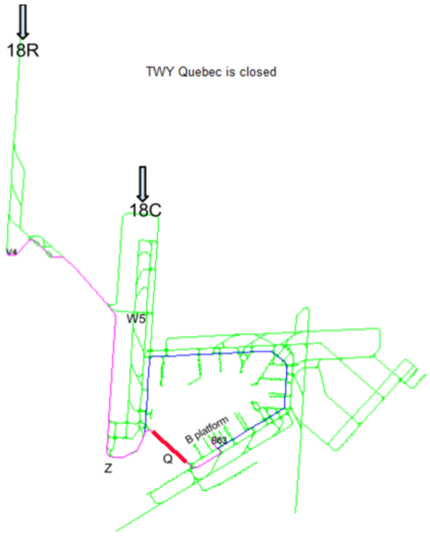

Figure 13 Taxi routes from RWY 18R to gate B63 via Z

Since aircraft weights have an impact on the taxi speeds Δt, the simulation distinguished between medium and heavy aircraft, with he latter having typically lower taxi speeds. Consequently, the Δt of heavy aircraft is higher than that of medium aircraft, as can be seen from the values for W5 and Z given in Table 3.

Table 3 Δt from RWY 18R to B-platform via W5 and Z

Taxi route	Traffic distribution	Medium aircraft Δt	Heavy aircraft Δt
Via W5	68%	Δ2.84 min	Δ3.43 min
Via Z	32%	Δ6.57 min	Δ7.51 min

However, the airline data available did not consider Δt via W5 and Z separately but grouped these together for an average Δt for all inbound movement from 18R to B-platform. Therefore a weighted average Δt for the simulation was computed by multiplying the Δt for each taxi route by the traffic distribution or load for that taxi route, and then dividing the weighted sum by the total traffic both taxi routes, as illustrated in equation 1.

$$\Delta t_{avg} = \frac{\Delta t_{W5} * traffic_{W5} + \Delta t_{Z} * traffic_{Z}}{total\ traffic} \tag{1}$$

The historical data showed that the traffic distribution of taxiing via W5 and Z was 68% and 32%, respectively. Using Equation 1, the average values of Δt for medium and heavy aircraft were found to be Δ4.05 min and Δ4.75 min while the average Δt of all aircraft from the airlines was estimated by them to be Δ3-4 min, as shown in Table 4.

Table 4 Average Δt of the model, comparing to airlines' analysis (18R → B-platform)

Medium aircraft	Heavy aircraft	*Airlines' historical value*
Δ4.05 min	Δ4.75 min	*Δ3-4 min*

The simulated values are slightly higher than the historical values. The reason might be: the estimated taxi speeds used in the model are lower than the real taxi speeds, which lead to longer-than-reality taxi times. Eventually, simulated Δt is higher than historical Δt.

2.2 Inbound taxi time from runway 18C to B-platform

Similarly, Figures 14 and 15 show the simulated taxi routes from to gate B63 after landing on runways exits W8/W7 and exit W6 respectively. Using similar method as in the previous Section, the Δt for taxiing from runway 18C to B-platform was calculated, with 18C's exits being W7, W8 and W6 for B63 as the final destination. The simulated results are summarized in Table 5.

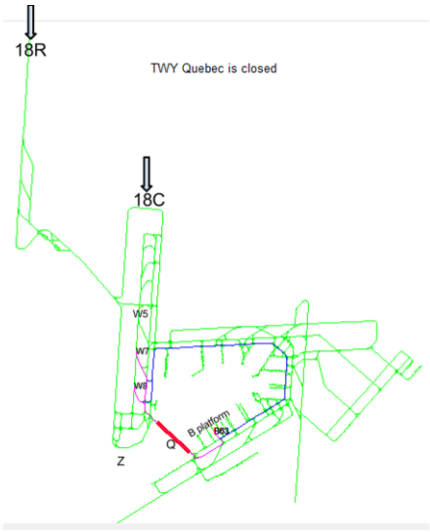

Figure 14 Taxi routes from RWY 18C's W6 to gate B63

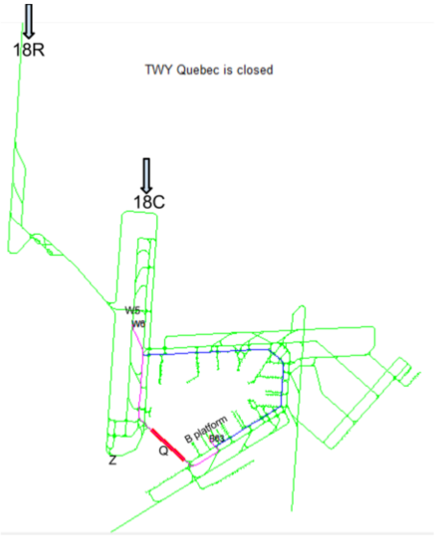

Figure 15 Taxi routes from RWY 18C's W7 & W8 to gate B63

Table 5 Δt from RWY 18C to B-platform, comparing to airlines' analysis

Runway exits	Medium aircraft	Heavy aircraft	*Airlines' historical value*
W8	Δ7.42 min	Δ8.81 min	*Δ2-6 min*
W7	Δ5.73 min	Δ6.8 min	
W6	Δ3.43 min	Δ4.07 min	

It is evident from Table 5 that the airlines did not keep track of the names of runway exits for each flight movement, and therefore this complicates the validation of the simulated values. Therefore, the frequency at which runway exits W8, W7 and W6 were used was not available. The aircraft endeavor to leave the runway first and therefore their preference is W6, then W7 then W8 so one can say that this preference will lead to a great use of W6 etc and so the simulated value Δt compares more favorably with the airlines' historical value of Δ2-6 min.

2.3 Inbound taxi time from runways 18R and 18C to C-pier

The analysis was again carried out for C-pier, which is further north-east from the B-platform. As a consequence, Δt in this case should be smaller than Δt when aircraft taxi to B-platform. C08 is the representative gate of C-pier which is located in the middle of C-pier and the simulated routes are illustrated in Figure 16 and 17.

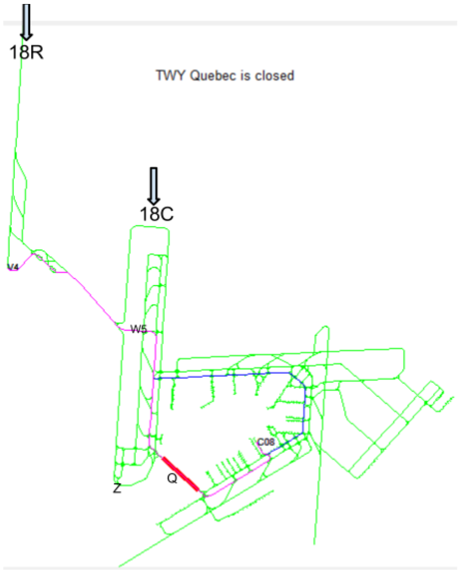

Figure 16 Taxi routes from RWY 18R to gate C08 via W5

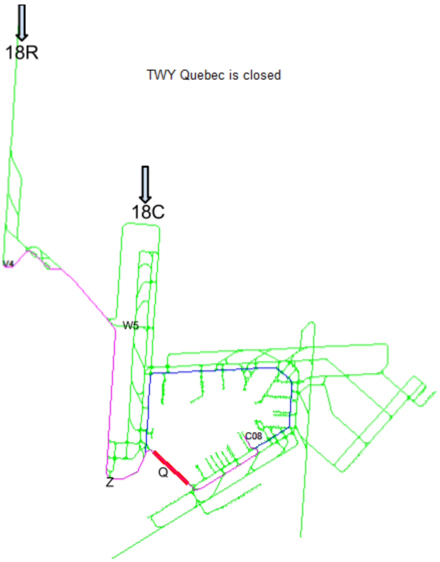

Figure 17 Taxi routes from RWY 18R to gate C08 via Z

The values of taxi times from runway 18R to C-pier are given in Tables 6 and 7

Table 6 Δt from RWY 18R to C-pier via W5 and Z

Taxi route	Traffic distribution	Medium aircraft Δt	Heavy aircraft Δt
Via W5	68%	Δ0.51 min	Δ0.61 min
Via Z	32%	Δ4.42 min	Δ5.05 min

Table 7 Average Δt of the model, comparing to airlines' analysis (18R → C-pier)

Medium aircraft	Heavy aircraft	*Airlines' historical value*
Δ1.08 min	Δ2.05 min	Δ*1-5 min*

Similarly, the taxi routes from runway 18C to C-pier are described in Figures 18 and 19. The values of Δt when aircraft is taxiing from runways 18C to C-pier is presented in Table 8. It can be seen from both runways (18R and 18C), the simulated Δt fit well in the range of historical data which is Δ1-5 min. Furthermore, values of Δt are smaller than those when aircraft taxi to B-platform, as expected. There is one case with heavy aircraft landing on W8 where Δt is higher than that of the airlines data of Δ5.47 min > Δ1-5 min. This situation is a more extreme case compared to the rest of the results as heavy aircraft have lower taxi speed, and W8 is closer to the south of the airport, conspiring to give such a high Δt.

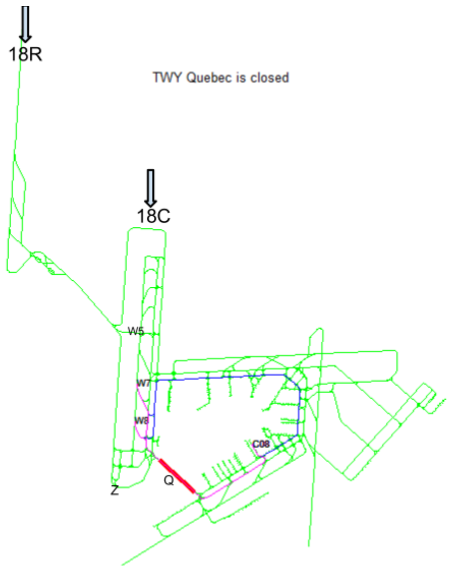

Figure 18 Taxi routes from RWY 18C's W7/W8 to gate C08

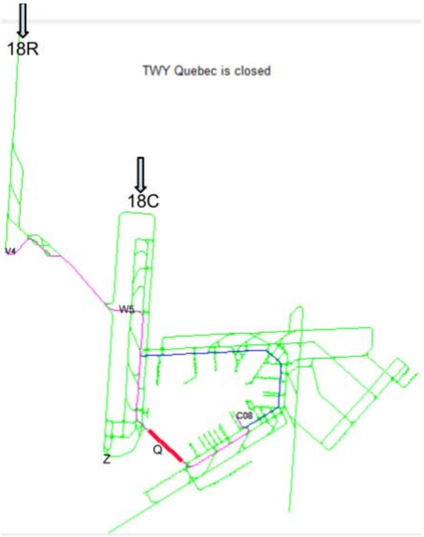

Figure 19 Taxi routes from RWY 18C's exit W6 to gate C08

Table 8 Δt from RWY 18C to C-pier, comparing to airlines' analysis

Runway exits	Medium aircraft	Heavy aircraft	*Airlines' historical value*
W8	Δ4.61 min	Δ5.47 min	*Δ1-5 min*
W7	Δ2.92 min	Δ3.46 min	
W6	Δ0.61 min	Δ0.73 min	

3) Estimated impact on fuel burn, emissions and cost the simulation

The results from the simulation are presented in Table 9 for the various landing cases on the left for runway, exit and gate respectively, for the various aircraft types. The results are presented for the A319 representing a medium weight category aircraft and the 744 representing a heavy aircraft. The total simulated distance, time, fuel burn, CO2 and cost are first quoted and then the 'Extra' values due to the taxiway delays. For example the most extreme case is for land at 18C, exiting on W8 and going to gate B63 for a 744. The total distance, time, fuel burn, CO2 and cost are seen to be 5.7km, 15.2mins, 626.2 kg of fuel' 1979kg of CO2, and 409.4 Euros cost respectively. Of this the contribution arising from the taxiway delay 3.3km, 8.8mins, 363.8kg fuel, 1150kg CO2 and 237.8 Euros cost respectively, i.e. over 50% of the original. However, the averages for the totals can be seen to be 6.81km, 14.7mins, 413.33kg fuel, 1306 kg CO2, and 270.2 Euros while the impact of taxiway delays were calculated to be 1.9km , 4.3mins, 119.2kg fuel, 376.6kg CO2 and 77.9 Euros.

Table 9 Simulation results for various delay cases with respect to fuel burn, emissions and direct cost

Movement	Start	End	Aircraft	Fuel	D. S[km]	T[min]	F. M[kg]	CO2[kg]	C[€]	Ex. S[m]	Ex. T[min]	Ex. M[kg]	Ex.CO2[kg]	Ex. C[€]	Ex. FTC[€]	Delay cat.
Land 18R via W5	V4	B63	A319	0,8	8	14,9	185,1	585	121	1527	2,8	35,3	112	23,1	100,8	Low
Land 18R via W5	V4	B63	B744	0,8	8	18	743	2348	485,7	1527	3,4	141,9	448	92,8	387,6	Low
Land 18R via Z	V4	B63	A319	0,8	11,1	19	236,7	748	154,7	3829,9	6,6	81,6	258	53,4	237,6	Medium
Land 18R via Z	V4	B63	B744	0,8	11,1	21,8	900,2	2845	588,5	3829,9	7,5	310,5	981	203	855	Medium
Land 18C	W8	B63	A319	0,8	5,7	12,8	158,8	502	103,8	3306,4	7,4	92,3	292	60,3	266,4	Medium
Land 18C	W7	B63	A319	0,8	5,5	12,3	153,3	484	100,2	2552,9	5,7	71,2	225	46,6	205,2	Medium
Land 18C	W6	B63	A319	0,8	5	11,2	139,6	441	91,2	1527	3,4	42,6	135	27,9	122,4	Low
Land 18C	W8	B63	B744	0,8	5,7	15,2	626,2	1979	409,4	3306,4	8,8	363,8	1150	237,8	1003,2	Medium
Land 18C	W7	B63	B744	0,8	5,5	14,6	604,4	1910	395,1	2552,9	6,8	280,9	888	183,6	775,2	Medium
Land 18C	W6	B63	B744	0,8	5	13,3	550,3	1739	359,8	1527	4,1	168	531	109,8	467,4	Low
Land 18R via W5	V4	C08	A319	0,8	7,5	13,9	173,1	547	113,1	273,2	0,5	6,3	20	4,1	18	Low
Land 18R via W5	V4	C08	B744	0,8	7,5	16,8	694,7	2195	454,2	273,2	0,6	25,4	80	16,6	68,4	Low
Land 18R via Z	V4	C08	A319	0,8	10,6	18,1	225,6	713	147,5	2576,1	4,4	54,9	173	35,9	158,4	Low
Land 18R via Z	V4	C08	B744	0,8	10,6	20,8	858,1	2712	561	2576,1	5,1	208,8	660	136,5	581,4	Medium
Land 18C	W8	C08	A319	0,8	5,2	11,6	144,3	456	94,3	2052,6	4,6	57,3	181	37,4	165,6	Low
Land 18C	W7	C08	A319	0,8	5	11,2	138,7	438	90,7	1299,1	2,9	36,2	114	23,7	104,4	Low
Land 18C	W6	C08	A319	0,8	4,5	10,1	125,1	395	81,7	273,2	0,6	7,6	24	5	21,6	Low
Land 18C	W8	C08	B744	0,8	5,2	13,8	569	1798	372	2052,6	5,5	225,9	714	147,6	627	Medium
Land 18C	W7	C08	B744	0,8	5	13,2	547,2	1729	357,7	1299,1	3,5	143	452	93,4	399	Low
Land 18C	W6	C08	B744	0,8	4,5	11,9	493,2	1559	322,4	273,2	0,7	30,1	95	19,7	79,8	Low
			Average scores		6,81	14,725	413,33	1306,123	270,2	1921,74	4,245	119,18	376,6088	77,91	332,22	

The initial cost *C* and actual cost of delay *Ex. C* included in Table 9 refer solely to the cost to the airline of fuel burn. However, Cook and Tanner (2010) have estimated the arrival management/base/full tactical cost of delay for both the 744 and A319 for 5mins at 570 Euros and 180 Euros respectively. Consequently, Table 9 also includes in the final column an estimate of the full tactical cost associated with taxiway delay *Ex. FTC* by using a FTC/minute rate of 114 Euros and 36 Euros per minute, calculated from the afore quoted costs. Consequently, it can be seen from the final column in Table 9 that for the most extreme case of the land on 18C, exiting W8, and proceeding to gate B63 for the B744 had an estimated full tactical cost of 1003 Euros, as compared to the fuel burn component estimated by the simulation to be 238 Euros. In addition it can be seen that the average full tactical cost is estimated at 332 Euros as compared to 78 Euros for fuel burn. However, the FTC is in fact not linear with delay time where Cook and Tanner for example estimate that at 15mins the FTC is 2290 Euros and 720 Euros for the 744 and A319 respectively, representing an increase from 114 Euros to 152.7 Euros per minute of delay for the 744 and an increase from 36 Euros to 48 Euros per minute of delay for the A319. As the delay for the extreme case for the 744 was almost nine minutes one might expect the FTC to be closer to 1150 Euros while the average delay of 4.25 was quite close to the 5mins value quoted by Cook and Tanner but the estimate in Table 9 may be a little overestimated due to the crude linear form being used herein.

4) Conclusion

For aircraft taxiing to B-platform from runway 18R, the simulated results seem to be slightly higher than historical data. For aircraft landing on runway 18C's exit W8 and taxi to both B-platform and C-pier there is difficultly comparing the data as the airlines do not distinguish between the exits W6, W7 and W8 but the results might again seem a little higher. This is perhaps explained by the closer positioning to the gates for exits W6 and W7 respectively. All of the cases from 18R and 18C seem to compare very favorably, with the simulated values for 18R perhaps being on the low side. In addition, all the costs of the delays relative to distance, time, fuel burn, CO2 emissions and direct financial cost (due to fuel burn) where also included to highlight the impact on performance. In addition it can be seen that the average full tactical cost is estimated at 332 Euros as compared to 78 Euros for fuel burn.

However, these delays associated with arrival management will certainly result in higher fuel burn costs for the extra minutes calculated. This was easily calculated from the model and also used to estimate the impact on unwanted emissions. There is also the unwanted disruption to passengers and one could also estimate the opportunity cost to the passenger but perhaps here it is the increasing frustration of passengers already taxiing from 18R for 15mins and now having an addition 7 mins. in one extreme case that was shown. For the airport it is more difficult to estimate the impact as a taxiway delay can be managed in order to not impact too much on airport capacity, where certain airports in the US even adapt the policy of immediate push back and queuing waiting aircraft on the taxiways. However, one would expect some impact on capacity and also congestion leading to increased workload for operators and reduced capacity.

For the airlines, one would probably conclude that minutes of delay due to small taxi time increases are not that significant in influencing the ability to accommodate extra flights during the day. However, the impact on tight turnaround times, e.g. 30mins for low cost flyers, could be very significant in influencing the possibility of achieving the subsequent departure times and the knock-on effect perhaps leading to loosing subsequent landing slots etc.

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Scheduling a hybrid flowshop with parallel machines for aircraft assembly production

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The new P2/HFS|Prec|C_{max} scheduling problem is found within an aerospace fuselage manufacturing environment and is a combinatorial problem addressed using dispatching rules. A newly proposed dispatching rule, named 'batch and match', was created by exploiting the combined elements of a) product assembly characteristics and b) processing time on a shared resource, is used to find solutions for minimizing makespan and waiting time for ten fuselage sets. A new manufacturing tool incorporates models for calculation of makespan and waiting time in the system. The best schedule, found using the new dispatching rule and a weighting system for ranking makespan and waiting time, was DCAB (LI), this schedule gives a reduced makespan of 2.61% against the benchmark longest imminent operation rule. The DCAB (LI) schedule also shows a reduction in waiting time of 53.5% per fuselage set created. This 'batch and match' dispatching method performs better than other rules and offers a solution to shared resources that limit processing in hybrid flowshops with precedence constraints.

Keywords: Hybrid flowshop, combinatorial problems, dispatching rules

Nomenclature

ω = weights for the combination and comparison of metrics
C_{max} = the completion time of the last job on the last fuselage created
$f_{i,j}^{k}$ = finishing time of job i on machine j for fuselage number k
i = refers to the job number
j = refers to the machine number
k = refers to the fuselage number
$O_{i,j}^{k}$ = operation number for job i on machine j for fuselage number k
$s_{i,j}^{k}$ = starting time of job i on machine j for fuselage number k
$t_{i,j}^{k}$ = processing time of job i on machine j for fuselage number k

I. Introduction

Aerospace manufacturers are constantly striving to improve production whilst meeting the demands of customers. The move in recent years has been to change from dedicated production lines to mixed product flowlines. This introduces a complex scheduling problem as using mixed lines also results in shared resources. In this work dispatching jobs to a shared resource that serves a hybrid flowshop (assembly system) is examined. The shared resources are in parallel and are constrained thus providing a new combinatorial problem classified as P2/HFS|Prec|C_{max}.

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Despite research on the application of dispatching rules in many other areas of industrial manufacturing including the packaging industry[1], car manufacturing[2], textiles[3], and the canned fruit industry[4], dispatching within the aerospace manufacturing arena has yet to be covered. Dispatching rules provide a method to solve challenging combinatorial problems in a relatively short time for a given planning horizon. The reduction of makespan has been identified as the performance measure of interest for this industry, reducing the makespan saves the company production time and reduces the amount of work in process (WIP) in the system. The primary driver for all scheduling procedures is to provide reliable customer service, defined by the number of jobs delivered to the customer on time. The secondary driver is to manufacture the product in the most cost effective manner, reducing production costs were possible and striving to lower WIP. Bombardier Aerospace Belfast is an aircraft manufacturing plant that specializes in the assembly of fuselage, wing and nacelles units. In this report, the scheduling of a constrained factory resource is examined. The critical constraint resource is an auto-rivet machine set which automatically rivet frames and stringers to the aircraft skin panels. The factory has eighteen fuselage contracts, with various panels making up each fuselage, however all of these panels require auto-riveting to avoid the labor intensive alternative. The CRJ700 assembly system is one such contract, consisting of a number of expensive jigs and workstations that form an A-shaped flowshop as shown in Fig. 1.

In this hybrid flowshop the panels are joined to create barrel sections, and in the case of the CRJ700 contract, four barrel sections make up a fuselage. Auto-riveting of the frames and stringers onto the skin panels reduces the labor intensity of the process. The auto-rivet machines improve factory efficiency but must service upwards of four thousand aircraft skin panels a year and must be carefully scheduled as time lost at the constrained resource is time lost in the whole factory.

It is a focus of the master schedulers to ensure that these machines are scheduled in such a way that demand is met subject to other constraints of the factory, such as time allocated for repair, failure and breakdown and availability of manpower. In this manufacturing system, the auto-rivet machines are considered the first workstation in the system and are an independent set of parallel machines feeding the A-shaped flowshop downstream. The CRJ700 manufacturing system is examined using dispatching rules in order to provide a means to improve the performance of the system with regard to the metrics of makespan and waiting time. Reducing makespan has the potential to reduce the overall cost of the fuselage build because the time to create it is less. Reducing makespan also allows schedulers to work to tighter deadlines and allows for greater tolerance should any problem occur thus improving customer service reliability. Similarly, waiting time found within the system is material idle time, which is an unnecessary holding of material. This means that the cost held in these panels could have been used for some other factory opportunity during that period. For one contract, the contribution of waiting time may be somewhat small, but for all eighteen-fuselage contracts completed within the factory the contribution of waiting time could be significant and therefore could result in large opportunity costs. Opportunity cost is the money that could have been used somewhere else in the system if it was available at that time. Opportunity cost is the loss of cash due to excess work in process in the manufacturing system.

Within the report a new manufacturing scheduling tool is presented, this tool operates using Microsoft Excel and Visual Basic for Applications (VBA) and includes constraints of the factory environment specific to aerospace manufacture. The tool uses mathematical models in order to calculate the makespan and waiting time for any number of panels sent to the auto-rivet machines. The cycle time and therefore the makespan, as well as the waiting time of the system depend on the sequence of panels sent to the auto-rivet machines. This work challenges the traditional method of scheduling, which is, working panels in the queue, longest job first (longest imminent operation). In this report, comparisons use the longest imminent operation (LI) dispatching rule as the benchmark for testing a proposed batch and match dispatching rule where the objectives are to minimize the makespan of the system and the waiting time in the system.

II. Problem Statement

The problem outlined below is classified as $P2/HFS|Prec|C_{max}$. $P2/HFS|Prec|C_{max}$ explains that there exist two, identical parallel machines that process all jobs, after processing on the shared parallel machine resource jobs are passed to stage two where riveting is finished manually before assembly at the proceeding stages three to five. The objective is to find a solution schedule to minimise the maximum completion time in the system, where the completion time of system depends upon the order of processing of the jobs on machines 1 and 2. This provides an NP-Hard combinatorial problem. The parallel machine shared resource is seen as stage one in the process flow-chart, Fig. 1, seen below. Figure 1 represents the manufacturing assembly line of the CRJ700 fuselage where the machine numbers, j, accompany each station in the diagram.

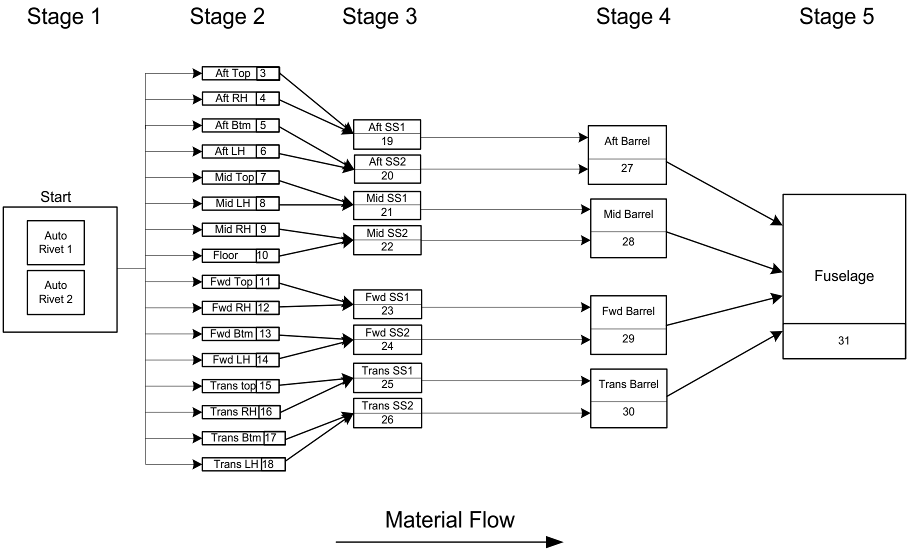

Figure 1. Example parallel machine set and subsequent hybrid flowshop.

In total, there are sixteen panels required to combine in order to create one CRJ700 fuselage barrel. At stage one, stringers and frames are riveted onto the fuselage skin panel, this process can be carried out on either of the two auto-rivet machines. At stage two, each panel has an individual workstation, this space is used to manually complete the riveting process, checking and repairing rivets and adding value to the panel. At stage three panels are joined to make super-shells, at stage three panels spend some time idle until the partner work pieces arrives for joining, the idle time is known as waiting time. At stage four, there is a further waiting time as the super-shells are joined together and must wait until the partner arrives at the workstation. At workstation four, two super-shells join to create a barrel section; this effectively means that each barrel comprises four panels. The four, barrel sections are combined at the fifth stage to complete the aircraft fuselage, the barrel sections are known as, transition, forward, mid and aft barrels. The list of jobs that are processed on each machine in the system are summarized in Table 1 below.

The combinatorial problem arises from the order that jobs are sent to the shared resource and thus the makespan and waiting time of jobs can vary greatly. The current method of dispatching jobs to the shared resource is using the longest imminent operation rule. The objective of this work is to challenge the LI schedule by examining the assembly procedure and the reducing the makespan (C_{max}) and waiting time, W, for a number of fuselage assemblies. The following two models represent the mathematical formulations combined within the new manufacturing tool. Model 1 considers the minimization of the makespan and model 2 considers the equations required to calculate waiting time. Table 2 below considers Eqs. (1) – (14) which are the set of constraints that must be taken into account for the calculation of both makespan and waiting time.

Table 1. Showing the job names and numbers, i, of those jobs worked at given machine numbers j. Note that the jobs 1 to 16 are worked on either machine 1 or machine 2 and job numbers in parentheses are assembly operations.

Machine Number, j	Job name as seen in Fig. 1	Corresponding job number i, processed at machine
1 or 2	Aft Top, Aft RH, Aft Btm, Aft LH, Mid Top, Mid LH, Mid RH, Floor, Fwd Top, Fwd RH, Fwd Btm, Fwd LH, Trans Top, Trans RH, Trans Btm, Trans LH	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16
3	Aft Top	1
4	Aft RH	2
5	Aft Btm	3
6	Aft LH	4
7	Mid Top	5
8	Mid LH	6
9	Mid RH	7
10	Floor	8
11	Fwd Top	9
12	Fwd RH	10
13	Fwd Btm	11
14	Fwd LH	12
15	Trans Top	13
16	Trans RH	14
17	Trans Btm	15
18	Trans LH	16
19	Aft Top + Aft RH = Aft SS1	(1+2)
20	Aft Btm + Aft LH = Aft SS2	(3+4)
21	Mid Top + Mid LH = Mid SS1	(5+6)
22	Mid RH + Floor = Mid SS2	(7+8)
23	Fwd Top + Fwd RH = Fwd SS1	(9+10)
24	Fwd Btm + Fwd LH = Fwd SS2	(11+12)
25	Trans Top + Trans RH = Trans SS1	(13+14)
26	Trans Btm + Trans LH = Trans SS2	(15+16)
27	Aft Top + Aft RH + Aft Btm + Aft LH = Aft Barrel	(1+2+3+4)
28	Mid Top + Mid LH + Mid RH + Floor = Mid Barrel	(5+6+7+8)
29	Fwd Top + Fwd RH + Fwd Btm + Fwd LH = Fwd Barrel	(9+10+11+12)
30	Trans Top + Trans RH + Trans Btm + Trans LH = Trans Barrel	(13+14+15+16)
31	Aft Top + Aft RH + Aft Btm + Aft LH + Mid Top + Mid LH + Mid RH + Floor + Fwd Top + Fwd RH + Fwd Btm + Fwd LH + Trans Top + Trans RH + Trans Btm + Trans LH = Fuselage	(1+2+3+4+5+6+7+8+9+10+11+12 +13+14+15+16)

Table 2. The constraints that must be considered within the mathematical models

Operations	Constraint
$O_{i,j}^{k}$ where $1 \le i \le 16$ *and* $3 \le j \le 18$	$s_{i,j}^{k} = s_{i,j'}^{k} + t_{i,j'}^{k}$ (1) where j' = 1 or 2
$O_{(1+2),19}$	$s_{(1+2),19}^{k} = \max\left\{ f_{1,3}^{k}, f_{2,4}^{k} \right\}$ (2)
$O_{(3+4),20}$	$s_{(3+4),20}^{k} = \max\left\{ f_{3,5}^{k}, f_{4,6}^{k} \right\}$ (3)
$O_{(5+6),21}$	$s_{(5+6),21}^{k} = \max\left\{ f_{5,7}^{k}, f_{6,8}^{k} \right\}$ (4)
$O_{(7+8),22}$	$s_{(7+8),22}^{k} = \max\left\{ f_{7,9}^{k}, f_{8,10}^{k} \right\}$ (5)
$O_{(9+10),23}$	$s_{(9+10),23}^{k} = \max\left\{ f_{9,11}^{k}, f_{10,12}^{k} \right\}$ (6)
$O_{(11+12),24}$	$s_{(11+12),24}^{k} = \max\left\{ f_{11,13}^{k}, f_{12,14}^{k} \right\}$ (7)
$O_{(13+14),25}$	$s_{(13+14),25}^{k} = \max\left\{ f_{13,15}^{k}, f_{14,16}^{k} \right\}$ (8)
$O_{(15+16),26}$	$s_{(15+16),26}^{k} = \max\left\{ f_{15,17}^{k}, f_{16,18}^{k} \right\}$ (9)
$O_{(1+2+3+4),27}$	$s_{(1+2+3+4),27}^{k} = \max\left\{ f_{(1+2),19}^{k}, f_{(3+4),20}^{k} \right\}$ (10)
$O_{(5+6+7+8),28}$	$s_{(5+6+7+8),28}^{k} = \max\left\{ f_{(5+6),21}^{k}, f_{(7+8),22}^{k} \right\}$ (11)
$O_{(9+10+11+12),29}$	$s_{(9+10+11+12),29}^{k} = \max\left\{ f_{(9+10),23}^{k}, f_{(11+12),24}^{k} \right\}$ (12)
$O_{(13+14+15+16),30}$	$s_{(13+14+15+16),30}^{k} = \max\left\{ f_{(13+14),25}^{k}, f_{(15+16),26}^{k} \right\}$ (13)
$O_{(1+2+...+16),31}$	$s_{(1+2+...+16),31}^{k} = \max\left\{ f_{(1+2+3+4),27}^{k}, f_{(5+6+7+8),28}^{k}, f_{(9+10+11+12),29}^{k}, f_{(13+14+15+16),30}^{k} \right\}$ (14)

Where the value for job number i in parentheses, (i), seen in the Eq.s (1-19) denoting joining of jobs in the assembly operations at machine j.

Model 1

Equation (15) is used to compute the makespan for the system and is the objective function for the first model considered.

Objective: Min $C_{\max}$

$$C_{\max} = f_{(1+2+...+16),31}^{\max} - \min\left(s_{i,1}^{1}, s_{i,2}^{1} \right) \tag{15}$$

Minimization of Eq. (15) allows for the reduction of the makespan value and is dependent upon the sequence of jobs processed on machines 1 and 2. The sequence of operations $O_{i,j}^{k}$ performed on the auto-rivet machines are responsible for the starting times of the assembly operations $O_{i,3-18}^{k}$ as denoted by constraint Eq. (1).

Model 2

Model 2 contains the mathematics required to calculate the waiting time present in the system. Waiting time is present in the system when a panel (f_{ij}) that requires assembly with a mating panel (f'_{ij}), remains idle until its partner arrives at the appropriate workstation. Waiting times are only considered at the stages where panels are joined to make super-shells, barrels and the final fuselage. The objective function for waiting time can be seen in Eq. (16) below, and is the function used to calculate the waiting time between the last three stages in the manufacturing system.

Objective: Min W

$$W = \sum_{k=1}^{k} \sum_{j=19}^{31} W_{i,j}^{k} \tag{16}$$

Where Eq. (16) can be further broken down to calculate waiting time at stage three, four and five as shown in Eqs. (17 – 19) respectively.

$$\sum_{j=19}^{26} W_{i,j}^{1} = \left| f_{1,3}^{1} - f_{2,4}^{1} \right| + \left| f_{3,5}^{1} - f_{4,6}^{1} \right| + \left| f_{5,7}^{1} - f_{6,8}^{1} \right| + \left| f_{7,9}^{1} - f_{8,10}^{1} \right| + \left| f_{9,11}^{1} - f_{10,12}^{1} \right| + \left| f_{11,13}^{1} - f_{12,14}^{1} \right| + \left| f_{13,15}^{1} - f_{14,16}^{1} \right| + \left| f_{15,17}^{1} - f_{16,18}^{1} \right| \tag{17}$$

$$\sum_{j=27}^{30} W_{i,j}^{1} = \left| f_{(1+2),19}^{1} - f_{(3+4),20}^{1} \right| + \left| f_{(5+6),21}^{1} - f_{(7+8),22}^{1} \right| + \left| f_{(9+10),23}^{1} - f_{(11+12),24}^{1} \right| + \left| f_{(13+14),25}^{1} - f_{(15+16),26}^{1} \right| \tag{18}$$

$$W_{(1+2+...+16),31}^{1} = \max\left(f_{(1+2+3+4),27}^{1}, f_{(5+6+7+8),28}^{1}, f_{(9+10+11+12),29}^{1}, f_{(13+14+15+16),30}^{1} \right) - \min\left(f_{(1+2+3+4),27}^{1}, f_{(1+2+3+4),28}^{1}, f_{(1+2+3+4),29}^{1}, f_{(1+2+3+4),30}^{1} \right) \tag{19}$$

In order to minimize these values the use of dispatching rules is proposed, providing a new schedule for the manufacturing system seen in Fig 1.

III. Literature

Over 40 years of research now exists for combinatorial type problems in scheduling shops. Literature for production systems including jobshops, flowshops[5, 6], parallel machine [6] shops and hybrid flowshops [7, 8, 9] have been compiled. Researchers use triplet notation in order to classify problems. Common notation is α|β|γ where the notation for shop structure is α, β is the set of constraints further influencing the problem and γ represents the objective function. The problem in this paper uses parallel machines to feed a hybrid flowshop final assembly plant. The shop is further constrained by precedence requirements between stages of the shop, where the objective function to be considered is the makespan, C_{max}. Therefore, the problem classification is P_2/HFS|Prec|C_{max}. Complexity of problem is another element previously tackled [9] and in the case there is a list schedule where any job can enter the first machine the problem is Non-polynomial hard in the strong sense [10, 11].

An NP-Hard problem is one in which there is no known polynomial algorithm, so that the time to find a solution increases exponentially [12,5]. If there are n jobs, there are n! (Factorial) possible sequences of work, of which, any sequence could be an optimal schedule.

Previously identified methods for solving combinatorial problems include heuristics and meta-heuristics. Recently meta-heuristics have been the preferred method for solving problems in both parallel and hybrid flowshop scenarios. Such meta-heuristics include simulated annealing, tabu search and genetic algorithms. Simulated annealing involves calling a local search many times until a non-improving solution is reached, when this happens the solution found may not be optimal so a random search is carried out to reduce the possibility of getting 'stuck' in a local minima. Tabu search [13] algorithms also search the design space, recording tested sequences in a tabu list, the tabu list provides the basis for future sequences as any sequences on the list will not be used again. The method was introduced by Glover [13] in 1990. Cao, Chen and Wan [14] examine a combinatorial, general parallel machines problem with machine holding costs using a heuristic algorithm to obtain near optimal solutions based on a tabu method. Janiak [15] introduces three constructive algorithms and three hybrid algorithms based on simulated annealing and tabu search. The quality of Janiak's constructive solutions is poor; however, the meta-heuristic technique improves the solution but the authors report difficulty in finding an optimal lower bound. Genetic algorithms differ from the other methods as they use a pool of solutions called chromosomes, initial testing leads to the re-combination of some of the best chromosomes, forming a new population until an optimal solution is found. These meta-heuristic methods present good results for makespan minimization in academic problems. However, the limitations of meta-heuristic methods are that they require increased computational expense and time when compared with heuristic methods. Computational power and time may not be a problem in academia but it is of significant importance in the aerospace manufacturing environment. Scheduling decisions in aerospace are made on a daily or hourly basis; engineers cannot wait for the algorithms to run, as any time could delay the entire plant. This means that meta-heuristics are not suitable for this industrial scenario.

The alternative to meta-heuristics is the more simple heuristic procedures such as list scheduling or dispatching rules. Dispatching rules tend to be simple, logical sequences obeying certain mathematical rules or precedence conditions. Surveys on dispatching rules have been carried out by Panwalker and Iskander [16] and Blackstone *et al.* [17]. Many of the rules recorded are simple priority rules, where, in a set of n jobs, a precedence number is given to each job according to the rule chosen. This precedence order determines the sequence of jobs entering the manufacturing system and therefore the order in which they are processed. There are a number of well-known sets of rules:

I. Rules involving processing time
    a. Shortest imminent operation (SI)
    b. Longest imminent operation (LI)
    c. Fewest remaining operations
    d. Most remaining operations
    e. Shortest remaining processing time
    f. Longest remaining processing time
    g. Greatest total work
    h. Total operations
    i. First in first out (FIFO)
    j. Last in first out (LIFO)
II. Rules involving due dates
    a. Earliest due date (EDD)
    b. Minimum slack time (SLACK)
    c. Least slack per operation (SLACK/OP)
    d. Earliest operation due date
III. Rules involving shop characteristics or job characteristics other than processing time or due date
    a. Greatest dollar value
    b. Shortest number in next queue
    c. Random selection
IV. Cost rules
    a. Delay cost over time remaining (COVERT) [17]

Johnson [18] documents early work on dispatching in a job-shop, where the goal of this sequence was to minimize the makespan of the machines. This well-known example is an algorithm using the shortest processing time (SPT) rule, also known as the shortest imminent (SI) operation rule, in order to reduce the make-span for two machines. Many researchers have used the SI [19] rule and first-in, first-out (FIFO) rules as a benchmark for testing against newly proposed rules. The inverse of the SI rule is the LI rule, which processes the longest job first. Rajendran and Holthaus, [20] chose a number of simple rules in which to analyze a flowshop for a comparative study proposing five new rules derived from previous rules. Rajendran and Holthaus found that for machines with utilization above 85%, the best performing dispatching rule with relation to makespan minimization is process time plus work in next queue plus arrival time (PT + WINQ + AT). Rajendran and Alicke [19], address dispatching in bottleneck machines in order to try to maximize the throughput of a flowshop using the theory of constraints. Tying in dispatching rules as a method of control for a flowshop scenario, they developed rules centered upon Theory of Constraints (TOC). The PR-1 rule acts as a decision maker at the bottleneck machine and provides a schedule based on the arrival of jobs to the bottleneck and the earliest completion of these jobs [19]. Jimeno and Mokotoff [21] propose a constructive algorithm based on list scheduling and the longest remaining processing time rule, whilst progressively introducing more machines to the problem. Li and Yang [22] present a survey of non-identical parallel machine scheduling models, problems and algorithms including linear programming relaxation, exact algorithms and heuristics. Bouyahia *et al* [23] address a priori scheduling with updates for the probability of missed jobs in parallel machining examining the weighted flow time metric.

Despite a number of dispatching rules evident in the literature there are no examples of their use within the aerospace manufacturing environment. Industrial examples where dispatching rules are employed include; car manufacturing [2], shoe manufacturing [3], canned fruit industry [4], semi-conductor wafer fabrication [24, 25], packaging industry [1]. Agnetis *et al* [2] examine a highly automated manufacturing plant employing dispatching rules to a complex problem that deals with the additional constraint of varying product mix. Agnetis *et al* identify a minimum slack rule (pulling rule) which reduces the work in process for the plant and allows for increased rates of production over a long production period. Adler *et al* [1] present a flexible flowline in the multi-ply paper industry introducing a five-step algorithm that utilizes due date based dispatching rules. Adler *et al* found that the algorithm allowed improved quality and robustness regarding tardiness of orders. Similarly, work by Costa and Ferreira [3] is based on a flexible flowline in the shoe manufacturing industry. Costa and Ferreira identify a new rule called the Nearest Box rule that performs poorly against other well known dispatching rules for performance measures such as makespan and productivity were rules such as Least Work Remaining and Shortest Processing Time (SI) are superior. Parthanadee [4] examines dispatching in the canned fruit industry using setup dependent dispatching rules finding SPT to provide the best results for minimizing flowtime.

Both heuristics and meta-heuristics are useful within the bounds of well-defined academic combinatorial problems. However, for this industrial engineering application, the problem is based upon making decisions within a small planning horizon (one day) and therefore heuristics, in particular dispatching rules, allow a fast method to provide an ideal schedule for any situation.

IV. Dispatching method and modeling assumptions

Schedulers currently use the method of assigning jobs with the longest time to process to the auto-rivet machines first. Therefore, any comparisons of the manufacturing system will be tested against the longest imminent operation, dispatching rule. The auto-rivet machines can each process one job at a time, where the processing time depends upon the panel. The downstream stages two – five run at a constant processing rate of 32hrs. Dispatching rules provide a simple method of scheduling to provide a solution to the $P2/HFS|Prec|C_{max}$ NP-hard problem.

The proposed, ‘batch and match’, dispatching method is based upon the characteristics of the fuselage build. As previously mentioned, the fuselage is built in four sections, called barrels, where each barrel comprises four skin panels that are joined by the fuselage floor, frames, stringers, cleats and straps. Batching the panels of each section together and dispatching to the auto-riveter using the longest imminent operation rule allows for a mini-schedule of four jobs, following this step the four mini schedules are recombined to give a production schedule. In order for sequences to be denoted and organized neatly, each barrel section is assigned a corresponding letter, *i.e.* A = AFT, B = MID, C = FORWARD, D = TRANSITION.

Repetition of this procedure allows testing of the twenty-four possible sequences using match grouping. Furthermore, another set of twenty-four sequences are obtained using the shortest imminent operation rule as a method of scheduling panels within each barrel set.

The benefits of this method include having a smaller number of sequences to manage as the number of possible sequences falls from sixteen factorial, to four factorial.

The requirement for the tool is a job sequence for the auto-rivet machines. The tool has been created using Microsoft Excel and Visual basic for Applications. Following entry of a schedule, computed from the rules above, the user simply runs the model, computing values of makespan and waiting time for the schedule used. Some modeling inputs that are variable include; the processing time at each workstation, the number of auto-riveters available for processing and the number of fuselage sections that are required. Currently, the tool can calculate the waiting time at stage three, four and five as the system assumes that the panels arrive to the auto-riveters, at the start of processing. Furthermore there is no waiting time on workstation two machines due to the fact that as soon as work pieces are sent to the workstation, there is no other part constraint and the panel can be worked straight away. The waiting time calculation requires the finishing times of all jobs in the system

Activation of the model begins processing of the equations in order to determine the makespan of the system and the waiting time. The tool automatically computes both the values for makespan and waiting time at stages three to five of the manufacturing system. As with all models there are a set of assumptions that must be taken into account, these can be seen below.

1) The shop is under static conditions, that is at time t=0 it is possible to choose any job to process at stage one
2) Pre-emption of jobs is not allowed on any machine at any stage
3) Machines at each stage can only process one job at a time
4) Processing at panel joining stations can only occur when all of the required components are available at that stage
5) Failure, labour variability (processing time variability), is not considered
6) Set-up time for each machine is negligible
7) Transport time between stages is assumed to be included in the processing time

V. Results and Discussion

Fig. 2 shows the average waiting time of tested schedules calculated for ten sets of fuselage barrels created. The SI and LI rules produce 302hrs and 188hrs/set of average waiting time respectively. All of the sampled schedules with longest imminent operation show less waiting time. The panels that are scheduled in their respective fuselage barrel sections with the shortest imminent operation time perform slightly worse than the LI rule regarding the waiting time. The best schedule for average waiting time is ABCD (LI) at 85hrs. The schedule showing the highest average waiting time is the shortest imminent operation rule at 302hrs. Further sequences providing excellent performance for reduction of waiting time are DCBA (LI) and CDBA (LI), which represent waiting times of 87.4hrs and 91.8hrs respectively.

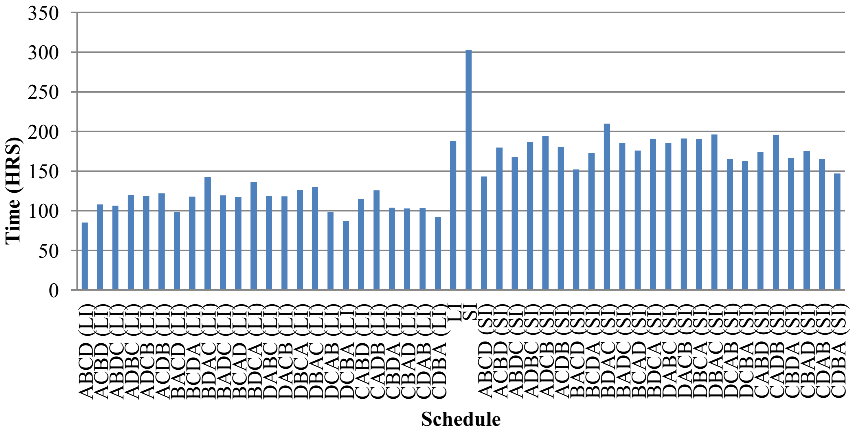

Figure 2. Showing the average waiting time per set for tested schedules.

Fig. 3 shows the waiting time displayed as a percentage of the LI rule schedules waiting time. Fig. 3 shows that many of the presented sequences allow for less waiting time compared with the LI rule. The schedules providing the most improvement to the reduction of the waiting time include ABCD (LI), BACD (LI), DCBA (LI), and CDBA (LI). The schedules mentioned previously also offer percentage savings of 45.2%, 53.3%, 46.5% and 48.8% respectively.

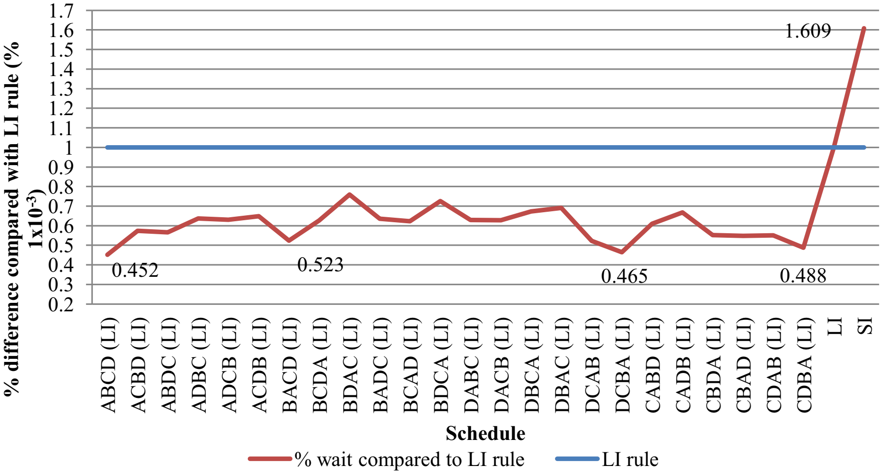

Figure 3. **Shows the percentage waiting time comparison between new schedules against the LI rule.**

Fig. 4 shows the makespan performance against the LI rule baseline. None of the schedules used with the SI rule show any decrease in makespan and therefore are not plotted. A number of LI schedules provide increased completion time performance as they reduce the makespan. A number of schedules show a reduction in the maximum completion time. Six schedules show improvement greater than 4hrs for a production run of ten fuselages. The schedules that show this improvement are ADCB (LI), ACDB (LI), DACB (LI), DCAB (LI), CADB (LI) and CADB (LI). As can be seen from Fig. 4, DCAB (LI) and CADB (LI) schedules perform very well resulting in savings of 17.8hrs and 17.61hrs respectively which correspond to 2.61% and 2.58% savings in makespan when compared with the LI rule. For a large production run, changing the LI rule to either of the two schedules mentioned above will save the company money in the form of reduced WIP and opportunity cost.

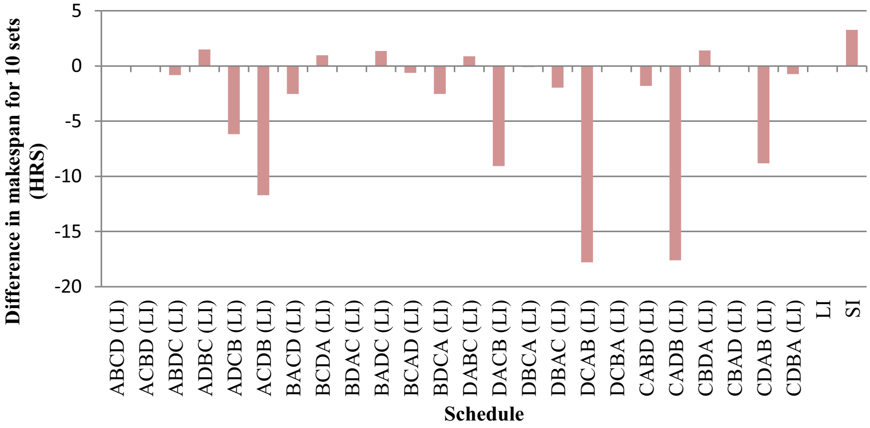

Figure 4. **Shows the makespan comparison against the LI rule for completion of ten fuselage sections.**

To compare further, a weighting of both the completion time and the waiting time is created using a weighted system as seen in Eq. (20), Q is the weighted value, ω_1,ω_2 are the values for the weights.

$$Q = \omega_1 C + \omega_2 W \tag{20}$$

The weights values for the Fig. 5 below are $\omega_1 = 0.05$ and $\omega_2 = 0.95$.

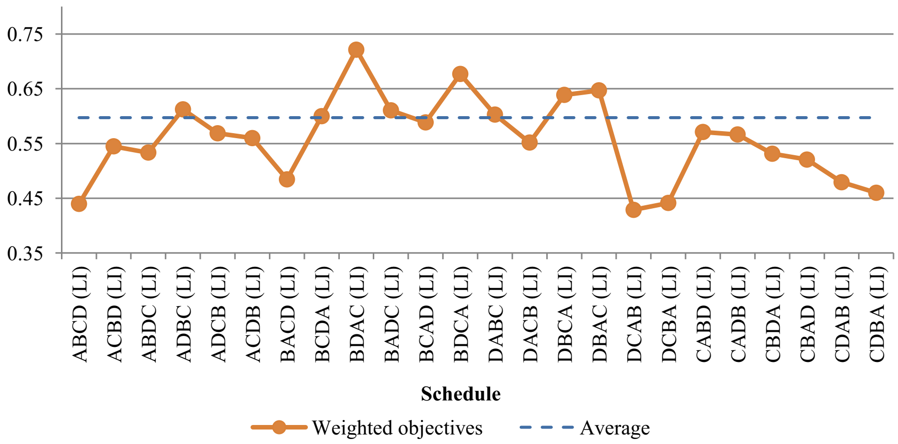

Figure 5. **Plot of the multi-objective weightings for each schedule.**

As two metrics are tested using the tool, a weighting system evaluates the best sequence for both measures. Fig. 5 shows the plot of the multi-objective values of makespan and waiting time. The lowest value of this metric shows the overall strongest rule for the system depending on the weightings given to each metric. For this examination, the weight was geared toward the waiting metric as the most important. This is because additional waiting time is additional WIP in the system and reducing WIP is more important to the company. The most effective schedule for both metrics, shown in Fig. 5 is DCAB (LI). The DCAB (LI) schedule provided a value of 0.429, which is 0.168 below the average value. This value is sensible as the average waiting time for this schedule is 98.2hrs, fourth lowest and the reduction in makespan against the LI schedule is 2.61%, which is the highest makespan saving.

Improvement of the cycle time at the auto-rivet stage can only be achieved by leveling the job processing between both of the auto-rivet machines. Therefore, the combination of equally scheduling stage one, along with keeping a schedule that allows panels of the same barrel to be completed close to each other in the schedule provides an approximate solution to the static case of manufacturing for this P2/HFS|Prec|C_{max} system.

VI. Conclusion

For the special P2/HFS|Prec|C_{max} scheduling problem associated with the aerospace industry, a dispatching method that takes advantage of the fuselage build characteristics and the longest imminent operation rule is proposed. For the manufacturing problem in question, under static conditions, a lower bound for the makespan and waiting time has been found using a new manufacturing tool that calculates equations designed to capture the makespan and waiting time. The motivation of this work derives from a company push to reduce work in process inventory by scheduling the shared resources in the factory to better effect. The dispatching rule presented offers a fast approximate solution reducing a problem design space from 16! schedule options to 4! schedule options. Furthermore the dispatching method is easy to set up for any fuselage build scenario and is quick to run in the event that a fast solution is required. Production runs took approximately thirty seconds to complete on an Intel i5 laptop with 8 GB of DDR3 RAM. For the P2/HFS|Prec|C_{max} scheduling problem presented the dispatching method presents results better than the current dispatching rule for two metrics, makespan and waiting time. The combination of spreading the workload evenly as possible across the auto-rivet machines, along with keeping a schedule that allows similar barrel panels to be completed close to each other in the auto-rivet schedule allows for best practice for schedule creation. The dispatching method presented uses the characteristic of the assembly, *i.e.* that coupling panels must be scheduled close to one another in the auto-rivet schedule.

Comparisons between generated schedules were made against the LI rule as it closely approximates the rule that the company currently use to schedule jobs to the auto-rivet machines. Findings show that for a ten fuselage set run the makespan value is 2.61% less using the DCAB (LI) schedule. This reduction in makespan will allow considerable savings for the company. Three sequences provide considerable savings in waiting time, these include ABCD (LI) 54.8%, DCAB (LI) 53.5% and CDBA (LI) 51.2%. Using a weighting system geared towards the reduction of waiting time the DCAB (LI) sequence is found to be most useful for minimising both metrics.

The dispatching method presented clearly offers savings in waiting time and makespan against the current method of scheduling (LI rule) that the partner company uses. In general, this method of scheduling is useful for the $P2/HFS|Prec|C_{max}$ problem. The significance of this work is that it introduces this new method of 'batch to match' dispatching which may also be useful in other assembly heavy industries such as car manufacture. Furthermore, the manufacturing tool presented can be easily integrated into the partner company's software framework and can be used immediately to provide scheduling decisions if panel sets are known at the auto-riveters. The presented tool can be modified in order to allow its use at other shared factory resources within the plant. The current limitations of the tool involve modeling constraints as the models do not yet include dynamic conditions. Dynamic models closely represent real manufacturing scenarios in that they include problems such as machine failure and repair, labour allocation and transport and set-up times. A further limitation of the model is that it currently only examines the dispatch of one fuselage contract out of a possible eighteen contracts. Therefore future development of the tool should incorporate more contracts with the mathematical models and tool and should include dynamic modeling, making the tool even more applicable for scheduling in the aerospace factory.

VII. Future Work

The conclusions from this work are found from the study of the static work environment. As the real life manufacturing scenarios are dynamic, the opportunity exists to expand this study to consider the dynamic scheduling environment. In the real life scenario, there are aspects of machine failure, delivery delays, material shortages, breakdowns or machine failure and employee error and learning. The inclusion of a mechanic that allows for examination of waiting time at the first workstation would also be interesting.

In order to implement these features additional models are required within the presented tool. Such features include a method of probability distribution to accurately approximate failure within the system. A distribution that identifies the arrival time of panels to the pre auto-rivet buffer will allow a waiting time measurement at the first processing stage. Finally, the computations and considerations associated with labour allocation will give a true representation of the dynamic environment. The new features will allow the decisions planner or scheduler the tools to run 'what if' scenarios and make informed, knowledge-based decisions to effectively schedule the manufacturing system.

This examination of a new dispatching rule has introduced the problem type in this manufacturing system $P2/HFS|Prec|C_{max}$. Currently this manufacturing model considers one of the eighteen aircraft fuselage types. Future expansions of the mathematical model should consider a larger range of aircraft fuselages. Expansion of the models make the tool a more robust scheduling option providing accurate data on the dynamic aerospace manufacturing industry and allowing a means to adapt quickly to resolve scheduling problems.

Acknowledgments

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Surplus Value Sensitivity and Subsystem Analysis

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Current design methods used within the aviation industry include the Systems Engineering (SE) methodology. Many products produced using this approach experience both scheduling and financial overruns resulting in a loss of value for the design. Recent developments in design have seen the introduction of the Value Driven Design (VDD) methodology which is an enhancement on the traditional SE approach. As this methodology is still in its infancy, many issues need to be clarified and developed before VDD can be fully implemented within the industry. One such issue is the development of subsystem value functions. To date, these local value functions only look at each individual subsystem in turn which results in an isolated design procedure as per SE. The main results from this work see the introduction of a Value Influence (VI) factor which enables interactions between these low level subsystems to be accounted for, thereby moving away from the current isolated approach. Further work will be required to fully develop these VI factors across multiple subsystems to ensure reliable, accurate calculations of value can be undertaken.

Keywords: Value Driven Design, Subsystem Interactions

Nomenclature

C_D	= Developmental costs
$C_{D\&C}$	= Delay and cancellation costs per flight, including the likelihood of a delay and cancellation occurring
C_E	= Externality taxes per flight, including environmental taxes for noise and emissions
C_M	= Manufacturing costs per aircraft
C_{OP}	= Operating costs per flight, including direct and indirect operating costs
F_y	= Flights per year
$N_{a/c}$	= Number of aircraft produced, including test and production standard aircraft
r_c	= Multiplier based on the discount rate and program life for customers
r_p	= Multiplier based on the discount rate and program life for manufacturers
$R_{P\&C}$	= Revenue per flight generated from passengers and cargo
V_S	= Surplus value

I. Introduction

As improvements in design continue to be made, there is always a demand for better value from the next generation of aircraft, be it in performance capability, environmental efficiency or any other design feature. A key concern with these future aircraft is that they need to remain profitable taking all costs and design capabilities into account. Traditional design procedures such as Systems Engineering (SE) are struggling to fulfil conflicting customer and legislative requirements whilst producing satisfactory, economically viable designs.

Fanthorpe *et al.*[1] shows this concern of maintaining profitable designs to be well founded as schedule and cost overruns now appear to be common practice with new designs. This problem is not confined to the aerospace industry and some major overruns in past years have been the Chevy Volt, which is reported to have doubled its manufacturing costs during design as well as Airbus A380 and Boeing 787 which saw a cost overrun of $6 billion and $2.5 billion respectively.[2-4] As can be determined from Collopy and Hollingsworth[5], these

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[§] PhD Candidate, School of Mechanical and Aerospace Engineering, Queen's University Belfast, BT9 5AH, AIAA Member overruns and scheduling delays are not due to recent changes in design practices; for example, current defence system developments are overrunning approximately 78% in cost and 63% in schedule. On examination of the above statistics, one conclusion which can be made is that improvements in the SE process are needed to ensure any and all future designs remain economically viable for all concerned (manufacturing companies, customers and all other product stakeholders).

Recent developments within the industry have been the Value Driven Design (VDD) initiative. This approach can be defined as "an improved design process that uses requirements flexibility, formal optimisation and a mathematical value model to balance performance, cost, schedule and other measures important to the stakeholders to produce the best possible outcome"[6]. One of the main differences between this approach and SE is that "the architecture selected by the [traditional systems engineering] process is generally that which produces an acceptable level of performance at the lowest cost"[7] whereas VDD enables the designers to select the product which will provide the system's stakeholders with maximum value.[8] Within this paper, an overview of the VDD methodology will be provided along with detailed information on the objective function used within the current work.

This paper will show that by recognising that the subsystems of an aircraft are dependent on one another, value is impacted. As the value of a subsystem is linked to the value of the overall system through sensitivity studies, this paper looks at a number of these investigations showing how they can be used to calculate subsystem value. These studies were found to be necessary in order to develop the subsystem value objective functions.

Ultimately, the key focus of this paper is to show that the subsystem dependencies need to be accounted for when calculating both subsystem and product value; this will be achieved via an example linking subsystem and system value to the aforementioned sensitivity studies.

II. Value Driven Design

Value Driven Design is not a new design method; it is an enhancement on the traditional SE methodology and provides a framework which enables its users to assess and compare methods, processes and products.[9] It uses economics to improve the systems engineering process to aid in the design of large, complex systems and "provides an objective numerical evaluation methodology which is a major improvement over multi-objective approaches because of the clear indications of which technologies are superior, the balanced consideration of performance and cost and the more accurate attribution of value to the technologies"[10]. When fully developed, this process offers a robust approach to design which takes numerous factors such as cost and performance into account whilst providing the product stakeholders with the maximum value design.[11]

To ensure VDD is used to obtain the best, most valuable design, this methodology or design framework must be repeatable and transparent. Therefore, the decisions made must be clearly traceable and given the same information, the same conclusion must always be reached irrespective of designer experience.[12] These requirements play an important role in the determination of objective functions which form the basis of any VDD analysis; this will be discussed in more detail in section IV.

When comparing VDD to systems engineering, there are a number of similarities in that both methods make use of design procedures such as traditional sizing exercises and it has been said that one advantage VDD has over SE is that it "makes the goals of the conceptual design phase stand out with greater clarity"[13]. The VDD approach is more likely to produce the most valuable product as it continuously searches for the best design whereas the conventional requirements based approach is only concerned with finding a feasible solution which meets all customer requirements.[14]

To aid model development the phases within the VDD approach were outlined in Cheung *et al.*[12] In summary, the key steps within this method are as follows: determine the design stakeholders; develop an objective function (value model) which combines all stakeholder values into a common mathematical function; define and calculate product and component extensive attributes; calculate product value and finally use a sensitivity analysis to define component value functions in order to determine how changes in component parameters affect product value. For the studies completed to date as well as future developments, a surplus value objective function has been utilised.

For more detailed information on Value Driven Design and surplus value, refer to Refs. 5, 6 and 12 through 16.

A. Surplus Value Objective Function

As stated above, VDD makes use of a mathematical expression known as an objective function in order to evaluate designs. For the work undertaken by the author, the selected objective function is surplus value. Surplus value has been defined as reservation price minus manufacturing and operating costs; where reservation price is the maximum revenue which can be generated from a product in the absence of competition and has been referred to as a theoretical limit on price.[11] For this work, surplus value has been denoted as V_S and is defined using Eq. 1.[16] This expression (Eq. 1) enables the economic aspects of design to be brought to the forefront of the design process thereby enabling the designer to consider multiple factors such as potential revenue, operating costs and development costs.

$$V_S = r_p N_{a/c} \{ r_c F_y (R_{P\&C} - C_{OP} - C_{D\&C} - C_E) - C_M \} - C_D \tag{1}$$

Using this measure, a designer will be able to predict which design will offer maximum profit as well as determine how much a particular product will cost during the development, manufacturing and operational stages of its lifecycle.

An analysis tool incorporating Eq. 1 has been developed using Microsoft Excel and Visual Basic software. This tool enables the user to quickly get an understanding of how value is determined for a particular design. Traditional design procedures such as sizing exercises are fully implemented within the tool meaning that if design features such as passenger capacity or material type is changed, weight and other dependent factors are automatically updated. Through the use of this code, the relationships between value and top level factors such as operating costs and aircraft weight have been analysed (results can be found in later sections).

III. Problem Overview

From previous work it can be seen that, as a design method, VDD has great potential; however, as it is still in its infancy, there are many issues which need to be clarified and developed before the method can be fully implemented within industry.[5, 10-16]

Previous studies, such as the work undertaken by Cheung *et al.*[12] has seen the early developments of subsystem value functions. This work has shown that these lower level subsystem functions are derived from the top level objective function (surplus value) through the inclusion of system attributes (Eqs. 2 and 3).

$$v = \sum_{j=1}^{m} \left(\sum_{i=1}^{n} \frac{\partial V_S}{\partial x_i} \frac{\partial x_i}{\partial y_j} y_j \right) \tag{2}$$

$$V_S = f(x), x = f(y) \tag{3a}$$

$$\therefore V_S = f\{f(y)\} \tag{3b}$$

Where V_S is the aircraft surplus value, x refers to aircraft attributes (for example, weight, fuel burn, manufacturing costs) and y is the attributes of the subsystem. Table 1 shows this derivation from top level surplus value to subsystem value for an engine blade.

Table 1: System Value Hierarchy for Engine (adapted from Ref. 12)

Level	System	Value
Level 1	Aircraft	V_S
Level 2	Engine	$v_{eng} = \sum_{j=1}^{m} \left(\sum_{i=1}^{n} \frac{\partial V_S}{\partial x_i} \frac{\partial x_i}{\partial y_j} y_j \right)$
Level 3	Turbine	$v_{turbine} = \sum_{k=1}^{p} \left(\sum_{j=1}^{m} \frac{\partial v_{eng}}{\partial y_j} \frac{\partial y_j}{\partial z_k} z_k \right)$
Level 4	Blade	$v_{blades} = \sum_{l=1}^{r} \left(\sum_{k=1}^{p} \frac{\partial v_{turbine}}{\partial z_k} \frac{\partial z_k}{\partial t_l} t_l \right)$

These value functions are linear, assuming that all of the local variables are independent. While this works within a single subsystem, there are clear examples where there are interactions across major subsystems; for example, engine weight clearly affects wing weight. Therefore, what appears to be an increase in value for say the engine may result in a decrease in value for the wing. Thus, the local subsystem value may not be sufficient to support design decisions

To summarise, there has been great difficultly when trying to understand how changes made at a low subsystem level will impact overall system product value. It is because of this that the detailed development of subsystem value functions which account for all hierarchical and lateral interactions both within the individual subsystem and across other subsystems is of great importance. Though the development of these interactive, dependent system value functions, a pathway from the top level (surplus value) system down through to the lower system levels will be clear to see. This pathway or linkage system is necessary in order to determine how a change in a system parameter or attribute affects all subsystems as well as product value.

IV. Subsystem Analysis

To aid in the development of subsystem value functions which account for interactions, a number of sensitivity investigations have been completed on a baseline design. To date, the main studies have been categorized as design, business and cost factors; however, as the range of product and subsystem attributes is increased, these sensitivity investigations will be updated to ensure all required information can be obtained. This section will provide more information on these previously neglected terms as well as the way in which they can be included within the current VDD mathematical expressions.

A. Sensitivity Studies

It is known that the impact of parameter variability on surplus value is of great importance with regards to the successful design of next generation aircraft. Initial sensitivity studies have been completed using an Excel spreadsheet tool which incorporates a full initial sizing design analysis within the determination of value. Based on the fact that the analytical relationships between value and cost are now known, the next logical step was to investigate the sensitivities between these key factors in order to show how a designer can begin to influence the key design drivers.

To begin, an overview of past studies has been provided. This then moves on to discuss two additional investigations:

1. A study on fuel costs and how this impacts surplus value
2. A study on the impact of surplus value on the operational life of the aircraft

Table 2 outlines the main parameters which have been analysed to date long with key results. Within these existing investigations, the factors which have been analysed can be categorised as cost, business and design factors; key variables which have been studied are operating cost per flight, passenger load factor and the average number of flights per year.

It is important to realise at this point that these results are all case study specific and refer to typical 150 seater passenger aircraft flying from London Heathrow to Glasgow International airport. Baseline assumptions are:

i. The aircraft is made from conventional aluminium alloys.
ii. An economy load factor of 75% as been assumed.
iii. Business load factor has been assumed to be zero as it is a short haul flight.
iv. An economy ticket price of $160 has been calculated based on ticket prices for a range of flights due to take place between these destinations in the next 12 months.[17,18]
v. Fuel prices were taken to be $3.23 per gallon.[19]

Table 2: Summary of results obtained from sensitivity studies (updated from Ref . 20)

Category	**Parameter to be investigated**	**Impact on surplus value**
Cost	Operating cost per flight (C_{OP})	A linear relationship with a negative correlation is found when analysing the impact of C_{OP} on surplus value (V_S). For this case study, a 1% increase in C_{OP} results in an approximate 22% decrease in V_S.
	Externality cost per flight (C_E)	A linear relationship with a negative correlation is found when analysing the impact of C_E on V_S. For this case study, a 1% increase in C_E corresponds to an approximate 3% decrease in V_S.
	Manufacturing cost per aircraft (C_M)	A linear relationship with a negative correlation is found when analysing the impact of C_M on V_S. For this example, a positive surplus value is experienced until C_M approaches $60 million per aircraft. For this case study, a 1% increase in C_M corresponds to an approximate 3% decrease in V_S.
Design	Passenger Capacity (N_{pax})	The relationship between passenger capacity and surplus value is not fully linear. There are discontinuities at approximately 35, 100 and 150 passenger capacities. These correspond to an additional charge placed on the aircraft due to noise pollution.[21] As well as this, above 100 passengers, an additional flight attendant is required for every additional 50 passengers.
	Passenger Load Factor (LF)	A linear relationship with a positive correlation is found when analysing the impact of passenger occupancy on V_S. For this example, surplus value is positive for load factors above 70%. For this case study, a 1% increase in LF corresponds to an approximate 27% increase in V_S. This increase is due to increased revenue.
	Design Range (R)	The relationship between design range and surplus value is non-linear. If the mission flight distance is not changed to coincide with the design range, value decreases as the full capability of the aircraft is not being utilised.
	Flight Distance (R_{flight})	If all factors related to flight distance (design range and ticket price) are connected, a positive correlation between R_{flight} and V_S is seen. As flight distance increases, design range and ticket price also increase which all combine to produce an overall increase in value.
Business	Number of annual flights (F_y)	A linear relationship with a positive correlation is found when analysing the impact of annual utilisation on V_S. For this case study, a 1% increase in F_y corresponds to a 10% increase in V_S.
	Number of aircraft to be produced ($N_{a/c}$)	The relationship between $N_{a/c}$ and V_S is non-linear. It is expected that this is the result of high initial manufacturing and developmental costs.

The full results from these studies, including analytical expressions and graphical illustrations can be found in Mullan *et al.*[20]

1. *Fuel Prices*

The effect of fuel prices on value is of great importance as current trends show this cost to be increasing (Fig. 1). It has been reported that "world demand for oil is projected to increase 37% over 2006 levels by 2030, according to the 2007 US Energy Information Administration's (EIA) annual report"[22]. The largest factor in terms of fuel price is the price of crude oil, followed by the refinery costs and taxes. Therefore, as the price of oil increases, fuel prices will also increase which will ultimately decrease surplus value.

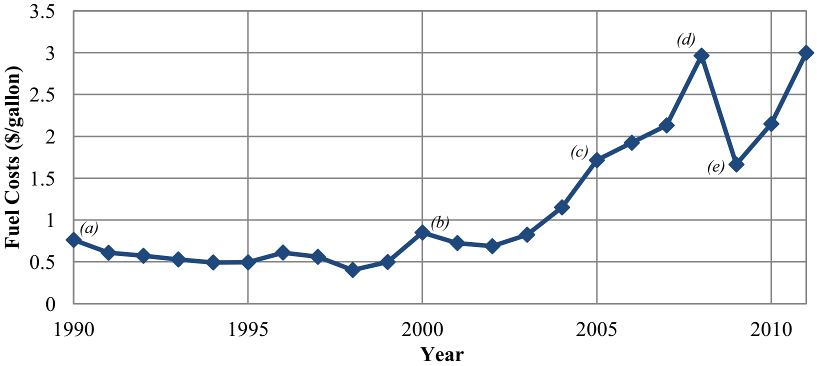

Figure 1: Fuel Price Variations from 1990 to 2011 *(a) Increase in prices around 1990 coincides with Desert Storm Operations (b) Oil prices tripled due to a worldwide increase in the demand for oil (c) This increase in price was due to a combination of disasters; the impact of the war in Iraq following the 9/11 attacks reduced the oil supply and the Gulf of Mexico oil supply suffered disruptions due to a number of hurricanes (d) Some refineries were forced to close due to hurricanes (Ike and Gustav) (e) Economic recession has resulted in a decrease in oil and fuel prices. (Adapted from Ref.* 23*)*

These uncertain fuel prices have an effect on not only the cash flow of an airline but also on the overall value of the aircraft and this uncertainty will be much more detrimental to the value of the design if operating costs remain key to the development of an economically valuable aircraft.

Using the aforementioned case study, a range of fuel prices were examined to quantify the impact on surplus value; Figs. 2 and 3 illustrate the relationship between fuel prices, operating costs and surplus value. From this, it can be seen that as fuel prices rise, for every 1% increase in the price per gallon, operating costs increase at a rate of 0.5% and surplus value decreases at a rate of 11%. It is important to remember at this point that these results are specific to the previously discussed case study.

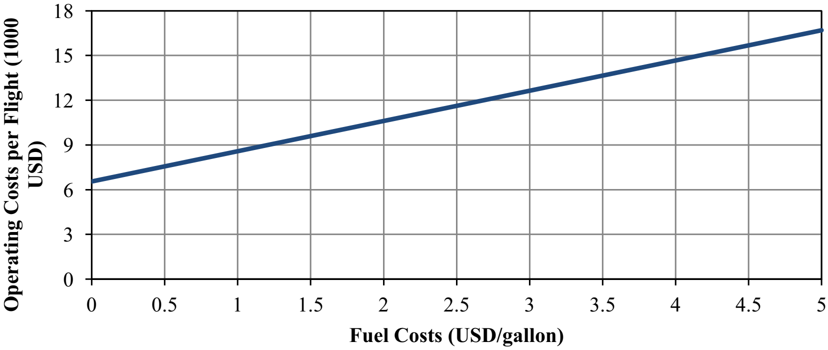

Figure 2: Graph showing the relationship between fuel prices per gallon and operating costs

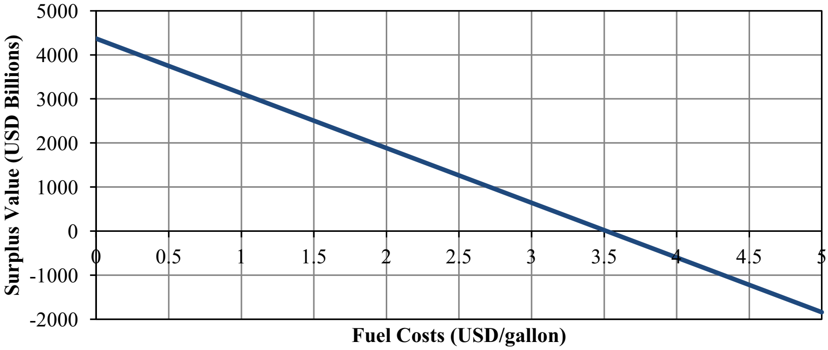

Figure 3: Graph showing the relationship between fuel prices per gallon and surplus value; a negative correlation can be seen with surplus value approaching zero when fuel prices reach $3.50 per gallon

2. Operational Lifetime

Another important output from surplus value is the viable operational life of the aircraft. Figure 4 shows that as the price of fuel increases, surplus value decreases and consequently, the range of viable operational life also decreases. For example, with today's fuel price of £3.23 per gallon[19], in order to have a positive surplus value, the aircraft must be designed to operate between 19 and 47 years. If fuel prices were to increase by 5%, the surplus value would decrease resulting in a decreased range of viable operational lifetime (between 22 and 40 years). Likewise, if fuel prices were to decrease, the surplus value would increase and the viable range of operational lifetime would increase to between 17 and 53 years.

More work is required to improve upon this study. Currently, the viable lifetime is in relation to a positive surplus value, however, it does not account for the fact that each stakeholder within the system must have an acceptable amount of value in order for the design to move forward. Therefore, enhancements to the current surplus value equation are needed which show satisfactory benefits for each stakeholder. This change may result in a smaller window of opportunity with regards to a successful design; however, it would ensure all relevant stakeholders gain some value from the chosen system design.

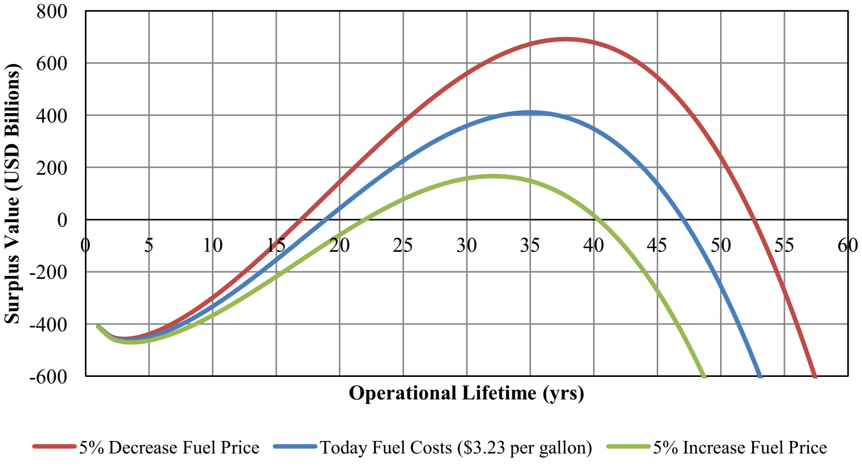

Figure 4: Graph showing the relationship between surplus value, aircraft operational lifetime and fuel price per gallon

Each of these sensitivity studies have been concerned with a high level aspect of value however, what has not been considered is what will happen if value is changed at a lower system level? If changes are made within individual subsystems within a product, in order to ensure reliable information is computed, it is important to fully understand how this change will not only impact overall product value but also how it will affect other subsystems. It is the intention that these aforementioned sensitivity studies will be utilised in the development of subsystem value functions. As discussed in Cheung *et al.*[12] subsystem value functions can be derived from the top level objective function using sensitivity studies. These subsystem equations are linked to both the overall product surplus value as well as individual subsystem attributes through the inclusion of these sensitivities and so further developments are needed within this area.

B. Subsystem Value Functions

Before subsystem value functions can be fully developed taking all interactions (both lateral and hierarchical) into account, the dependencies which exist must be quantified. Taking a simple system including the wing and the fuselage, many interactions can be highlighted (Fig. 5). Assuming the parameter of interest is the wing chord, changes in this parameter greatly affect not only the structural design of the wing but also the structural design of additional subsystems such as the fuselage. This implies that changes made in the wing which affect wing weight will also have an impact on the weight of other systems; in particular, changes in wing weight affect fuselage weight. Figure 5 highlights some of the interactions between the wing and fuselage when wing chord is changed. This figure in no way claims to illustrate all interactions but is provided as a means of highlighting existing interactions across subsystems.

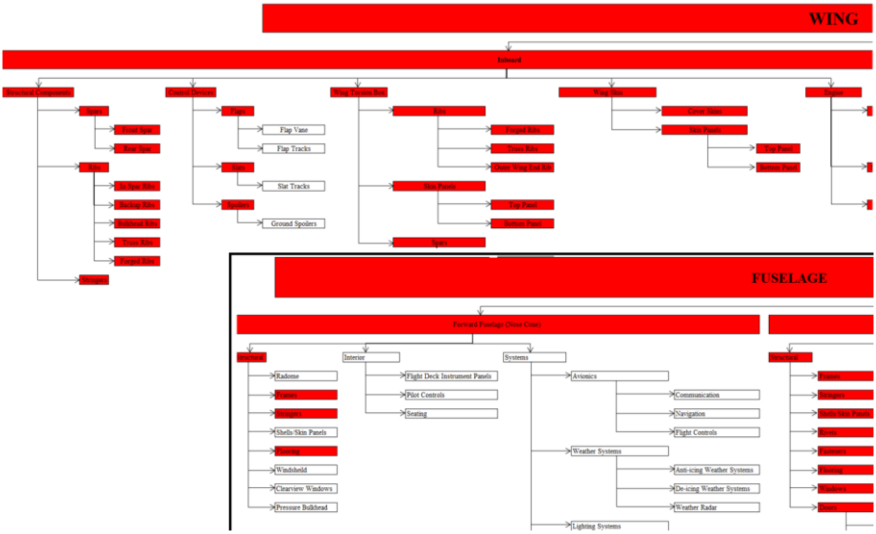

Figure 5: A simple visualisation of the interactions which occur between the wing and fuselage due to an induced change in wing chord. The shaded cells show the physical structures which may be affected by changes made to the wing chord.

Current work has strived to develop subsystem value functions; however as discussed in section III and Table 1, these functions only refer to the hierarchical connections within individual subsystems. If a subsystem value function was to be developed for the wing or fuselage, typical systems attributes which may be considered would be weight and manufacturing costs. It is not uncommon for these subsystem attributes to experience dependencies on one another; for example, manufacturing cost is a function of weight. However, when considering attributes across different subsystems, this dependency is not accounted for. Table 1 explicitly shows that the current method of developing these low level subsystem value equations does not account for these dependencies and only include interactions within different levels within the one subsystem.

Table 3 and Table 4 show a simple breakdown of subsystem value equations for the wing and fuselage respectively. To simplify this study, a limited number of product (system) and subsystem attributes have been investigated. These tables show how these attributes have been used in conjunction with the surplus value function and Eq. 2 to derive subsystem functions for the wing and fuselage. The sum of the individual horizontal rows denotes the change in value due to changes in product attributes (shaded in yellow) and the sum of the individual vertical columns refers to the change in value due to changes in system attributes (shaded in blue). Note that not all system attributes will affect all product attributes, for example, a change in the manufacturing cost of the wing will have no bearing on the overall product weight. These tables refer to a top level breakdown analysis of value and are determined using a sensitivity analysis based on a generic description of the value equation (Eq. 1).

Table 3: Wing Value Components

		Wing System Attributes		
		Weight (w_{wing})	Manufacturing Costs ($C_{man\ wing}$)	
Aircraft Attributes	Weight (W)	$\frac{\partial V_S}{\partial W}\frac{\partial W}{\partial w_{wing}}w_{wing}$	–	$\frac{\partial V_S}{\partial W_{\mid wing}}$
	Manufacturing Costs (C_M)	$\frac{\partial V_S}{\partial C_M}\frac{\partial C_M}{\partial w_{wing}}w_{wing}$	$\frac{\partial V_S}{\partial C_M}\frac{\partial C_M}{\partial C_{man_{wing}}}C_{man_{wing}}$	$\frac{\partial V_S}{\partial C_{M\mid wing}}$
		$\frac{\partial V_S}{\partial w_{wing}}$	$\frac{\partial V_S}{\partial C_{man_{wing}}}$	

Table 4: Fuselage Value Components

		Fuselage System Attributes		
		Weight (w_{fus})	Manufacturing Costs ($C_{man\ fus}$)	
Aircraft Attributes	Weight (W)	$\frac{\partial V_S}{\partial W}\frac{\partial W}{\partial w_{fus}}w_{fus}$	–	$\frac{\partial V_S}{\partial W_{\mid fus}}$
	Manufacturing Costs (C_M)	$\frac{\partial V_S}{\partial C_M}\frac{\partial C_M}{\partial w_{fus}}w_{fus}$	$\frac{\partial V_S}{\partial C_M}\frac{\partial C_M}{\partial C_{man_{fus}}}C_{man_{fus}}$	$\frac{\partial V_S}{\partial C_{M\mid fus}}$
		$\frac{\partial V_S}{\partial w_{fus}}$	$\frac{\partial V_S}{\partial C_{man_{fus}}}$	

As can be seen, there is no cross-over between these two tables. For example, only considering these two tables, there appears to be no link or interactions between the weight of the fuselage and the weight of the wing. This connection is known to exist as fuselage size and weight is a function of passenger numbers and aircraft takeoff weight. This parameter needs to be considered when designing a wing as the weight of an aircraft has a direct relationship to the lift which the wing needs to produce which in turn affects the size and weight of this system.

From Tables 3 and 4, the value of the wing and fuselage are as follows. For these functions, only the selected attributes are considered.

$$v_{wing} = \frac{\partial V_S}{\partial W}\frac{\partial W}{\partial w_{wing}} w_{wing} + \frac{\partial V_S}{\partial C_M}\frac{\partial C_M}{\partial w_{wing}} w_{wing} + \frac{\partial V_S}{\partial C_M}\frac{\partial C_M}{\partial C_{man_{wing}}} C_{man_{wing}} \tag{4}$$

$$v_{fus} = \frac{\partial V_S}{\partial W}\frac{\partial W}{\partial w_{fus}} w_{fus} + \frac{\partial V_S}{\partial C_M}\frac{\partial C_M}{\partial w_{fus}} w_{fus} + \frac{\partial V_S}{\partial C_M}\frac{\partial C_M}{\partial C_{man_{fus}}} C_{man_{fus}} \tag{5}$$

Where: $C_{man\ fus}$ = Manufacturing cost of the fuselage
$C_{man\ wing}$ = Manufacturing cost of the wing
w_{fus} = Fuselage weight
w_{wing} = Wing weight
v_{fus} = Fuselage surplus value
v_{wing} = Wing surplus value

If lateral interactions between these two subsystems are to be included (which they should be in order to make the design decisions repeatable and traceable), Eqs. 4 and 5 become:

$$v_{wing} = \frac{\partial V_S}{\partial W}\frac{\partial W}{\partial w_{wing}} w_{wing} + \frac{\partial V_S}{\partial C_M}\frac{\partial C_M}{\partial w_{wing}} w_{wing} + \frac{\partial V_S}{\partial C_M}\frac{\partial C_M}{\partial C_{man_{wing}}} C_{man_{wing}} + VI_{f,w} \tag{6}$$

$$v_{fus} = \frac{\partial V_S}{\partial W}\frac{\partial W}{\partial w_{fus}} w_{fus} + \frac{\partial V_S}{\partial C_M}\frac{\partial C_M}{\partial w_{fus}} w_{fus} + \frac{\partial V_S}{\partial C_M}\frac{\partial C_M}{\partial C_{man_{fus}}} C_{man_{fus}} + VI_{w,f} \tag{7}$$

Where $VI_{f,w}$ is a Value Influence (VI) factor which aims to quantify the impact the fuselage has on the wing value and $VI_{w,f}$ is the VI factor which shows the impact of the wing on fuselage value. It is these factors which will include the lateral connections across subsystems (Eq. 8)

$$v_{wing} = \underbrace{VI_{w,w}}_{\substack{\text{Hierarchical connections} \\ \text{within the wing system}}} + \underbrace{\sum_{i=1}^{n} VI_{i,w}}_{\substack{\text{Lateral connections across the wing and all} \\ \text{subsystems where } i \text{ refers to subsystems such} \\ \text{as the fuselage, engine and empennage}}} \tag{8}$$

These VI factors must be developed for all subsystems if they are to be used within the VDD process. Once fully developed, these subsystem value functions may be used within the decision making process to analyse value sensitivities to parameter changes across multiple subsystems as well as aiding the detailed trade off studies which must take place within an aircraft design procedure.

1. Wing-Fuselage Interaction Example

Many of the advancements within aircraft design strive to save weight, either from the structure as a whole or from individual components. For this example, assume a weight savings of 10% has been achieved for the wing. As wing weight (w_{wing}) traditionally accounts for 10% of the takeoff gross weight (TOGW), this equates to a reduction of 1% in TOGW[24]; if we assume TOGW is to remain constant, this weight savings can be replaced by payload. It is then expected that this would increase the surplus value of the aircraft as revenue would be increased. Taking the changes in wing weight into account, the question to be asked is, what happens to the value of the fuselage?

The case study for this example is a 150 seater passenger aircraft flying from London Heathrow to Glasgow International. Initial design show a maximum passenger capacity of 150, however, taking the weight savings of the wing into account, this number can be increased if TOGW is to remain constant.

A potential 1% change in TOGW equates to an approximate weight of 1800lbs for this type of aircraft. Assuming a passenger (plus baggage) weighs 200lbs, this initial savings means the aircraft has the potential to carry an additional nine passengers. However, if the number of passengers is increased, the structural weight of the fuselage must also be increased to cope with the extra structural load. Therefore, the change in payload weight will not equal 1% of TOGW; further adjustments to the design will be required if TOGW is to be maintained.

Assuming that the fuselage is a simply supported beam with a peak bending moment dictated by the load experienced by the structure, if the weight supported by the fuselage is increased by 1% TOGW, the peak bending moment will also increase. If the fuselage bending moment increases by 1%, changes in the fuselage cross sectional area are required in order to maintain the stress experienced by this structure (refer to Eq. 9).

$$\sigma = \frac{My}{I} \tag{9}$$

As the relationships between bending moment, cross sectional area and fuselage structural weight are linear, a 1% increase in bending moment results in a 1% increase in area and subsequently, a 1% increase in fuselage structural weight (w_{fus}).Therefore, in order to determine the actual weight which can be used to increase passenger numbers, an iterative procedure based around Eq. 10 is necessary.

$$\Delta TOGW = \Delta w_{PL} + \Delta w_{fus} \tag{10}$$

Where Δw_{fus} is the change in the fuselage structural weight and Δw_{PL} is the change in payload weight.

Initially, for this aircraft type, the combined weight of the fuselage structure and payload is approximately 30% of TOGW[24] but if the payload is to be increased by 1% of TOGW, the fuselage-payload weight fraction would increase to 0.31. For this example, the payload weight fraction was initially 0.18 (for 150 passengers). Substituting the gain in TOGW for additional payload sees this weight fraction increase to 0.19 (159 passengers). This equates to an increase in 5.5% increase in payload weight; surplus value also increases by a factor of 2.6.

However, if interactions were to be included within this analysis, a change in w_{fus} is required to carry the extra load. If the fuselage-payload weight fraction was originally 0.3 and the payload weight faction was 0.18, it can be easily determined that the fuselage structural weight fraction was 0.12. Using this, it was calculated that, initially, w_{fus} was approximately 21600lbs. A 1% increase in w_{fus} results in a total fuselage empty weight of approximately 21816lbs. Therefore, the total change in fuselage weight (empty weight and payload weight) is:

$$\Delta w_{(fus+PL)} = \Delta w_{fus} + \Delta w_{PL} = 2016 lbs \tag{11}$$

As this change in weight is greater than 1% TOGW (1800lbs), the change in w_{fus} must be taken out of the weight given to carry additional passengers. Therefore, the real increase in payload can be calculated using Eq. 12.

$$\text{Real Increase In Payload} = \Delta TOGW - yw_{fus} \tag{12a}$$

$$\Delta TOGW = x\ W_{PL} + yW_{fus} \tag{12b}$$

Where x and y are the percentage increases in the payload and fuselage structural weight respectively.

For this example, x is 5% and y is 1% (directly related to the 1% increase in the fuselage-payload weight fraction). This data then results in a real change in payload weight of approximately 1584lbs. Assuming each passenger (plus baggage) weighs 200lbs, this real increase equates to no more than an additional seven passengers. Some key results from this example is that the payload weight fraction and fuselage empty weight fraction have been increased to 0.188 and 0.122 respectively as a result of a 10% weight savings in W_{wing}.

This change from nine to seven additional passengers was then examined to quantify the impact the inclusion of the interaction has on value. Due to the fact that the changes in empty weight are relatively small, it was assumed that costs (such as manufacturing and development) do not experience any significant changes and so, the changes in passenger numbers can be looked at in terms of revenue increases and the corresponding change in value. Table 5 is used to summarise these key results.

Table 5: Key results from wing-fuselage interaction analysis

Is the interaction analysed?	Passenger Numbers	Payload Weight Fraction	Fuselage Structural Weight Fraction	Percentage change in value when compared to baseline results (%)
No	159	0.190	0.120	160
Yes	157	0.188	0.122	125

By comparing the results in Table 5, it can be seen that by neglecting the interactions which are present within the subsystems, a true representation of the changes in value cannot be obtained. It is important to understand that the inclusion of these interaction factors not only has an effect on overall surplus value but they can also impact other key parameters or variables within a design. To show this, the study on viable operational life was repeated taking into account the additional passenger numbers; Fig. 6 shows the results from this analysis.

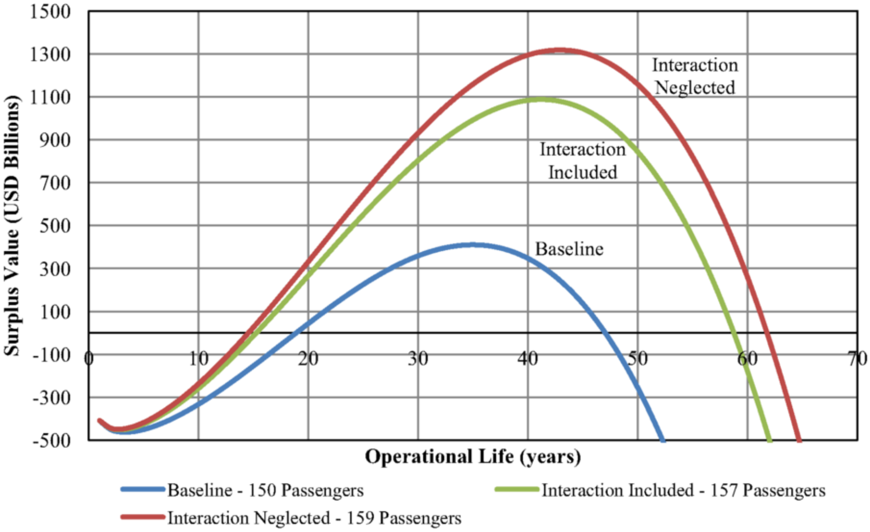

Figure 6: Graph showing the relationship between surplus value, aircraft operational lifetime and passenger numbers taking subsystem interactions into account

This figure highlights the fact that these interactions impact multiple aspects of any design. An increase change in passenger numbers obviously increases surplus value due to an increase in revenue, however, this study illustrates the fact that the change in passenger numbers also impacts the viable operational life. Table 6 summarises the key results from this study.

Table 6: Key results from viable operational life study taking the interaction between the wind and fuselage into account

Is the interaction analysed?	Maximum Value (USD Billions)	Optimum Operational Life (years)	Range of Viable Operational Lifetime (years)
Baseline case – no change in wing weight	410	35	19 - 47
No	1320	43	14 – 62
Yes	1080	41	15 – 59

This study can be improved by including changes in costs as well as weight; however, it is clear to see that the inclusion of these interactions can dramatically change surplus value and so, should be a vital factor in any design decisions.

V. Future Work

Future work will see the development of a physical architecture surrounding the subsystems within an aircraft. This will be used to provide a visual representation of the interactions which are known to exist and must be included within subsystem value functions.

Through the work completed to date, this existence of subsystem interactions has been seen to be real and have real impact on value. Therefore, the next step is to perform detailed studies in order to define the formulation of these interaction coefficients or factors (VI) more clearly. These will then be used to show how changes at a low subsystem level can impact individual subsystem value as well as overall product value.

VI. Conclusion

The main aim of this paper was to show that subsystem dependencies and interactions need to be accounted for when calculating both subsystem and overall system value. This aim was achieved using a simple example which shows the interactions between wing weight and fuselage weight.

Results showed that neglecting subsystem interactions over estimated an increase in V_S by 35% and added four years to the viable operational life. Such over optimistic predictions in value leads to risk and error in decisions. Accounting for these interactions gives a more realistic estimate of the project life and value attainable from the system.

Further, by neglecting these interactions, local subsystem value functions only refer to the individual subsystem resulting in an isolated design procedure much like that of Systems Engineering. This paper introduces Value Influence factors which can enable designers to account for any and all interactions and dependencies across multiple subsystems and therefore, move away from any isolated design approach.

Ultimately, the results presented in this paper, which were based around the impact the wing has on the fuselage, emphasise the need to account for these interactions as they significantly impact overall product surplus value. Further investigations focusing on the physical interactions which are present within aircraft subsystems are needed to aid in the development and clarification of the aforementioned VI factors and so, future work will concentrate on this.

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Subliminal Control on CDA final descent operations

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In this article a final descent approach procedure is evaluated that performs near-idle descents of tightly sequenced arrivals over a curved approach path towards a single heavy loaded runway. An operational concept is applicable in which a Final Approach Spacing Tool (FAST) assists the Controller with advisories to maintain stability of the arrival flow. Calculated small subliminal control instructions are processed automatically, whilst other more significant required instructions are assumed to be given by the Controller. This process is modelled in MATLAB / Simulink, using an aircraft performance model with realistic modelled flight dynamics, including randomised uncertainties. Simulation results demonstrate significant stability differences for including or excluding assistance by subliminal control instructions. Also, the model gives indications for the maximum achievable runway throughput of an arrival runway in segregated mode fed by a dedicated flow of near-idle CDA operations. The achievable reactivity of the control loop is decisive to improve control on arrival sequence stability, whilst pro-active measures will help to increase the stability.

Nomenclature

m = meter
s = seconds
deg = degrees
kts = knots
cwl = Controller Workload
arr/hr = arrivals per hour

I. Introduction

Implementation of Continuous Descent Approach (CDA) procedures from Top-of-Descent for dense arrival flows at hub airports is one of the major challenges for advanced ATM in Europe. Several projects under the EU programme, SESAR, are addressing the validation and implementation of procedures to accomplish early and highly accurate sequencing at the Initial Approach Fix (IAF), whilst also final descent procedures are investigated [Ref. 1, 2 and 3]. CDA arrival flows during peak hours on final descent will be tightly sequenced, and will have to follow a relative long curved descending approach path under minimal spacing conditions. This part of the descent is sensitive for instability due to the dynamics of aircraft operations, the manoeuvring process and the limitations of ATCos to intervene under near-idle continuous descent conditions. It is proposed in this article to

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increase the stability of the arrival sequence by pro-active measures and, in addition to control instructions by the ATCo, to have automatic control instructions at subliminal level. A Final Approach Spacing Tool (FAST)[4] calculates instructions required to achieve optimal stability of the arrival conditions at the runway. As long as possible, automatically generated instructions are submitted within a small pre-defined tolerance window around the actual executive clearance instruction. These instructions are small heading corrections to intercept a slightly moved waypoint, but whenever this is not sufficient to maintain separation, the ATCo is advised to give heading instructions intercepting a waypoint as a traditional procedure solving separation problems. The pilot and aircraft's Flight Management System (FMS) are expected to implement the stretched or reduced approach path, and to intercept the Final Approach Fix (FAF) a predicted time lapse earlier or later.

The objective of the research, presented in this article, is to demonstrate the effects of subliminal control in high density traffic performing continuous descent operations. To do so, a concept was developed to support subliminal control. This concept, based on subliminal control instructions during final descent, is implemented in a model-based fast-time simulation process to simulate long tight sequences of an arriving flow over a curved approach path to land at an arrival runway in segregated mode. Several runs are processed to compare the performance of arrival operations under different conditions with subliminal control measures activated or de-activated. Also, sensitivity analysis is performed to compare wind effects, traffic mixes and the frequency of submission of subliminal control instructions. The results are promising and beneficial for all stakeholders involved [Ref. 5].

This paper describes, background and context, followed by a small outline of the concept and the plan to conduct the experiment. Thereafter, the experiment is described, its results and the analysis of results. At the end, some conclusions are added.

II. Background and context

One of the major areas of innovation in ATM is to enable Continuous Descent Approaches (CDAs) for dense arrival flows at hub airports. The justification is that CDAs are fuel efficient and environmental friendly compared to traditional procedures. The problem, however, is that these continuous descending flights are difficult to control. Highly accurate planning, guidance and control is required to accommodate these tightly sequenced procedures, using scarcely available runway capacity. In addition, these hub airports are allocated often in airspace areas, where airspace for dedicated arrival flows is missing and where CDAs are to be separated from other departing and arriving traffic flows. The best achievable result will be often to find the compromise of flying near-optimal, near-idle descent profiles with accurately sequenced, planned and controlled arrival operations.

The aim of early arrival management in SESAR is to deliver tightly sequenced flights over the IAF with a tolerance of ±30 s., compared to an ideal sequence planning [Ref. 3, 12 and 13]. By applying time-based separation, the arrival flow over the IAF is prepared in principle to land with ensured separation, as long as the separation can be maintained during the final descent path. A major problem during final descent is that minimal separation has to be preserved over a considerable distance-to-go whilst near-idle flight profiles are difficult to manage and control. Tight sequencing and the flight dynamics of aircraft makes the queue of arriving flights to a critical queuing problem as soon as the number of succeeding flights increases and disturbances will occur. Because maximum throughput is a primary requirement of airspace users, the question is if equally high throughput levels can be maintained compared with traditional approach procedures, benefitting from an established altitude by levelling-off, vectoring and holding.

The problems to be solved, are to mitigate possible queuing instability and to solve the lack of controllability on descent operations. From queuing theory it is well-known that instability is sharply dependent on critical separation distances, and flow robustness will increase by stable separation and a more evenly distribution of demand. Also known from queuing theory is the impact of guidance and control quality and control-loop frequency on stability of the queue. The ATCo-Pilot control loop (also by datalink) is relatively slow, conservative in timing and not subtle in its decision making. Every well-tuned automation process will perform better regarding its frequency, its accuracy of decision making and precision of timing [Ref. 6 and 7].

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[4] A prototype of FAST was developed by NATS [Ref. 4].

This dilemma is understood, and for example ASAS applications are considered sometimes as a solution to improve the robustness of spacing of final descent CDAs in lower airspace. These applications, however, mainly focus on self-separating air traffic where each aircraft contains a control module that separates the own aircraft from the target aircraft, making use of available state information of the surrounding aircraft. The states information available to each control module is defined as the 'information structure'. Research by Slater and Chu shows that increasing the amount of information available to each control module significantly improves the sequence's performance with respect to maintaining separation minima and stability [Ref. 6 and 7]. Since it is not yet feasible in self-separating traffic to achieve the state information of all aircraft in the sequence and since coordination problems are not yet solved, optimal performance can not be reached by these applications in the near future. Fortunately, all required information will be available on the ground: By making use of ADS-B signals and radar data the relevant information can be retrieved by a centralised ground-based controller. This forms the basis of the choice to use a ground-based tool in the concept under investigation.

In this article, a concept of subliminal control on CDAs is proposed and evaluated. The advantages of the concept are significant:

- Subliminal instructions are natural extensions of traditional instructions and are compliant with the traditional way of ATCos to perform executive control on air traffic.
- All exception handling is naturally dealt with. Whenever, the Controller intervenes this will overrule the subliminal instruction clearance in force.
- The Controller monitoring task will decrease in effort when the stability of the sequence will increase.
- The validation and verification is relatively simple because there is one centralised algorithm which determines the optimal distribution of sequenced flights as well as the instructions needed to accomplish the most robust distribution of flights under control.
- Transition is relatively simple because the frequency of advised instructions may augment gradually and also a seamless transition can be supported from manual instructions by R/T to automatic instructions, uplinked and processed.
- Insufficiently equipped flights, not able to participate in the subliminal control process, can be treated in a natural way, possibly increasing workload, but never excluding the applicability of the algoritme.

In addition, there are specific advantages to apply ground-based centralised subliminal control:

- Once there is one supervising algorithm to regulate the arrival flow, the algorithm may promote frontloading when this improves robustness.
- Also, relaxation by increased spacing can be part of the decision making process. This is possible only because it is part of an ATM strategy, implemented under responsibility of the ANSP, and endorsed by the authority of the Executive Controller.
- Finally, the ATCo can decide to delay or advance flights by instructing vectors, which allows better control over descent manoeuvring flights than speed corrections, and therefore also subliminal control instructions can do the same.

All together, a subliminal control algorithm can be developed to maximise robustness and stability of the flow, and this is expected to allow higher throughput under more stable operational conditions. Ultimately, subliminal control is expected to enhance Controller's capabilities where there are physical and mental limitations of what the human being can accept and deliver.

III. Operational Concept

Final descent CDAs are difficult to control. Typically up to 30 NM out, at an altitude of 7.000 ft or above, the arrival sequencing is assumed to be accomplished already. The requirement in SESAR is to deliver CDAs at the Initial Approach Fix (IAF) with an accuracy of ±30s [Ref. 3]. It can be assumed that the arrival sequencing is not yet established in a perfect tight and time-based separated way, but the arrival flow will be orderly sequenced and at most a merging process with another arrival flow might still be needed; in all other respects the remaining descent of each flight is following a continuous descending curved approach path along a down-wind and cross-wind leg to intercept a Final Approach Fix (FAF), and thereafter the ILS for landing. (See the example, derived from a CDA final approach path for Schiphol, Amsterdam, Rwy 18R, Figure 1, and further also Ref. 5).

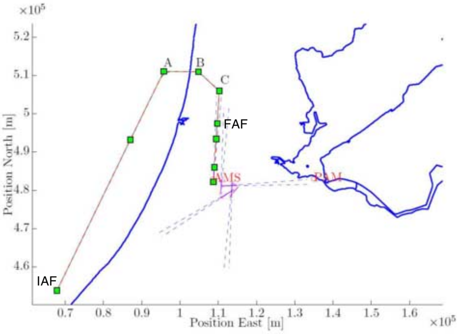


Figure 1. Lateral profile of near-idle CDA final descent ground track, used to assess benefits by subliminal control

The problem and limitation in controlling final descent CDAs is the tight sequencing over a considerably long descent path, the dynamics of the aircraft limiting the ability to maintain minimum spacing and the limitation of the Controller to react in an adequate way to correct for deviations. In the ideal case, of an undisturbed near-idle descent, there is no intervention. However, when interventions are needed, the control loop of ATCo and pilot is simply not precise and accurate enough to correct for deviations of dense flows and, at the same time, to maintain the near-idle descent profile. Traditional instructions are typically with a tolerance of:

- 10 kts. for speed instructions,
- 10 deg. for heading instructions to stretch or to shorten the curved approach path, and
- A frequency and response on instructions that should not exceed probably one instruction per 3 minutes per flight, depending on the number of flights under control and the required precision of giving instructions in due time. The achievable frequency is limited after all by all other ATCo tasks like surveying, monitoring, decision making and problem solving.

Automation support may help to alleviate the task of the ATCo. Short-term trajectory prediction will be used in support of monitoring, conflict detection, and problem solving by short-term conflict alerts and the planning of medium-term separation at the runway. FAST, the Final Approach Spacing Tool, will calculate periodically, based on time-based separation, a distribution of arrivals that is optimised for flow robustness by:

- Advancing flights whenever flights are reducing maximum throughput by performing unnecessary large separation,
- Relaxation of estimated separation whenever planned sequencing allows slightly delaying flights and whenever there is opportunity to delay.
- Slightly advancing flights whenever there is opportunity to advance and whenever the traffic load behind the actual flight suggests creating more space for other arrivals.
- Whenever the calculated subliminal measures are not sufficient to ensure safe separation of the arrival sequence, an ATCo advised instruction is calculated correcting for the foreseen separation infringement, and at the same time, disabling subliminal control for that flight.
- Whenever this is not sufficient to support ensured separation, an ATCo advice is calculated to instruct a flight to leave the sequence.

The simulated final descent CDA procedure comprises:

- The flight approaches the IAF with known predicted approach path and landing time. The ETA is made available (by assumed down-linking), and the optimised distribution of the actual arrival flow is calculated. The ATCo is assumed to give a clearance for the planned CDA, and thereafter the subliminal control mechanism is activated.
- FAST calculates periodically, with intervals between 1 and 3 minutes, instructions to implement an optimised descending flow. The optimised conditions imply an optimisation towards stability with best possible spreading of arrivals in the sequence, creating "robustness". The algorithm shall take into account conflict-free routing along the descent path and at touch-down [Ref. 5].
- Subliminal instructions consist for example of waypoint heading instructions determined by moving a significant waypoint with a continuous varying off-set of values between -1000m and +1000m. The instructions are directly implemented without intervention, or during an implementation transition process, by limited intervention for approval by ATCo and Pilot.
- Other advised instructions are implemented by ATCo-Pilot intervention, and thereafter the flight is excluded from further subliminal control instructions.

- Instructions by ATCo-Pilot intervention are either vector instructions to pass over off-set waypoints with discrete displacements between for example 1000 to 5000 meter, or instructions to remove the flight from the sequence. In the last case, the aimed throughput can not be maintained and, after leaving the sequence, the flight shall re-enter the sequence and will create therefore significant flight inefficiency and overhead in workload.
- The procedure shall guarantee in this way that all flights will pass the FAF and runway threshold with ensured safe separation, except those flights removed from the sequence.

This concept is implemented within a model-based experimental environment using MATLAB/Simulink. This model is as realistic as possible regarding the simulated flight performance and dynamics, but physical transactions and human interactions are not modelled. The aim is to assess the validity of application of subliminal control techniques for control on dense arrival flows during final decent operations, and to validate achievable benefits in terms of throughput, workload, flight efficiency and safety.

IV. Set-up and Conduct of Experiment

A. Experimental objectives

The model-based experiment on final descent CDAs has been set up to give answers on the impact of queuing behaviour on throughput, controller workload, flight efficiency and safety:

- **Capacity (Throughput)**: Throughput is most critical for acceptance of CDA procedures in dense flows in operational service at large airports. The flow dynamics has direct impact on achievable peak load throughput and sustainable throughput.
- **Capacity (Controller workload)**: Subliminal control aims to reduce workload by positively influencing the stability of the descending traffic flow. The experiment observes when flow stability is impacted negatively, and when ATCo intervention is required. The observations address only differences in workload for different scenarios, and therefore the measured results will have relative and indicative significance.
- **Efficiency**: The performance of CDAs is anyhow flight-efficient compared to traditional arrival profiles; however, this difference is not assessed because traditional procedures are not modelled. The experimental observations that directly impact flight-efficiency are the aborted CDAs, and these numbers will give a strong negative indicator for the feasibility to perform final descent CDAs for that specific scenario.
- **Safety**: The model calculates so-called Peak-Flow Robustness (PFR), which relates the planned density of arriving traffic peaks to actually realised density of these peaks. The reason to introduce this performance indicator is that subliminal control instructions are aiming to implement a more balanced distribution of arriving flights over time compared to non-intervening scenarios, for which only human-modelled ATCo intervention is available to ensure separation. The outcome gives an indication of the achievable balanced spread of arriving traffic, and the associated robustness of the sequence is an indicator of reduction of possible safety alerts and hazards.

Along these lines of performance measuring, three hypotheses were posed to asses the validity of the concept:

1. **Ensured separation**: High-density CDA sequences supported by FAST and using subliminal control instructions will accomplish increased stability of separation of arrivals.
2. **Decreased workload**: Use of subliminal control on high-density CDA sequences will decrease the extra workload required to ensure safely separated arrivals.
3. **Sustainable throughput**: Support by subliminal control will increase the sustainability of high density throughput of CDAs significantly.

B. Modelling aspects

The modelled fast-time simulation experiment simulates one representative CDA approach path, assuming this path to feed one runway, passing three movable waypoints by a down-wind and cross-wind leg (see Figure 1). Each waypoint can be selected for subliminal instructions by offsets up to a maximum of ±1000m, and for emulated ATCo instructions by offsets between +1000m and +5000m or between -1000m and -5000m (not advised in the experiment). This will allow to calculate (small) vectoring track corrections in parallel to the nominal approach path at subliminal as well as ATCo controlling level, both contributing to perform separation ensured landings (see Figure 2). When it is not possible in this way to maintain the sequence and to ensure separation, a flight will be removed from the sequence. Regarding this procedure, two issues are to be noticed:

- Operations to re-insert removed flights into the sequence are not modelled. These CDA-aborted flights are disregarded, and are only taken into account as decrease in throughput and increase in workload.
- The concept requires de-confliction along the tracks and the runway; however, the present modelling supports de-confliction at the runway only. This may require some extra constraining conditions, possibly resulting in a (slight) decrease in throughput.

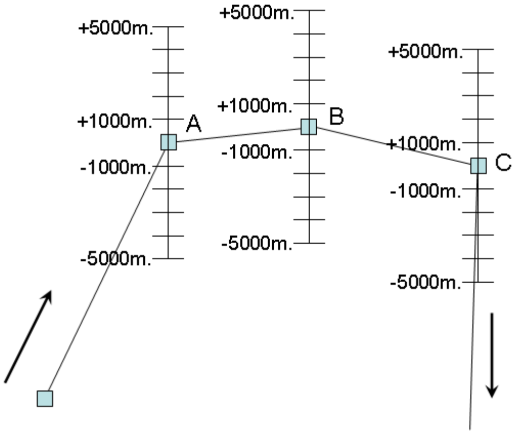


Figure 2. Illustration of options for subliminal vectors (±1000 m.) and ATCo advised vectors (between ±1000 m. and ±5000 m.) over 3 waypoints on the cross-wind leg.

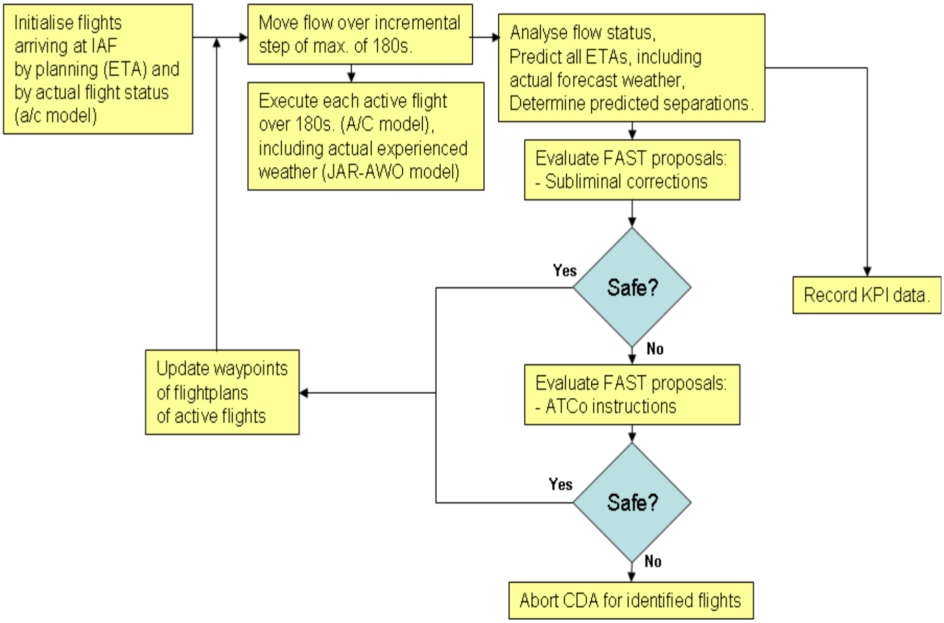


Figure 3. CDA Final descent subliminal control simulation model

The MATLAB model can be decomposed in several components (see Figure 3). The following components are discussed below:

- Aircraft and weather modelling
- Trajectory prediction
- Evaluate FAST proposals

- ***Aircraft and weather modelling***:

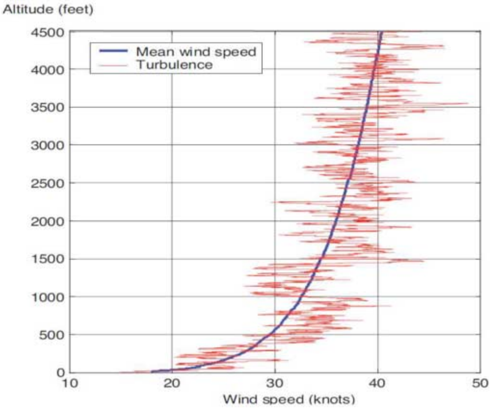


Figure 4. Example of processing emulated wind conditions in final descent, including turbulence

The research performed for the subject of interest requires high quality aircraft modelling. The reason is that queue stability in final descent is part of the flight that is subject to highly dynamic aircraft performance behaviour, and, moreover, precisely the flight dynamics can be one of the main causes of queuing instability. The AMAAI modelling toolset of NLR (Aircraft Models for the Analysis of ADS-B In-trail Modelling) is developed to offer sensitivity on flight performance behaviour caused by flight dynamics. This toolset is exactly satisfying the requirements to simulate this phase of flight with sufficient realism (Ref. 8). This simulation toolset simulates an aircraft's flight trajectory using point-mass performance data, applying a full set of 3D point-mass equations of motion, and supports state-of-the-art modelling of flight dynamics. The modelling of functionality to control the aircraft's flight dynamics is based on the so-called Total Energy Control System (TECS), and the modelling of meteo conditions is based on the JAR-AWO model, generating a wind speed profile including turbulence modelling. See Figure 4, and also References 9, 10 and 11.

- ***Trajectory Prediction:***

A strongly simplified trajectory prediction facility had to be developed in order to keep the complete CDA-flow simulation model manageable regarding model complexity and processing time. Therefore, a table-driven trajectory predictor was designed, sufficient elaborate to run the experiment. This trajectory predictor was dimensioned to support 3 AC-types (B747-400, B737-800, F-100), 3 way-points, including 4 displacements for each waypoint, 3 wind speeds and 3 wind-speed directions. The trajectory predictor table was generated by running the model for all identified trajectories, and during processing runs predictions were determined by interpolation. The tabulated predictor was appropriate to generate predictions for small deviations between IAF and FAF, but it yields simplifications that might be more significant than the anticipated future difference between the quality of airborne and ground-based trajectory prediction.

- ***Evaluate FAST proposals:***

All flights in final descent are periodically checked for the need to optimise their track by small vectors over one or more of the three waypoints. Subliminal corrections are typically smaller than ±20s. by waypoint shifts of a maximum of ±1000m. Given all flights in-trail for final descent, the optimal distribution can be derived from the achievable most robust distribution of flights. This gives a slightly wider distribution in general than the minimum separation. Thereafter, individual flights and their flightplans are updated, possibly pro-actively, with corrections that yield small track extensions as well as track reductions.

When subliminal corrections fail to ensure separation for a flight, this flight is selected for an ATCo advised instruction by discrete waypoint displacements between 1000m and 5000m, which leads to corrections up to typically a maximum of ±60s. Whenever a flight is selected for an ATCo instruction, further subliminal corrections are disabled for this flight. Moreover, ATCo instructions are selected only to ensure separation by delaying the following AC, and not to optimise the distribution of flights over the descent path.

When also ATCo instructions fail to ensure separation, the descent procedure is aborted. The flight is assumed to be removed from the sequence, and disregarded. The flight is also not considered anymore for landing results, which leads to decreased throughput and increased workload.

C. Conduct of experiment

The conduct of the experiment was executed by running one sequence of 40 flights for a large number of variations on one traffic scenario. One scenario variable yields randomised variations of arrival times over the IAF, and another randomised variable created gust variations if wind was applicable. Randomised values for the IAF flight arrival variable determined 5 different scenarios processed systematically each time in order to generate some statistical significance. The other scenario variables were applied partly systematically, forming the Baseline research, and partly ad hoc by individual runs, performing some sensitivity analysis.

The air traffic demand of each scenario consisted of the same order of 40 sequenced flights, arriving over the IAF, and those 40 flights consisted of:

- 12.5% Heavies, represented by B747-400 (5 flights)
- 37.5% Mediums, represented by B738-800 (15 flights)
- 50% Mediums, represented by F-100 (20 flights)
- No Lights

Based on minimal standard separations, this would require 3870s. landing time, leading to a theoretical maximum achievable flow density of 37 arr./hour for this specific scenario.

The Baseline research consisted of 40 variations of running each time these 5 scenarios of IAF arrival time variations. These 40 variations were obtained by (See Table 1):

1. Switching subliminal control "On"/"Off", and assessing and comparing effects of subliminal control on achievable separation at the runway.
2. Adding 3 gaps of ~1 minute per run, and assessing the impact of some slack time on robustness of sequence stability by comparing "Gaps" with "No-gaps".
3. Processing 5 different levels of density of air traffic demand, varying from 1.1 to 1.5 times the minimal required separation time (excluding the gaps), and assessing the impact of variations of flow density. This yields planned flow-density scenarios with the following characteristics (including 5 Heavies):
    - 33 arr./hour (tightness 1.1x minimum separation)
    - 31 arr./hour (tightness 1.2x minimum separation)
    - 28 arr./hour (tightness 1.3x minimum separation)
    - 26 arr./hour (tightness 1.4x minimum separation)
    - 24 arr./hour (tightness 1.5x minimum separation)
4. Processing with wind "Yes/No", whilst wind "Yes" was set to wind of 10 kts. at ground level, parallel to the runway and opposite to landing.

Table 1. Variation in scenarios by Modelling experiment, Baseline research (200 runs)

Exp. Run	Sublim. Ctrl On/Off	Gaps / No-gaps	Wind Yes/ No	Density 33 arr/h	Density 31 arr/h	Density 28 arr/h	Density 26 arr/h	Density 24 arr/h
1-5	On	No-gaps	No	5x	5x	5x	5x	5x
6-10	Off	No-gaps	No	5x	5x	5x	5x	5x
11-15	On	Gaps	No	5x	5x	5x	5x	5x
16-20	Off	Gaps	No	5x	5x	5x	5x	5x
21-25	On	No-gaps	Yes	5x	5x	5x	5x	5x
26-30	Off	No-gaps	Yes	5x	5x	5x	5x	5x
31-35	On	Gaps	Yes	5x	5x	5x	5x	5x
36-40	Off	Gaps	Yes	5x	5x	5x	5x	5x

Resuming, the Baseline experiment allowed assessing the impact of changing variables on 5 different scenarios of a fixed set of 40 flights. The other stable and fixed variables were:

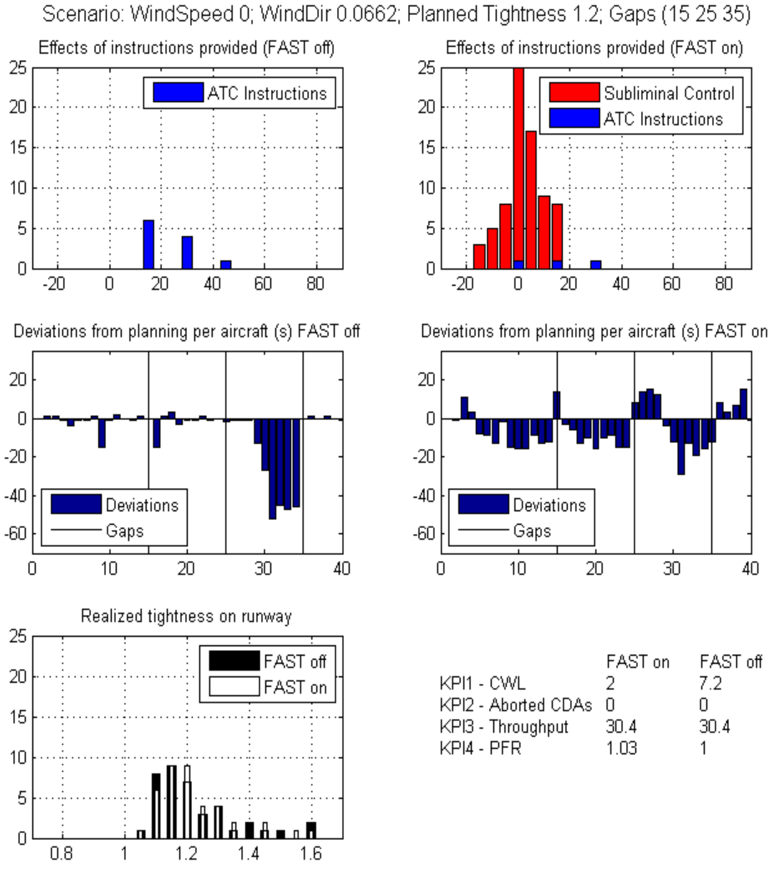
- The planned nominal CDA profile being the same profile for each AC type, apart from calculated instructions.
- The types of aircraft, although representative, were limited in this experiment to 3 different types of aircraft only.
- The aircraft weight was always the nominal reference weight, being default for all flights.

- The wind was limited to standard wind of 10 kts. parallel to the runway, when wind "Yes" was selected, and always the same amount of uncertainty by gust modelling was added.
- The planned and controlled IAF arrival conditions were set in all scenarios with randomised ±30s. accuracy, arriving over the IAF with a uniform randomised distribution and in fixed order.

The additional sensitivity analysis aimed to get a view on those areas that were excluded from more systematic research. The extra scenarios, processed to perform sensitivity analysis, were:

1. An extra scenario to process a sequence of Medium-type aircraft only and to assess increased throughput.
2. A scenario with ±20 degrees cross-wind in order to assess the impact of some varying wind conditions on planning, control and throughput.
3. Scenarios with a calculation loop frequency of 90s. instead of 180s. to assess the impact of higher feed-back loop frequency on the convergence, guidance and planning by subliminal control. The default frequency of 180s. is close to human performance, and the expectation is that a higher frequency feed-back loop would be more successful in correcting deviations.

All together, the Baseline research required to process 200 runs, and the Sensitivity analysis another 240 runs that were processed and analysed. The questions to be answered by analysis, were, how these scenario variations would perform, and next to assess under varying conditions how successful they were to achieve ensured separation, decreased workload and sustainable throughput.



	FAST on	FAST off
KPI1 - CWL	2	7.2
KPI2 - Aborted CDAs	0	0
KPI3 - Throughput	30.4	30.4
KPI4 - PFR	1.03	1

Figure 5. Example dashboard with overview of 2 runs ("FAST on"/"FAST off")

D. Measured and observed Key Performance Indicators (KPIs)

The applicable Key Performance Indicators (KPIs) were related to:

- Measuring (extra) Controller Workload (Cwl) by number of instructions to correct the sequencing by deviating from the common CDA near-idle profile,
- Measuring time differences to assess planning corrections and actual separation,
- Measuring runway throughput per hour, and
- Measuring Peak-Flow-Robustness (PFR) (see above).

These KPIs were assessed for each pair of runs, assessing by default the impact of subliminal control ("FAST on") on successful final descent arrival operations, and comparing this with ("FAST off"), calculating and executing advisories to ATCos only. Figure 5 gives an example for one pair of runs with one flight "Fast-off" and one flight "FAST-on". The first two pictures show number of planning corrections against time-to-win/time-to-lose in seconds; the second two pictures show deviations from planning for each flight in the sequence; and the last picture shows the distribution of realised separations at touch-down for both runs.

This figure represents one pair of runs with given tightness (1.2), and therefore with given demand (31 arr./hour) and by definition with almost identical throughput. The in real-life achievable throughput is determined by those experimental runs that processed the sequence with separation control with acceptable quality to adopt that process in real-life. The more robust and stable the realised separations at touch-down, the more likely that this mode of operations turns out to be acceptable and sustainable.

V. Results and Analysis

A. Results by individual runs

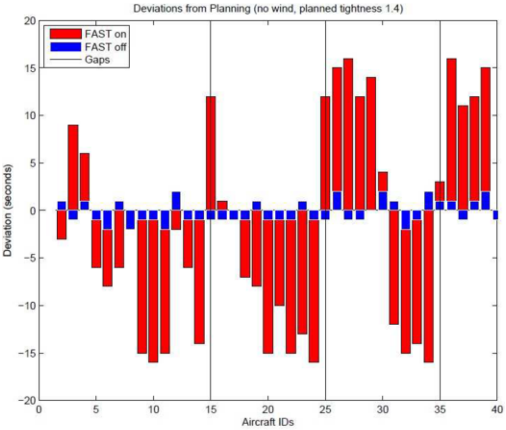


Figure 6. Example of optimising the spread of arrivals benefitting from gaps in the sequence

The graphical results of pairs of runs could show the success of application of subliminal control for some, but not for all, pairs of runs. The beneficial effects of one successful pair of runs (Figure 5) will demonstrate:

- Comparing the number and corrective size of instructions, "FAST on" adds a relative large number of small instructions, causing a decrease in the required number of ATCo instructions. This is the expected positive effect to reduce (extra) workload by flightpath corrective instructions. Whenever possible, subliminal control takes action pro-actively to increase the stability of a sequence of separated flights.
- Looking at the resulting deviations from planning per flight, there is a noticeable difference between activated subliminal control ("FAST on") and "FAST off". In the "FAST off"-case, and without corrective instructions, only "noise" will be visible, when actual performance deviates from predicted performance. Only at a late stage, forced intervention leads to knock-on effects (for flights 29-34 in Figure 5). In the "FAST on" case, however, subliminal control makes active use of available spare capacity to make the arrival flow more robust against separation problems. Small front-loading and delaying instructions help to reduce the chance of disruptive effects. (See for another example with gaps in the sequence in front of ACs 15, 25 and 35, Figure 6.)
- Also in Figure 5, the distribution of actually separations at landing, shows less tightly separated landings for the subliminal assisted arrival flow. This is very beneficial if it helps to reduce the chance that arrivals are removed from the sequence by aborting the descent procedure.

- Finally, the KPIs summary of this example presents no aborted CDAs (which is quite essential), decrease of extra workload by subliminal control, and enhanced Peak Flow Robustness. This last entity indicates a more favourable distribution of arrivals over available time, and essentially this is the same as what is presented by slight improvement of "Realized tightness on runway", Figure 5.

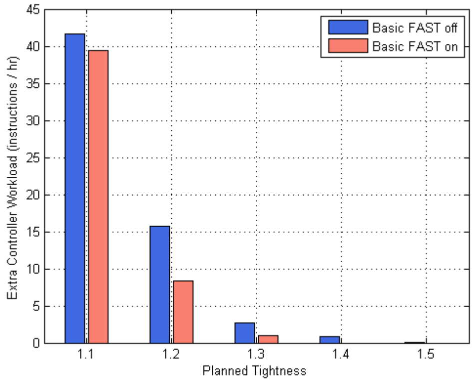


Figure 7. Controller workload, Basic flows, no wind

B. Baseline research

The following figures show KPI results of Baseline research:

1. Results of the basic flows without wind of a sequence of 40 flights for different arrival densities,
2. Figures for the same scenarios without wind, but now including gaps, and
3. Figures for the same scenarios, but now including gaps and including wind.

Figure 7 presents Controller workload (Cwl) for the basic flows. At very high density (tightness 1.1, 33 arr./h), there is anyhow high workload by Controller intervention, and subliminal control was often disabled, and could not be effective any more. Most effectively Cwl decreased by support of subliminal control for tightness 1.2 (31 arr./h) and 1.3 (28 arr./h), but for 1.4 (26 arr./h) and 1.5 (24 arr./h) there was not much to do anymore to safely separate the sequence; the arrival flow was already robust by low density of demand.

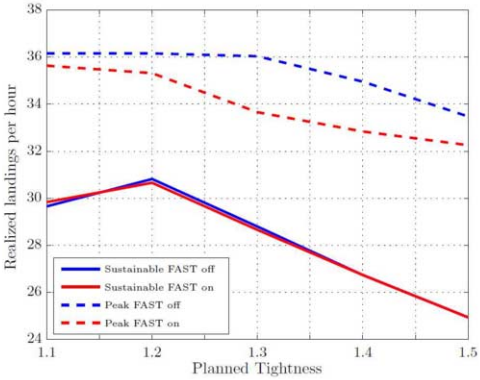


Figure 8. Throughput, Basic flows, no wind

Figure 8 presents throughput for the basic flows:

- Sustainable throughput is equal to demand, in principle, and as long as aborted CDAs will not cause any decrease of throughput. Above 31 arr./hour (tightness 1.2) the number of aborted CDAs is unacceptably high for this nominal scenario.
- Peak density throughput is a more complex variable. FAST is not able to improve traffic distribution for high flow density, and at low density the peak load is expected to be almost equal for "FAST on" and "FAST off".
- Most favourable, subliminal control contributes at tightness 1.3 to keep the peak density low at a more safe and robust level.

Figure 9 presents Peak Flow Robustness for the basic flows. For this most simple case, the result is straightforward. For very high densities, there is no opportunity to improve the robustness since subliminal control is

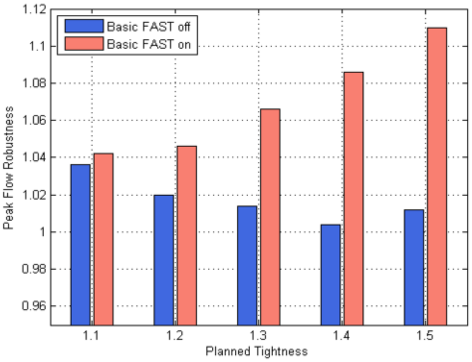


Figure 9. Peak Flow Robustness, Basic flows, no wind

continuously overruled by advices to ATCo (tightness 1.1); for higher tightness (lower flow density) the robustness improves.

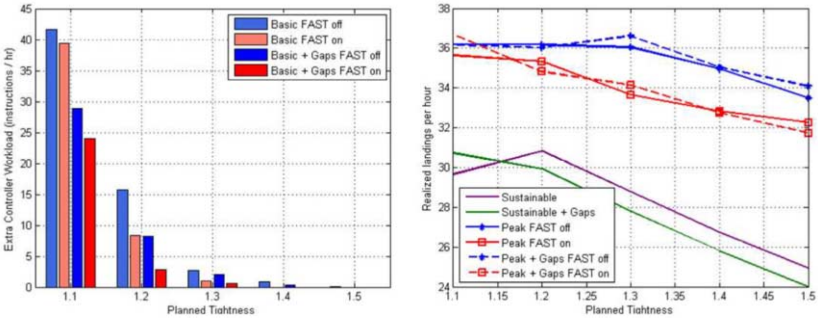


Figure 10. Controller workload (left) and Throughput (right), Basic flows, including gaps, and no wind

Figure 10 (left) presents Controller workload (Cwl) with and without gaps for basic flows. The three gaps of one minute have positive effects on the number of required Controller instructions as well as on the effectiveness of subliminal control for the high density scenarios (tightness 1.1 and 1.2).

Figure 10 (right) presents throughput with and without gaps for basic flows. Gaps are causing a slight decrease of throughput, but offer opportunities to increase the stability of the flow. The positive effect is demonstrated for tightness 1.1 (33 arr./h). The sustainable throughput increases because the number of aborted CDAs decreases. Also, subliminal control benefits from gaps when the observed peak load slightly decreases, suggesting an improved spread of tightly sequenced flights.

Figure 11 presents PFR with and without gaps. Again, the gaps offer always some opportunities to improve the observed PFR. Essentially, PFR values benefit from gaps to increase robustness by "FAST on", except for tightness 1.5 where there is not much to win anymore.

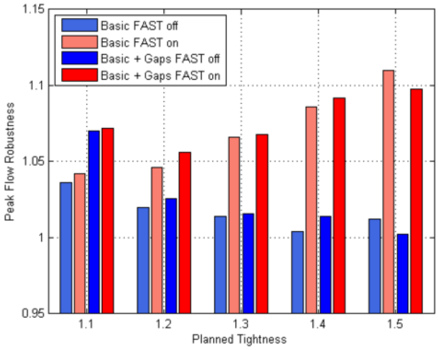


Figure 11. Peak Flow Robustness (PFR), Basic flows, including gaps, and no wind

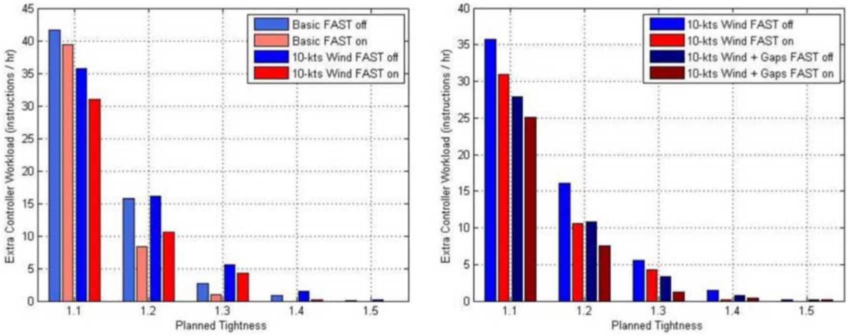


Figure 12. Basic flows, Controller workload, no-wind/wind (left) and Controller workload, wind/wind+gaps (right)

Regarding peak flows, it should be noted that peaks of dense traffic are selected from scenarios with varying levels of flow density. This yields 4 peaks within 40 flights (100%) for traffic tightness 1.1, and 1 peak of 2 flights (5%) for tightness 1.5. The conclusion is that PFR values deserve most confidence if there are several peaks comprising a significant part of the traffic.

Figure 12 presents the effects of wind on workload, processing the Baseline flows. The outcome of all "wind"-results is less evident than results without wind, which is caused very likely by the relative heavy impact of unpredictable effects on corrective measures. This tends to converge to a general conclusion that predictability and quality of information provision is likely to determine the boundary conditions for feasible control on tight sequences of flights. Other constraining conditions may exist as well, but at least, high quality weather prediction data (now-cast information), seems to be indispensable for dense CDA final descent procedures.

The effect of wind on Controller workload is negative, significant more instructions are to be given under a modest wind scenario, including uncertainty by turbulence. The pre-arranged gaps are improving the situation, and "FAST on" helps to reduce the need for instructions. The most acceptable option regarding (extra) workload starts from flow densities of 28 arr./hr (tightness 1.3).

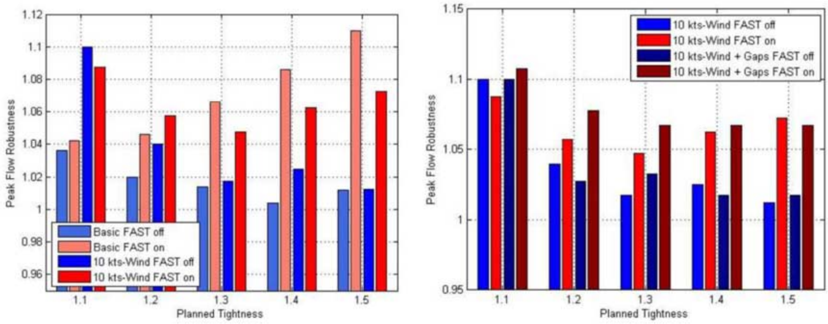


Figure 13 – Basic flows, Peak-Flow Robustness, no-wind/wind (left) and Peak-Flow Robustness, wind/wind+gaps (right)

The next picture of the basic flows, Figure 13, presents the effects of wind on Peak-Flow Robustness (PFR). Positive effects are almost drowned out by noise effects due to wind. Subliminal control measures give some evidence for positive effects for well manageable flow densities (tightness 1.2 and above).

Finally, Figure 14, shows a histogram of CDA aborted flights for several runs. As can be seen, there are few CDA-aborted flights under no-wind conditions, whilst this number is unacceptably high for all wind scenarios. In this context, four remarks are to be noticed regarding these CDA-abort cases:

- The process decides to a CDA-abort when ATCo track deviation instructions, moving fixed waypoints 5000m., is not sufficient anymore to maintain separation. In real-life, this may lead to interrupt CDA operations temporarily, and resuming CDA operations later on. This is practised at some airports already today for low density CDA arrival traffic.
- The CDA-abort procedure is activated by detection of separation violation problems. The violation problem comprises often only a few seconds, and the distribution, observed under wind conditions, have few outliers above 15 s. (see Figure 15)

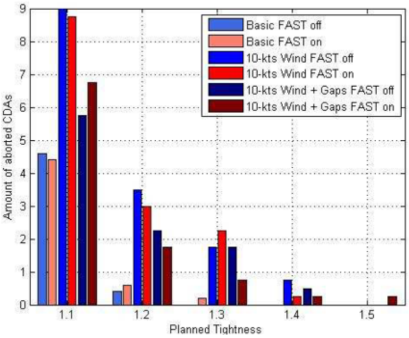


Figure 14. CDA aborted flights for wind/no-wind scenarios

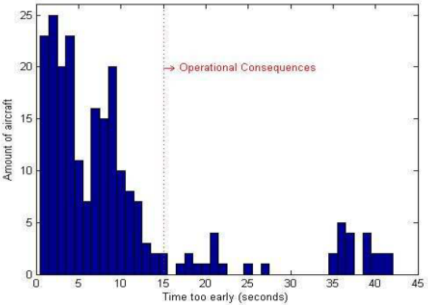


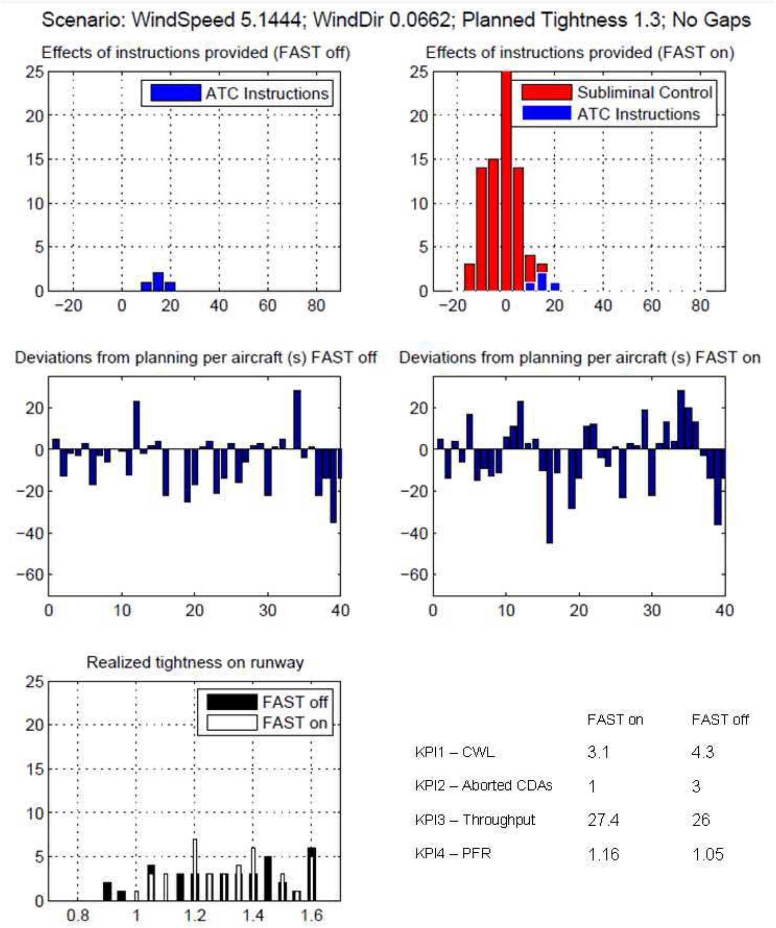
Figure 15. CDA aborted flights for wind scenarios, distribution of separation violations

- An important cause of separation problems is identified by problems with trajectory prediction, causing a difference between planned and realised trajectories. In the experiment, this is caused by a table-driven interpolation process, in real-life this maybe caused by differences between observed weather conditions and experienced weather conditions, and/or by deficiencies in quality of ground-based trajectory prediction models. (See wind effects, Figure 16, second row graphs.) There is no evidence that real-life tolerances are more or less significant than the experienced tolerances under the modelled wind conditions. Anyhow, information on wind conditions has a significant impact on the quality of CDA advisories and subliminal control measures, and high quality predictability is therefore clearly key to success.
- All measures to ensure separation were processed in the model for arrival planning and flight execution by applying time-based separation instead of distance-based separation. This is in compliance with expected future standards of operation. [See for example SESAR Ref. 2 and 3.] However, it should be noted that throughput under these operational procedures is suffering less reduction of capacity by head-wind conditions than distance-based operations. Nevertheless, the throughput decreases, but this is caused by prediction problems and aborted CDAs (See Figure 14 and Figure 15). The measured sustainable throughput varies for tightness 1.3 for example from 28 arr./hour for the no-wind conditions to 26 arr./hour for 10 kts. head-wind.

Stemming from the observed PFR-results and CDA-abort numbers, the question arises, how large the deviations are that have to be corrected and how unpredictable deviations relate to the impact of small subliminal control actions? How effective is the planning information and does it allow controlling flow stability under weather uncertainty caused by ordinary wind conditions?

Firstly, looking at the results above, the size of observed deviations is evidently wind-dependent and also the lack of ability to correct is wind-dependent. This leads to a conclusion that the model has to be improved yet for its main feed-back loop, calculating corrections for executed deviations and executing these corrections.

Looking in more detail to experienced wind conditions, the analysis above showed some of the characteristics of operations with wind. Figure 15 showed the distribution of observed infringements of separations measured over 4.000 flights processed under head-wind conditions. Another indication for the relationship between observed track deviations and calculated and instructed subliminal control measures is given by Figure 16, comparing a "Fast-off"/"Fast-on" run for "Wind-on", "No-Gaps" conditions. With "Fast-off" a few ATC instructions are causing deviations from planning, all other deviations are caused by wind, with "Fast-on" the deviations are composed from wind and subliminal control measures. The actually processed sequences of flights suggest that under the present modelled conditions the deviations and the corrections are similar in size and frequency, whilst subliminal control is still able to have some success in realised tightness on the runway. Nevertheless, this result suggests also that improvement is still possible.



	FAST on	FAST off
KPI1 – CWL	3.1	4.3
KPI2 – Aborted CDAs	1	3
KPI3 – Throughput	27.4	26
KPI4 – PFR	1.16	1.05

Figure 16 - Example dashboard with overview of 2 runs ("FAST on"/"FAST off"), wind on, tightness 1.3 (28 arr./hour)

C. Sensitivity analysis

Three cases were investigated briefly to get a better feeling of the weak and strong points of the concept for subliminal control on final descent operations:

- Processing a scenario without Heavies will assess throughput under simplified conditions,
- Processing cross-wind scenarios will assess some variations on wind sensitivity, and
- Processing subliminal control with double update frequency will assess the impact of feed-back accuracy on measured performance levels, expecting enhanced control on separation planning.

The first issue, to process a scenario without Heavies, gave simple evidence. The throughput of a flow of 40 Mediums increases from the measured mixed-scenario throughput of 28 arr./h for a planned tightness of 1.3, to a throughput of 30 arr./h for the same planned flow density.

The second scenario to process cross-wind scenarios, gave evidence as well. In-flight control procedures are influenced by applicable head-wind or tail-wind components. The (subliminal) control measures are subject to reduced or extended periods of control over the same track distance, and therefore the effectiveness of control measures is expected to increase by head-wind and to decrease by tail-wind. This is confirmed by experimental results.

The third one to evaluate, a double update frequency scenario, comprises to process a scenario which performs a re-planning every 90s., instead of every 180s. Evaluating the results of processing this scenario was the most complex and demanding one. The increase of accuracy by higher frequency competes with loss of accuracy due to limitations of predictability. The results showed some improvements by the higher update rate, but this was not convincing. It yields a conclusion that the modelling, in particular trajectory prediction, has to be refined in order to be in better balance with the update rate. Also, the allocation of waypoints could be improved possibly by enabling maximum correction potential. Finally, it should be noted that wind impact and subliminal control corrections are similar in size, and in order to be effective, this impose high requirements on the correctness of prediction and calculated corrections. Also, this gives way to further improvements.

D. Impact of Subliminal Control on Capacity and Throughput

Four KPIs were analysed, each having their impact on runway capacity whilst operating CDAs:

- **Controller workload**: Workload is correlated with traffic density in the first place. The tighter the sequence, the more extra workload is needed to solve separation problems.
- **Number of aborted CDAs**: The number of aborted CDAs was artificially high in the experiment due to simplified decision making, but the number of aborted CDAs decreased systematically due to increased sequencing stability activities with "FAST-on".
- **Throughput**: During experimental runs, the measured throughput received direct benefits only by reduction of the number of aborted CDAs; in other respects throughput was equal to demand and thus input to each scenario.
- **Peak Flow Robustness (PFR)**: Experimental runs could demonstrate systematic improvement in performance by measuring PFR. This increase of PFR value indicates that traffic is distributed in the sequence in such a way that the risks of hazards and sequence disruption will decrease by application of subliminal control.

The challenge of operating CDAs is to maintain high density throughput in a sustainable way to cope with traffic demand. Therefore, the central question of this research can be formulated as:

> ***"Is support of subliminal control on continuous descent operations, in addition to conventional air traffic control, improving the sustainability of high density throughput?"***

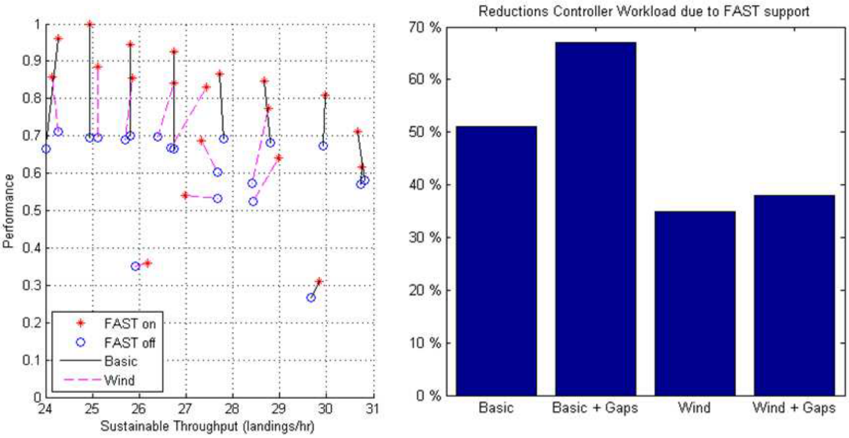


Figure 17 - Differences in performance with and without subliminal control, summarised over all scenarios(left) and the reduction in (extra) controller workload due to subliminal control(right)

To answer this question, the results of the experiment are combined in two figures, summarising experimental results and their outcome (see also Ref. 5):

- Figure 17 (left) presents relative performance improvements for three KPIs against applicable throughput for all scenarios. "FAST-on" is systematically performing better, whilst "No-wind" has a higher score than scenarios with wind. The conclusion is that subliminal control improves the performance of final descent CDAs which may support a higher level of sustainable throughput.
- Figure 17 (right) presents the percentage of saved (extra) workload due to subliminal control, and "extra" means in this context extra to maintain the stability of the sequence.
- Figure 18 presents the realised separations at touch-down by a histogram that counts the relative separation of each landed pair, which takes into account differences in relative landing intervals imposed by the arrival flow density (traffic demand). The picture demonstrates that "FAST-on" is able to support enhanced control over dense arrival flows by realising separations close to the average separation. And, as a consequence, enhanced control over realised separations at touch-down will support the justification of decreased landing intervals.

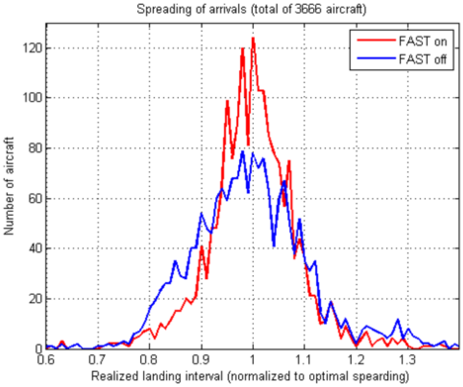


Figure 18. Distribution of separations at touch-down, including (FAST-on) and excluding (FAST-off) subliminal control

VI. Conclusions and Recommendations

The concept to increase stability of final descent CDA arrival operations by subliminal control has definitely some very attractive features, and application of the concept will support the justification of decreased landing intervals. The achievable benefits are described by the concept and partly demonstrated and validated by the model-based experiment:

- Control by lateral vectoring is easier and more intuitive to perform by ATM during descent, whilst control on the vertical profile is left to the aircraft.
- Subliminal control instructions are refined extensions of control instructions given by nature by ATCos, and whenever the ATCo gives an instruction, this will overrule subliminal control in an intuitively understandable way.
- The implementation of subliminal control can be done seamless and gradually, starting from low-frequent manual advisories. Another option is for example to uplink subliminal instructions automatically, whilst pilots may accept commands manually. This will make the introduction more acceptable and will allow mitigating potential hazards.
- The operational concept can be brought to operation, operating independent of traffic mixes and airborne equipment available, and operating under full responsibility of the ANSP.
- The benefits of implementation of subliminal control are increased stability of CDA arrival queues, whilst saving workload and preserving highest possible throughput.

The results and analysis of the experiment show that subliminal control works optimal under moderate conditions with not extreme high-density arrival flows and whenever planning and prediction are not too much challenged by unpredictable deviations, caused in particular by wind. Given the number of observed CDA abort cases, the need to enforce the stability of the final descent arrival flow seems evident, but in most evaluated runs it was demonstrated that subliminal control could provide the means to improve flow stability. Improvement was reached by taking pro-active measures to slightly advance or delay arrivals. It can be concluded from the experiment that subliminal control is able:

- To support **ensured separation** by increased robustness of the CDA final descent arrival flow,
- To decrease the **ATCo workload** required to maintain stability and to ensure separation, and
- That higher **sustainable throughput** is achievable when using support by subliminal control, by enhanced control on separation.

Given the present results it can be recommended to continue research on this very critical part of an operational concept to operate CDAs of dense arrival flows at hub airports. Improvement of stability of these flows in final descent is likely to become ultimately the most critical issue of these operations. Two concrete proposals for continuing this research could be:

- The model developed in MATLAB/Simulink operates fairly well under nominal conditions. The modelling of aircraft behaviour and control measures works fairly well as well. What can be improved, is the trajectory prediction function and the relationship between predicted wind and experienced wind. Also, enhanced determination of arrival target values may help to be more effective in small-scale corrective decision-making, and this will improve the quality of subliminal control measures as well as the advisories for Controller interventions.
- The model is quite detailed in modelling flight dynamics and experienced wind conditions. The present research has accomplished procedures to correct for deviations and to increase flow stability. It would be worth to validate the complete model on real-life applicability. This could be executed in a passive mode by recording and assessing real-life CDA operations under low density conditions and to compare CDA control measures with the present level of modelling.

To continue research in this way could be the most effective way to bring the concept to operation. It helps that the concept is appropriate to be implemented in a step-wise and incremental way. As soon as the algorithm generates well applicable advisories, the tool can be brought to operation by generating appropriately dimensioned advisories with a manageable update frequency, taking into account Controller workload. Whenever such a semi-automatic process provides the benefits as expected, more automation can be added.

Abbreviations

AC	- Aircraft
ADS-B	- Automatic Dependent Surveillance Broadcast
AMAAI	- Aircraft Models for the Analysis of ADS-B based In-trail following
ANSP	- Aeronautical Service Provider
ASAS	- Airborne Separation Assistance System
ATCo	- Air Traffic Controller
ATM	- Air Traffic Management
CDA	- Continuous Descent Approach
Cwl	- Controller workload
ETA	- Estimated Time of Arrival
FAST	- Final Approach Spacing Tool
IAF	- Initial Approach Fix
ILS	- Instrument Landing System
JAR-AWO	- Joint Aviation Requirements-All Weather Operations
FAF	- Final Approach Fix
KPA	- Key Performance Area
KPI	- Key Performance Indicators
NLR	- National Aerospace Laboratory of the Netherlands (NLR)
NM	- Nautical Mile
PFR	- Peak Flow Robustness
R/T	- Radio / Telephony
Rwy	- Runway
SESAR	- Single European Sky ATM Research and Development Programme
TECS	- Total Energy Control System
TUD	- Technical University of Delft

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Adaptive Automation Support for Time-Based Operations in ATC

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Future Air Traffic Control Officers (ATCOs) will have to monitor closely whether aircraft are compliant with given time constraints. This time-based guidance will be a new task compared to current operations where the timely precise adherence to flight plans is not a high priority. This additional requirement will produce new task loads, especially in approach control, where the main task of the ATCOs is to implement conflict-free optimized landing sequences with aircraft of different performance characteristics and wake vortex classes. It is anticipated that from medium traffic load on, the task load will increase to a level that ATCOs couldn't cope without the use of decision support tools (DST). They may even be forced to delegate the time-constraint monitoring completely to the automation. In the DLR project Aviator II a usability study was conducted to evaluate an advanced arrival management system that behaved adaptive to the workload apperception of ATCOs. In three sessions a SME (subject matter expert) worked on a medium traffic scenario with the support of this adaptive DST. After a training and a test run, the SME filled out a usability questionnaire with a focus on the adaptive functioning. The paper describes the concept and implementation of the adaptive DST and summarizes first results regarding the potential benefits of such an innovative feature in a controller working position.

Nomenclature

4D-CARMA = Four Dimensional Cooperative Arrival Manager
AA = Adaptive Automation
A/C = Aircraft
ACC = Area Control Center
AMAN = Arrival Manager
ANSP = Air Navigation Service Provider
ATM = Air Traffic Management
ATC = Air Traffic Control
ATCO = Air Traffic Control Officer
CTA = Controlled Time of Arrival
DFS = Deutsche Flugsicherung GmbH
DLR = Deutsches Zentrum für Luft- und Raumfahrt
DST = Decision Support Tool

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HF = Human Factors
HMI = Human Machine Interface
IAF = Initial Approach Fix
ISA = Instantaneous Self Assessment
OPTIMAL = Optimised Procedures and Techniques for the Improvement of Approach and Landing
R/T = Radio Telephony
RTA = Required Time of Arrival
SDD = Situation Data Display
SESAR = Single European Sky ATM Research Programme
SME = Subject Matter Experts
TMA = Terminal Manoeuvering Area
TP = Trajectory Predictor

I. Introduction

A. State of the Art Approach Controller Support

An overall and precise planning of a flight from the gate of departure to the gate of arrival is a main element in all future ATM concepts like SESAR[1] or NextGen[2]. In such a planning process a flight will get time constraints for all its phases, which will have to be implemented in a smooth and efficient way. The general use of DSTs in the whole ATM-System will be essential to meet these requirements of time-based operations. The work reported here is addressing an add-on to the DLR Arrival Manager (AMAN) prototype 4D-CARMA (4 Dimensional Cooperative Arrival Manager)[3,] that implements an adaptive automation basic approach.

In arrival management, the runway capacity is the bottleneck that frequently produces an overcrowding terminal maneuvering area (TMA). AMANs are a means to avoid overcrowded TMA by controlling the flow en-route before reaching the initial approach fixes (IAF), where aircraft (A/C) are handed over from Area Control Centers (ACC) to TMA. Although there is a long tradition in developing DSTs for approach controllers, only few of them are operational at big European hub airports[4]. The poor deployment of AMAN is due to the fact that there is no easy way to benefit from an advanced system producing optimized sequences and according guidance advisories when the other sectors around are not planning with strict time constraints. Strictly time-based ATM concepts propagate a timely adjustment of A/C separation at the IAF by displaying to the sector controllers at an early stage time-to-lose, time-to-gain advisories.

TMA controllers, with their roles as pickup and feeder, perform the task of implementing the sequence of incoming flight on the centerline and final segments before touchdown. However, as no operational AMAN in Europe is producing timely precise guidance advisories for the TMA controllers, TMA controllers are still working without or with restricted AMAN assistance nowadays. It can be assumed that they would benefit from a DST that produces timely precise guidance advisories, like 4D-CARMA.

B. Statement of Problem

The implementation of the concept of time-based operations will be accompanied by an increased automation of ATCO's future working position. As consequence the controller task will be changing from active traffic guidance to more passive monitoring of automation, with occasional tactical decision making in unexpected and unforeseen situations[5]. This elevated level of automation is supposed to reduce the controller's workload significantly while ensuring safety. However, an increase of the level of automation may also create negative effects, like loss of situation awareness when clearances are no longer based on the controller's mental picture[6]. Another effect may be reduced safety and productivity due to operators who are mainly busy in monitoring the automation. One negative effect that arose under scrutiny is that delegation of tasks to automation systems can also cause a degradation of operating skills[7].

ATCOs current skills and competencies will still be required for future ATM systems, as they will have to maintain control during exceptional situations like system breakdowns or emergencies without being able to rely on support from automated systems[8]. This circumstance evokes new ways of how to design automation systems. One possible approach refers to the concept of adaptive automation (AA). Unlike traditional concepts of automation which are rather static, adaptive automation dynamically adjusts its method of operation according to the situational demands and to the operators` states and needs.

The issue of AA in ATM is still more of a research framework (see[9]). Although there is literature on AA design in general[10], the concept has still not found its way into operational use in ATM. However, our approach points out a possible design of an adaptive DST that is able to support air traffic controllers in time-based operations. It is able to visualize timely precise guidance advisories and separation aids. Controllers' workload is balanced by providing this special timing assistance during high workload. Figure 1 is a schematic display of workload attenuation. The workload peaks are shown in red and their attenuation as a green curve. Attenuation is carried out by the automation algorithm when workload is perceived as high.

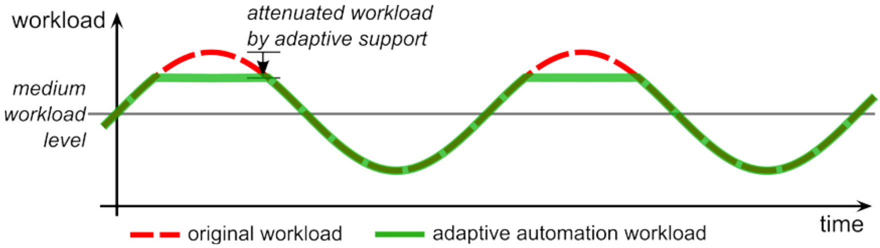


Figure 1. Attenuated Workload under Workload Peaks.

II. Research Question

A. ATC Core Tasks of Approach Controllers

We briefly outline the core tasks of approach controllers and the possible effects of adaptive automation on the future role of approach controllers. In conjunction to that, the concept of time-based operations and 4D-CARMA as an important support tool will be briefly described. Finally, we will introduce our new adaptive automation framework for an ATM application in the approach control.

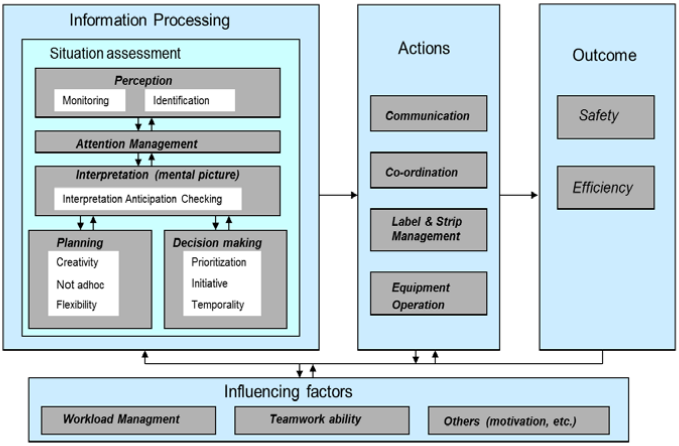


Figure 2. Cognitive and Operational Core Tasks of an ATCO.

When considering core tasks of approach controllers (see Figure 2[11]), a general distinction between cognitive and operational core tasks could be useful:

The information processing encompassing the perception of the traffic situation, and its interpretation to build-up and maintain a mental picture of the actual traffic situation, serves in turn as a basis for decision and planning processes in routine and conflict situations. The mental model enables the ATCO to anticipate future traffic situations and plan the traffic strategically[12]. Another cognitive core task regards the decision making when the controller has to intervene into the current air traffic situation. Based upon existing operational rules and regularities as well as on situation-dependent procedures the ATCO has to issue different kinds of clearances.

In comparison to cognitive tasks, the operational core tasks of approach controllers relate to service tasks, e.g. planning of flight sequences, allocation of runways, and assurance of vertical and horizontal separation of A/C.

When outlining the operational tasks of a TMA controller, the different related working positions including the pickup, the feeder and the departure controller have to be taken into account, although the latter working position will not be considered in this paper. The pickup assumes the traffic from the sector border at the initial approach fix (IAF) and establishes their landing sequence respecting the separation rules in TMA environments before transferring them to the feeder. The pickup informs the crew about the intended approach procedure as well as the planned runway for landing. The feeder assumes the traffic handed over by the pickup and guides the A/C into the final approach. The feeder implements the final approach sequence especially optimizing the separation with respect to A/C wake vortex classes.

B. Automation for Core Tasks in Time-Based Operation

The actual method of operation of approach controllers shows their work under the following premises: the operator giving clearances to the controlled A/C, determines the trajectory profile and thereby knows how the profile is planned. Automated conformance monitoring is not possible, separation rules and calculation are (still) distance-based.

In contrast to that, time and trajectory based planning will significantly influence the method of operation in many ways:

- not all trajectories will be planned by the controller, timely precise implementation will become a constraint to be considered,
- automatic conformance monitoring will be possible and appropriate alarms will be integrated into the DSTs,
- times over waypoints calculated with the trajectory will be propagated to other ATC stakeholders and thereby control other processes,
- A/C with negotiated trajectories have to be managed together with A/C that have still to be guided by clearances over R/T.

Due to this increase of complexity in controller tasks SESAR emphasizes augmented automation, i.e. the deployment of highly sophisticated DSTs. The ANSPs, developers of advanced DSTs and HF experts need to consider problems arising with the strong execution of automated systems.

For an AMAN strong execution may mean: all trajectories are planned and deconflicted on ground, every possible advisory for a controller command is shown timely precise on the display. The ATCOs may feel as a robot reading commands from the display and getting out of the loop. The timely planning is not the intuitive method of operation for controllers; they usually prefer distance-based method of operation. So the typical problems connected to automation of controller tasks are likely to occur:

- workload increase by time-based guidance as not people friendly method of operation,
- workload increase by uncertainties about A/C trajectory profiles not controlled by the ATCO,
- frustration by feeling patronized,
- loss of skills,
- friction loss by different strategies of planning and guidance of DST and ATCO.

That is why investigating new adaptive automation frameworks for air traffic control can become a challenging research issue of the future. They aim at avoiding the addressed problems by:

- adapting the level of automation support to the controllers' workload,
- counteracting loss of skills by reducing support functions in times of medium or low workload.

C. Related Work

Currently there are barely research findings concerning the effectiveness and usability of AA in safety critical environments as for instance in the area of air traffic control. However, Kaber and his research group[13] carried out investigations based on simulations of safety-critical-systems. The task performance on a secondary task (monitoring a gauge on a display) was used as a workload indicator that triggered the AA. The automated assistance in terms of AA provided different conditions which assisted the subjects on a particular stage of information processing. In the information acquisition condition, for instance, the automation actually tracked an aircraft. In the decision making condition clearance advisory aids were offered to the subject. Hereby it was shown that the effectiveness of AA depends on the information processing stage of human-machine-system. Kaber concluded, that AA is well suited to the information processing stage of information acquisition and action implementation, which means it seems to be more useful for lower sensory and psychomotoric functions. Whereas the AA for decision aid may induce even more cognitive processing of multitask information, for example prioritizing aircraft for clearances. AA induced cognitive conflicts may be related to ineffective implementation of the AA, i.e. AA is highly dependent on the trigger criterion which is set in order to allocate AA to the subject. AA therefore needs to be investigated regarding its timing and output-complexity, especially if it runs the risk of producing a "cognitive overhead" rather than improving the performance of the overall system, and in particular, of the operator. It is therefore also necessary to consider the authority of the ATCO as the actor-in-command who decides whether to accept or reject the (offered) AA, especially when the point of time and the level of assistance is viewed as inappropriate by the ATCO.

Another study of Sauer et al.[14] examined the effectiveness of different forms of adaptive and adaptable automation under low- and high-stress conditions, in the form of different levels of noise. Three types of variable automation (adaptive event-based, adaptive performance-based and adaptable serving as a control condition) were compared empirically. After training session, participants were tested during a 4h session under noise exposure and quiet conditions. The results for performance suggested no clear benefits of one automation control mode over the two others. However, it emerged that participants under adaptable automation adopted a more active system management strategy and reported higher levels of self-confidence than in the two adaptive control modes. Furthermore, the results showed higher levels of perceived workload, fatigue and anxiety for performance-based adaptive automation control than the other two modes.

D. Aviator II Adaptive Automation Research Prototype

The DLR AMAN research prototype 4D-CARMA is compliant to the SESAR requirements. It comprises an engine that is calculating trajectories with respect to the landing time on ground. This is a prerequisite to generate guidance advisories at all approach phases and run deconflicting algorithms. 4D-CARMA already features support functions, as timelines, the display of advisories with precise timing, and additional visual aids for spacing on the final approach segment[15]. The controller-task of the feeder can e.g. be supported by using an extra mileage-metering scale or the display of target projections on the centerline[16]. For Aviator II 4D-CARMA was refined by utilizing the design philosophy of adaptive automation, where specific support functions will be switched on or off incrementally, as a function of the current ATCO's workload[17]. It is hypothesized that this adaptive automation attenuates workload peaks.

From adaptive automation philosophy we derived the following components to be part of every adaptive DST:

- determination of workload indicators,
- assessment of workload,
- support level layout algorithm,
- adaptive human-automation interface.

4D-CARMA is a modular system, where every function is encapsulated in a distinct module. For use in Aviator II 4D-CARMA was extended by a so-called AdaptiveSupport module that implements the main new components mentioned above. Input by the ATCOs is interpreted for workload assessment and the adaptive support level is determined and launched by the system to influence the layout of the HMI.

The adaptive support is implemented for two HMI features that are switched on and off on the display according to the current support level. Timely precise landing of A/C is a special challenge for the feeder controllers. They have to take into account the separation minima according to the wake vortex classes of the A/C in the planned sequence together with the CTA at the runway threshold. So we decided to restrict our first AA prototype to this role in the approach controller working position. The implementation of the two features in Aviator II is described as follows:

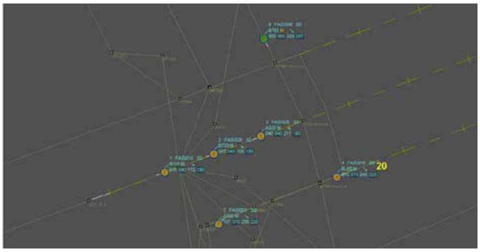
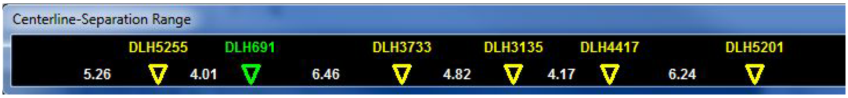


Figure 3. Countdown Display for Timely Turn-to-base Command.

A countdown *cd* (depicted in Figure 3 as a yellow 20) at the label of an aircraft is shown when it is planned to turn to base in *cd* seconds. This countdown starts at 30 seconds before the turn to base manoeuvre and supports the controller to give timely precise turn commands.

A mileage-metering scale (see Figure 4) showing the actual distance between aircraft on the centerline in nautical miles, aircraft colour encoding depicts the wake vortex class: yellow for *medium* and green for *heavy.* As controllers are used to implement the separation in nautical miles instead of seconds the mileage delivers augmented information to that displayed in the timeline. The controller is supported when guaranteeing separation on the centerline.


Centerline-Separation Range

DLH5255 DLH691 DLH3733 DLH3135 DLH4417 DLH5201

5.26 ▽ 4.01 ▽ 6.46 ▽ 4.82 ▽ 4.17 ▽ 6.24 ▽

Figure 4. Mileage-Metering Scale Display.

We expect that experts will assess this adaptive function of 4D-CARMA to be a considerable method for controller workload attenuation. The outlook section contains a discussion about the research questions following the experiments.

III. Method

A. Experimental Setup

The following section describes the experimental setup that was used for the preliminary enquiry processed in May 2012.

As depicted in Figure 5, the test person in the role of the feeder sits in front of five displays with the situation data display as the main window in front. On the left the electronic flight strip bay is located. On the right the 4D-CARMA generated support functions mileage and timeline are shown. On the outmost right position the ISA HMI is located where the test person has to input her/his self-assessed workload. The additional head-up display of timelines with controlled times of arrivals (CTAs) at the IAFs merely serves as an indication of the future traffic entering the TMA.

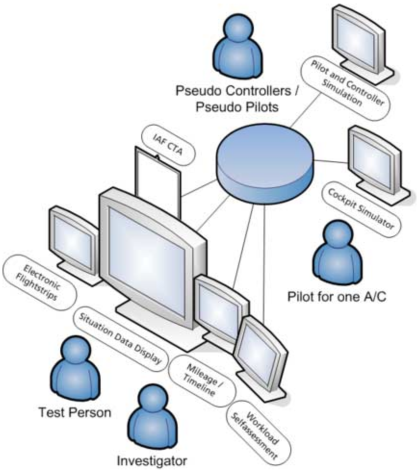


Figure 5. Experimental Setup.

Pseudo controllers take up ACC and pick-up positions. They guide the traffic until it is transferred to the feeder. All A/C are simulated by pseudo pilots except one that is simulated by a fully equipped simulation cockpit operated by an extra pilot.

Table 1. States of Support Displays.

Actual state / Action	Mileage	Countdown
green	-	-
red	+	+
green, 1x yellow	-	-
green, 2x yellow	+	-
red, 2x yellow	+	-
red, 1x yellow	+	+

As stated before, the support level is determined by the support level layout algorithm, which is based on the instantaneous self-assessment (ISA) of the ATCOs' workload. The ISA human-machine interface is realized analog to traffic lights (see Figure 6). The user is recurrently asked by the experiment leader to estimate her or his workload as high, medium, or low and click on the corresponding colour button. Depending on the human input all support functions are switched on, all support functions are switched off or only the mileage metering scale is active (see Table 1). The bottom lines are indicating the status of all support functions that are on duty or not during a scenario.

Figure 6 shows the self-assessment workload HMI indicating active mileage information and inactive countdown displays. Just before turning a feature on or off the concerning entry is highlighted by an orange coloured frame around it.

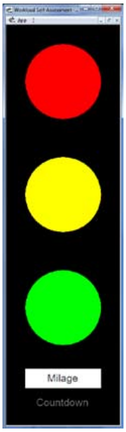


Figure 6. Workload Self-Assessment Display.

B. Scenarios

Basis for the scenario setup are real flight plan and radar data from a high traffic period of two hours at the Frankfurt airport in Germany. This should be a special challenge for approach controllers as it simulates the TMA of a big European hub. The scenario contains a mix of aircraft of heavy and medium weight class and one light, planned to land in staggered mode on the two parallel runways 25R and 25L, which have to be operated dependently.

C. Test Persons

Three test persons, all active approach controllers from DFS, the German ANSP, had to operate in the role of a feeder controller. They controlled the flights from the downwind segments to the final approach fixes short before the threshold. Controllers with long time experience and those who just started work two years ago were involved in the experiments.

Figure 7. Test Person, Investigator during Simulation Run.

D. Simulation Runs

In a first briefing the controllers were instructed how to use the simulator and the ISA HMI. The different systems working together during a trial were described. The investigators presented the operation mode of the AMAN, its support functions and the concept of adaptation.

The simulation runs lasted about one hour. The task load, counted as number of A/C to be handled simultaneously, was permanently rising over time. The trials differed in the setup of the automation that the experts (ATCOs) had to work with. In the first condition, the ATCO operates with a non-adaptive AMAN under varying traffic load. Two specific support functions are continuously active. In the second condition, an adaptive version of the AMAN assists the ATCO. Its support functions were switched on or off incrementally, depending on the results of recurrent system inquiries. In both conditions the ATCO was asked to rate his current workload level by using the ISA. As all controllers were well trained approach controllers the chosen scenario proved not to be dense enough to produce high mental workload in general.

At the end of the simulation runs the ATCOs filled in a questionnaire concerning the usability of the AA prototype they had used (see Table 2). We tried to ask specifically to the AA feature in order to avoid a usability rating for the Situation Data Display or the functionality of the AMAN itself.

Table 2. Items of the questionnaires concerning the usability of the AA prototype (sorted by importance).

No.	Item
1	I found that the milage and countdown function of the adaptive AMAN were well integrated.
2	Data finding was quick and easy.
3	I trusted the support functions outputs.
4	The system support functions were active when I needed them.
5	I did not take advantage of the system support functions at any time.
6	The information was displayed timely to manage the traffic in a safe manner.
7	The dynamic support functions helped me to perform timely precise guidance.
8	I think the behaviour of the adaptive support functions were easy comprehensible
9	I found the adaptive AMAN unnecessarily complex.
10	I needed to learn a lot of things before I could get going with this system
11	It was always clear for me which support function was active.
12	The adaptive system behaved in conformance to my expectations.
13	The visualization or the handling of the dynamic support functions disturbed or confused me.
14	I appreciate fonts, type, dimension, colour and meaning of the graphical and textual information of the support functions.
15	I think that I would like to use the adaptive AMAN frequently.

IV. Results

Figure 8 shows the average approval and importance rankings in the range of 1 to 5 concerning the usability questions. The rankings in the statistics are sorted by importance.

In the end there was no settled view on the question if the test persons liked the adaptive setup during the simulation runs. The following statements are extracted from the usability questionnaire the controllers answered after the second run with active adaptive component.

- Support functions for timely precise guidance are rated to be very useful.
- One controller would even like to have timely speed advisories displayed to get closer to the planned CTA.
- The majority of controllers were always aware which support functions were active but all of them would prefer this information to be integrated into the SDD itself.
- The mileage display should also become part of the SDD.

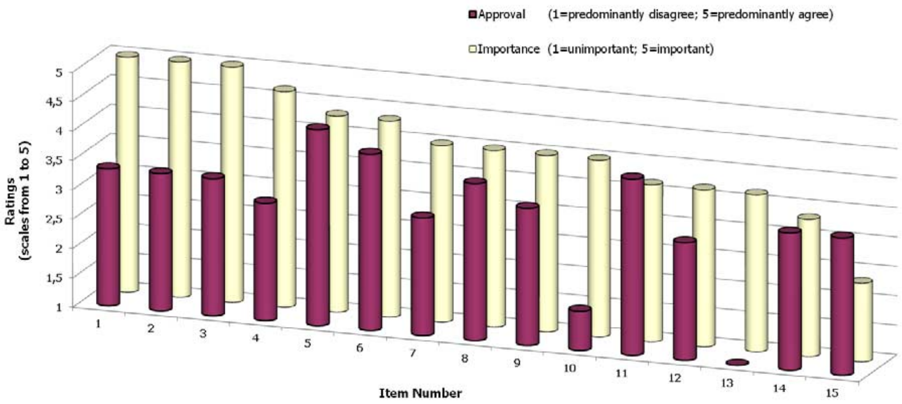


Figure 8. Approval of statements concerning the usability of the adaptive AMAN (sorted by importance); see Table 2 for reference.

- The majority of controllers prefer to switch on or off the support functions by themselves on short notice.
- The user interface of the support functions was easy to learn and did not disturb or confuse them.
- Data finding was rated from predominantly quick and easy to very difficult.
- Similar big differences can be found regarding the complexity in using the adaptive system.
- One controller stated that this mode of operation takes some of his creativity in work.
- Only one controller stated that adaptive system behaviour was not conforming to his expectations.

V. Discussion

Finally we can conclude that the preliminary trials delivered a valuable consideration of the adaptive support system by the SMEs. Several hints for improvement will be integrated in an updated version of the prototype. The trials did not yet deliver a result that can easily be interpreted. It therefore remains an open question whether the implementation of adaptive support functions in an ATM decision support tool could lead to valuable outcomes. However, further research on adaptive automation support for controllers is expected. It would lead to the following main questions to investigate:

- how to identify the appropriate indicators for controller workload (eye tracking data, speech recognition, mode of operation interpretation),
- how to identify the appropriate support functions and their timely deployment,
- how to design a layout for the indicator of active functions.

Nevertheless, the investigation gives indication that support for timely precise guidance is a research issue to work on with. It is indispensable for reaching the so called step 3 of the SESAR goals to implement performance based ATM. Research on controller support systems has to close the gap between the present-day guidance procedures of controllers and those defined in the concept of business trajectory.

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Optimizing Nightly Schiphol Traffic through Time Based Operations

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Under the umbrella of SESARs Atlantic Interoperability initiative to Reduce Emissions II (AIRE II) program, NLR, LVNL and KLM have teamed up to develop a novel arrival management system to improve nightly operations at Amsterdam Airport Schiphol using time-based operations. At night, aircraft often tend to arrive in bunches at the Amsterdam FIR, resulting in sequencing (e.g. vectoring) before TMA entrance. This disturbs their CDA and leads to inefficiency. This is not necessary as modern flight management systems are able to accurately predict their time of arrival. In addition many aircraft are able to share this information with the ground using data link. In this project, the partners have created a ground based planning system that interfaces with most aircraft via data-link. Aircraft down-link their ETA-threshold. These form the basis for an optimized planning that is aimed at preventing bunching in the FIR. To realize the planning, flight crews are requested to use their RTA functionality. The system has been tested in a live-trial for four consecutive nights. Bunching is significantly reduced and the amount of top-of-descent CDAs that can be flown is subsequently increased, resulting in less fuel burn and emissions.

I. Introduction

ONE of the key objectives of the SESAR project is to increase ATM efficiency and thereby reduce emissions. An important step to achieve this ambitious goal is the transition towards time based operations. One of the promises of time-based operations is to increase efficiency of arrival management while lowering fuel cost. Currently most larger airports have some form of Arrival Manager (AMAN) implemented in their system. Although AMAN have advanced over the years, they are often hindered by two factors: the quality of the (ground based) Trajectory Prediction (TP) and the size of their planning horizon. Although TPs have advanced over the years, their predictive quality is often not sufficient enough to be used for time-based operations. In addition, the size of the planning horizon is often limited by sector and FIR boundaries. This limits the implementation of time-based operations as these require accurate estimates of the time of arrival and early planning to be able to efficiently manage the arrival stream.

Under the umbrella of SESARs Atlantic Interoperability initiative to Reduce Emissions II (AIRE II) program, NLR, The Dutch ANSP LVNL and KLM have teamed up to develop a system innovation to improve nightly operations at Amsterdam Airport Schiphol using time-based operations. As Schiphol lies in a densely populated area, strict regulations are in effect concerning noise abatement. This has resulted in the creation (by Dutch law) of so called *night transitions*. These transitions are mandatory

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fixed routes in the Schiphol TMA. As a result of these fixed routes, aircraft need to be sequenced before they enter the TMA as vectoring inside the TMA should be refrained from (except of course for safety reasons).

If multiple aircraft enter the Dutch FIR around the same time, in a so-called *bunch*, they are sequenced (e.g. by vectoring) before they enter the TMA by the area controller. Such sequencing obviously disturbs the Continuous Descent Approach (CDA) of such a flight. The goal of the arrival management system developed within this project is therefore to prevent bunches from occurring and, as such, increasing the percentage of undisturbed Top-Of-Descent (TOD) CDAs that are flown during night-time.

Modern aircraft have Flight Management Computers (FMC) that are able to give reliable predictions of Estimated Times of Arrival (ETA). Because of the mandatory transitions, accurate ETAs for the threshold can be calculated as well. In addition, modern aircraft have Required Time of Arrival (RTA) capabilities that allow aircraft to use a closed-loop process to arrive at a certain point at some predefined time. Although aircraft are equipped with numerous data-link capabilities, most ANSPs are not able to interface efficiently with these aircraft. As a result, only a few (limited) operational trials have been executed that use these potentially promising technologies for time-based operations. The arrival management system developed within this project builds on three pillars:

1. using FMC derived data to generate a planning
2. using data-link for communication to the aircraft to increase the planning horizon
3. using the RTA functionality of the FMC to realize the planning

The system generates an optimal schedule based on the down-linked ETAs. As the generated sequence ensures sufficient separation between the aircraft, it is expected that bunching is significantly reduced if aircraft follow the planning. This should result in an increase of the number of undisturbed TOD CDAs that can be flown.

The ATM community in Europe[1] and the U.S.[2] have adopted the concept of Trajectory Based Operations (TBO) (also called Trajectory Management) and System Wide Information Management (SWIM) as a potential solution to increase ATM efficiency. In SESAR, the *Business Trajectory* is proposed as the basis for such trajectory operations. The business trajectory, a 4D trajectory which expresses the business or mission intentions of the airspace user, including any prevailing constraints, is the SESAR designation of what is referred to as *4D Trajectory* in the Trajectory Based Night Time CDA concept of this project. It is built from, and updated with, the most timely and accurate data available.

Use of RTA functionality has been recognized as an enabler for flight efficiency and capacity[3]. It has been frequently analyzed in an simulated environment (see for example Ref. 4). It was shown that performance is better than when ground issued speed targets are used. Although the amount of flight trials using RTA has been limited, they have shown the potential of the functionality[5,6,7,13].

The potential for data-link in an arrival management setting has been recognized, see Refs. 8 and 9. These papers also emphasize the importance of accurate onboard weather information.

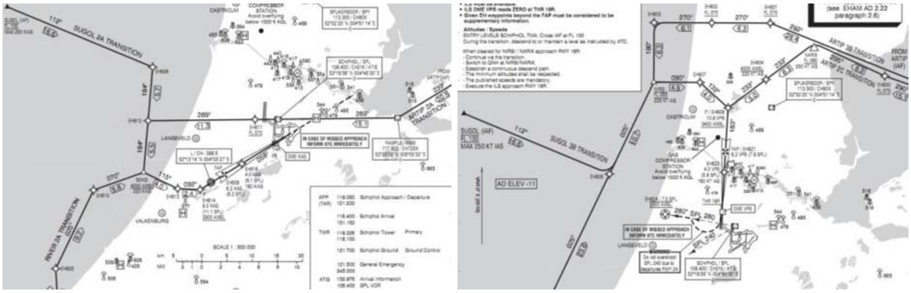


Figure 1. Night instrument approach charts for (a) Runway 06 and (b) Runway 18R

II. Background

A. Night time operations at Schiphol

At Amsterdam Airport Schiphol (AAS), night-time CDAs have been in operation for almost 15 years. Schiphol's CDAs have originally been defined with the purpose to avoid noise annoyance in the greater Schiphol airport area. CDAs have been defined as a lateral path, a so-called *transition,* within the Schiphol TMA. Below FL70 no vectoring is allowed anymore and a continuous descent is flown as often as possible while following the transition (see Figure 1 for the transitions for runways 06 and 18R). The transitions are embedded in Dutch law and are applied very strictly. ATC the Netherlands applies night time CDAs as much as possible during night-time hours from 11:00pm till 06:30am. However, during the early morning hours, typically after 04:00am, long haul traffic arrives at Schiphol Airport in bunches. Often it is not possible for ATC to allow traffic to continue on their pre-planned TOD CDA due to conflicts between inbound aircraft. In these situations ATC reverts to vectoring inbound traffic or uses holding patterns to delay flights for sequencing and to maintain safe separation. However, vectoring creates extra track miles, disturbs the CDA, and causes extra fuel burn and emissions. In Figure 2 examples of vertical profiles are shown for inbound flights landing on runway 06. In the first graph, the flights are not part of a bunch. As can be seen only some (short) level-offs occur leading to small increases of fuel burn. In the second graph the same type of profile is shown in case bunching *does* occur. As can be seen from the figure, this results in long level-offs which translate directly to large amounts of additional fuel burn.

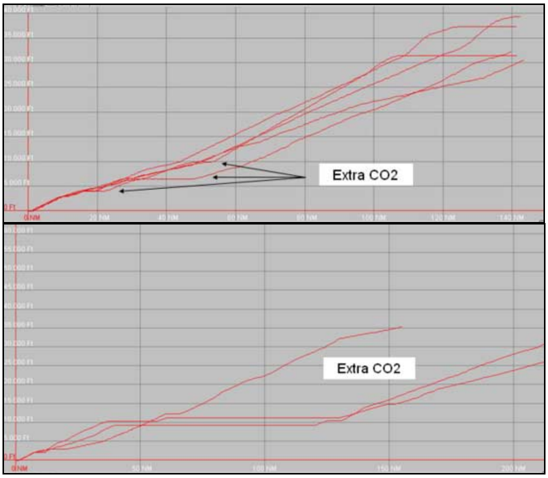


Figure 2. Vertical profiles for (a) flights that are *not* part of a bunch and (b) flights that *are*

B. Schiphol inbound traffic at night-time

Figure 3 shows the number of inbounds during the night at Schiphol Airport for a two month period (May-June 2010). These are split in 15 minute periods. As can be seen from the figure, the largest probability for bunching to occur lies after 4.30am. Between 2.00am and 4.00am, the traffic density is so low that almost no bunching occurs. Outside the holiday period, most aircraft arriving at night are heavies. Figure 4a shows an overview of the aircraft types involved in the night operation.

On average, almost 60% of the nightly inbound flights are KLM flights (Figure 4b). Transavia is part of KLM. The next largest other airline is Delta Airlines. Together these three account for more than 75% of the inbound flights.

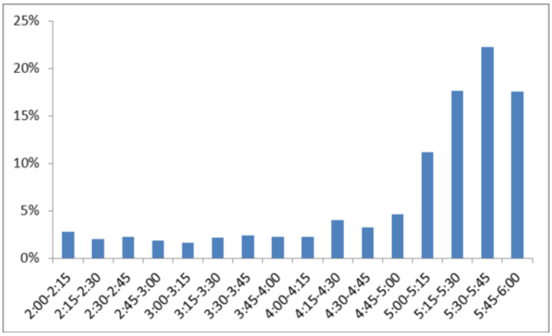


Figure 3. Traffic density during night time

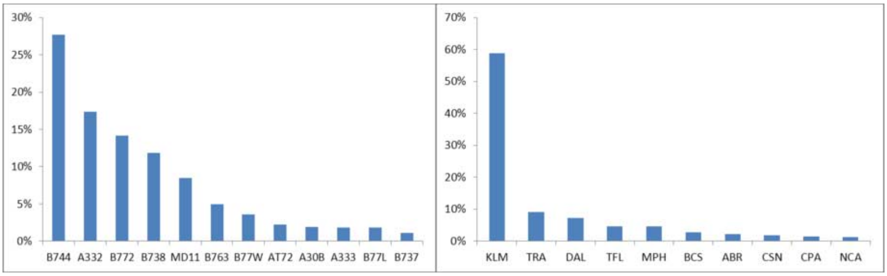


Figure 4. Airlines (a) and aircraft types (b) involved in Schiphol nightly operations. Items accounting for less than 1% are omitted.

C. Goal of the AIRE initiative and cooperation

In SESARs AIRE initiative one of the enablers for CO_2 reduction is *cooperation*. This cooperation is combined with the implementation of new concepts that build on *existing technology*. By cooperation between different stakeholders the project team aims to maximize the benefits from CDAs by enabling as many participating inbound aircraft as possible within the time-frame to fly an undisturbed CDA via the published transitions. An optimal CDA needs to be initiated from TOD and should be flown untouched. In the Netherlands, TOD lies outside the Dutch FIR. In this light, coordination with upstream sectors is vital for the success of the project. Therefore *Maastricht Upper Area Control* (MUAC) and *National Air Traffic Services* (NATS) provided assistance to the team wherever possible. As a result the planning system is able to plan aircraft well before TOD. To further increase airline participation, *Delta Airlines* provided assistance wherever possible to be able to interface with their aircraft as well. To maximize the number of participating aircraft, all other airlines arriving in the nightly time-frame were contacted and received information about the trial. These flights were coordinated using R/T by MUAC and NATS. As a result, almost 100% of the nightly traffic participated in the trial.

The challenge in this project is to increase the percentage of undisturbed CDAs of these flights during night time operations at Schiphol airport. The goal is to maximize fuel savings and emission reductions.

III. The planning system

The task for the planning system is to collect aircraft derived data, generate a planning based on this data, and to share it with the flight crews and ATC. The planning system consists of a ground based platform which has a data-link to the Operations Control Center (OCC) of the participating airlines. As most airlines are able to communicate with their aircraft using ACARS, the planning system is able to directly send and receive data to and from the aircraft. This section describes the various parts of the planning system and their interaction.

A. System overview

The planning system works by collecting reliable ETAs at the runway threshold of all inbound aircraft. These are then used as the basis for a planning algorithm that generates a schedule with Planned Times of Arrival (PTA) such that bunches are prevented. We use the term PTA instead of CTA because the times are merely requests to the pilot and not clearances. Modern Flight Management Computers (FMC) have accurate estimates of the times of arrival at, for example, waypoints and the threshold. These estimates can be better than their ground based counterparts such as Trajectory Predictors because they are calculated from the actual algorithms that fly the aircraft and can take into account information like aircraft weight and airline preferences. An important prerequisite is that the aircraft have proper weather information loaded into their FMC.

Usually such on-board ETAs are not shared with ANSPs because there is no easy means to exchange this type of information with the aircraft. As the goal of the planning system is to prevent bunches and as a result save fuel and emissions, a large planning horizon is necessary to influence aircraft in an early stage to realize the planning while minimizing fuel usage. As aircraft are well outside radar coverage at that stage, the use of ground based Trajectory Predictors (TP) is difficult.

To overcome the above problems, data-link is used as a means for the planning system to send/receive information directly to/from the FMC. To be able to down-link realistic ETAs, the FMC of the aircraft must be programmed with proper route information (including the right nightly transition). After sharing their ETA at the threshold, aircraft receive a PTA that they are requested to follow. Summarized, the planning system works in the following way:

1. Well before the planning horizon, aircraft identify themselves as being inbound Schiphol.
2. The planning system responds by sending information about the active transition and runway.
3. The runway and transition are programmed in the FMC by the flight crew and the aircraft communicates a reliable ETA-threshold to the planning system.
4. The planning system collects all ETAs from inbound aircraft and uses these to generate an optimal schedule in which each aircraft is assigned a PTA.
5. The PTAs are communicated back to the flight crews which are requested to use their RTA functionality to realize the PTA.

B. Interfacing with the aircraft

KLM uses the Aircraft Communications Addressing and Reporting System (ACARS) data-link to exchange information between its Operations Control Center (OCC) and the aircraft. The aircraft are able to downlink FMC derived data as ACARS messages. In addition, the flight crew is able to use some more advanced features such as accepting or rejecting certain requests from OCC. This existing infrastructure was used as the basis for communication between the planning system and the KLM aircraft (see below: "Message exchange").

As other airlines only have one or a few nightly inbound aircraft to Schiphol per week, it was too much effort to set up data-links with each airline. For these aircraft the assistance of NATS and MUAC was requested. As they maintain R/T contact with the aircraft when they pass the planning horizon, they serve as an intermediate between the planning system and the aircraft.

For Delta airlines, which has frequent nightly flights to Schiphol, another solution was created that lowers the amount of coordination between LVNL and the upstream ATSUs. The planning system HMI is web-based and uses regular internet connections (see IIID). This gave Delta airlines the opportunity to link with the planning system using web-based forms. Delta airlines used their existing data-link to request/send information from/to its aircraft. The responses were entered in the planning system by a ground based employee using the web interface. For the controllers of LVNL, this was a transparent process; for them there was no difference between aircraft with a direct data-link and aircraft for which the web-based solution was used.

C. Message exchange

To communicate efficiently with the KLM aircraft, a set of messages was defined (see Figure 5 for the message flow). First the planning system needs to be aware of all inbound flights. For this purpose an identification message is send by the aircraft about 90 minutes before landing. The next step is to ensure that the FMC calculates its times based on the proper runway and transition. Therefore the system responds with a message containing this information. As the planning horizon was set to 70 minutes, the flight crew has enough time to enter this information into the FMC. Some minutes before the planning horizon is reached, the aircraft sends its ETA for the threshold. The planning system collects the ETAs for all inbound flights and generates the optimized planning. About 60 minutes before ETA threshold, the planning for a specific aircraft is frozen and its PTA is uplinked The flight crew can then respond by either accepting or rejecting this PTA. In case of a reject, no additional negotiation is performed. Finally, there is a message that is broadcasted to all aircraft in case the trial is cancelled.

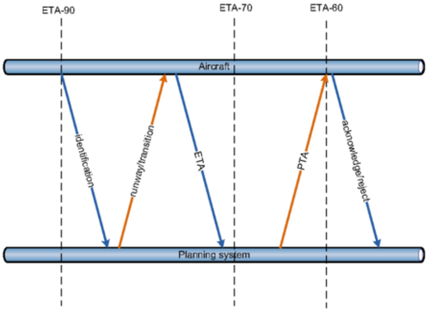
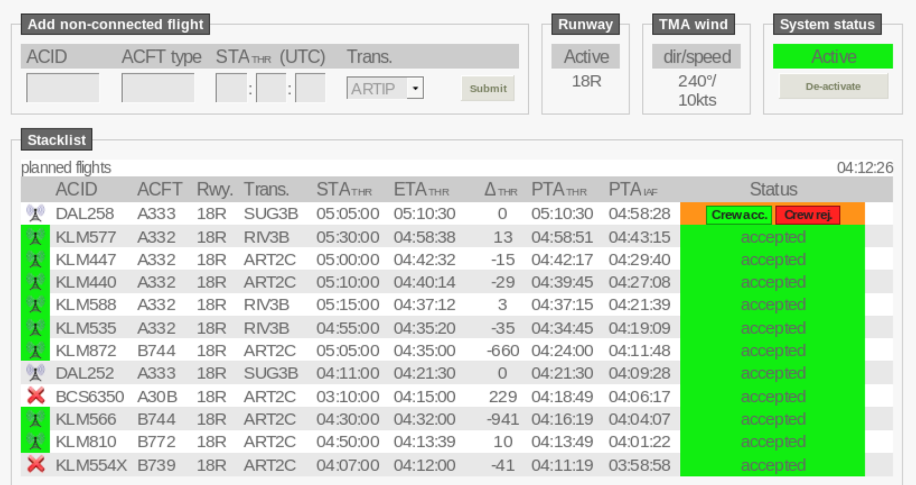


Figure 5. Message exchange flow

D. HMI

An HMI was necessary to present the planning to the controller such that he/she is kept in the loop and is able to track planning progress. The HMI is a (secure) web-based application that can run on any computer with a browser and internet connection (see Figure 6 for a screenshot). This makes interfacing with the planning system easy. The HMI shows the list of planned aircraft, their planned transition and runway, the PTA at TMA entry and the PTA and ETA for the threshold. Finally it shows the status of the aircraft. The following statuses can be distinguished:

Expected	the flight has identified itself as being inbound Schiphol
Waiting ATCo response	flight has been planned, waiting for ATC approval to send PTA
Waiting crew response	the PTA has been sent, waiting for the crew response
Final status	
Accepted	the flight crew accepted the PTA
Rejected	the flight crew rejected the PTA



Add non-connected flight

ACID | ACFT type | STA THR (UTC) | Trans. ARTIP | Submit

Runway

Active: 18R

TMA wind

dir/speed: 240°/ 10kts

System status

Active

De-activate

Stacklist

planned flights 04:12:26

	ACID	ACFT	Rwy.	Trans.	STA THR	ETA THR	Δ THR	PTA THR	PTA IAF	Status
	DAL258	A333	18R	SUG3B	05:05:00	05:10:30	0	05:10:30	04:58:28	Crew acc. Crew rej.
	KLM577	A332	18R	RIV3B	05:30:00	04:58:38	13	04:58:51	04:43:15	accepted
	KLM447	A332	18R	ART2C	05:00:00	04:42:32	-15	04:42:17	04:29:40	accepted
	KLM440	A332	18R	ART2C	05:10:00	04:40:14	-29	04:39:45	04:27:08	accepted
	KLM588	A332	18R	RIV3B	05:15:00	04:37:12	3	04:37:15	04:21:39	accepted
	KLM535	A332	18R	RIV3B	04:55:00	04:35:20	-35	04:34:45	04:19:09	accepted
	KLM872	B744	18R	ART2C	05:05:00	04:35:00	-660	04:24:00	04:11:48	accepted
	DAL252	A333	18R	SUG3B	04:11:00	04:21:30	0	04:21:30	04:09:28	accepted
✗	BCS6350	A30B	18R	ART2C	03:10:00	04:15:00	229	04:18:49	04:06:17	accepted
	KLM566	B744	18R	ART2C	04:30:00	04:32:00	-941	04:16:19	04:04:07	accepted
	KLM810	B772	18R	ART2C	04:50:00	04:13:39	10	04:13:49	04:01:22	accepted
✗	KLM554X	B739	18R	ART2C	04:07:00	04:12:00	-41	04:11:19	03:58:58	accepted

Figure 6. Screenshot of the planning system during one of the trial nights

Before the trial started, for the controller to know which aircraft to expect, a provisional list of expected flights was entered in the system based on a flight list provided by EUROCONTROLs flow management (CIFLO). These were later automatically correlated to the actual flights.

The HMI was also used by the controllers to enter missing information. This is information about aircraft that have no data-link with the system (e.g. non-KLM and non-Delta Airlines). These are coordinated by telephone with the upstream ATSUs. Their responses (e.g. ETA threshold) are entered in the system by the controller.

For the airlines that interface with the planning system using a web-based solution, a second HMI, based on the controller HMI was developed. Using this HMI, Delta Airlines was able to enter the appropriate information in the planning system. For the controllers this was a transparent process such that there was no visible difference in how KLM and Delta Airlines flights participated.

E. Scheduling algorithm

At the heart of the planning system lies the planning algorithm. Its task is to generate an optimal schedule based on the down-linked ETA times (which are assumed to be the optimal times for the aircraft). The scheduling problem is an example of a so-called on-line scheduling problem (see Ref. 11 for an overview). On-line in this respect means that the algorithm does not have access to the whole input set beforehand, but rather learns it peace-by-peace, or in this case when the system leans about new inbound aircraft. The planning problem is translated to a *mixed integer linear* program and solved with an appropriate solver. It builds on previous results[14,15] in this area with some novel additions such as the ability to freeze flights, combine flights from the same direction and optimize sequences using aircraft specific final approach speeds. Details of the algorithm can be found in Ref. 12. Some highlights of the algorithm are depicted below:

- The algorithm takes the down-linked ETAs as a starting point and assumes that those are the most optimal times for the aircraft to arrive.
- It is able to take maximum time to lose, maximum time to gain into account, equivalent to SESARs ETA min/max definition.
- Flights are optimized using their wake-category but also different constraints such as flight dynamics of specific aircraft types can be used.
- Flights are frozen after passing a certain horizon.
- Slots can be reserved for pop-up traffic (this functionality was not used during the AIRE-II trials).
- Possibility for negotiation of the PTA before it is frozen (this functionality was not used during the AIRE-II trials).

F. System design

A schematic overview of the planning system is depicted in Figure 7. It shows all components and actors of the planning system. The planning system consists of several components to plan, coordinate and communicate planning information. At the hearth is the planning server that is responsible for communication, HMI and planning.

The planning system communicates using secured internet connections. To send/receive information with KLM aircraft, it sends its messages to KLM which then forwards these to the aircraft and vice versa. For Delta Airlines, communication goes via a web interface which is operated by a Delta Airlines employee. For the LVNL controllers, there is no difference between the two ways of communicating. For other aircraft (about 5%-10%), R/T is used by the upstream ATSUs after coordination by telephone. Flight crew responses are entered in the system by the ATCo. During the trial, the controller HMI was presented on a laptop at LVNL's operations room.

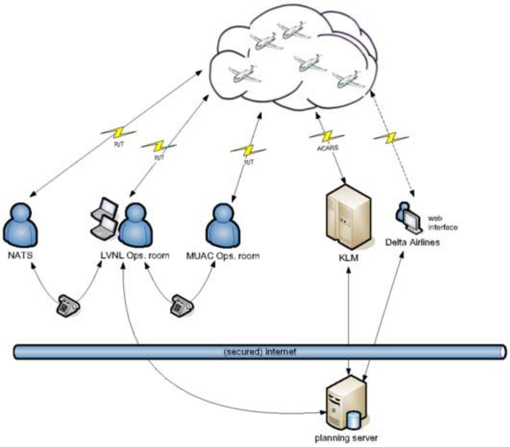


Figure 7. Overview of the planning system

IV. Concept of Operations

The detailed concept of operations can be found in Ref. 10. Below a summary of the procedures at ATC and the flight deck is provided. During the nightly trials, an extra controller was scheduled to operate the planning system and to coordinate with upstream ATSUs. Prior to each test night, a go/no-go decision was taken by the ACC supervisor. This decision was taken after the evening briefing at 08:00pm Local Time (LT). The main criteria used for this decision were whether or not transitions were active and if a runway change was expected during the test execution. The latter would lead to inaccurate ETAs. In case the trial was called off, the experiment leader notified all involved parties and personnel. Participating aircraft received a cancellation message. Below follows a summary of the concept of operations.

Preparation Phase

- A NOTAM was created prior to the start of the trial to announce the trial.
- Flight crews were briefed with an information package from their airline a few days before the flight.
- For the night of operation the planning system had a CIFLO based list of flights scheduled to land between 04:00 and 06:00. The planning system made this information available to the controllers.

- Supervisor (SUP) Amsterdam area control (AMS ACC) in coordination with AMS approach control decided to initiate the AIRE-II trial for the night of operation, the outcome of his/her decision was made available to the planning system.
- AMS ACC controller made the expected landing runway available to the planning system.
- Flight crews were briefed to request a direct to the IAF as soon as practicable, preferably starting not later than 90 minutes prior to landing (this results in more accurate ETAs).
- Flight crew checks/inserts expected transition and landing runway received via an ACARS text message in the active flight plan of the FMC.

Initiation Phase

- Well before the planning horizon, KLM aircraft received a weather update that was loaded into their FMC.
- The planning system generated an optimized planning. Prior to up-linking the PTA, the AMS ACC controller confirmed the PTA.
- The flight crew received the PTA from the planning system.
- The flight crew accepted or rejected the PTA as appropriate and shared its decision with the planning system.
- Inbound flights without a data-link were coordinated with adjacent centers. Appropriate information was entered into the system by the controller.

Execution Phase

- The execution phase began when the flight crew implemented the first RTA Speed command.
- The flight crew monitored the progression of the operation to ensure that the PTA remained feasible.
- The controller monitored the procedure execution while providing separation assurance as usual.
- If the controller determined that termination of the PTA Operation was necessary for efficient flow of traffic, or due to separation concerns or the existence of other abnormal conditions, the controller reverted to non-PTA procedures. The controller notified the flight crew via voice. Suspend/resume was out of scope in the trial.
- If the flight crew decided that the operation could not be continued, or determined the need for resumption of non-PTA Operations for other reasons, they terminated the PTA Operation. The flight crew notified the controller via voice.

Termination Phase

- If the aircraft reached the defined threshold, the PTA Operation was terminated and operations reverted to non-PTA procedures.
- In case of non-nominal termination operations also reverted to non-PTA procedures.

V. Flight trials

In the course of the project several trials were executed to iteratively test (parts of) the planning system. In total 124 flights were involved in these trials. The final full functional trial was conducted during six consecutive nights starting in the night from November 20 to November 21, 2011 and ending in the night from November 25 to November 26. Due to heavy fog, transitions were not flown during the first two test nights and the trial was subsequently cancelled for those nights. As a result four usable test nights remained including a total of 71 flights. The results presented in the remainder of this chapter are based on this final trial.

The aircraft types that were observed during this test period are presented in Figure 8. The Airbus A330, Boeing 747 and Boeing 777 formed the majority (76%) of the inbound flights accounting for 33%, 30% and 13% of the total number of flights respectively. The Boeing 737NG, Boeing 767, Boeing MD11 and ATR72 formed the second group (21% in total) with respectively 7%, 6%, 4% and 4% of the total number of flights.

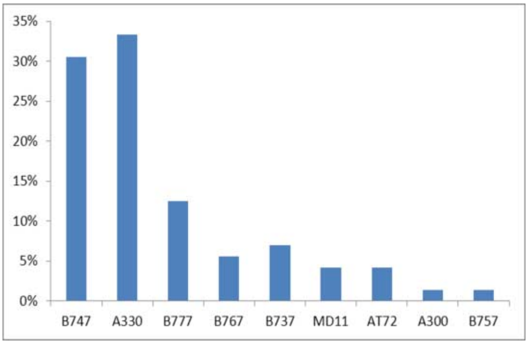


Figure 8. **Traffic mix during the trial nights**

Some characteristics of the planning process during the trial are depicted in Figure 9. A Planned Time of Arrival was generated for 91% of the inbound flights. Typically, one or two flights received no PTA each night. The reason for this lies in the fact that these flights had no data-link and arrived from the south (flights from the South are only a limited number of minutes under control of MUAC prior to transfer to LVNL). This deficiency was known beforehand and accepted. Secondly, non-connected aircraft are entered into the system prior to the start of the trial based on the CIFLO list. Some aircraft were ahead of schedule and as a result their landing time was just inside the time interval of the trial, which was unexpected.

Of the generated PTAs, about 90% were sent to the aircraft. The remaining ones were rejected by the ATCo (e.g. because there was no traffic around a flight or when an PTA was generated very late).

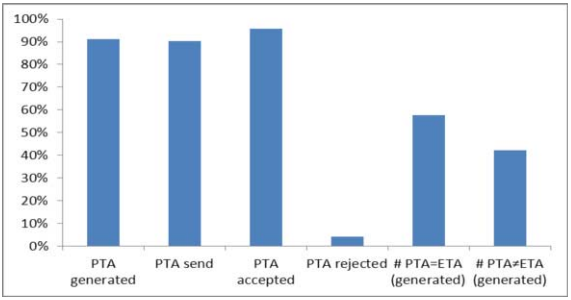


Figure 9. **PTA characteristics of the 4 test nights**

In case a PTA was sent, it was accepted by the flight crew in 96% of the cases, 3 PTAs in total were rejected. After debriefing the pilots, the reasons for the rejects appeared to be the following: During night operations aircraft often get a direct to a waypoint offered by the adjacent sectors, typically to either the IAF (e.g. ARTIP) or the starting point of the Standard Arrival Route (e.g. NORKU or DENUT). For aircraft from the South a direct DENUT influenced the planning process. In three cases a direct DENUT was given *after* the PTA was generated, sent and accepted by the flight crew. In two of these three cases the PTA was subsequently rejected because the flight crew was unable to further reduce speed to make the PTA (because of the shorter route). In the third case the aircraft, although it didn't reject the PTA, couldn't slow down anymore and subsequently landed approximately 3 minutes before the accepted PTA. Another reject was sent because the aircraft experienced turbulence and the flight crew didn't want to apply speed control to make the PTA. Although the PTA was rejected, the aircraft in the end landed only 17 seconds behind its PTA. Finally, it was observed that in 58% of the cases the PTA that was sent to the aircraft was equal to the ETA as calculated on-board the aircraft.

Table 1 shows an example of 4 aircraft that were part of a bunch at the moment of planning. Under regular operation, three of these aircraft would have entered the FIR at about the same time and would have been vectored, leveled-off or have been under speed control to be de-bunched. The table shows (column 2) that all 4 aircraft had an ETA within 6.5 minutes, three even had an ETA within 40 seconds. Column 3 shows the PTA that the planning system generated given the ETAs. In column 4, the ΔT value shows the TTL/TTG for the aircraft. The last column shows the actual time of arrival at the threshold. In Figure 10 two corresponding radar snapshots are shown. In Figure 10(a), it can be seen that the two groups of two aircraft are individually de-bunched. Figure 10(b) shows that also the two groups are mutually de-bunched. Together the four aircraft form a nice sequence. All aircraft were able to fly an (almost) undisturbed top of descent CDA.

Table 1. De-bunching example

Call sign	ETA	PTA	ΔT	ATA
KLM535	4:35:45	4:34:45	-60	4:34:48
KLM588	4:36:00	4:37:15	75	4:37:14
KLM440	4:36:25	4:39:45	200	4:41:12
KLM447	4:42:17	4:42:17	0	4:43:21

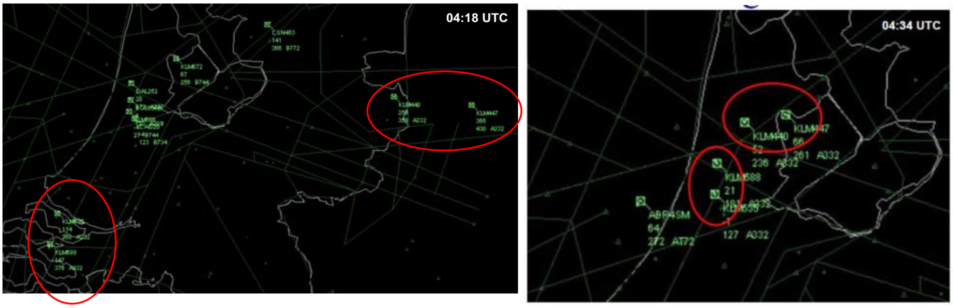


Figure 10. Radar snapshots of the aircraft (a) at 04:18 UTC and (b) at 04:34 UTC.

VI. Results

The goal of the planning system is to prevent bunching and, as a result, allow more aircraft to fly an undisturbed Continuous Descent Profile. In this section calculations are presented that show the environmental benefits that were achieved using the planning system.

A. Descent profiles

The impact on the overall descent profiles of flying towards an RTA at the runway threshold has been analysed. Out of the 11 de-conflicted flight pairs that were analyzed, only two trailing flights showed a level segment, three had a reasonable idle descent profile, one didn't have an idle descent profile and the remainder performed good idle descents. The speed efficiency (close to their nominal speed profiles, constant or accelerating or decelerating during the descent) was remarkably good for the trailing aircraft of the de-conflicted pairs, for the leading flights the speed efficiency was less optimal. In summary, flights that are successfully de-conflicted often show an efficient descent.

The flight profiles of the flights of the four test nights in November 2011 consisted of 21 full idle profiles, 20 reasonably idle profiles and 9 non-idle continuous descent profiles. In total 23 of the flights had to level off during the descent, in many cases due to a FL100 constraint at the Initial Approach Fix. Analysis revealed that in particular the correctness of wind and temperature information is key to an efficient time-based operation, but also the uncertainties in the flown routes (i.e. late direct to instructions) do influence the efficiency of the flown descent profiles.

B. Environmental benefit indicators

An indication of the yearly environmental benefits is estimated based on data of the trial. The total time the aircraft had to loose or gain was determined for each test night This was based on the planning conflicts determined by the planning system and subsequently the delta time given to individual aircraft. In normal operation (without the planning system), the controller would have delayed a flight after FIR entry until enough separation would have been created. This is usually done by vectoring, thus adding track miles. Using the planning system, this same delay is absorbed linearly by using speed control over a longer period. We assume that the latter does not influence fuel flow. The difference in how delay is absorbed between current operation and the trial is depicted in Figure 11.

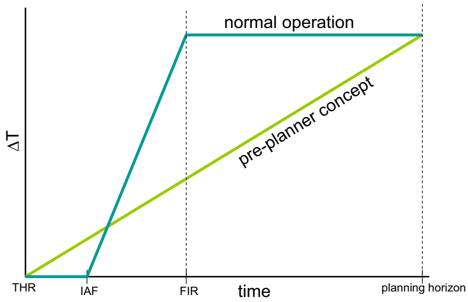


Figure 11. Difference in absorbing delay between normal operation and the trial

Summation of the individual delta times gives the total delta time for a particular night. This total delta time is an indication of the (in)efficiency of the arrival flow. During nights with a low total delta time the traffic demand is well spread and ample opportunities exist to fly undisturbed descents. During nights with a high total delta time the opposite is true.

Table 2 provides an overview of the total delta times for three of the four test nights. The night of 24 November can be considered as an average test night regarding bunching.

The night of 25 November had some light bunching and the night of 26 November contained some heavy bunching. The total delta time was on average about 850 seconds per night.

A weighted fuel flow has been estimated given the traffic mix during the November test period and given fuel flow data that KLM has provided for their fleet. The basic assumption is that the total delta time in current operation is flown in level flight at FL100 with a speed of 250 KIAS (typical TMA entry conditions for bunches), and with the pre-planning process it is assumed that this delta time is corrected during cruise and descent by speed corrections only (i.e., no fuel penalty). The positive effect on fuel consumption of flying parts of the cruise flight phase and the descent at lower speed (a lower Cost Index closer to the minimum fuel strategy) is not included in this estimate, but on the other hand also the speed instructions (used in combination with radar vectoring) to delay flights in current operations is not included. More importantly, an altitude constraint at or below FL100 is currently in effect at TMA entry. Lifting this constraint is expected to contribute a lot to the efficiency of the Top of Descent CDA especially when the transition is long (such as for runway 06). Overall it is the project team's opinion that the numbers presented in the table are conservative.

Table 2. Estimated yearly environmental benefit indicators

Night	Total ΔT (s)	Total fuel benefit (kg)	Total CO_2 benefit (kg)
24 November	924	1480	4670
25 November	498	800	2520
26 November	1124	1800	5680
average	848.7	1360	4290
365 nights		497110 (497 tons)	1565910 (1566 tons)

The weighted average fuel flow as determined to be 96.3 kg/min. Given the average delta time of 848.7 seconds, the indicator of fuel benefit for inbound traffic to Schiphol, in the 04:00am to 06:00am (local time) timeframe, is in the order of 1360 kg per night. And as 1 kg fuel equates to 3.15 kg CO_2, the CO_2 benefit indicator in this timeframe is 4290 kg. On a yearly basis the benefit indicators would cumulate to 0.50 kilo tonnes fuel and 1.57 kilo tons CO_2 for Schiphol alone. See also Table 2.

VII. Conclusions and future work

In the Night Time CDA's at Schiphol airport project, the Dutch ANSP LVNL, KLM and Dutch aerospace laboratory NLR have jointly developed and demonstrated a system innovation to introduce time based operations for nightly inbound traffic. The team has developed procedures, data-links and a planning system that tries to minimize the amount of intervention necessary for inbound traffic to optimize CDA operation.

The planning system and necessary procedures were iteratively developed and the total system and all procedures were tested during four consecutive full night tests in which nearly 100% of the inbound flights participated. From these nights, it can be concluded that the concept worked. Using the planning system with good cooperation with adjacent centres, the team has proven to be able to significantly reduce bunching in the Amsterdam FIR. There is a direct relation between preventing bunches from occurring and the amount of fuel used in the descent phase. An educated guess has been given about the amount of CO_2 that can be saved when using the planning system and its procedures. An indication of the fuel benefits is 0.5 kilo tonnes on a yearly basis, this equates to approximately 74 kg per flight, which is almost 50% more than the estimate at the beginning of the project. It should be emphasized that this fuel benefit indicator does not yet include the benefits of lifting TMA entry restrictions. The fuel benefits presented in this paper can therefore be considered a lower bound.

The pioneering factor of the concept of operation was relatively high. It has been demonstrated that the planning process works, but also valuable lessons have been learned from the limitations of this process and the chosen implementation. Live trials with RTA time based procedures at this scale are relatively unique. The lessons learned are therefore valuable for future time based operations (i.e., SESAR step 1). Important lessons have to do with procedures (and their workload), coordination with adjacent centers, technical issues, controller and pilot briefing and differences between aircraft types. Some important lessons can be found below, a more thorough description can be found in Ref. 16. SESAR projects 4.3, 5.6.1, 5.6.4 will benefit from this AIRE-II project as project partners are involved in these operational projects.

Valuable lessons learned include:

- There is a trade-off between flexibility, for example in accommodating direct clearances, and the ability to deal with bunches. Sometimes a bunch or a tight de-bunched sequence may fully eliminate the advantages of a direct clearance. The time gained by a direct clearance could result in a situation that the aircraft arrives in the middle of a de-bunched sequence and consequently has to absorb a delay resulting in vectoring at low altitudes.
- There is a need for an increase in traffic flow awareness on the flight deck: the system works to optimize the overall traffic flow and not the individual aircraft, i.e. low altitude tactical operations due to last minute changes should be prevented as much as possible. Stable and predictable flows are key. Sometimes this may be to the disadvantage of an individual flight.
- RTA performance is currently strongly dependent on the aircraft type. Obviously, time based operations benefit from state-of-the-art FMC RTA functions.
- Aircraft without the capability for data-link were involved in the trial by using voice communication. Although the adjacent centers successfully supported the trial by providing coordination by telephone, the procedure was considered too laborious, and should not be considered in a (pre-)implementation concept.
- As ETAs tend to fluctuate over time, aircraft must provide accurate ETAs not too long before reaching the planning horizon.
- For controllers to be able to keep track of ETA progress, regular ETA updates should be available to the controller *after* the aircraft has received its PTA. During the trial, an interval of 5 minutes was used for this purpose. Alternatively an ETA update could be send in case the difference between actual and reported ETA exceeds a certain threshold.
- Often weather information in the FMC is relatively old (more than 10 hours is no exception). The ETA and subsequent RTA performance is highly dependent on the quality of the onboard wind and temperature information used to calculate the ETA. It is strongly recommended to provide aircraft with updated weather information during the flight before it is planned.

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Concept of Operations for Air Traffic Management by Managing Uncertainty through Multiple Metering Points

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This paper presents an operational concept for Air Traffic Management, and in particular arrival management, in which aircraft are permitted to operate in a manner consistent with current optimal aircraft operating techniques. The proposed concept allows aircraft to descend in the fuel efficient path managed mode and with arrival time not actively controlled. It will be demonstrated how the associated uncertainty in the time dimension of the trajectory can be managed through the application of multiple metering points strategically chosen along the trajectory. The proposed concept does not make assumptions on aircraft equipage (e.g. time of arrival control), but aims at handling mixed-equipage scenarios that most likely will remain far into the next decade and arguably beyond.

I. Introduction

TRADITIONAL Air Traffic Control (ATC) activities involve the separation and sequencing of airborne aircraft by the controller monitoring the progress of each aircraft and projecting ahead to where they think the aircraft will be in the future. Inaccuracies to this methodology result in large separation standards that limit the number of aircraft that a controller can safely provide service to. Recently, the focus on global warming and CO_2 emissions has provided additional drivers to the call for efficient aircraft operation. These competing issues are compounded by the forecast increases in world air traffic unless action is taken.

In response, the International Civil Aviation Organisation (ICAO) developed the Global Air Traffic Management Operational Concept (GATMOC)[1]. Implementations of GATMOC are represented by NextGen in the United States[2], Single European Sky ATM Research (SESAR) in Europe[3], and the Australian ATM Strategic Plan (AATMSP) in Australia[4; 5]. While there are distinct differences between these programmes, in essence they all introduce a paradigm shift from current airspace-focused ATM to trajectory-focused ATM commonly referred to as Trajectory Based Operations (TBO). Essential to TBO is to increase the level of automation of ATM systems and improve on its interoperability with advanced airborne automation systems, such as the Flight Management System (FMS), to strategically separate trajectories. However prior to the specification of technological requirements, an appropriate concept of operations needs to be determined detailing how to achieve TBO.

A. Arrival Management and Continuous Descent Operations

Arguably arrival management poses the greatest challenge to TBO because of merging traffic streams to the same destination. Often an arrival manager exists at the destination airport setting the landing sequence based on the runway acceptance rate and other operational factors. This sequence is embodied by specific time-based landing slots the individual aircraft in the sequence need to achieve. Currently for most operations around the world, controllers effect the sequence through issuing of tactical instructions within the Terminal Area (TMA). While such methods maintain maximum runway capacity, it does not allow individual aircraft within the landing sequence to optimise their operation given a certain set of constraints and hence conduct an efficient descent.

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Much attention is given around the world to develop a concept of operations that improves on current arrival management by allowing onboard automation to conduct a descent along an efficient profile that better reflects the user intentions and preferences. ICAO refers to such operations as Continuous Descent Operations (CDO)[6]. CDO provide the FMS or pilot with more freedom to manage the descent but brings with it uncertainty to ATC regarding the aircraft's performance and profile. Traditionally, arriving aircraft are controlled through controller initiated step-down descents and sector hand-off agreements to eliminate these elements of uncertainty. To improve on this situation, firstly it needs to be understood how an aircraft plans and executes the descent.

B. Aircraft Descent Guidance Strategies

Geometrically an aircraft navigates along a two dimensional track over the ground which it can achieve with a very high degree of accuracy. The accuracy this track is maintained can even be specified to fractions of a mile[7]. In terms of the remaining dimensions altitude and time, the problem is more complicated and particularly for descent as multiple descent guidance strategies exist.

1. Speed Managed Descent

During a speed managed descent, elevator control is applied to maintain the target Mach or Calibrated Airspeed (CAS) while maintaining idle thrust[8; 9]. A disturbance will be balanced by altitude, i.e. potential energy. If for example the aircraft encounters more headwind than what was predicted by the forecast used in the descent planning phase, the planned descent path is too shallow to be flown at the target speed while maintaining idle thrust. Elevator control is applied and the aircraft is pitched down to maintain the target speed and the aircraft deviates from the planned path.

2. Path Managed Descent

During a path managed descent, elevator control is applied to maintain the planned geometric descent path at idle thrust[8; 9]. A disturbance will be compensated by speed variations, i.e. kinetic energy. If again the aircraft encounters more headwind than forecast, the planned descent path cannot be held at the target speed while maintaining idle thrust. Elevator control is applied and the aircraft is pitched up to maintain the path causing the airspeed to decrease. If required, thrust may be added through throttle control when the airspeed deviates too far below target (auto-throttle or manual). Or similarly, speed brakes deflection (manual) might be required when the speed deviates too far above target.

3. RTA Managed Descent

Some modern FMSs have been equipped with the Required Time of Arrival (RTA) functionality. If a time constraint is specified at a waypoint on the active flight plan, the FMS will attempt to eliminate the difference between the RTA time and the current Estimated Time of Arrival (ETA). On cruise this can be done by either speeding up or slowing down. On descent, a profile change could achieve the same result while maintaining the throttles at idle position.

The RTA descent can be flown as either speed or path managed. In a RTA speed descent the target speed schedule is respected and updated if the current Estimated Time of Arrival (ETA) exceeds the RTA with some threshold value. In a RTA path descent the path is respected where again the speed schedule (upon which the path is based) is updated if the current ETA exceeds the RTA with some threshold value. The speed schedule is based on the Cost Index (CI), so effectively the RTA algorithm varies the CI such that ETA equals RTA.

C. Problem Statement

As the RTA functionality enables an aircraft to achieve a time constraint with high accuracy as proven in several flight trials[10], this mode of operation is considered by SESAR and also NextGen as the backbone of their respective concept of operations to deliver TBO. However, and as will be further argued in this paper, the use of the RTA function has some drawbacks.

Assigning time constraints to points on an aircrafts trajectory results in excess fuel burned, increased engine wear and reduced ride quality as the aircraft continually adjusts its target speed to achieve the assigned time[11]. In addition, and for the descent, the change in target speed schedule comes with change in descent profile[12]. In fact the reduced uncertainty of arrival time at the time-constrained point is transformed into uncertainty of the aircraft's behaviour into that point and beyond that point[13]. As a result two initially separated aircraft both flying to respective appropriately set time-constraints over the same lateral track can infringe separation between them while attempting to achieve the constraint. As a solution time separation between following aircraft could be increased potentially leading to lost longitudinal capacity. This problem has not yet been solved and research is ongoing[14; 15].

Aircraft operation manuals specify the path descent to be most appropriate to meet altitude constraints, ensure (final) approach stability and for fuel economy[16]. However such a descent provides the lowest temporal predictability of the trajectory. Previous work by the authors argued that while temporal predictability is lower compared to other guidance strategies, a path managed descent provides a more predictable descent as a whole due to a consistent descent profile[13]. During a path managed descent, and with three of the four dimensions of the reference trajectory actively controlled, only time remains open. Therefore, is it possible to allow aircraft to perform a path managed descent and manage the uncertainty, then fully contained in the fourth dimension time, strategically using ATC automation rather than tactically with manual controller intervention?

II. Time-Based Sequencing

Prior to answering the question stated at the end of the previous section, some more background information needs to be provided about time-based sequencing. This section will commence to discuss current sequencing procedures in Melbourne, Australia.

A. Arrival Management in Melbourne

Air traffic management techniques for Melbourne manage on average five to six hundred operations per day[17] in a structured terminal area within thirty nautical miles of the airport. Airlines flight-plan the most optimal route to a final route point and then direct to the airport. When the flight is within an hour from Melbourne, controllers issue a standard arrival clearance giving a clear lateral path (Standard Terminal Arrival Route (STAR)) from the final route point to the threshold of the duty runway: vertical constraints ensure separation from departures and jets have a separate path from slower turbo props. Effectively, procedures and airspace are setup for the automation of the aircraft to plan and conduct a continuous descent arrival.

The Eurocat ATC system used in Australia constructs a rudimentary trajectory from the flight plan, performance tables, weather forecast, and position updates which is used by an arrival manager to determine a sequence based on defined parameters such as runway acceptance rates. The sequence is promulgated to enroute controllers in the form of a time ladder showing time to lose by the final route point or Feeder Fix. Controllers ensure the aircraft achieves the specified time at the Feeder Fix with a tolerance of ±60 seconds by implementing a solution based on their own experience and generally occurs after the aircraft has commenced descent. After the Feeder Fix, approach controllers will typically use radar vectoring to fine tune the sequence to maintain runway capacity. Figure 1 shows for a particular arrival how these current sequencing procedures interfere with the preferred descent profile as computed and managed by the onboard automation.

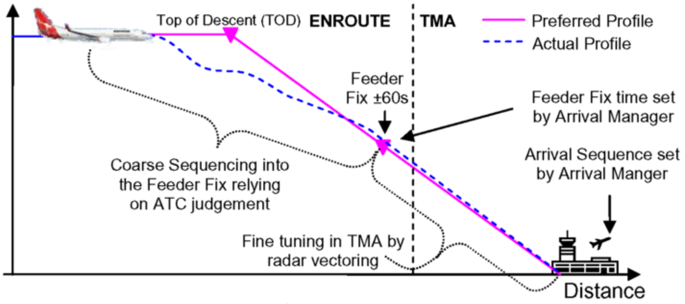

Figure 1. Cross section of current sequencing techniques to Melbourne.

The picture at Figure 2 shows the lateral tracks of 732 arrivals as sequenced by the techniques above. Through the aggregation of the aircraft tracks in the picture the shape of the published STAR path can clearly be seen. The indication from this picture is the terminal route structure is good and most aircraft actually fly the full path to the runway threshold. The reason for aircraft not flying the full path to the threshold would be a timing issue where the aircraft had to be adjusted by vectoring to maintain separation and runway capacity. It can also be inferred from this picture that if the timing

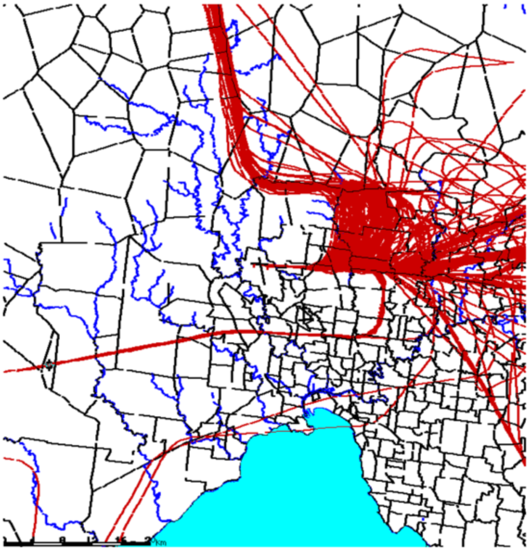

Figure 2. Tracks from 732 aircraft arriving Melbourne runway 27.

was better then less controller intervention would be required or necessary leading to more efficient operations.

The discussion about current arrival management into Melbourne shows that consistent processing of aircraft within the TMA is possible through time-based metering at the TMA entry. Controllers mentally derive speed and route instructions to meet the Feeder Fix time issued by the proprietary arrival manager Maestro. These instructions are mostly based on experience of the individual controller and certain rules of thumb. As these mental techniques only provide sufficient accuracy for a very short prediction horizon, the issuing of the tactical sequence instructions is often left as late as possible and when the aircraft has already commenced descent. Ideally, these speed and route instructions given by the controller should be issued prior to Top of Descent (TOD) such that the FMS can incorporate these additional constraints to optimise its descent while aiming to meet the required time at the Feeder Fix. Therefore, the key role for automation in ATM to play is assist the controller by deriving the right instructions to be issued using models and amounts of supporting data impossible for a human to process. The benefit of specifying speed (and route) instructions to achieve the Feeder Fix time over the use of the RTA function will be discussed later.

B. Speed And Route Advisor (SARA)

Following similar logic, the Speed And Route Advisory (SARA) system has been developed for Amsterdam Schiphol Airport. The objective of SARA is to deliver advisories on speed and/or routing in order to achieve a predetermined time at the Initial Approach Fix (IAF)[18]. An initial accuracy target of ±30 seconds for concept development has been chosen. The SARA speed and route advice is calculated according to local preferences. At first only speed advice is attempted in order to achieve the required IAF time, if speed only does not suffice, additional track miles are added.

Real-time simulations showed that with the use of SARA the variability of arrival times at the IAF was reduced compared to the baseline scenario in which controllers attempted to meet the time through conventional techniques, also controller workload was significantly reduced with use of the SARA tool[19]. Operational trials provided similar results, however because of Amsterdam's complex airspace structure, speed advisories could often only be given after the aircraft has left cruise altitude[20]. This results in some complications to the pilot as the ability to re-plan the descent based on a new speed clearance is limited once descent has been commenced.

C. Enroute Coarse Sequencing

It needs to be noted that speed instructions given around or just after TOD only provides limited sequence resolution to a TMA entry point in the order of 120 seconds. Often much larger delays need to be absorbed by aircraft to fit in their landing slot, thus requiring coarse sequencing to be performed prior to TOD.

This is also considered one of the drawbacks of using the RTA functionality to resolve a delay. As the RTA algorithm changes the CI in order to meet the time constraint, effectively its only degree of freedom to do that is the target speed schedule which makes the situation very similar to issuing a speed instruction by a controller. Again if more delay needs to be absorbed than the RTA function can achieve with CI alteration, controllers will need to revert back to conventional techniques to affect the sequence, at least to shift the aircraft into the envelope of the RTA function.

III. Proposed Concept of Operations

The prime focus of the proposed concept is to allow aircraft to primarily operate in a stable, predictable and constant manner to achieve the business goals for that flight. ATC will be able to issue timely proactive instructions to the aircraft ensuring a conflict free trajectory with minimum affect on aircraft efficiency. Initially it will concentrate on the arrival portion of the flight with objective to allow a continuous descent, and incrementally expand to cover the whole flight including departure.

A. Philosophy

The role of ATC is to separate aircraft which includes arranging them into a landing sequence for the runway threshold. Assuming the controller is not required to navigate the aircraft it will be allowed to operate unconstrained; operated by its flight management system in an automated mode at the maximum efficiency possible to a company determined profile. When the ATC flight data system knows the aircraft has become airborne or departed, it projects ahead and creates a landing time. How accurate this prediction is depends on a number of inputs and sometimes is subject to a large uncertainty. What is known about the flight is that it WILL land at a time in the future however what is uncertain is what the exact time will BE. Uncertainty surrounding an estimate will affect the capacity of a system. Reducing the uncertainty for this is far more difficult. When uncertainties overlap, ATC will probably intervene with a flight to maintain separation.

From a controller perspective and if the aircraft is on its own, it doesn't matter whether the aircraft is earlier or later than the original estimate as no intervention will be necessary. In today's environment should there be another aircraft and the uncertainty of the two aircraft overlap it would cause the controller to consider a last minute path intervention to maintain separation. The future concept of TBO is based on and can only work with accurate trajectory prediction and avoiding last minute tactical intervention.

Controllers use trajectory prediction continually to identify future conflicts and issue timely instructions to sequence and avoid the conflict. A controller's ground system can only predict a trajectory with sufficiently accurate results and minimal uncertainty, when all component parts are known. To simply nominate a time at a waypoint ahead of an aircraft without knowing how the aircraft will operate to achieve that time (RTA function) does not support a concept based around a trajectory synchronised between ground and air. In addition after meeting the time constraint it is not guaranteed that further downwind waypoints will be passed on time[13]. A more logical solution is to have the aircraft controlling to a consistent descent path computed by its FMS; i.e. a known lateral track combined with the vertical component; the path managed descent. As sequencing to an airport is and conceivably will always be managed by the ground, accurate arrival-time estimates must be maintained by any ground system. These times, even though they may be sourced directly from the aircraft still show too large an uncertainty to be used for TBO and maintain an acceptable arrival rate to an airport[21; 22]. For TBO, what is required is a process or system for the ground to have accurate trajectory prediction coupled with a concept of how to practically resolve associated uncertainty.

B. General Concept

To enable a continuous descent to occur for an aircraft, it must be sequenced and facilitated with all other operations. To enable the aircraft automation to operate to the threshold without problems with route discontinuities and manual pilot intervention a couple of assumptions are required:

- A structured terminal area with runway linked STARs enabling the FMS to compute a continuous descent profile within a set of given constraints.
- No adverse weather

Assuming an aircraft can be sequenced to permit it to descend continuously to the threshold; it must be sequenced to a point prior to it commencing descent and thus enabling its descent to be continuous but at a time desired by controllers. Ideally too, for consistency this point should be a defined distance prior to the planned descent point of each aircraft. This clearly poses a problem as the descent point for all aircraft is a result comprised of many inputs: path, level, speed, weather and weight. Therefore the commencement point of descent for an aircraft can either be made known to the ground system by down linking it, flight planning it, or ground estimation. Due to the variable location of TOD as an aircraft encounters winds in flight different to forecast, a better sequencing point is a point defined at a minimal distance prior to TOD. This new sequencing point will be called the Outer Fix and will be nominally 20 nautical miles prior to the top of descent first calculated for an aircrafts trajectory. The Outer Fix is a point created in the ground system only as a sequencing point and is not a flight planned point. A requirement will be for an arrival manager to provide not only a sequence time at the Feeder Fix, but also at each aircraft's Outer Fix. The latter time will be based on a nominal descent speed schedule for that aircraft type.

The outer sector controller will achieve the scheduled Outer Fix time with a tolerance of ±60 seconds through cruise speed and if necessary route adjustment (similar to SARA). In general the further out the action is applied, the greater the delay that can be achieved and still provide a continuous descent arrival. Effectively, the job of the outer sector controller has not changed, but instead of sequencing the aircraft to the Feeder Fix with ±60 seconds the aircraft will be sequenced with the same accuracy to the Outer Fix.

At or prior to reaching the Outer Fix the aircraft will be advised with a descent speed schedule to achieve the scheduled Feeder Fix time. In case the Outer Fix time is passed exactly at the scheduled time, this speed schedule will in theory be the nominal schedule. However as the tolerance for the Outer Fix is ±60 seconds, any deviation from the scheduled time (which propagates to a deviation of the Feeder Fix time and the threshold time), should be resolved by a change in the nominal descent speed schedule. The deviation from the scheduled time at the Outer Fix should therefore be within the tolerance as the ability to absorb delay (or make up time) with just a change in speed schedule for the descent is limited (refer to SARA). It is important the controller is timely alerted if an aircraft will not achieve the Feeder Fix time; this is to enable the amended descent speed to be assigned to the aircraft and entered into the FMS prior to actually commencing descent. Note that while a specific descent speed is assigned, the aircraft is still expected to perform a path managed descent but with the path calculated for the assigned speed. It is expected that the aircraft might not adhere accurately to the target speed. Later in this paper it will be discussed how this problem is resolved.

Complementary to the tolerance for the Outer Fix time is a tightened tolerance for the Feeder Fix reduced to ±30 seconds. This tolerance needs to be achieved by issuing a descent speed schedule, and hence sets an accuracy requirement to the derivation of that speed schedule. Note that this tolerance is similar to SARA and was demonstrated to be achievable for over 80% of the trial flights[20].

Beyond the Feeder Fix normal procedures will be applied to fine tune the sequence to a final tolerance of ±10 seconds at the runway threshold and maintain runway capacity. With the tolerance at the Feeder Fix reduced to ±30 seconds, the need for radar vectoring within the TMA should be reduced and the published STAR in a figure like Figure 2 should become even clearer.

In summary, sequence resolution will be a three phase approach (if necessary):

1. Coarse sequencing or the largest delay occurring before the Outer Fix and descent commencing.
2. Fine sequencing by assigning a specific descent speed so the aircraft automation adjusts its descent point and path to cross the Feeder Fix at the desired time.
3. Precise sequencing using radar vectoring similar to techniques of today but expected to be used far less often due to the tighter sequencing to the Feeder Fix.

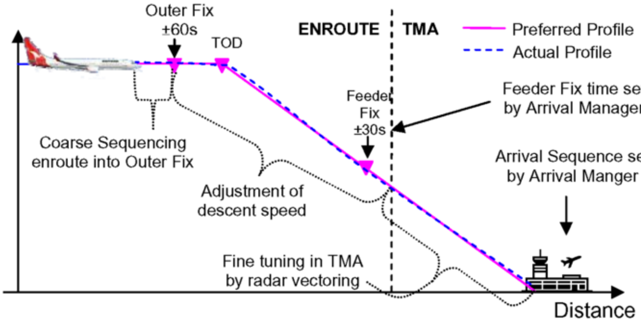

Figure 3. Proposed sequencing concept using Outer Fix.

The diagram in Figure 3 portrays how this would be achieved by shifting the coarse sequencing prior to descent. If the coarse target has been achieved then the ±30 seconds time target for the Feeder fix permits the aircraft to descend without lateral adjustment and any variation to the Feeder Fix can be corrected by assigning a descent speed prior to the aircraft commencing its descent. A descent speed assigned prior to commencing descent will cause the aircraft automation to recalculate the descent path for the changed speed resulting in an amended time at the Feeder Fix. The aircraft will descend continuously to the runway at the amended speed controlled by the cockpit automation and unintentionally achieve the controller desired time at the Feeder Fix (within the tolerance). For a controller to fine tune the sequence further, the option to vector and position the arriving aircraft appropriately still remains. It is expected unless necessary this practice will be discouraged.

C. Detailed Concept

The proposed concept is about understanding and managing the uncertainty of an aircraft flight path such that many trajectories can be operated in unison and harmony. In Figure 3, for each location there is a defined time that is recognised as having an acceptable tolerance that must be achieved for the system to work. This concept suggests methods to achieve the times within the applicable tolerances while allowing the aircraft to operate consistently and as efficiently as possible.

1. Process

- A landing sequence will be determined at the arrival airport considering all associated requirements e.g. demand, acceptance rate etc.
- Times in a sequence will be defined in seconds and a "slot" will be maintained for scheduled aircraft until any delay precludes them achieving the reserved time.
- The arriving aircraft trajectory will be transposed to meet the landing time defined by the sequence giving adjusted times for the Feeder and Outer Fixes.
- Outer Fix - a ground generated point specific to a particular flight 20NM prior to the TOD of that aircraft. As TOD likely differs between aircraft, it will be different for all aircraft.
- Feeder Fix – effectively entry point for the terminal area.
- Descent to be on the lateral track, continuous from cruise level to achieve the times for the metering points with the following increasing tolerance for accuracy. Outer Fix time ±60 seconds, Feeder Fix ±30 seconds, Threshold ±10 seconds.
- Coarse sequencing to the Outer Fix will be via cruise speed or route adjustment.
- Fine sequencing to the Feeder Fix will be via assigned speed for descent.
- Precise sequencing to the runway will be via radar vectoring as required.
- ATC, supported by ground automation will take proactive steps to facilitate aircraft operating to the airline defined profiles.
- All aircraft will be processed the same way although less equipped aircraft may require more manual intervention.

2. Supporting Technology

ATC will be supported by a ground-based Trajectory Predictor (TP) with sufficient accuracy including the following requirements:

- The TP will continually monitor aircraft conformance to the sequenced trajectory.
- The TP will alert the controller if the arrival time estimates are outside the tolerance for a point.
- The TP will calculate solutions to efficiently resolve for the aircraft, a method to regain the sequenced trajectory.
- The TP will use input acquired from ground and airborne sources (data-link). The predicted trajectory is based on synchronised aircraft *intent* between FMS and ATC, but the predicted *trajectory* is not necessary equal to that of the FMS which will be detailed later in this paper.

These accuracy requirements will be discussed later.

3. Staged Sequencing through Multiple Metering Points

Stage 1: Coarse sequencing identified to be required well prior to top of descent.

- The TP identifies the aircraft will arrive at the Outer Fix outside of the buffers for the assigned time i.e. greater than ±60 seconds different.
- The TP suggests a resolution to ATC to amend the current trajectory to adjust the arrival time to the Outer Fix sequence time.
- Cruise trajectory amendment could occur a second time.
- If the sequence time achieved then aircraft will descend at desired/nominal speed schedule.

Stage 2: Fine sequencing to occur during descent but identified prior to descent commencing.

- The TP identifies the aircraft will arrive at the Feeder Fix outside of the buffers for the assigned time i.e. greater than ±30 seconds different.
- Prior to commencing descent the TP suggests to ATC an amended descent speed to adjust arrival time to Feeder Fix sequence time. The expectation is for the aircraft to conduct a path managed descent with the path based on the advised descent speed.
- If the Feeder Fix sequence time is achieved then aircraft will continue at assigned speed.
- ATC continues to have option of radar vectoring if necessary.

Stage 3: Precise sequencing to occur within TMA, but identified prior to the aircraft passing the Feeder Fix.

- Aircraft not touched unless necessary.
- The TP identifies the aircraft will arrive at the threshold outside of the buffers for the assigned time i.e. greater than ±10 seconds different.
- ATC uses radar vectoring if necessary to fine tune sequence (but only in a limited manner as ensured by meeting previous sequence tolerances).

IV. Clarification and Example

1. Uncertainty

To aid the reader's understanding of uncertainty related to aircraft estimates consider the following: Figure 4 and similar graphs in this document compare aircraft location in distance from the destination to a time axis. In Figure 4 an aircraft is at a point prior to descent and from its current position, path and speed a TP calculates an ETA for TOD, Feeder Fix and the runway threshold. Effectively, the dashed line provides a reference to the ETA at a particular position ahead of the aircraft continuous with distance. These estimates contain some uncertainty as the models for aircraft intent, aircraft performance model and forecast weather are not perfect. The uncertainty can be statistically quantified through historical performance of the respective TP[21; 23]. Logically, the further out an estimate is made, the larger the related uncertainty associated with that estimate. The blue shaded area provides an indication of the uncertainty, quantified as the historical 95% containment area, as it grows with prediction horizon (distance away from current position). These models are similar to those developed by EUROCAE Working Group 85 (WG85) for ETA uncertainty in both open loop and closed loop (RTA) operations based on the sources of this uncertainty [24; 25].

For the trajectory based operations of the future it is logical to state that the more accurate the prediction is and therefore the smaller the uncertainty, the better operations can be planned. However there will always be an associated value of uncertainty and this uncertainty will need to be managed.

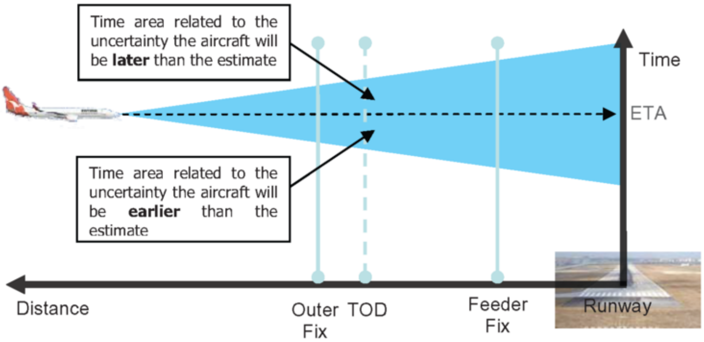

Figure 4. Proposed sequencing concept using Outer Fix.

2. Example in Practice

Suppose that the aircraft in Figure 4 is assigned with a scheduled time of arrival (STA) at the runway threshold by the arrival manager (see Figure 5). From this STA, subsequently STAs for the Feeder Fix and Outer Fix can be derived. Similar to the line indicating the ETA continuous with distance, a line can be added to indicate the STA continuous with distance; this continuous STA coincides at the Outer Fix and Feeder Fix with the respective discrete STA values. Therefore in Figure 5, the STA lines provide an indication of where the aircraft should be in order to be 'on schedule'. In the example the ETA line is above the STA line and hence currently the aircraft is late. Previously the different tolerances for the Outer Fix, Feeder Fix and runway threshold were presented and are these are also indicated in Figure 5.

The aircraft shown in Figure 5 is late to its assigned sequence time and the runway estimate uncertainty shows the aircraft will most likely not achieve its sequence time at the runway without intervention or issuing a new sequence time.

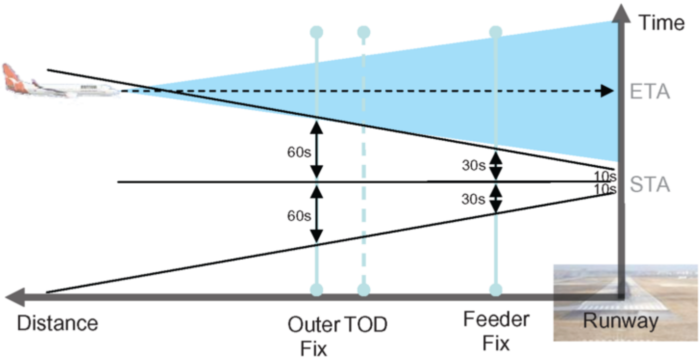

Figure 5. First sequence instruction into Outer Fix affected.

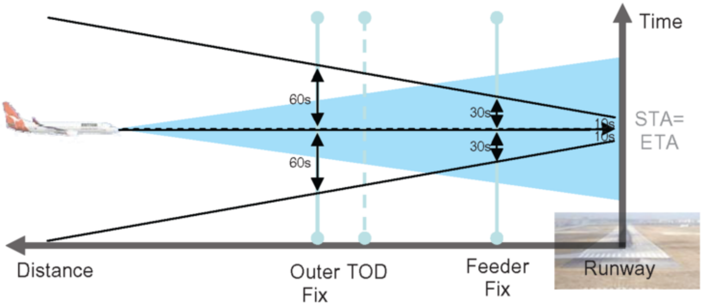

Figure 6. First sequence instruction into Outer Fix affected.

In the proposed concept, the TP computes a cruise speed amendment, and if necessary a route amendment, to affect the sequence resolution into the outer fix. These sequencing instructions can be issued in a proactive manner via data-link if the aircraft is sufficiently equipped. Data-link capability is particularly useful for such application as it both provides a means to accurately transfer the instruction to the cockpit and then to monitor conformance. With speed (and route) advisory, the aircraft's ETA line now coincides with the RTA line as indicated in Figure 6. However because it is so far out – prior to descent – the prediction uncertainty delta of the estimate at the runway and Feeder Fix is larger than the target time window. However in terms of the Outer Fix the uncertainty is entirely contained within the tolerance because of the first sequence instruction. Therefore the aircraft is permitted to proceed without further intervention to at least the Outer Fix, and with the expectation of a continuous descent thereafter. But as the uncertainty at the Feeder Fix is larger than the tolerance, the descent speed for that continuous descent might have to be adjusted.

The situation would need to be monitored by the controller assisted by ATC automation until the aircraft comes close enough to a target window (e.g. Feeder Fix) such that the uncertainty for its respective estimate is entirely contained within the tolerance. Practically what it means is that if the uncertainty is not fully contained within the target window, there is a probability larger than 5% that any sequence instruction derived by the TP is not effective. With effective it is meant that the aircraft is

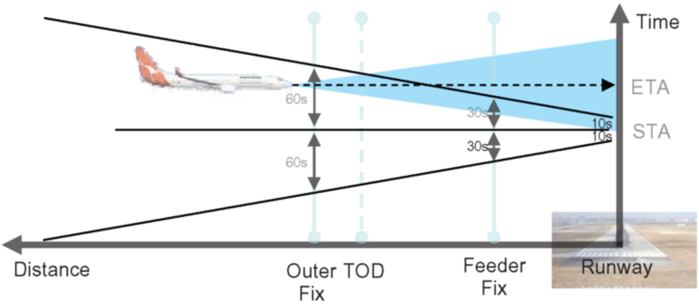

Figure 7. Aircraft late, but within time window at Outer Fix but not at Feeder Fix.

making the target window with the derived instruction.

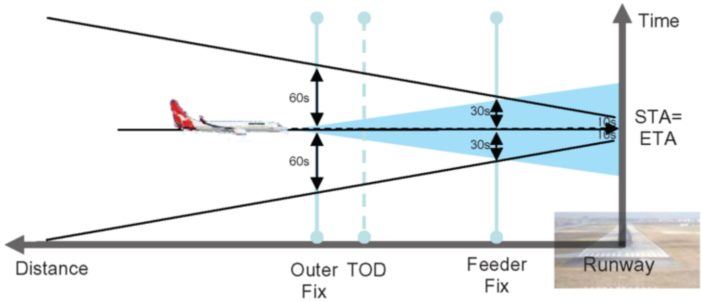

Figure 8. Second sequence instruction into Feeder Fix affected.

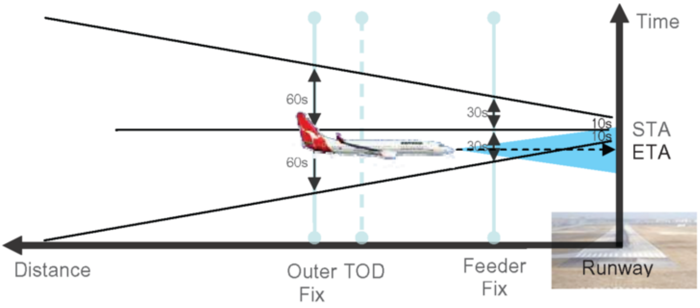

Figure 9. Aircraft on descent in tolerance but threshold ETA early.

Now consider Figure 7, the aircraft has progressed and the ETA has drifted away from the STA as there is no closed-loop control in the time dimension. Still the aircraft will achieve the target window at the Outer Fix within acceptable buffer but not the Feeder Fix. Therefore a descent speed higher than nominal will be derived by the TP and delivered to the aircraft to shift the ETA at the Feeder Fix to the STA (Figure 8). The applied speed should be maintained until mandated speed changes e.g. 250 knots IAS below ten thousand feet. This intervention issued before TOD will enable an efficient and continuous descent at a speed that puts the aircraft back into the defined sequence position. Note that for the speed instruction to be effective, the uncertainty of the ETA as derived by the TP and used to determine the speed adjustment, needs to be less than the Feeder Fix tolerance of ±30 seconds.

The aircraft in Figure 9 will achieve the Feeder Fix within the target window but will be outside the target window for the threshold (early). Consequently the aircraft will require radar vectoring to achieve the time at the runway. This is very similar to today however it is expected to be required for far less flights than today, and to a smaller extent as the Feeder Fix is passed with higher accuracy than today. This radar vectoring should occur between passing of the Feeder Fix and the start of an instrument approach or RNP arrival procedure.

3. Sequence Resolution Space

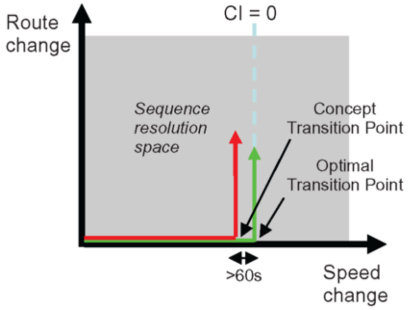

Figure 10. Sequence Resolution Space.

It was previously mentioned that the coarse sequencing into the Outer Fix will be effected firstly through cruise Mach number change and a route amendment will be made if speed adjustment alone is not sufficient. In theory, and assuming a delay needs to be absorbed in an efficient manner, this transition point coincides with the cruise speed at which the Cost Index (CI) is zero (minimum fuel speed) (Figure 10). Inclusion of the descent makes the problem more complex as also descent speed schedule needs to be taken into consideration[26]. In terms of the proposed operational concept it is undesirable to sequence an aircraft into the Outer Fix using the full capability of speed adjustment. If for example an aircraft has been instructed to fly at zero CI and due to normal time drift the Outer Fix is passed early, there is no possibility remaining to resolve this drift with a speed change into the Feeder Fix, i.e. the degree of freedom of a speed change in the sequence resolution space has been exhausted (in one direction). ATC then may have to revert to conventional procedures to affect the sequence which most likely will impact on the efficiency the descent is executed. Therefore, the transition point after which a route amendment should be made to affect the sequence into the Outer Fix, should leave sufficient buffer within the speed change degree of freedom to allow for the ±60 seconds tolerance at the Outer Fix to be resolved plus a TP uncertainty buffer.

Study is required to determine the most efficient methodology to lose time into the Feeder Fix in the context of the proposed operational concept.

4. The Need for Accurate Ground-Based Trajectory Prediction

Until now one major assumption has been made about the proposed operational concept: a sufficiently accurate TP is available to derive instructions to deliver aircraft to the different metering points within the target window. In fact, the minimum required performance of the TP is set by the target windows of the metering points and the sequence horizon.

It has been demonstrated that the uncertainty of an estimate derived from the TP (and therefore also of a sequence instruction derived from the TP), needs to be smaller than the target window in order for an instruction to be effective. The combination of the accuracy of the TP and the target window therefore directly sets the maximum horizon. Any instruction derived from the TP beyond this horizon is less than 95% effective. This horizon can be easily determined from the size of the target window and the slope of the uncertainty cone as the latter is a quantification of the TP performance. Thus in generic terms, the slope of the *uncertainty* cone related to the performance of the TP needs to be smaller than the slope of the *target* cone, and thus setting the accuracy requirement for a TP supporting the proposed concept of operations.

The cruise phase of flight generally involves a stable wind and level flight making the prediction of times from the calculated groundspeed relatively simple. The descent phase of flight occurs through a significant band of winds and varied aircraft performance driven by the airline priorities on the day and makes this a much more difficult problem. In relation to the concept, the critical requirement for the TP would be to derive speed instructions that delivers an aircraft to ±30 seconds accuracy at the Feeder Fix. These speed instructions need to be derived when the aircraft is approaching the Outer Fix but not later than crossing the Outer Fix (requirement for horizon). Therefore predictions of the ETA at the Feeder Fix need to have at least this accuracy and preferably better.

In previous research work the authors investigated the accuracy of the TP currently operational in Australia's EUROCAT ATC system and compared it to predictions made by the aircraft's FMS and the experimental Airservices TP (ATP). For a large number of Boeing 737-800 (B738) flights that conducted a non-intervened continuous descent predictions made by the three systems for the ETA at the

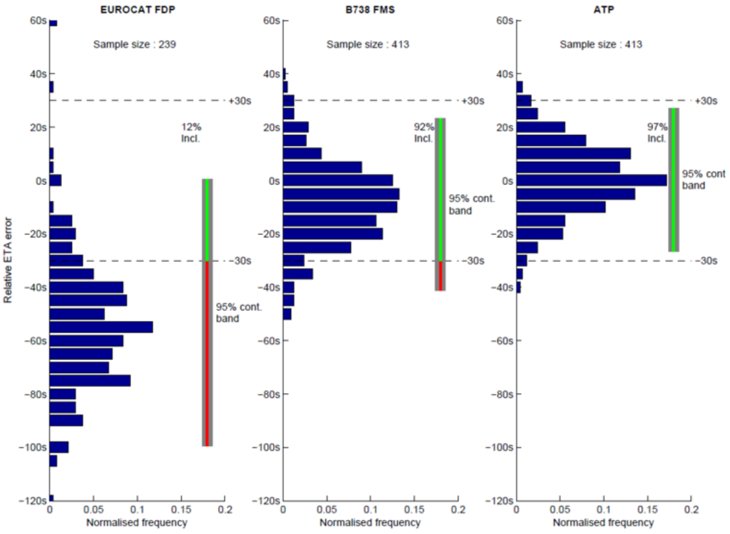

Figure 11. TP performance comparison.

Feeder Fix were compared. In each case the prediction was made when the aircraft was at the position of the proposed Outer Fix. The results are given in Figure 11.

It is clear that with the FDP trajectory estimates of the current ATM system this operational concept cannot be considered as only 12% of the sampled flights meet the accuracy requirement. Other operational concepts around the world promote the use of estimates down-linked from the aircraft's FMS. As with FDP estimates, the accuracy requirement of 95% is only met for 92% with this aircraft and FMS combination. Previous research on other aircraft and FMS combinations has indicated similar or lower performance[21; 22] leading the authors to believe that accurate trajectory prediction can only be achieved when information available by the FMS in the air and by ATC on the ground is appropriately combined[27].

The experimental ground-based Airservices TP developed by these authors does meet the accuracy requirement with 97% within target. ATP appropriately combines data extracted from the FMS via Future Air Navigation Systems (FANS) and data available on the ground, and takes into account the active guidance strategy (path managed descent)[27]. In essence ATP is able to predict the deviations from the target speed as a result of holding the path at idle thrust. Integration of these speed changes results in an improved ETA at the Feeder Fix. It was previously mentioned that in the proposed concept an updated speed schedule is expected to be flown path-managed to maintain a consistent and predictable profile. Supported by the latter prediction algorithms the speed deviations associated with the path managed descent, and hence the reduced temporal predictability, do not pose a problem.

While in all these cases aircraft down-linked information was available, current research work is being performed to configure ATP for non data-link equipped aircraft. It is expected that some degradation in accuracy will occur, however if critical parameters to the prediction process can be communicated to ATC via voice, and with the application is system learning techniques, this degradation should be minimal. In essence however, equipped and non-equipped aircraft will be processed the same.

5. Energy Management

Flying an aircraft efficiently is all about effective energy management. The reference trajectory computed by the FMS can be seen as the realisation of the acquiring (climb) and dissipation (descent) of the total energy (kinetic and potential) possessed by the aircraft. Therefore, if any inaccuracies exist in computing the reference trajectory, this trajectory will not accurately reflect the total energy possessed by the aircraft at different stages in the flight. On descent, it is this error in predicted total energy that subsequently needs to be managed with an appropriate guidance strategy. The energy error is therefore closely related to the uncertainty in the descent trajectory executed by the aircraft. The dimension(s) in which this uncertainty is (are) contained is a direct result of the selected descent guidance strategy.

Effectively, the guidance strategy balances the error in predicted total energy using either potential or kinetic energy. When balancing with potential energy, the reference altitude profile will be departed (e.g. speed managed). When balancing with kinetic energy, speed (and time) will be affected (path managed). Note that departing the reference altitude profile will also indirectly affect time[13]. Energy can also be added through the application of thrust or dissipated through the application of speed brakes. Either way it will be the guidance strategy commanding these active energy management actions.

In summary, the deviations (in all dimensions) from the reference trajectory can be seen as a measure of the error in the total energy as predicted by the FMS and thus forms a measure of uncertainty in the predicted trajectory.

When a TP computes a descent trajectory, effectively it implicitly determines the total energy that will be dissipated on descent. Logically, the better the total TP model (forecast conditions, intent and aircraft performance), the better the estimate of the dissipated energy and the less the uncertainty

Consider Figure 12, the left column represents the *actual* energy that is dissipated over the FMS computed descent path, the middle column the value implicitly determined by the FMS, and the right column the value found by ATP after simulating the execution of the descent. The FMS predicted energy for descent is reflected in the geometry of the descent profile it computed. ATP takes the path from the FANS trajectory data, and hence follows this same descent profile. However, the ground-

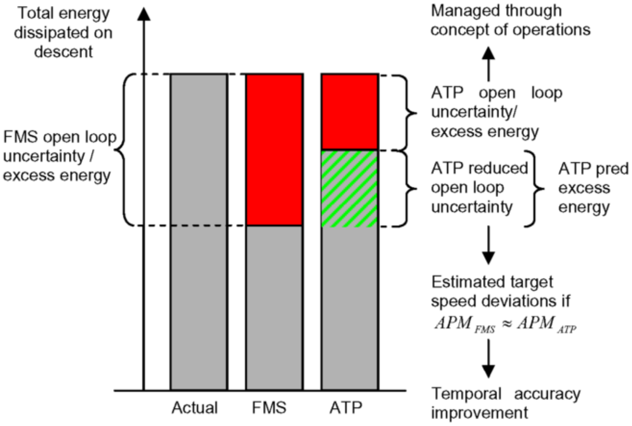

Figure 12. TP performance comparison.

based forecast model used by ATP is of much higher resolution and precision than the one held by the FMS. Therefore, ATP is able to estimate some of the excess energy on as discussed in much detail in Ref [27]. The remaining excess energy, which is a measure of the remaining uncertainty in the system, will need to be managed through the concept of operations.

When applied to the RTA functionality, it is effectively the energy error represented by the red top in the FMS bar that needs to be accounted for by additional fuel burn (or dissipated through speed brake deployment) at some stage prior to landing as discussed into detail in Ref [13]. If a ground based TP is able to predict the fourth dimension of the trajectory of an aircraft descending in path managed mode better than the FMS, and the remaining uncertainty (i.e. energy error) can be managed through a concept of operations as proposed in this paper, it then seems unnecessary for the aircraft to compensate for the energy error and thus consume additional fuel.

V. Comparison with Other Concepts and Concluding Remarks

Both SESAR and NextGen propose that aircraft will be assigned times at waypoints which they must achieve with a high accuracy (RTA functionality). In order to do this, the free variable or dimension in their operation which they will use to control to the assigned time is their speed. Any unexpected speed change by an aircraft will cause increased workload to a controller as the impact of such a change is assessed. Different FMSs can have different RTA algorithms, and even with the same algorithm, depending on the forecast winds entered in the FMS and other specific settings, different speed schedules can be computed and also updated differently. As previously mentioned two initially separated aircraft both flying to respective appropriately set time-constraints over the same lateral track can infringe separation between them while attempting to achieve the constraint. A concept relying on airborne equipment to meet time constraints is therefore not "set and forget" but requires continuous monitoring by controllers.

Instead, this paper proposes a concept in which aircraft are permitted and expected to operate consistently without unexpected changes to their operation which induces additional uncertainty. The concept envisions aircraft to conduct a continuous descent in path managed mode. In path managed mode the aircraft can conduct a continuous descent along a consistent descent profile with the uncertainty contained in the temporal dimension of the trajectory. ATC is subsequently supported by accurate ground-based trajectory prediction to manage this temporal uncertainty though metering at strategically chosen points along the aircraft's trajectory. Instead of being ATC-focused, the concept aims to focus on the consistent and efficient operation of aircraft.

The concept promotes the use of data link to share trajectory related information between crew/FMS and ATC. The use of data link allows strategic clearances to be issued expeditiously and efficiently rather than late tactical interventions issued by voice although that always remains an option if required. ATC procedures in this concept do not widely deviate from today's procedures and therefore it is envisioned the concept can successfully deal with mixed-equipage scenarios.

This concept is attempting to facilitate aircraft operating efficiently and predictably. It is the opinion of the authors, an operational concept based on the consistent processing of all aircraft has the highest likelihood of being successfully implemented prior to the end of this decade.

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The Turkish Aviation System and the Strategy of Turkish Airlines

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We sketch the history and development of the Turkish aviation system and we analyze the position and strategy of Turkish Airlines as the major player in this system. Turkish international aviation was liberalized in 1983, but domestic aviation was only liberalized in 2003. Combined with Turkey's economic development, this opened up the aviation system and ensured its growth. Turkish Airlines was the first company in the system, established 1933. It is still the dominant player, shaping the system as well as profiting from its growth. We provide a strategic analysis of Turkish airlines based on data from 2001 to 2011. We analyze the qualitative development of its business model, the quantitative development of its financial value creation, and the (in)consistencies between these.

I. History of the Turkish Aviation System

THE foundation of the Airlines Administration and Government Operation in 1933 led to the establishment of Turkish Airlines and to the commencement of air transportation in Turkey. The first civil air transport started with "Turkish Airmails" with a small fleet of five airplanes (DGCA, 2009).

The management of Turkish airports and the regulation and control of Turkish airspace are performed by the General Directorate of State Airports Authority (GDSA), which has carried out its services under different names and statutes since 1933. Its facilities and equipment constitute the vital infrastructure of Turkish Civil Aviation. The GDSA has continued providing services as a state owned enterprise since 1984 (DHMI, 2012).

Turkish Airlines got its current name in 1955 and Turkish Airlines Inc. was reestablished to pursue its activities as a single carrier on the 1st of March in 1956 (Turkish Airlines, 2012a).

One of the other developments in this period was the foundation of USAŞ in 1958 - a ground-handling company with the leadership of Turkish Airlines Inc.. It offered aircraft ground-handling services to foreign airline companies flying to and from Turkey as well as to Turkish Airlines. In 1987, the company was split into two companies: USAŞ Aircraft Catering Services and HAVAŞ Ground Handling Co. in 1987 (HAVAŞ, 2012).

In the same year Celebi Ground Handling Inc. was founded at Ankara Esenboğa Airport as the first privately owned ground-handling services company in the Turkish aviation industry. This company provides ground-handling services to airline companies in Turkey and Europe. Celebi Ground Handling Inc. provides services to more than 250 carriers, the majority of which are international airlines flying to and from Turkey (Celebi, 2012).

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With the rapid growth and technological advances in the world aviation, the Administration of Civil Aviation was founded in 1954 within the Ministry of Transportation and Communication to ensure compliance with the rules of international aviation and to regulate and inspect the aviation activities in Turkey (Korul & Küçükönal, 2003). The administration was restructured in 1987 under the name of Directorate General of Civil Aviation and became financially autonomous and formed its current management structure in 2005 (DGCA 2009).

During 1958-1983 Turkish Airlines was the only air carrier of the country, serving national and international destinations. In 1983, the 50th year after its establishment, it was operating in three continents and carried 30.000 tons of cargo and 2.5 million passengers with a fleet of 30 aircraft (Turkish Airlines, 2012a).

A. Developments after 1983

Until 1983, only public companies were allowed to operate in the air transport industry in Turkey. Turkish Airlines, flag carrier of the country, was the only airline dominating the domestic market and serving international destinations. All airports were state owned and operated by the public entities.

During this period, air transportation industry was restructured. With the enactment of the Civil Aviation Law, private companies were allowed to operate in air transportation industry in Turkey. The main objective of Civil Aviation Law is to regulate activities in air transportation industry by taking into account domestic and international regulations and relations. Many private airline companies entered the market and the industry experienced a significant growth by deregulation of air transportation industry in 1983. Although the Civil Aviation law started liberalization in the industry, it had not been able to set up a competitive environment as in the other countries and initially led to an increase in Turkish Airline’s monopoly (Çetin & Benk, 2011).

In the framework of the modernization and standardization programs, Turkish Airlines began to modernize its fleet, to upgrade service standards and focus on international markets rather than domestic market. However, some private airline companies have ceased their operations and have gone bankrupt because of some difficulties and challenges such as a shortage of working capital, the disadvantage of operating with relatively old aircraft, lack of maintenance and other infrastructure facilities and of qualified personnel and not enough government support (Korul & Küçükönal, 2003). Wikipedia lists over 70 defunct airlines in Turkey (Wikipedia, 2012a).

Continuing this development trend until the first half of the 1990’s, the air transportation industry was negatively affected by of the Gulf Crisis in 1990 and the Asian economic crisis in 1988. To recover these negative effects, airline companies reorganized their operations and personnel and rescheduled their fleets. The air transportation industry slowly began to recover in the early 2000s, only to be hit by the severe Turkish financial and economic crisis of 2000-2001 and the dramatic terrorist attacks in the United States of September 11, 2001. These events led to dramatic declines in passenger and cargo traffic.

Until the 2000s, state support given to Turkish airlines was not given to private airlines, which led to unfair competition and caused bankruptcies, complicating operations especially in times of crisis. Therefore, the Minister of Transportation of the period initiated the necessary legal arrangements to restructure the system for private airlines and to support companies especially engaged in air transportation for tourism in Turkey. Low cost airlines business were encouraged in answer to the demand for domestic flights, which had very high ticket prices due to the Turkish Airline’s monopoly on the sector (Korul & Küçükönal, 2003).

B. Liberalization of the industry in 2003

The year 2003 was a turning point for the air transport industry in Turkey. Until 2003, the industry was not open to competition. Turkish Airlines was the monopolist performing all scheduled domestic transport in Turkey. Other private airline companies could operate only if Turkish Airlines did not have a scheduled flight to this point. According to regulations of the Civil Aviation Law, private airline companies could have permission to operate in domestic market only by:

- Flying to destinations to where Turkish Airlines had no flight,
- Flying to destinations where Turkish Airlines had a flight, but at times when Turkish Airlines did not schedule a flight,
- Flying when Turkish Airlines could not meet demand.

In October 2003 the government put a new policy into practice and erased all the barriers preventing private airlines to enter the domestic air transport market. With this liberalization, some taxes on domestic flights were also lifted and airport service charges were reduced. As a result, the cost of operations for airlines companies fell and this reflected on the ticket prices. This liberalization process started competition in domestic market and airlines offered cheaper flights and better service quality. The most important effect of this liberalization was the dramatic increase in the number of passengers carried in domestic flights (Gerede, 2010). In 2011 seven airlines provide air transportation and fly to 48 airports in the Turkish domestic market.

Table 1 shows the development of the Turkish airline industry between 2003 and 2011. It can be seen that a significant growth took place in passenger traffic, cargo traffic, number of aircraft and number of flights (DHMI, 2012). Table 2 shows the airlines currently operating from Turkey (adapted from Wikipedia, 2012b). This table reflects the situation as of May 2012.

While Turkish Airlines carried 8.5 million passengers to 25 destinations from two centers in 2002, a total of 58.3 million passengers were carried by 7 airlines from 7 centers to 48 domestic destinations in 2011. Further impact of the liberalization of 2003 was seen on the international flights. Competition on the domestic market led to a significant increase in the number of international passengers. Private airlines started to fly international destinations (Çetin & Benk. 2011). The total number of international passengers jumped from 25 million in 2003 to 59 million in 2011. The number of international destinations increased from 60 in 2002 to 157 in 2010.

Next to the growth in volume, the aviation system also grew in breadth. As an example, if we just take the Turkish Airlines group, we see the number of businesses and/or joint ventures in the group strong increasing from 2006 onwards (Turkish Airlines annual report 2010):

- Turkish Technic: maintenance repair and technical support services
- SunExpress, charter carrier
- Turkish Do&Co: catering services
- Atlas Jet, low-cost and domestic carrier
- Turkish Engine Center (TEC): engine maintenance, repair and overhaul services
- Bosnia-Herzegovina (B&H) Airlines: Balkans carrier
- Turkish Ground Services (TGS), ground handling services
- Turkish Airlines Cargo: cargo transport services
- Turkish Opet Aviation Fuels: fuel storage and fuel supply services
- Goodrich Turkish Airlines Technical Service Center: engine maintenance and repair services
- Turkish TechnicZorlu O/M: maintenance, repair and overhaul services for industrial gas turbines
- Turkish Cabin Interior Systems Industries: design, manufacture, logistical support, modification, and marketing of aircraft cabin interior systems and components

All those group or related companies provide services not only to Turkish Airlines, but to airlines flying within, to and from Turkey as well.

II. The Strategy of Turkish Airlines

Turkey's flag carrier, Turkish Airlines, was established on May 20, 1933, under the name of "State Airlines Administration" as a Department of the Ministry of Defense. It started operations with a fleet of 5 aircraft with a total seat capacity of 23. In 1935, its administration was transferred to the Ministry of Public Works. Its name was changed to "General Directorate of State Airlines" in 1938. It began to be operated under the Ministry of Transportation since 1939 (Turkish Airlines, 2012).

Turkish Airlines was reshaped in 1955 as a corporation managed and operated under private law, and was renamed Turkish Airlines Inc. It was reclassified as a State Economic Enterprise on November 9, 1984. Until 1983, Turkish Airlines was the only airline dominating domestic and international flights. The privatization of Turkish Airlines goes back to the 1990's. An initial public offering was made in 1990 and 1.83% of the company's shares were offered to the public. Then two secondary public offerings were held in 2004 and 2006, where the share of the government's ownership in Turkish Airlines fell below 75% and 50%, respectively. As a result of this privatization process, the company ended to be a state enterprise by May 2006 (Turkish Airlines, 2012).

Turkish Airlines has currently become one of Europe's most successful airlines by achieving a stable growth since the deregulation of the market in 1983 and the liberalization in 2003. That growth can be seen in Table 3 summarizing the passenger, mail and cargo traffic carried and flights performed by Turkish airlines between 1933 and 2011.

Table 1. The development of the Turkish airline industry between 2003-2011 (source DGCA, 2012; compiled by the authors)

	2003	**2004**	**2005**	**2006**	**2007**	**2008**	**2009**	**2010**	**2011**	**CAGR 2003-2011**	**Total Growth rate 2003-2011**
Number of aircraft	162	202	240	259	250	270	299	333	347	9.9%	114%
Number of domestic flights	156.582	196.207	265.113	341.262	365.177	385.767	419.422	497.862	581.271	17.82%	271%
Number of international flights	218.405	253.286	286.867	286.139	323.291	355.998	369.047	421.549	460.218	9.76%	111%
Number of over flights	154.218	191.056	206.003	224.774	247.099	269.172	277.584	293.714	290.346	8.23%	88%
Total Flights	529.205	640.549	757.983	852.175	935.567	1.010.937	1.066.053	1.213.125	1.331.835	12.23%	152%
Millions of domestic pax.	9.147	14.461	20.529	28.774	31.949	35.832	41.227	50.575	58.329	26.06%	538%
Millions of international pax.	25.296	30.596	35.042	32.880	38.347	43.605	44.281	52.225	59.018	11.17%	133%
Millions total Passengers	34.443	45.057	55.571	61.654	70.296	79.437	85.508	102.800	117.347	16.56%	241%
Domestic cargo traffic	188.979	262.790	324.597	389.206	414.294	424.555	484.833	554.710	611.691	15.82%	224%
International cargo traffic	775.101	901.559	979.644	971.344	1.131.890	1.219.459	1.241.512	1.466.366	1.617.594	9.63%	109%
Total Cargo Traffic	964.080	1.164.349	1.304.241	1.360.550	1.564.184	1.644.014	1.726.345	2.021.076	2.229.285	11.05%	131%
Number of Bilateral Agreements	81	81	84	86	88	90	107	111	117	4.70%	44%

Table 2. Airlines currently operating in Turkey (source Wikipedia, 2012b; adapted by the authors)

Airline	Type of business	ICAO code	Start of operations	Fleet
ACT Airlines	Cargo	RUN	2004	8 cargo (1 of which wide body)
Anadolu Jet	Passenger domestic and international; charter	AJA	2008	20
Atlasjet	Passenger domestic and international	KKK	2001	14 (1 of which wide body)
Borajet	Passenger regional and business	BRJ	2010	5
Corendon Airlines	Passenger domestic and international	CAI	2004	10
Freebird Airlines	Passenger (charter)	FHY	2001	7
Izair	Passenger (charter)	IZM	2006	7
MNG Airlines	Cargo	MNB	1997	11 (cargo)
Onur Air	Passenger domestic and international	OHY	1992	33 (10 of which wide body)
Orbit Express Airlines	Cargo	OAC	2008	2 cargo wide body
Pegasus Airlines	Passenger domestic and international	PGT	2005	37
Saga Airlines	Cargo	SGX	2004	4 cargo
Seabird Airlines	Business or leisure	N/A	2012	2 ("Twin Otter")
Sky Airlines	Passenger domestic and international	SHY	2001	13
SunExpress	Passenger domestic and international; charter	SXS	1990	28
Tailwind Airlines	Passenger (charter; wet lease)	TWI	2012	1
Turkish Airlines	Passenger domestic and international; Cargo	THY	1933	174 (37 of which wide body); 6 cargo (2 of which wide body)
ULS Airlines Cargo	Cargo	KZU	N/A	N/A

Table 3. Development of Turkish Airlines between 1933 and 2011

	1933	1943	1953	1963	1973	1983	1993	2003	2011
Passengers	460	5.691	181.980	323.133	2.535.871	2.552.148	6.099.032	10.420.000	32.648.000
Flights	N/A	N/A	10.699	19.051	39.109	29.253	67.442	100.807	265.656
Fleet size	5	14	33	34	26	30	N/A	65	179
Mail	1.112 kg	43.239 kg	156.089 kg	421 tons	1.527 tons	2318 tons	3970 tons	4.899 tons	12.796 tons
Cargo	N/A		2.648.354 kg	2474 tons	13.025 tons	30.660 tons	64.970 tons	117.923 tons	375.042 tons

Sources: Kline, 2002; Turkish Airlines annual report 2003; Turkish Airlines, 2012b; compiled by the authors

We start our analysis of Turkish Airlines in 2001 - a watershed year in the Turkish economy. After a severe financial and economic crisis, Turkey started its economic march upward that continues until today, putting it in the top-20 economies of the world and with a positive outlook.

As the flag carrier of Turkey, Turkish Airlines is a reflection of the growing economic confidence of Turkey over the last decade. The front page of Turkish Airlines' 2001 annual report proudly reads: "rising above the crisis, we attained success" (Turkish Airlines annual report 2001). In a year in which the Turkish economy was in crisis and the year that many other full-service airlines in the world suffered severe losses, in part because of the 11 September tragedy, Turkish Airlines was able to show modest profits. In the airline transport industry, only the low-cost carriers such as Easyjet and Ryanair rivaled such performance.

A. Market trends

The Turkish aviation market is characterized by a number of trends, partly mirroring the world market. The first trend is a strong increase of demand, higher than the world market, with a compound annual growth rate of 26% for the domestic market and 11% for the international market between 2003 and 2011 (Turkish Airlines, Full year 2011 results presentation). This demand increase is mediated by large economic fluctuations, of which the financial and economic crisis of 2008-2009 is a prime example. For Turkey, specifically, though, the financial and economic crisis of 2000-2001 was more disruptive to airline operations.

As a consequence of the market growth, large numbers of competitors have entered the market, thereby increasing competition. For Turkey, specifically, this increase in competition came late because the market was only fully liberalized after 2003. Examples of competitors emerging in the first half of the decade were Atlasjet, Corendon Airlines, Sky Airlines and Pegasus Airlines (see also table 2). Onur Air was already active since the beginning of the 1990's. The Turkish Airlines group wholly or partly owns two other major operators, Anadolu Jet and Sun Express.

A specific characteristic of the increasing competition is the emergence of the low-cost carriers. For the Turkish market, Pegasus Airlines and Atlas Jet are prime examples of airlines that use a low-cost, no-frills, low-price model to capture significant market share. This leads to a continuous pressure on ticket prices, and a continuous pressure for full-service airlines like Turkish Airlines to justify their higher ticket prices with better service. Such better service, in turn, creates an upward pressure on cost: better staff, more investments in aircraft and management systems, in marketing and brand building.

The rising cost of fuel, which is worldwide and hits all airlines, whether they are full-service or low-cost or somewhere in between, adds significantly to the upward pressure on the costs. As the fuel prices increase and decrease erratically (though with a long-term upward trend), fuel price hedging becomes increasingly necessary.

The rise of internet-dominated sales channels makes pricing and capacity planning easier and contributes significantly to the process efficiency of airlines. The reverse is that, for passengers, it is easier to compare fares, which adds to the downward pressure on ticket prices.

Finally, the importance of environmentally and socially sustainable business is growing. This puts pressure on airlines to increase their operational efficiency (e.g., passenger load factor), and to renew their fleets to ensure the use of the most fuel-efficient aircraft.

B. Business model evolution

For the analysis of the evolution of Turkish Airlines business model, we use a framework originally developed by Van Asseldonk (1998) and adapted by the authors. The framework is a grid with on the vertical dimension the type of business based on the nature of the company's business processes and on the horizontal dimension the basis drivers of financial value creation (see figure 1).

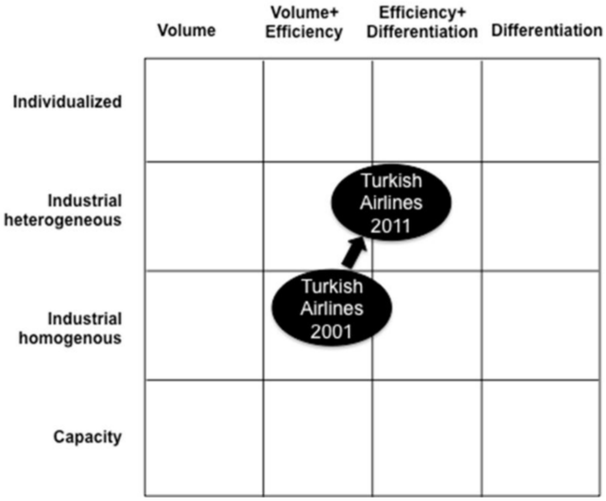

Figure 1. Turkish Airlines business model evolution 2001-2011

The vertical dimension consists of four archetypical types of business. Capacity companies are resource-driven companies that mainly provide capacity and do not have a well-defined "product". Examples are consultancy or IT companies selling hours, transport companies selling cargo capacity, or traditional craft companies selling skilled labor capacity. In the airline industry, charter companies or wet-lease companies are good examples.

Industrial companies have defined clear product-market combinations. Homogenous industrial companies have singular or very focused bundles of product-market combinations. The archetypical example is the T-Ford, a singular and completely standardized product. In the airline industry, the low-cost carriers are good examples offering simple, standardized service. Industrial heterogeneous companies offer multiple product-market combinations, usually in response to market demand for differentiated services. The variation in product-market combinations can range from quite modest to mind-boggling complexity. Most industrial companies, e.g., the present-day car companies fit in this model. In the airline industry, the full-service carriers usually conform to this model, offering a variety of in-fight and additional service to different kinds of customers.

Individualized companies offer their customers individualized experiences, which are often based on a platform based on which which many products and services can be combined. Such companies are often part of networks or "business ecosystems" around these platforms. Examples can be found in the converging ICT and media sectors (e.g., Apple, Facebook, Google, Samsung or Sony).

The framework is fairly well applicable to the airline sector, although the differences between low-cost and full-service carriers are less radical than between archetypical "homogenous" and "heterogeneous" companies. Low-cost carriers can, for example, still fly to a large number of destinations. Conversely, even with a full-service carrier, the degrees of freedom in choice for the passengers are limited.

1. Analysis of the business type

We can now analyze the position of Turkish Airlines on the vertical dimension. Apart perhaps from the first few years of its existence, Turkish Airlines never seems to have been a real capacity company. It has for most of its history provided scheduled flights to an increasing number of destinations, which is a characteristic of an industrial model. From the beginning on, Turkish Airlines has moved upwards on the dimension, providing more variety to the customer. Before 2001, the prime examples of this movement are (Turkish Airlines, 2012a):

- The start of international flights in 1947, and, of course, the continual increase in international destinations ever since.
- The start of the specific "product" of Hadj flights in 1953 to facilitate the annual pilgrimage.

- The establishment of SunExpress in 1989, as a clear separate offering; in fact, mainly a charter company taking care of "capacity" business.
- The start of three different classes of service on long-haul flights in 1993: first class, business class and economy class.

In the period of our analysis, we see a large number of additional movements toward more product and service variety (based on the Turkish Airlines 2001-2010 annual reports):

- In September 2001, ticket sales through internet began, enabling reservations and ticket purchases for all flights to be made via internet.
- From 2003 onwards, the activities technical maintenance and flight-training center take a more important position in the company's strategy. In 2004, a major investment of over $200 million was started for the technical maintenance activities. From the end of 2005, these activities were incorporated in the Turkish Airlines Technic and Turkish Airlines Training companies, providing their services to a wide variety of airlines operating in, to and from Turkey. At that moment the fast-growing maintenance market for Turkey was estimated at $550 million; the revenue goal for Turskish Technic was $500 million in 2010, representing a major additional business.
- In 2003, the IT infrastructure of the Miles&Miles customer loyalty program was extended to enable increasing differentiation in services for cardholders.
- From April 2005, flights were scheduled from the new airport Sabiha Gökçen on the Asian side of Istanbul. In the years following, this airport increasingly becomes a second hub.
- In 2006, after the "full privatization", the decision was taken to join the Star Alliance, which would significantly enlarge the network, destinations and services to be offered to the customers. Turkish Airlines became a full member of Star Alliance in the beginning of 2008.
- Also in 2006, Turkish Airlines began with the creation and operation of VIP-lounges for Miles&Miles members and business and first class passengers. The 2006 annual report reads: "The aim is attaining 1 in service quality".
- The company made large steps in dynamic revenue management, connected to the pricing on the website. This is a crucial enabler for applying different prices based on variations in demand. In 2007 this is extended with a pricing program that enables instant responses to the pricing of competitors.
- Catering service is set to improve by the creation of Turkish Do&Co, a joint venture between Turkish Airlines and the Austrian firm Do&Co. In the following years, this will deliver Turkish Airlines record scores on customer satisfaction with the catering: over 95% of "extremely satisfied" customers. In later years, this is crowned with multiple service quality and "best on-board catering" awards.
- Finally, in 2006, a start was made with renewing the cabin concepts to provide more comfort and service to passengers. In 2008 the first class and business class experiences are significantly upgraded. In 2010, an additional "comfort class" was introduced, providing more seat width and legroom than economy class for an additional fee.
- In 2007, investments are made in Customer Relationship Management systems and in customer-orientation training of crew and staff.
- In 2007, a plan is announced for a new service under a new brand. In 2008 Anadolu Jet is announced, which will adopt a low-cost carrier model, with standard, but high-quality service. In the words of the annual report "Rather than seeking to increase our share of an existing market, Anadolu Jet's marketing strategy instead sought to create a new market …"
- In 2009, an additional mobile sales channel is offered, enabling passengers "to perform all stages of ticketing, check-in and boarding procedures from their mobile phone." In 2010, a "Fly Turkish" mobile app is added to facilitate mobile services.
- In 2009 Turkish Airlines Technic establishes a partnership with Pratt&Whitney and jointly created the Turkish Engine Center (TEC), enabling know-how and technology transfer, and therefor improvement of the technical service portfolio.
- Also in 2009, Turkish Airlines partnered up with the HAVAŞ ground handling company to form Turkish Ground Service (TGS) as a joint venture.

Altogether the above actions resulted in Turkish Airlines becoming the European airline with 4-star Skytrax ranking in all categories. In the framework, each action listed above is a clear step toward increased variety and choice for passengers, putting the business of Turkish Airlines now firmly into the "Industrial heterogeneous" class.

2. Analysis of the value drivers

The horizontal dimension of the framework consists of the basic drivers of financial value creation (Van Asseldonk, 1998). Volume indicates the focus on turnover growth: "more of the same". Efficiency reflects a focus on process efficiency and lowering cost. Differentiation reflects a focus on proving unique – differentiated from the competition – products and services, and the ability to convert this uniqueness in higher prices. Going only by the layout and content sections of the annual reports, we can already get an initial idea on the positioning of Turkish Airlines on the horizontal dimension. The annual reports from 2001 until 2005 devote most space in the non-financial parts to discussion and reporting of operational measures, such as numbers of passengers, available seat kilometers or passenger and cargo load factors. The same focus can be read in the message of the chairman. Additionally, there is a strong focus on showing the volume growth of the business and quality and reliability are stressed. Such a focus is typical of companies in the "volume+efficiency" position: they focus on carrying out their process efficiently yet also excellently, they focus on the growth in volume of their business, and finally they try to combine volume growth and process efficiency to gain economies of scale. The money earned in this way is invested in further process improvement, i.e., even higher efficiency and excellence, and in capacity increase to enable further volume growth. It is a very strong and successful combination, as is proved in the airline sector by the low-cost carriers, most of which operate in this way. Without in any way classifying Turkish Airlines between 2001 and 2005 as a low-cost carrier, we see the same characteristics in the annual reports.

The 2006 and 2007 annual reports provide a fairly clear inflection point. The operational reporting and attention for quality and growth are still there, but the focus shifts toward reporting on the diversification of the business (e.g., Atlas Jet in 2007, 2008), the increase of passenger services (e.g., loyalty program, catering), customer satisfaction, the brand image (especially 2010 annual report) and the global mission and initiatives of the company. While the company still proudly presents its growth numbers, it is aware that there are limits to growth. One line from the 2007 annual report is especially telling: "As a result of increasing competition in the sector, shrinking profit margins and the first glimpses of consolidation, a sustainable presence cannot only be built upon growth but must also give equal importance to sustainable profitability." To ensure that, the company proposes to make effective use of internet and other technology, to optimize marketing and fleet strategies, and to improve process efficiency and effectiveness. This shift in focus clearly positions the company into the "efficiency+differentiation" position of the vertical dimension of the framework. In the airline sector, this would be a typical position for a full-service airline: it is big enough to enjoy economies of scale, but the necessity to grow fast has disappeared. Processes are still efficient and excellent, which is a necessary condition to keep up customer satisfaction and to add differentiated services. Of course the cost structure of those processes is different than for the low-cost carriers: a more varied fleet, more varied sales and service channels, better passenger information and better service concept. This means that cost will be higher, putting pressure on the company to improve process efficiency. This is complemented, however, by services that are different and in some crucial aspects better than the competition. For such services, a higher price can (and should!) be charged.

In table 4 below we show the results of our detailed textual analysis of the highlights, chairman's message, strategy and operations sections of Turkish Airlines' 2001 to 2010 annual reports. This detailed text analysis largely confirms the initial impressions. The 2006 but especially the 2007 annual report convey very high ambitions to break away from the focus on growth and toward a focus on being the best in terms of performance and service. In 2010, because of the consequences of external cost pressures, this ambition is less clearly stated and there is a partial return to stressing operational excellence.

Table 4. A detailed textual analysis of Turkish Airlines' 2001-2010 annual reports

	Volume drive	**Efficiency drive**	**Differentiation drive**
2001	-Extension of domestic services -Limits to growth from Sept 11 attacks	-Ticket sales through internet (e-commerce) -Cost reduction measures and personnel reduction -Closing and combining of destinations -Quality oriented corporate culture -Investments in operational and IT systems to continue	-High-quality associated brand name
2002	-N/A	-Capacity utilization -Passenger load factor -Customer satisfaction -High standard of quality service -Cargo tracking facilities	-Customer satisfaction
2003	-Global network carrier rather than local market serving -Passenger numbers -Limits to growth from SARS -Stalled capacity -Flexible pricing (to keep up growth in face of stalling demand and competition) -Expanding the network	-Increased passenger load factor -Tons of cargo -Quality -Call center improvements	-THY Maintenance Center toward globally effective center -Miles&Miles software to offer service variety -Growing reputation
2004	-Efforts to maintain market share -Promotional fares; aggressive stand against competitors -Extension of the fleet; toward 20 million passenger capacity -Increase in number of passengers -Growth-oriented strategy -Maintenance center expands	-Price discounts to balance capacity -Cost studies performed -Electronic ticketing on domestic flights -Passenger load factor -Cargo load factor	-Maintenance Center will not only handle THY business but will also provide services to domestic and international customers
2005	-Increase in number of passengers -Further growth -New long-haul planes	-Enhanced service quality -Fuel prices -Foreign currency effects -High safety performance -Watch the cost development	-Turkish Technic established -Turkish Flight Training established
2006	-“The fastest growing airline of Europe” -Extension of routes -Growth in aircraft, number of pilots and flights per day -Unprecedented increases in business volume	-Quality certification -Good call center -Zero fault, high quality, customer satisfaction -“The aim is attaining 1 in service quality” -SunExpress to start scheduled services -Dynamic revenue management	-Turkish Airline Technic inc. established -Decision to join Star Alliance: “we are in the league of giants” -“...aiming to fly to every point in the world” -Creation of VIP lounges -“The aim is attaining 1 in service quality” -Catering in partnership with Do&Co -Renewed cabin concept
2007	-March towards a global player -Achieved growth targets -“Dream: at 100th anniversary: 250 aircraft; be a global player in every sense of the word” -Others grow 4,1%, THY 16%	-Achieved quality targets -Integrated process management -Quality awareness, quality circles, quality improvement teams	-Socially responsible activities mentioned -New business units: low-cost carrier and cargo -Skytrax 4-star rating -Focus on customer satisfaction -Flexible pricing system -“Success is not just growth, but also new products and quality services” -CRM system and customer orientation training

Table 4 (ctd). A detailed textual analysis of Turkish Airlines' 2001-2010 annual reports

	Volume drive	**Efficiency drive**	**Differentiation drive**
2008	-Decision to purchase 105 new aircraft until 2023 -Doubled passengers and triples revenues over past 5 year -Others contract 1,7% THY grows 15,1% -Goal to become one of Europe's four largest airlines	-Call center outsourced -Quality principles -ISO14001 environment management system -Fast-rising fuel cost	-Member of Star Alliance -Anadolu Jet started -Turkish Technic makes joint venture with Pratt&Whitney -Begin offering first-class service -Improvements in business class experience -In-flight services constantly on the rise
2009	-Other contract 3,5%, THY grows 11% -Anadolu Jet strongly growing, adding international destinations	-Turkish Technic as first center to obtain EN/AS9100 Aviation Series and the ISO9001:2008 Quality Management System Certificates -Launch of enterprise resource planning (ERP) project to restructure business processes, increase operational efficiency and more effectively deliver products and services to passengers -Quality awards -Risk management (fuel price hedging) -ERP project with SAP Turkey -Call center: cost fell and quality increased	-Diversifying sales channels with mobile telephone website -Reinforced identity as a global airline -Among Europe's most profitable airlines -Further investments in training -Service awards -Sustainability -Turksih Engine Center (TEC) established together with Pratt&Whitney -Turkish Ground Service (TGS) established together with HAVAŞ
2010	-In global top 10 airlines in terms of number of flight destinations -4th position in Europe's passenger market share -Anadolu Jet growth and expansion	-External cost pressures: especially fuel prices -Many operational numbers again provided -"With competition becoming increasingly tougher in today's aviation industry, financial discipline has emerged as one of the most crucial keys to achieving sustainable growth. Fully aware of this fact, Turkish Airlines continues to carry out its long-term, value-based growth program by shaping it around the principle of effective cost management"	-"Discerning brand investments and successful results are enabling Turkish Airlines to advance confidently on the path of sustainable growth" -Number of different businesses in the group strongly increasing -Best onboard catering / world's best catering in economy class -Sponsorships of FC Barcelona and Manchester United and lots of other sports sponsorships -Service Quality and Passenger Satisfaction Enhancement Program -Focus on superior, high- quality service to all guests -Cultural and social responsibility initiatives -Fly Turkish mobile app

C. Quantitative strategic direction analysis

Following the qualitative strategy analysis in the previous section, we will now make a quantitative analysis of the development in the value drivers: volume, efficiency and differentiation. This allows us determine whether what the company says it does in its annual reports it actually able to translate into financial performance. To make this analysis, we again use a framework developed by Van Asseldonk (1998) that was adapted by the authors. The framework measures developments in volume, efficiency and differentiation by proxy:

- Volume is measured as net sales
- Efficiency is measured as Volume divided by indirect operational cost
- Differentiation is measure as added value divided by Volume
- Performance, representing the operational cash performance per lira sales, is measured as Differentiation minus 1/Efficiency

- If we multiply Performance with Volume, we arrive at the cash created from operational activities

The results of comparable measurement for other companies have high face validity with higher management and external analysts. It has to be stressed, however, that it does not pretend to be an exact measurement. For every metric, choices have to be made which costs or benefits to include in it, as, for example: do we include foreign currency risks as "operational" or "non-operational" (we chose to classify it as "non-operational"). Choices have to be made whether or not to make corrections on hindsight when the company changed its way of accounting (we chose not to make any corrections and use the annual data as reported in that year's annual report). To calculate the measures we compiled a data file based on the financial figures in the company's 2001 to 2010 annual reports, plus the 12-months consolidated financial report over 2011. This data file is available from the authors upon request.

1. Performance-Volume analysis

The first quantitative analysis is that of Performance versus Volume. Capacity companies and industrial homogenous companies focus mostly on Volume, accepting declining performance as long as it does not become negative. Industrial heterogeneous and individualized companies focus mostly on increasing Performance, with Volume growth or decline as secondary importance, as long as volume is above a minimum efficient scale. Note that Performance consists of a combination of Efficiency and Differentiation.

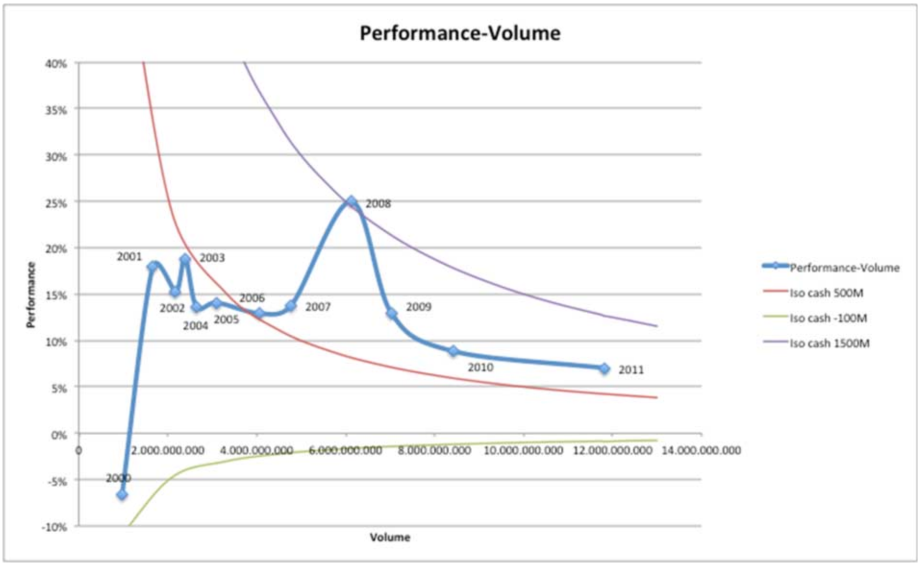

Figure 2. Turkish Airlines Performance-Volume analysis

In 2001 we see an impressive recovery from the 2000-2001 financial and economic crisis that hit the Turkish economy so hard. It is like 2001 the annual report, which proudly reads: "rising above the crisis, we attained success". After 2001, we see a Volume growth in every year, but it has to be kept in mind that inflation in Turkey was 53%, 47% and 22% in 2001, 2002 and 2003, respectively (average consumer price index over the year; www.inflation.eu). Still, 2001 shows a 20% inflation-corrected growth. The years 2002 and 2003 show contractions of around 17& and 12%, respectively, with passenger numbers being almost stable. In response to this, the company employed what the chairman euphemistically calls "flexible pricing". In the graph, we clearly see two consequences of this: 1) a decline in Performance with 5% (from 19% to 14%): or 5 kuruş less operational value per lira of sales, 2) in 2004, 2005, 2006 and 2007 Volume growth explodes, reaching over 20% in real numbers in 2006. The move is a success: the Volume growth that is realized more than offsets the loss in Performance, and from 2003 to 2007, operational cash created rises from around 450M lira to around 650M lira. During this period, Turkish Airlines constructs a basis to become less dependent on Volume growth in the future: building quality, investments in systems to improve process efficiency and gradually building differentiation potential by investments in branding and improvement of services. It works: it 2008 it all comes together in a historical year. Not only the Performance increases, also the Volume growth from previous years is still there. Net profits reach over 1.1B lira and operational cash exceeds 1.5B lira that year. It seems that the ambitions from the 2007 annual report are within reach. Not for long, because in 2009 the worldwide financial and economic crisis interferes, customers spend less and the competition from low-cost carriers increases. Note that in the same year, Anadolu Jet, Turkish Airline own low-cost carrier, performed above expectations. It is not enough to save the group financial performance. It seems as if Turkish Airlines bounces back to the model of the 2004-2007 period: accepting lower Performance to maintain Volume growth. It does not work this time: to maintain Volume growth in 2010, the company has to accept a hit in Performance. Operational cash created is lower than the year before, something that did not occur since 2004. As mentioned in the previous section and as can be seen in table 4 (2010, efficiency), the company realizes the position it is in and changes strategy to put more stress on efficiency and operational excellence. This seems to partly pay off in 2011: Performance still goes slightly down, but the company is able to compensate this with rising Volume.

2. Differentiation-Efficiency analysis

The second quantitative analysis is that of Differentiation versus Efficiency. Industrial homogenous companies, like the low-cost carriers, focus mostly on Efficiency. They try to sustain efficiency improvements while accepting declining Differentiation, i.e., lower ticket prices. Individualized companies focus mostly on Differentiation, with efficiency as a secondary issue. Industrial heterogeneous companies have the most difficult job here. They have to balance differentiation and efficiency, and cannot afford a single-minded focus on one aspect. Given that competition and external cost increases make it almost impossible to increase Differentiation and Efficiency at the same time, the best such companies can hope to do is to improve the one, while keeping the other at least constant. Note that keeping Efficiency constant does not equal "doing nothing": the company has to do the best it can just to stay in the same place and fight the external cost developments. The same goes for differentiation: higher prices can in theory be asked for better and more varied services, but since the competition is also improving its offerings, such price increases are often impossible.

In the D-E chart, we see the same impressive recovery from the 2000-2001 crisis. Given the operational focus of the annual reports from 2001-2005, we would expect to see growing efficiency as a result thereof. And indeed, this is what we see. Again, in 2003, we clearly see the effects of the flexible pricing policy: a continuous decline in differentiation until 2006. In these years, because of the combined effects of operational efficiency investments and Volume growth, the Efficiency is continually increasing. As we already knew from the Performance score between 2004-2007, there is no improvement in the Differentiation-Efficiency combination. All that happens between 2004 and 2007 is a trade-off where lower Differentiation is compensated by higher Efficiency. We can only conclude that, in this period, any company investments in Differentiation potential, such as increased services and customer satisfaction are not (yet) paying off.

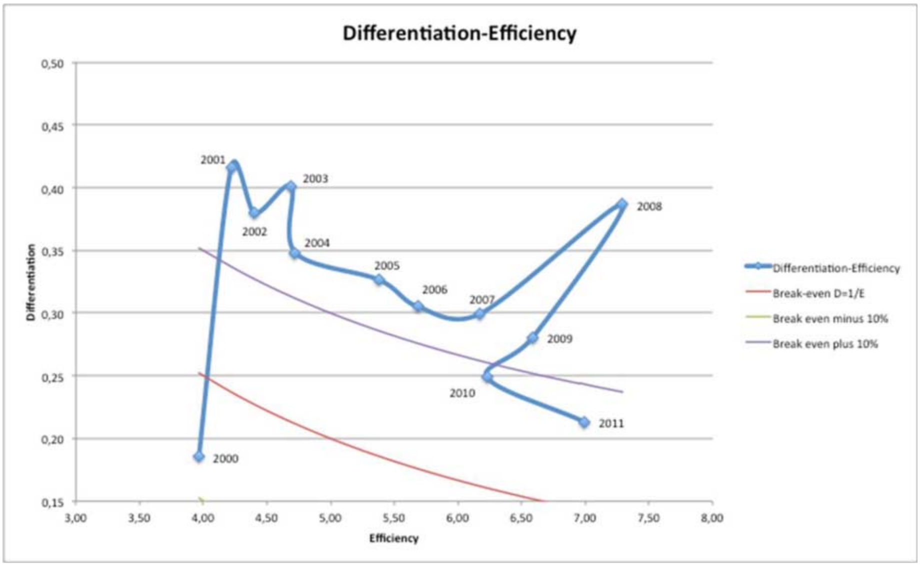

Figure 3. Turkish Airlines Differentiation-Efficiency analysis

In this graph, too, we see the exceptional nature of Turkish Airlines' performance in 2008: both Efficiency and Differentiation increase, which is a rare occasion for any company. As if all investments in Differentiation potential of the past years are paying off in one year, while the Volume and Efficiency growth from the 2004-2007 model still persist. The "dream" of the chairman's message in the 2007 annual report seems to become reality in just 5 years instead of the 25 years he envisioned. The 2009 crisis hits hard: because of the crisis, the company apparently tried to fall back to the successful 2004-2007 model. This means a decrease in Differentiation, which is not a problem in itself, were it not that Turkish Airlines is now a company with cost structure of a (full-service) differentiator and the revenue structure of a cost leader. The consequence is a fallback on both dimensions, which seems to put the company back on the track where it was heading after 2004-2007. For that to happen, the company should have changed course at the end of 2009 or beginning of 2010, to put full focus on Efficiency and operational excellence. Apparently, in that period, the company either did not recognize the danger, or was not able or willing to change course. The 2009 annual report is still boosting with self-confidence. Perhaps the still above-average Volume growth made the company somewhat less alert to the developments. One year later, in 2010, we see the turn: "With competition becoming increasingly tougher in today's aviation industry, financial discipline has emerged as one of the most crucial keys to achieving sustainable growth. Fully aware of this fact, Turkish Airlines continues to carry out its long-term, value-based growth program by shaping it around the principle of effective cost management." The 2011 figures show the result: a company that is back on track of its 2004-2007 Differentiation-Efficiency trade-off, though at a considerably lower Performance level.

III. Conclusion

This is where we are now: 2011 operational cash Performance was 7% and 2011 Volume growth in real terms was over 30%. Turkish Airlines is trading off lower Performance to higher Volumes and lower Differentiation to higher Efficiency. Financially speaking, this is the prototypical model of a low-cost carrier. Qualitatively, Turkish Airlines has the model of a full-service airline, with all the destinations, services, brand image and activities that are parcel and part of that model. Currently, the (qualitative) ambition and the (quantitative) financial results conflict with each other.

In our view, there are to be two important questions for the company to answer:

1. Is the current aviation sector situation the "new normal"?
2. If so, then how long is the current business and financial earning model sustainable?

The first question can essentially only be answered by the entrepreneur: the person with a vision, willing to take the risks and able to reap the benefits. Worldwide, there is a strong recovery from the 2008-2010 crisis. Of the important markets for Turkish Airlines, the USA outlook is still doubtful, Europe is in trouble, the Far East is relatively positive. The Turkish aviation market is booming and here the company should be able to reap benefits.

The second question is for the strategic management of Turkish Airlines to answer. How much lower can Performance get, before you are in low-cost carrier territory? How much Volume growth is necessary to compensate the low Performance? And: what kind of Volume growth will the market bear? Does the company realize the dire straits it is in? The quote from the 2010 annual report cited above suggests that the company is fully realizing the problem. The next sentence in the same 2010 annual report, however, reads: "Aviation Week, a leading aerospace industry weekly magazine, identified Turkish Airlines as the world's best airline in terms of financial health in 2010." This is, at best, a consolation: the current model combines the cost structure of a differentiator with the revenue structure of a cost leader. That is not a sustainable model, neither operationally, nor financially.

If Turkish Airlines wants to make the current financial earnings model sustainable, then it should accept that the dreams of the 2007 annual report might prove illusory. It should change course radically by focusing on Efficiency and operational excellence, as it did successfully between 2004 and 2007. The implication is for the moment to let go of the full-service concept in which in the past decade so much has been invested. The question is here: is the company able to put its dreams aside, at least for the coming few years?

The alternative is to move back to a financial earnings model that fits the full-service concept. Exactly because of the current cost structure and all the investments of the past years, Turkish Airlines still has a great capacity to Differentiate. The question here is: will the customer pay for it?

Such questions are not unique to Turkish Airlines: every full-cost airline struggles with comparable issues, some already for a longer period. For Turkish Airlines this is the first major test of its full-service ambitions. The current conditions of the Turkish aviation system are radically different from how they were ten years ago. As we showed in the first part of the paper, the Turkish aviation system is mature now. As we showed in the second part of the paper: the same is true for the strategic dilemmas of Turkish Airlines.

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Safety Management as an Aspect of Business Management

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Flight safety is a critical success factor for an airline. The whole airline organization plays an important role to achieve an acceptable level of safety but it has not yet been managed across all organizational levels as a business integrated system. Regulations issued by international authorities focus mainly on *what* kind of safety management activities should be executed. Safety science provides requirements for *how* the SMS should be structured. In this research I develop a model taking into account the *what* and the *how* to assist *where* to find safety topics. I will propose an airline safety management system which could become part of the airline organization business system. Both systems will be modeled using the same concept. One essential requirement is to translate operational safety into meaningful variables for each level of the organization. The Viable System Model and its foundation on cybernetics laws and principles will be used to describe an airlines control structure for managing the essential variable of safety. Every process needs to be managed to ensure a balance between efficiency and effectiveness. Cybernetics and the VSM in particular will be used to create in software an explicit organizational model including safety management to manage business concerns in the context of value production, under the increasing pressure of complexity and economy.

I. Introduction

Airlines, just like other businesses, must sustain a value exchange with their environment for survival. Passengers need to buy tickets for their flight, employees need to desire to work for the company to organize and execute the flights and investors need to provide financial means to buy aircraft and other assets. Value, therefore provides the context for organizational decisions, including safety management decisions.

Safety is a critical aspect for aviation and airlines. Accidents are very costly in terms of human live, equipment, environment and company image. Consequently an airline company requires an acceptable level of operational safety otherwise survival is uncertain. Safety needs to be managed vertically through the whole organization since all level decisions will impact on safety. Hence safety needs to be managed as an aspect of the business.

Many parties involved in the aviation industry are working on projects that will presumably (Achterbergh, Vriens 2010) increase safety even further. Regulatory bodies such as ICAO (International Civil Aviation Organization), IATA (International Air Transport Association), American FAA (Federal Aviation Authority) and EASA (European Aviation Safety Agency) are disseminating regulatory rules for safety management systems. All air service providers are working to develop their safety activities into compliant safety management systems due to upcoming regulations. These regulations and their supporting publications describe the SMS components and the requirement that safety management should be an integral aspect of the business (ICAO Safety Management Manual). The regulations mainly describe the *what* of SMS (Safety Management Systems) which is in itself insufficient to have effective SMS processes. The SMS components need to be enacted in managed processes. Safety science authors have put forward requirements for the structure for an effective SMS.

In this paper I propose a framework for management of safety integrated business in the context of value production. The framework will give a *how* answer to both mentioned requirements embedded in a value production decomposition of the organization. When a traditional functional decomposition of an airline organization is used into divisions such as flight operations, passenger services and ground services the context of value production might get lost. The consequence might

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be that the decision context isn't value production but division performance which is often a sub optimization which may even negatively affect other divisions' performance.

Management science can serve as a guide to develop business management systems including SMS. It reduces complexity and achieves a common language to model the business in the same way as the SMS is modeled. Safety management is a specific operationalization of management science, but in principle not different from other management topics. I will approach safety as a system control problem, using an appropriate theory called cybernetics and the adjacent areas of Control theory and CSE (Cognitive Systems Engineering, Hollnagel Woods 2005).

Safety is one of the many possible perspectives on performance. I will also discuss the factors that influence safety and other aspect performance. These factors are the result of organizational decisions and culminate in the flight operations. The relationships between organizational decisions and safety must be modeled and explained to become meaningful to all employees in an organization. Only if the relationship between one's work and safety is understood, safety can be part of decisions and (re)design criteria.

First I will introduce some relevant concepts for the modeling I use and what they mean for safety management. Then the VSM (Viable System Model) will be discussed which will service as the model for the organization and the model for the SMS. This is followed by safe flight operations design from a cybernetic perspective by nominating essential variables. The importance of value production for survival of the organization is discussed next. Then the aviation regulators and safety science SMS requirements are shown followed by a SMS modeled in VSM. Finally some screenshots of a software application that operationalizes all the concepts are explained.

II. Cybernetics

Organizations are like decision factories. Based on the understanding of their own situation and their relevant environment, people in organizations make decisions to achieve goals. Cybernetics as "the science of information and control in the machine and animal" as coined by Wiener in 1949 is concerned with goal directed system behavior. Cybernetics is a translation from the Greek 'steersman' conveying the image of dealing with disturbances and pursuing goals. The physical appearance of a system (machine or animal) is not important for cybernetic reflecting on systems behavior. Cybernetics is a trans-disciplinary science and used in areas of biology, sociology, engineering and many others. Management cybernetics is a specialization towards organizations its management and the challenges for achieving goals. Understanding some of the basic principles of cybernetics supports effective management.

A. Basic principles

Cybernetics provides a language that may need some introduction. Below are some of the basic principles that are used in the modeling.

1. System

A system is a concept with different definitions. Ashby (1956) describes a system as a set of variables chosen by an observer. The change of the variables over time represents the behavior of the system. A more popular notion of a system is the collection of parts, which may also be systems, which are connected, have interdependencies and show some coherent emergent behavior. System behavior in complex systems is more determined by the relationships between the parts than by the parts themselves. The physical manifestation of the system is not relevant for systems theory. Environment of a system is that what is outside the system and affected by the system and what is affecting the system.

2. Systemic versus systematic

Systemic means taking a systems perspective, focusing on the relation between the parts rather than on the parts themselves and is different from systematic but often confused. Systematic is in an organized manner and does not imply a systems view.

3. Variety

Ashby (1958) introduced the notion of variety as a measure for the number of distinguishable states a system can have. A (normal functioning) Dutch traffic light has a variety of three; red, amber and green. For complex systems, such as aviation and airline organizations, the variety is extremely high. At every moment a system and its environment can be seen as to occupy a state, the system state. This systems state is one of the variety possibilities. The system state space represents the possible variety of that system.

Another way of expressing variety is the number of distinctions that can be made (Ashby 1958). This introduces the observer since that is the one making distinctions. The properties of the observer such as his or her background determine the number of distinctions he or she can make. Without the capability to make distinctions all is equal and management is impossible. The count of variety is not important but the balance is.

Complex systems are high variety systems with many connections, dependencies, interacting and adapting agents (parts) . These systems cannot be fully understood and their development cannot be predicted (Snowden 2007, Hollnagel 2008).

4. Essential variables

Essential variables (Ashby 1952) are variables in a system that have to be kept within (physiological) limit for the system to survive in its environment. The variety of the essential variables should thus be limited. The human body has essential variables such as blood sugar level and body temperature. These variables must be kept within limits by the 'body management system' or we become sick when the variables approach the limits and we die if the variables exceed the limits. The concept of essential variables can also be used for organizations. I will use safety as an essential variable for airlines. Others essential variables could be finance, customer satisfaction, employees satisfaction, innovation rate, market position etc. Each business can nominate their own but it is argued that the set of essential variables is limited (Malik 2011). Some, if not all, variables just have to be accepted as essential, just like our body temperature which we can't choose ourselves as an essential variable. It is generally agreed that safety is essential for airlines.

5. Law of Requisite variety

The variety of the control system must be large enough to counteract the variety of the disturbances and maintain the variety of the essential variables within limits. This control principle is a consequence of what is called "the Law of Requisite Variety" (Ashby 1956). It is called a law since it applies to all regulating actions and no one can escape it. The Law of Requisite Variety states: "*only variety in the regulator (R) can force down the variety due to Disturbances (D);* variety can destroy variety**."**

6. Good regulator

Central to the science of cybernetics is the notion and control or regulation. For a regulator, (controller or manager are similar concepts) to be maximally successful in its function the regulator must have a model of that what is being regulated (Conan Ashby 1970). The variety of the model managers have about a problem limits the variety managers can expose on its operations (Fig 1.).

B. **Application**

These concepts applied on flight execution by pilots means e.g. that they can only deal with a failure (disturbance variety) if they can observe it (variety as distinction) and have means to act (variety in the regulator) upon the (possible) consequences of this failure (variety of essential variables).

These concepts applied on the SMS means e.g. that the SMS needs requisite variety to maintain the safety essential variable within limits. For the SMS to be effective, useful safety related distinctions (e.g. effects of organizational change, variety of disturbances) must be made and effective counter measures (variety of regulator) must be made or else disturbances may affect the essential variables of safety.

C. **Variety balancing**

The Law of Requisite Variety requires for effective regulation a variety balance between the system and its environment. If the variety balance is not managed or if the system lacks variety the essential variables are exposed to the disturbances from the environment and the system loses viability.

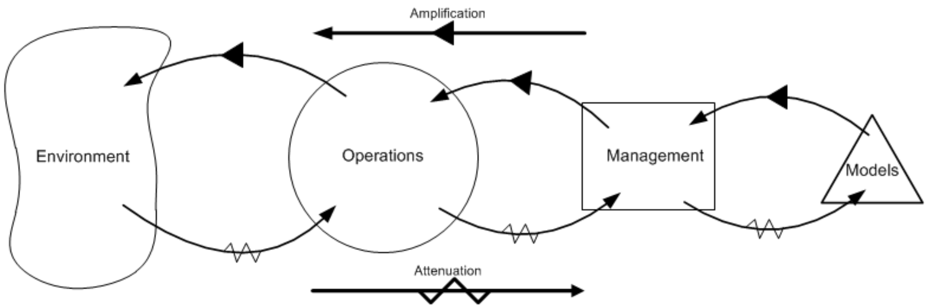

Figure 1. Basic work-system.

Fig 1. shows (Beer (1994) Clemson (1984)) a basic work-system with the relevant environment for particular operations, the operations itself, the function of management of the operations and the mental models available to the management function. For a balance in variety, the variety flowing (cascading) from left to the right must be attenuated (absorbed) and the variety from the right to the left must be amplified (increased) to achieve a balance. In this document management is a function and not a particular group of people. In my view everybody manages his own work and is therefore both manager and operator. Operations can be seen as 'the doing'; management can be seen as 'the thinking about'. This functional view is essential in cybernetics.

Since only variety can absorb variety, variety generators must be used to absorb (counteract) the incoming variety and to amplify the outgoing variety. Below are some examples of variety generators for a work-system flight and its environment.

Environment	Operations	Management
Weather (e.g. wind thunderstorms, snow) Number of surrounding aircraft ATC (Air Traffic Control) Etc.	Number of procedures Equipment Number of pilots (3 or 4 man crew) Experience of pilots Etc.	Experience and knowledge of captain and purser Company operational support Etc.

Safety management interventions can be classified as variety attenuator or as variety amplifier. An intervention on the wrong side of the variety balance will increase variety unbalance with possible tragic consequences. Below are some examples of variety balancing interventions that are used in the work-system flight.

Amplification	
Operations >> Environment	*Management >> Operations*
Advanced auto-flight systems (to balance ATC requests and increase number of type of approaches that can be flown) Weather radar (to balance weather variety) Etc.	Crew Resource Management training Policies (to increase effectiveness of crew collaboration) Pilot training (to increase the numbers of situations (e.g. technical failures) a pilot can deal with) Etc.
Attenuation	
Environment >> Operations	*Operations >> Management*
Aircraft anti-icing systems (to make the aircraft less sensitive to weather variety) Data-link communication with Air Traffic Control (to reduce communicational variety) Etc.	Standard operating procedures (to ensure standard(best) practices) Values and norms (to give guidance for solving problems that have no procedure) Etc.

D. Safety from a control perspective

Safety can be viewed from different perspectives. A perspective shapes the kind of interventions that will be made. A traditional view is that of broken components and non- compliance to procedures of people (the human as broken component). In ultra-safe industries, such as aviation, this view seems to have lost its effectiveness (Leveson 2004, Dekker 2005). This means that the interventions based on a safety analysis from this perspectives does not lead to overall safety improvements. Another view is a systems view on functional performance of a system (of systems). Unsatisfactory performance can be classified as a safety event (Hollnagel 2004). In the language of this paper safety is the ability to manage the safety essential variables within the desired limits.

E. Emergent properties

In general terms, sufficient for this paper, emergence is a concept to describe system behavior that cannot be contributed to individual parts of the system, but instead is the resultant of the interactions, interdependencies and adaptions of agents and parts in the system.

Safety is just one of the different perspectives on performance. Safety can thus be seen as a perspective on what the system does (Hollnagel 2008). Also Black (2009) describes safety as emergent property.

Safety as emergent property in a complex social-technical system cannot be controlled directly, but only indirectly. This indirect control, or rather influence, necessitates to focus on the design and maintenance of the flight operations, to create pre-conditions for safe operations, rather than only telling the operator what to do to stay safe. In complex systems weak signal monitoring can be used (as part of the event reporting system) to find positive or negative patterns of operations. Attractors are used to attract safe system behavior (Snowden 2005)

III. Safety management system as aspect system

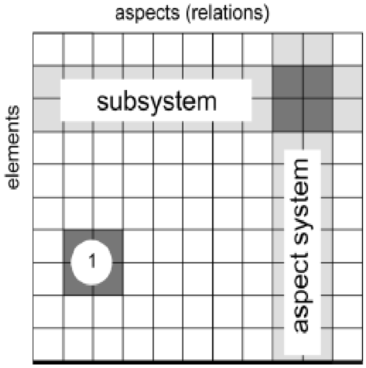

Figure 2. Aspect- and sub- systems

An aspect system (in 't Veld 1992) concerns all the elements of the larger business system but only a sub-set or single objective (Fig 1). All the aspects of the system are interdependent and combine in the total business system. Hale et al (1997) propose the SMS as an aspect system. Each aspect system is embedded in the environment of the other aspect system. This means all aspects are interdependent since a change in one results in changes in the others.

Currently, safety management has many characteristics of a sub-system approach. One of the reasons is that safety managers have been unable to translate the aspect of safety into relevant concepts for the different sub-system levels. E.g. network planning is not able to handle safety as aspect of their decision criteria, while some risk mitigation measures are very effective at this level, e.g. the risk of bird strikes. Bird strike probability is very much dependent on the time of the flight at the specific airport, and time of flight is a network decision.

IV. The Viable System Model

Viability, as used by Beer (1994), means the survival or preservation of identity in a changing environment. In a viable system the variety balancing act between environment and organization must function sufficiently. Three elements of a viable system are shown in Fig. 1. For clarity the three elements are shown separate while actual M (management) is part of O (operations) which is part of E (environment). In a viable system, the operations, those activities that produce the identity of the organization (e.g. flights for an airline), are regulated (through e.g. scheduling, accounting) by the management function. Organizational design (structure and processes) must include variety attenuation and variety amplification to provide requisite variety. Communication channels (reports, instructions, discussions etc.) must also have requisite variety for effective regulation, (e.g. a few lines in an air safety report provides insufficient variety for an effective intervention). The VSM describes five organizational functions which are together sufficient and required to support viability, these are enumerated as system 1 to 5:

1) System 1 Primary activities, implementation of the activities that define the nature of the business.
2) System 2 Conflict resolution, co-ordination, stability.
3) System 3 Internal regulation, monitoring, synergy, agreeing on autonomy and cohesion of system 1 at lower level.
4) System 3* Audit operations of system 1 based on an agreement (visit and look for unnecessary variety) between system 3 and its system 1s.
5) System 4 Intelligence, adaptation, scanning the outside for forward planning and strategy development.
6) System 5 Policy, ultimate authority, identity the norms and values that define the organization.

Systems 1, 2, 3, concern themselves with what is happening 'inside and now'. System 4 concerns itself with what might happen in the future, 'outside and then'. The rules of interaction between the two are determined by system 5.

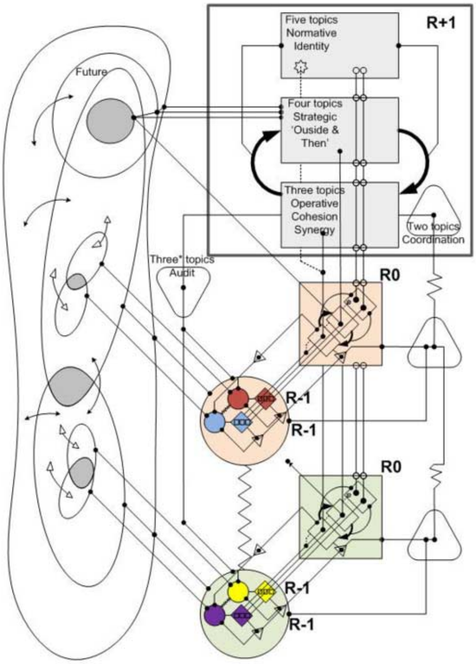

Figure 3. Viable System Model (3 recursions)

An organization, such as an airline company, can have viable parts such as passenger network transport and aircraft maintenance. Each of these viable parts can have again viable parts in it such as network regions or engine maintenance. (see also fig 5.) This demonstrates the concept of recursion (as a specific kind of level), where viable systems are embedded in viable systems and we can shift from one system-in-focus, to a higher or lower system-in-focus. In fig. 3 two viable systems are embedded in the system 1 of the system-in-focus. The VSM is not an organizational chart with people roles, departments and responsibilities but a model of the structure of the communication channels and interactions between the different organizational management functions. The VSM could also be seen as an information hierarchy where at each level only information from the lower levels is available. An issue must then be handled at a recursion where sufficient information is available.

I have argued (Dijkstra 2007) that the VSM also maps very well on the resilience-engineering concept as proposed by Hollnagel et al (2008). This means that the business- and SMS model based on and operated as the VSM provides important capacities.

V. Flight Operations design

The design of a flight, as a system, is the result of organizational decision about when to operate where, with what kind of equipment, what kind of vendors etc. The flight operation design options for an airline are limited by the regulations and what vendors (e.g. Airbus and Boeing) can deliver. The design must be aimed at safe flight operations. A safe flight means that the variety of the flight management system (crew and equipment) must have requisite variety to maintain the safety essential variables within limits. For the definition of safety I will refer to the concept of essential variables.

A. Flight safety essential variables

Based on the logic of the essential variables as explained above I have defined essential variables for a safe flight. ICAO defines safety in relation to absence of harm to people and damage to equipment. In the table below I show the people and airplane related essential variables.

System level	Essential Variables	Explanation
Aircraft	Airspeed	Airspeed is relative to the surrounding air and a variable in the aerodynamic envelope.
Aircraft	Altitude Height	Altitude is sensed by air pressure and a variable in the aerodynamic envelope. Height is distance between terrain and aircraft.
Aircraft	Ground track	A wrong ground track could result in an excursion of the runway during landing or take-off or collision with terrain during flight.
Aircraft / People	Accelerations	Strong accelerations in any direction may harm people especially when they are not seated with seatbelts fastened. Extreme accelerations may damage the aircraft structure.
Aircraft / People	AC Technical functioning	Failure of technical systems may result in the aircraft unable to fly, make a safe landing or maintain a viable environment for the occupants.
Aircraft / People	AC Structural integrity	Structural damage may render the aircraft unable to fly and or unable to maintain a viable environment (oxygen, temperature) for the occupants. Structural damage can occur when the aircraft hits another object (fuel cart, other aircraft) or the ground. Distance to other objects is therefore critical.
Aircraft / People	Distance to other objects	Structural damage can occur when the aircraft hits another object (fuel cart, other aircraft) or the ground. Distance to other objects is therefore critical.

I have not included the probability of an essential variable exceeding its limits. This refinement is not relevant for this paper. For the moment it is sufficient that if the aircraft arrives at an airport without passengers hurt and without damage we can speak of a safe flight.

B. Operational safety control influences

The flight (re)design must ensure effective control systems for these essential variables. Essential variables may go beyond their safety boundaries if the control system cannot absorb disturbances experienced during the flight execution. E.g. A severe wind-shear (disturbance) may cause the aircraft to lose altitude shortly before landing and crash before the runway (distance to other object). The unit of analysis for the flight essential variable control system can be viewed in another way then only the technical system provided by the aircraft manufacturer. I see the whole organization as constituting a layered essential variable control system. Each higher level decision is impacting on the lower level as a sort of pre-control (Schwaninger 1996). At the lowest level, the level of the flight execution, all influences come together in time and space and have their impact on operational safety control.

For more or less the same purpose but from different perspectives other categories of factors that influence (safety) performance are:

1) Basic Risk Factors (BRF), part of the TRIPOD model aimed at controlling human error (Groeneweg 2002)
2) Performance Shaping Factors (PSF), part of Human Reliability Analysis (HRA) modeling (Dougherty 1990)
3) Common Performance Conditions (CPC), Hollnagel (1998) wanted to include the context for a task as a whole instead of looking at individual events.
4) Delivery systems in the 'Dutch model', this is a set of management tasks that should enable safety operations. This model went through several development stages, initially should the delivery

systems deliver effective barriers, later the concept of barriers was replaced with operating in a safe envelope.

The first two taxonomies are mainly developed for modeling human error influences and calculate the Human Error Probability based on the view that a human is an information processor. The CPC from Hollnagel is more addressed at a human performance perspective rather than at a wider control system performance perspective. Lin (2011) proposes a next generation of the delivery systems based on her research into quantifying management influence on flight safety.

Further development of a set of safety control influencers is needed and this will be based on the concept of variety balancing showed in Fig. 1 the CPCs and a (VSM) model of flight execution. The challenge for safety management as variety balancing is to reduce the external variety and increase the internal variety of the safety control model, so it can maintain the safety essential variables within limits against a wider set of disturbances. E.g. Training and experience increases the models of the management function (the pilots) of safety flight execution. Each of the CPCs can disturb or improve the variety balance. The CPCs are shown on the variety balance in Fig. 4. A change in a CPC (e.g. more resources) can result in desired variety amplification or (e.g. poor training) in undesired variety attenuation.

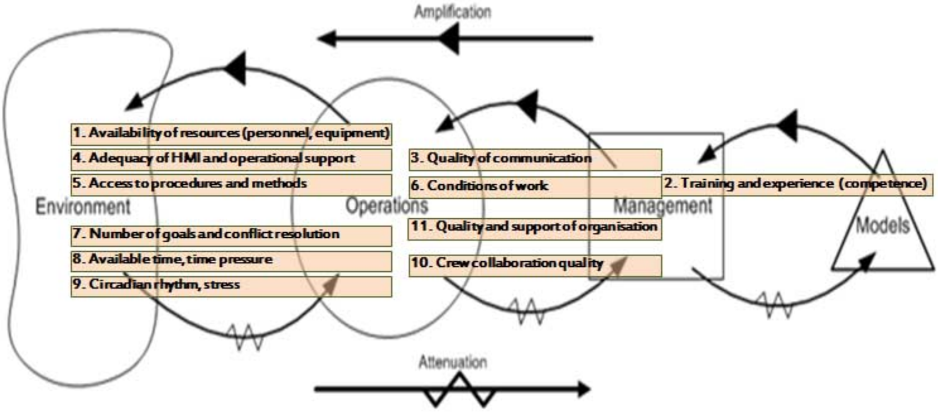

Figure 4. CPCs and their place in the variety balance

VI. Value production for organizational survival

Organizations can survive if they can sustain a value exchange with their environment. Value can be made more specified in the customer-, employee- and investor value and each value exchange must be sustained or the organization might vanish. The different values can be viewed as essential variables in the language of Ashby (1958). A poor safety record will negatively affect all three values and vice-versa. In a safety critical business such as aviation, safety can thus be treated as an essential variable.

A. Value as decision context

Value production is essential for survival and thus value production must serve as the context for business decisions. The complexity of an airline requires a logic to reduce it. The challenge is then to reduce the complexity of an organization into smaller systems while not losing the context of value production.

The logic of value production units (VPU) provides a way to reduce an airlines organizational complexity into smaller (VSM) systems and maintain value as a business decision context. Suppose a new destination is evaluated for a new route. This destination airport might give the airline a new flow of passengers via the hub, but it is located in mountainous area, with seasonal bad weather, air traffic control that is only used to local traffic, crew hotel facilities that are marginal to the normal standards. The business case for this new route should include all the essential aspects of the business including safety. To make the operation to, from and at the airport at an acceptable level, risk evaluations and mitigation measures must be found. The cost of the mitigation measures must be included in the business case. If safety management is a part of the operations part of the organization which is a sub-system, there is no natural infrastructure to include safety and the risk mitigating costs. The business case might then look more profitable without the risk mitigation costs. This is an example why safety management should be an aspect system.

B. Value Production Units of a hub and spoke airline

Airlines can be categorized by the structure of their flights network. Most low cost airlines fly point to point and provide no connecting flights. The passenger origins and destinations are limited by this principle. Another principle is the hub and spoke or network airlines. Via the hub many origins and destinations can be connected by just one transfer at the hub. I will use the network airline as an example to build a VSM VPU structure. British Airways, Lufthansa and Air France KLM are examples of network airlines.

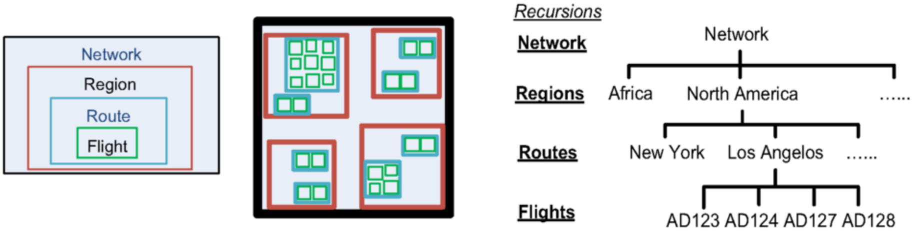

Figure 5. Systems embedded in systems

If we model a network airline the network can be taken as the highest recursion. It is the network way of offering transportation to the customer that determines part of the identity of the airline. The network in its totality is too complex to manage thus a reduction in complexity is required. The network can be decomposed into regions. The regions together constitute the network. Each region must be viable, for the network to be viable. Regions can be as large as South America or Asia and thus are still very complex to manage. The next step in decomposition can be the routes in each region. The regions remain viable if the routes remain viable. This is why we see airlines opening and closing new routes in search for more value production and thus viability. Since the value transaction with the customer is not on a route but on a flight we can decompose the route into flights that constitute the route operations. The frequency of flights on a route can be from one flight a week to several flights a day. It is at the level of the flight that a safe, comfortable flight is delivered to the customer.

This way of modeling provides us with viable systems embedded in viable systems. Each VPU has its own management and operations creating a sort of centralized and decentralized managed network structure. The autonomy of a flight is constraint by the route operations which is constraint by region agreements to fulfill the network requirements.

Now we discussed the cybernetic concepts for modeling an airline we will look at SMS requirements from regulators and safety science.

VII. SMS safety science models and regulations

SMS model requirements have been proposed by safety scientists and by aviation regulatory bodies such as ICAO, FAA and IATA.

A. SMS models from safety science

Hale (1997) describes safety management as a process that permeates all parts of the organization and in all phases from in service until out of service of organizational processes. In Hale (1997) several requirements for a SMS framework based on extensive literature research are listed:

1) It should model the complex, dynamic systems that the SMS exists in.
2) It must be able to focus in on elements of the system without losing the links to the whole model.

3) It must provide a common language to describe and model all aspects of the system.
4) It must be compatible with existing ideas and principles in safety management, quality management and the idea of the learning organization.
5) It must provide links to standard concepts used in management texts, e.g. the distinction between policy, procedures and instructions.
6) It should model both the primary (technological) processes with their risks and the management decisions which control them.

From this publication it can be concluded that the cybernetics and VSM approach to safety management in principle fulfills Hales SMS requirements.

Leveson (2009), referencing to the work of Rasmussen and Svedung (2000), proposes a control hierarchy in which the operation is placed at the lowest level. Upward in the hierarchy they model, in more or less the same language, operational management, company management and the regulator. From top to bottom each layer further specifies the operations. This model shows how flight operations are designed by many layers and several layers (regulators and government) are outside the direct influence of the airline companies. For Leveson putting safety constraints on system behavior is fundamental.

Somewhat similar to Leveson, based on a control theory and cybernetic perspective, Hollnagel (2008) describes five issues concerning safety management. These are the:

1) target, the way the target is operationalized into meaningful and manageable concepts.
2) control options, changing the way the organization and operation functions.
3) process model, a model of how safety is 'produced'.
4) nature of threats, the nature of the disturbances and threats that may reduce safety.
5) measurements, meaningful expression of safety performance which must be based on a model of safety.

Beard and Reyes (1999) were probably the first to propose a version of a SMS, namely a Fire Safety Management System (FSMS), using on the VSM theory. This FSMS is intended to maintain the fire risk of offshore operations at an acceptable level. Each VSM system has been assigned fire safety related issues as follows: System 1 is responsible for implementing fire safety policies in every offshore installation, System 2 dampens oscillations among all offshore installation operations, System 3 maintains the stability of system 1, System 3* is part of system 3; it is concerned with fire safety audit. System 4 deals with fire safety development and System 5 involves establishing fire safety policy. They are not explicit about the FSMS as an aspect system of offshore installations operations but the integrated view might be seen in their model drawings.

Since I use the same theory as the system safety scientists above their proposed SMS requirements can be used as references for the completeness of my SMS model.

B. SMS models from regulators

ICAO, IATA and FAA have published SMS regulations and guidelines. These are not scientific publications but aimed at users (state regulators, managers in airlines and other aviation related business) to provide them guidance and some explanations about SMS principles, structure and implementation issues.

The ICAO SMS manual version 2 lacks references to peer reviewed safety and SMS publications. This makes a review of the ICAO SMS theoretical foundations difficult. One of the objectives of the manual, stated in chapter one, is to provide 'knowledge of safety management concepts'. Some of the concepts the manual explains are the 'Reason organizational accident causation model', the 'SHEL' (Software Hardware Environment Live-ware) model and 'errors and violations'. Hollnagel (2004) classifies the Reason model as the second generation of accident models. Currently the third generation of accident model, the 'systemic accident models' are an attempt to overcome the limitations of the second generation. In a EuroControl publication (2006) Reason, Hollnagel en Paries revisit the 'Swiss Cheese Model' (SCM) and agree on the usefulness but also on the limitations. They state 'The SCM does not provide a detailed accident model or a detailed theory of how the multitude of functions and entities in a complex socio-technical system interact and depend on each other.'

Also Leveson (2004) and Dekker (2005) discuss the limitations of this second generation concepts. Common theories in the SMS safety science publications are the related theories of; control theory, systems theory and cybernetics. A word count in the ICAO SMS shows a single hit for systems theory.

The part where systems theory is mentioned states that knowledge of this theory is essential for the development of the concept 'Acceptable Level Of Safety' (ALoS). In the subsequent description of a hierarchy about indicators systems theory is not further discussed. The ICAO manual also lacks a basic control diagram showing feed-back and feed-forward principles which are the basis for a management system.

Based on the above observation I find the ICAO SMS is too narrow in providing safety management concepts and provides minimal support to integrate safety into the business. There might even be a risk that the ICAO regulations, if only based on their description of safety management principles, are incomplete from a systems, control and cybernetics theoretical perspective. The consequence could be that compliance does not lead to an effective SMS.

IATA has published (2009) an introduction to SMS based on the ICAO SMM. No theoretical basis is mentioned but the focus is on the activities that should be present in a compliant SMS.

The FAA has also published advisory material about SMS. The FAA SMS Advisory Circular AC120-92 (2010) states explicitly: 'The FAA SMS Framework is written as a functional expectations document. It stresses *what* the organization must do to implement a robust SMS rather than *how* it will be accomplished.' *Where and how* the SMS should be active and modeled is explained in this paper.

ICAO, FAA and IATA have agreed on the following SMS components:

1) Safety policy and objectives
    a. management commitment and responsibility
    b. safety accountabilities
    c. appointment of key safety personnel
    d. coordination of emergency response planning
    e. SMS documentation
2) Safety risk management
    a. hazard identification
    b. safety risk assessment and mitigation
3) Safety assurance
    a. safety performance monitoring and measurement
    b. the management of change
    c. continuous improvement of the SMS
4) Safety promotion
    a. training and education
    b. safety communication

It can be concluded that the safety science literature is mainly concerned with the 'how' of the safety management structure based and that the regulations and advisory materials are concerned with the "what" of SMS. A compliant SMS, based on regulations alone, does not mean effective per-se because airline company implementation needs to be control theoretical sound and that is not part of the compliance. An effective SMS based on safety science alone might not to be a compliant SMS, thus both should be included in an SMS proposal.

We can now use the requirements and cybernetic concepts to discuss the SMS modeled using the VSM.

VIII. VSM based SMS model

The correct VSM model of an SMS does not exist. The VSM can be used as a tool and the discussions that place between managers and modelers will create insights for both since the model poses questions such as what are primary activities (system 1), what are our safety norms and values (system 5). The software discussed below allows to test different models and show it to others.

Although a SMS might not be a viable system in the sense as Beer proposed we can still use the VSM concepts to model a SMS. The line of argument to do so is that safety is essential for an airline and safety needs to be managed since safety does not just occur. The management system that manages safety must, in order to be effective, contain the sufficient and required management functions. The VSM provides these functions. Kingston (1996) has explored the integration of health and safety using the VSM and concluded that it could be done but that the modeling was complex.

Another argument to model the SMS with the VSM is that if an airline's SMS does not contain the SMS components as stated in the regulations the airline's license to operate could be withdrawn. In that sense a compliant SMS is an essential variable for an airline organization.

A SMS should cover all safety related activities. These are both business activities that include the safety aspects and activities that deliver the know-how and support to handle safety issues. When we model this in the VSM we have at the highest recursion two operational units in Fig. 6 depicted as the SSMS (Safety Services Management System) and the CPC management system. Each of these two can be unfolded in its constituent systems as shown.

The business decisions at every recursion should be evaluated against each of the CPC in terms of variety amplification or attenuation and the net result of the variety balance on the safety control system of the flight. The effects on the variety balance should be hazard and risk analyzed; if undesired risk is noticed risk mitigation measures must be evaluated in terms of value production. Fig 6. shows how all the concepts are structured and connected. E.g. scheduling effects on the network level increase the environmental variety since it can schedule flights to busy airports in adverse weather situations. This must be counteracted by increase the internal variety by e.g. training.

The safety department is not the SMS but the SMS will span across organizational departments. The business is advised and supported by the safety department to take decisions that include safety in the context of their business processes. It is not the safety department that takes the safety decisions, they are working in a different context and do not carry business responsibilities.

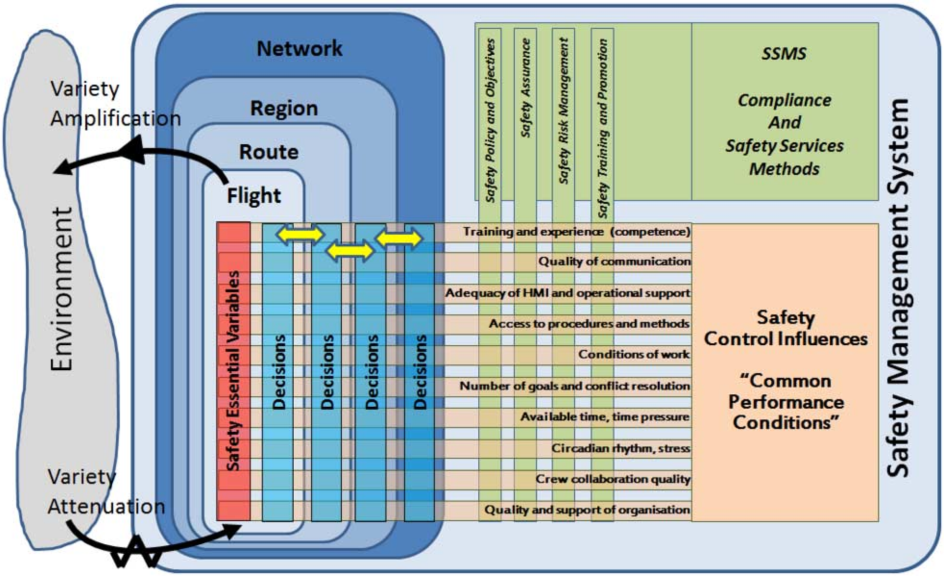

Figure 6. Intersections of business recursions, CPCs and SMS methods

A. The SSMS primary processes

The primary processes define the systems 1 in a VSM SSMS. As a start I propose to take the execution of the ICAO required SMS components as the SSMS operational units. This means that the SSMS provides the rest of the organization with proposals and development support for 'safety policies and objectives', 'safety promotion' and the subcomponents. Furthermore the SSMS manages the delivery of 'safety risk management' and 'safety assurance' support. By putting a VSM management structure around the component activities e.g. risk analysis, the sufficient and required management functions to maintain and improve the activities is enabled. The VSM model provides these functions and supports the responsible people to effectively and efficiently manage the activities.

Suppose we take risk analysis as example. When the SSMS views risk analysis as operational unit in a VSM structure the following answers have to be answered:

1) System 1 topics: What is it that our customer wants and what can we deliver?
2) System 5 topics: What are our safety ambitions, what is the identity of our risk analysis, what norms do we require, when shall it be used?
3) System 4 topics: What other risk analysis methods are there out in the world? Can we use them? Are there new regulations?
4) System 3 topic: How many risk analysis sessions can we provide? What are the required performance standard of these sessions? Is our method adequate, can we improve?
5) System3s: When do we audit a risk analysis session? What differences do we see across these sessions?
6) System 2: How can we coordinate between the risk analysis and our other services? What are the shared resources and how can these be divided?

This line of reasoning is the consequence of using the VSM and can be used for every SMS component we include in the model. The VSM provides a framework with issues which have to be taken into account. That is a benefit of using such as model. This way of modeling SSMS answers the requirements 1,2,3,4 and 5 as suggested by Hale and described above.

B. Management of safety pre-conditions via CPCs as primary process

Optimal CPCs support via the variety balance of the flight safety control system and thus improve safety performance. It is a management task to maintain the CPCs within acceptable limits across the organizational levels. In the proposed model I have nominated the CPC management as an operational unit (system 1) in the SMS. Doing so, it provides all the VSM functions such as: manage the interactions of the CPCs, to set quality standards for each CPC, provide resources and continuous improvement. This approach will improve the CPC set if required.

The tools and methods for risk management and safety assurance are provided by the SSMS.

IX. A software framework for managing safety as an aspect system of the business

An airline organization is a complex socio-technical system. Following the Conant Ashby theorem we must have a model of the organization for effective control. The law of requisite variety requires a high variety model to manage a high variety organization.

A. Mental models

In practice models of the organization are the partial, implicit, unverified mental models that reside in the heads of the managers. These fragmented models are supported by business balance score cards, performance indicators etc. The mechanisms that drive the indicators and values on the scorecards are often not made explicit and remain personal. Research has shown that often even apparent simple problems such as bath tub dynamics (Sweeny & Sterman 2000) can't be answered correctly by mental modeling. In 'The Logic of Failure' Dörner (1996) has shown that seemingly sensible steps in problem solving precede huge failure because of the *over-* simplification of the problems.

B. Software tool to amplify variety

There is a balance between complexity and usability. We can't use complex model without support. To amplify our variety we can use tools and therefor I have developed, together we two research friends (Steve Brewis and Richard Dijkstra), a software application. The software provides a building box for managers to model their organization using the VSM principles. By using the software, the managers can build a shared explicit model of the organization by combining all their individual knowledge. Without tools mental models can't evolve the complexity required for modern problems.

1. Business ontology

The VSM offers the required functional management and informational structure but lacks, due to its generic nature, the common business concepts such as department, processes, resources, products etc. Business concepts provide the language to discuss business issues. Together with Steve Brewis, a senior researcher, we developed a business ontology; a set of business concepts where each concept is required and together they are sufficient for a particular problem space. This ontology should provide sufficient variety to describe most relevant business issues but it should be limited enough to prevent unnecessary variety. The ontology was checked for completeness by comparing it to other ontologies such as Essential Architecture from essential®. The ontology was the basis of the software class and data structure design.

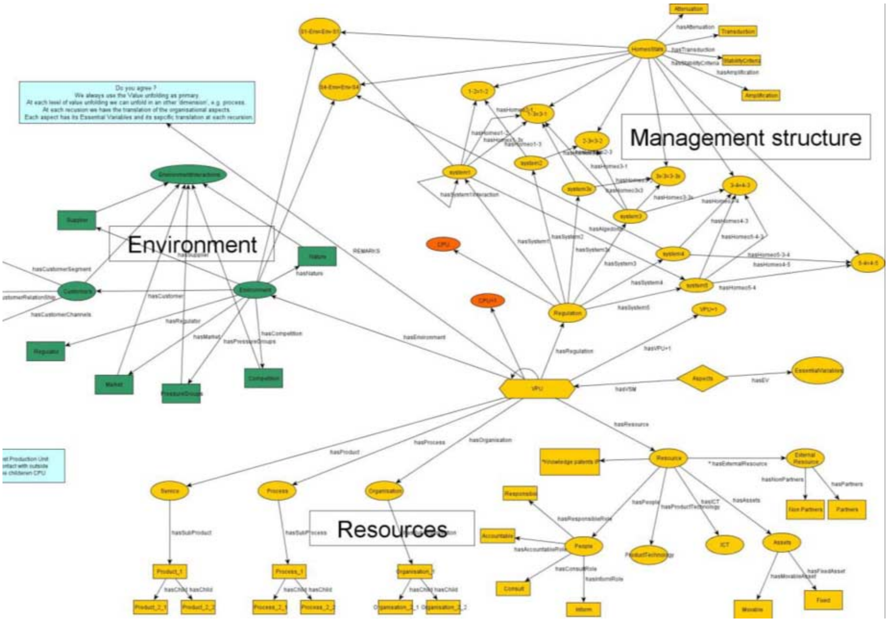

Figure 7. Business ontology

The ontology diagram shows concepts and relationships. An organization can be seen as a complex network with many relationships and interdependencies. The data model that we use can absorb most, if not all organizational relations, because we use the concept of a triple (subject predicate object) to define relationships. We use also graph structures to visualize an area of interest.

2. iManOps (I Manage Operations) business management software framework.

iManOps (working title) is the software we are developing in Python (Open Source object oriented programming language). We use this software to build, maintain and use a high variety organizational business model. A high level description of the ambition for the software is that it should serve as a navigation system to navigate the dancing complex value landscape in which an organization tries to remain viable. The landscape represents value, the dancing represents the complex nature since many interdependent actors influence the value landscape. A navigation system is required since we can never sit still, the organization must constantly adapt. We aim initially for the software to be used in an operations room (board room), facilitating decision making.

The structure of the organization defined in iManOps can be populated by data from the organization via linkages to the data warehouses. By using this data and the defined structure iManOps provides a VPU data view on the organization and its processes. In a sense iManOps provides the logic to create the value production units as virtual business units. A main function is to navigate through the value structure to the desired part of the organization and select that part as system-in-focus. Each system-in-focus is a VPU which has parents and children. These upward and downward relations are relevant to understand the behavior of the system-in-focus. This illustrates the systemic perspective. Within the context of a VPU the software can zoom into and navigate through a hierarchy of the resources and processes.

The view on the organization has different modes. A value selection shows the combination and high level summaries of the different business aspects. It is also possible to select a particular aspect, such as safety. In this aspect view only the aspect relevant issues (relations, processes etc.) in the selected VPU are visible. This could give us e.g. a view on the safety performance at route or region, or the safety hazards in the processes in the VPU of the flight. This is the area of integration between the business aspect and the safety aspect.

The software provides a systematical (structured) and systemic (relationships and interdependencies) approach to business and safety management. With this software we can test the consistency, completeness and applicability of the model we are building. By discussions in various businesses we test the concepts to get feedback that helps to improve the modeling and software. Below are some screenshots of the prototype.

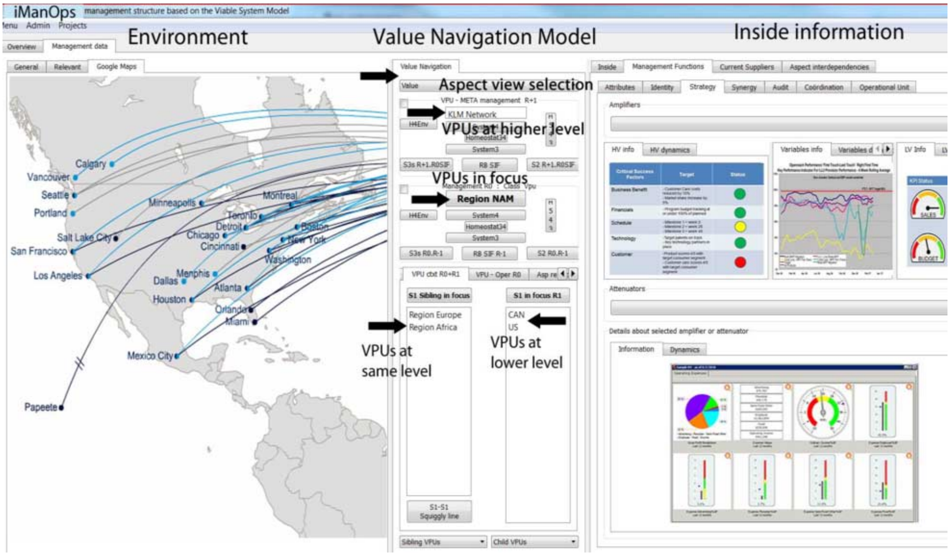

Figure 8. iManOps main window screenshot

The section in the middle is for navigation through the value structure control model. The buttons are for access to VSM functions and provide a context sensitive menu. The left section provides access to the relevant environment for the VPU selected as system-in-focus in the middle navigation tab. The relevant environment consists of; customers, competition, markets, pressure groups, media, regulators and suppliers (Hoverstadt 2008). These parties make the value landscape dance. E.g. a new route to Manila might be a good plan today but if the competition starts tomorrow with an A380 on the same route the value landscape goes down. This is the area where business opportunities and risks can be found that have to be considered and which shapes the internal behavior shown in the right hand section. The right hand section with inside information is where the traditional business balanced score cards and cockpit indicators are shown. An important difference with the popular dashboards and other indicators is the implementation of the control model in the middle section which would otherwise be only a mental model. The software makes the model very explicit which makes it almost intuitively understandable creating a shared mental model.

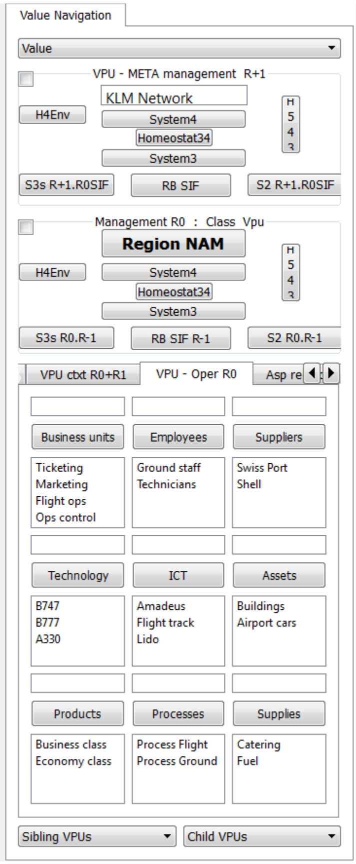

Figure 9. VPU Region NAM and its business entities.

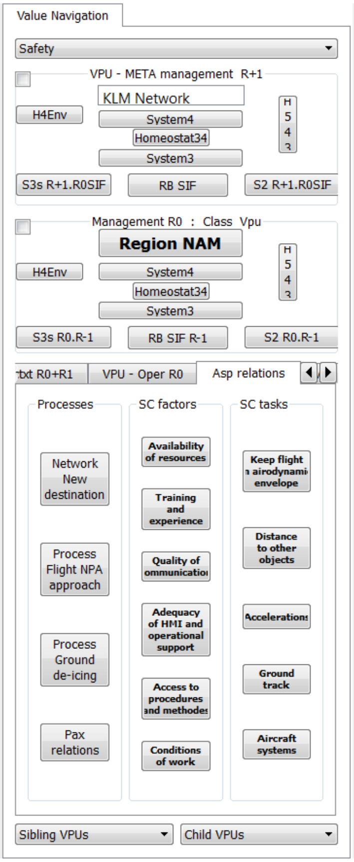

Figure 10. Safety perspective on VPU processes, safety in value context.

Fig. 9 shows the navigation tab with the 'Region NAM' in focus, and a value perspective. The tab 'VPU – Oper R0' shows the business ontology concepts. These are populated with the relevant data for this VPU in focus. Each of these concepts can be brought into focus to model its management process, e.g. the process flight must be managed.

Fig. 10 shows the same VPU in focus but now from a safety perspective. This is an operationalization from business and safety management integration in the context of a VPU. The business processes must be risk managed. The 'SC factors' represent in the prototype the CPCs. On the right are the 'SC tasks', there are the safety control tasks to maintain the operational flight safety essential variables within limits. Each combination of process, SC factor and SC tasks must be analyzed for hazards and risk mitigation. The costs of the risk mitigation must be evaluated in the context of the VPU. E.g. for a new destination (process) new training might be required (SC factor) to stay clear of object (mountains)(SC task).

Fig. 11 shows a graph with all the relations that currently are entered and generated by the application. A graph representation gives a richer view on the organization then spreadsheets and graphs provide special ways to interrogate the data which are hardly possible with relational databases. Every aspect of the graph; the size of the nodes, the thickness of the lines etc. can be used to show high dimensional data.

The next step for development is to try to populate the model with 'real' data and discuss the usability with relevant managers. Introduction of the new concepts in iManOps in an organization will probably create some anxiety. We try to add functionality to facilitate the discussions managers will have when that start modeling their organization. The result of the discussions is the model. Remarks can be registered for most of the items added to the model.

The iManOps framework is in principle generic, since the VSM is generic, and every organization can be modeled not just an airline. We will continue to develop extensions of generic functionality and specific plugin modules.

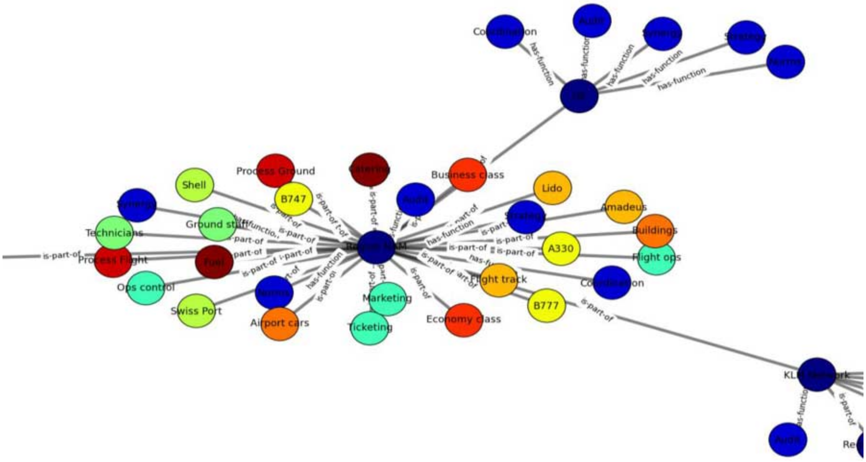

Figure 11. Business relations as network graph.

X. Conclusions

Complex challenges, such as integrating business management and safety management need rich requisite models. The VSM provides a generic structure that can be applied on every management problem. It also gives us the required variety amplification in a very efficient manner to deal with the complexity we encounter by its self-repeating nature. Regulations state *what* safety management components should be installed. Safety science provides us the theory and requirements for an effective SMS structure. In this paper I described *how* the regulations and safety science requirements can be modeled and also *where* the safety issue can be found. The VSM SMS approach enables and requires to model across all organizational layers for an aspect system model. The proposed model is based on a value production structure of the organization which provides the context for all business decisions including the safety aspects. This approach makes safety an aspect system of the business system. Software has proven to be critical in developing the required complex modeling and can be used during ongoing research to test alternative models in the challenge for continuous improvement and organizational viability.

A safety management system must not be viewed as an application running on a PC in the corner of the office it must be viewed as a business holistic system endowed with structure that it is able to adapt to situations it had never encountered and achieve continuous improvements. I hope that in this paper I have provided a new way of looking at management in general and safety management in particular by making the use of models explicit and providing the business and safety management system the capability to manage itself and achieve its goals.

XI. Acknowledgements

I like to thanks my think thank friend Steve Brewis for his continuous reflecting and checking my thinking and logic of reason. Also I like to thank my professor Andrew Hale for his patience and feedback. My brother Richard has been very helpful in converting the ontology design into software. I thank the grand system thinker Dries Blommers who sees relevant connections that others have never thought of and who has stimulated me to keep on going. I hope we can all continue on this exiting journey.

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Applying proven methods in a new environment: the case of LEAN in Business Aviation MRO

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Many authors claim that LEAN principles can be applied successfully in any industry. Although LEAN success stories are visible throughout the automotive sector and even in larger aerospace Maintenance, Repair & Overhaul (MRO) facilities, the implementation in smaller MRO organizations seem to be lagging behind. This research describes a study to translate LEAN principles and tools into a small MRO organization. A LEAN pilot project has been initiated within JetSupport B.V.'s work preparation department. Initial results show that large benefits in throughput can be generated. Additional recommendations are given that include mapping of the total value stream of the base maintenance process to prevent departmental sub optimization.

I. Introduction

THIS research describes a study to translate mainstream LEAN methodologies into the small aircraft Maintenance, Repair and Overhaul (MRO) environment of JetSupport B.V. In addition it discusses the application of Value Stream Mapping as LEAN tool in the work preparation process and recommendations on future steps for LEAN implementation.

In 2011 JetSupport was introduced to the LEAN methodology thru the participation in a roundtable discussion on LEAN MRO. Results from this discussion indicated that a relatively large group of small MRO providers in The Netherlands were either not using LEAN to optimise their processes or failing to sustain their efforts.

This observation suggests that these smaller MRO organizations are facing a double challenge. LEAN implementation seems to be hindered by typical small business characteristics such as lack of long term vision, limited resources and low volumes. And in addition the typical MRO work (i.e. high variation, unpredictable processes) does not allow for a quick translation of LEAN principles which are so abundantly available for the mainstream manufacturing facility.

Regardless of the sceptical view on LEAN for this particular sector, JetSupport showed an active interest in the subject and was ready for an experiment.

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A. Statement of problem

The research aims to overcome LEAN implementation obstructions by translating available LEAN best practices from literature and adapting them to JetSupport B.V. LEAN methods and tools are discussed and tested within the organization and recommendations for further LEAN implementation are given.

B. Theoretical background

1. LEAN, creating customer value and reducing waste

Defining LEAN is a challenging task. Some regard it as a set of tools to solve isolated problems, others as a set of guiding principles to radically change an organization.[1,2] LEAN could be defined as a set of tools and principles that in the end allow for an *efficient use of resources through the minimization of waste. Lean manufacturing focuses on reducing wastes and non-value adding activities of many types*.[2]

LEAN forces an organization to look at its processes thru the eyes of the customer and to optimize its processes accordingly. It revolves around a set of 5 core principles, being: (1) defining customer value, (2) identifying the value stream, (3) creating flow, (4) introducing pull, and (5) striving for continuous perfection.[3]

To establish an optimized process a set of LEAN tools and techniques are available such as value stream mapping, one-piece-flow, strandard work, kaizen, visual management, 5S, kanban, and just-in-time. Although it is important to understand the variety of tools available, and are summarized in Ref. 4 and Ref. 5, a detailed discussion would go beyond the scope of this paper.

2. Barriers to LEAN implementation

Many authors claim that LEAN methods can work in any company in any sector if the commitment is there.[3,6] Good examples of LEAN can be found in many larger production type of organizations such as Toyota, Boeing, and SCANIA where large savings and efficiency improvements are seen and LEAN is part of *daily business*.[7]

Introduction of LEAN into the large aviation MRO sector (e.g. KLM Engineering & Maintenance, Lufhansa Technik, FedEx) show that benefits can also be obtained in other areas than production alone.[8] Literature also shows that LEAN has even found its way into the Small and Medium Enterprises (SME).[9] LEAN implementation within small organizations however also brings along specific challenges not seen at larger organization. The industry focus for this particular research is on those companies that can be characterized as MRO and SME. From interviews and panel discussions held with representatives of several smaller Dutch MRO organizations, we concluded that a relatively large group of these organizations are either not using LEAN or failing to sustain their initiatives.[10]

We argue that LEAN implementation at these small MRO organizations are hindered by challenges particular to the small business in addition to the characteristics of MRO work. MRO work is often characterised by its extremely broad work scope, changing demand and unpredictable outcome of inspections followed by long, highly variable, repair times.[11] These characteristics seem to be far away from cases often described in available LEAN literature.

Others have concluded that it is the small business environment that brings specific challenges, inhibiting implementation of continuous improvements efforts such as LEAN. Small businesses often lack the required resources (i.e. time & money) to sustain LEAN efforts.[12]

C. Research question

Due to the lack of readily available best practices for a small MRO environment, this research is focused on identifying suitable LEAN principles for application within SME MRO companies, taking JetSupport B.V. as an example. The study includes facilitating a LEAN initiative within the work preparation department of JetSupport and recommendations for a long term LEAN initiative within the organization as a whole.

II. LEAN at JetSupport

A. JetSupport BV organization

JetSupport is an EASA approved aircraft maintenance organization that is identified as a SME. It is located at Schiphol Airport and is specialized in a wide range of technical services. With a staff of 55 people it offers base and line maintenance for the business aviation segment, including maintenance for public services like the Dutch coast guard. The business aviation segment is small (i.e. low volumes) and demanding.

Activities within the maintenance department evolve around two basic maintenance services, namely line maintenance and base maintenance. Line maintenance is characterized by ad-hoc problem solving, quick servicing of a variety of aircraft, usually on the tarmac, while base maintenance usually involves more labor intensive scheduled inspections that are only performed inside the available hangars.

JetSupport has been growing rapidly since the startup in 2001 and it has identified the need for process improvement to get more grips on their internal processes.[13]

The current organizational structure is that of a typical functional organization (Fig. 1). A maintenance manager is responsible for the aircraft maintenance process and manages the production department, the duty managers, material management and production support. The actual aircraft maintenance is performed under the responsibility of the production department where a team of ground engineers work to release the aircraft back to service. Production support creates the bill of work based on customer request and also gives general support in case technical questions arise during the maintenance process. Material management is responsible for provisioning and providing all material and tooling needed during the maintenance process. Part of material management is a stores facility, which houses the most common consumable materials and tooling.

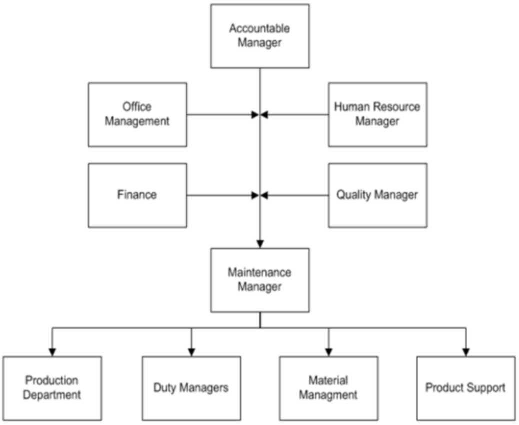

Figure 1. JetSupport Organization.

Since JetSupport is EASA certified it also has an appointed Quality Manager outside the line organization. The Quality Manager ensures regulatory compliance by the organization and reports directly to the accountable manager.

B. LEAN pilot project – JetSupport production support

A common way to start of with LEAN is the application of LEAN principles within a small and manageable pilot project. Therefore the current study was initiated within the JetSupport production support department. The process of interest was work preparation for storing an aircraft. During this process, production support generates a workpackage for the mechanics to prepare the aircraft for prolonged parking. In addition it gives instructions for continued airworthiness during the aircraft storage period. The output of this process is a workpackage consisting of work instructions, relevant technical documentation, and required material and tooling.

1. Defining customer value

One of the crucial starting points of LEAN is the definition of value,[3] which can only be defined by the customer. The design of a LEAN process revolves around maximizing customer value. Since the selected process is internal to the organization it is necessary to identify the internal customer to the process. The internal customer was defined as the production department, since this department receives the work package from production support. Value for this customer was defined as a *flawless, clear and timely* workpackage Any workpackage leaving the production support department or any process leading up to such a package should be designed so that this value is maximized.

2. The (current state) value stream

The value stream is defined as those processes necessary to bring the product or service to the customer. In a typical production environment this includes raw material flow, but also information flow from supplier to the customer. Defining the current state of the work preparation process is essential in identifying process waste and bottlenecks. A common LEAN tool used to identify the value stream is Value Stream Mapping as discussed in Ref. 14. During this process people from outside the process (i.e. internal customers and suppliers) and internal to the process (i.e. staff of production support) are involved to identify the current state of the process.

Figure 2. VSM (Current State) work preparation

Individual process steps and communication lines for the work preparation process were written down (Fig. 2). This was followed by the identification of the seven types of waste which where clearly present. Any additional problem or difficulties that surfaced during the meeting that had a clear negative effect on delivering a *flawless, clear and timely* work pack were also identified.

The current state consisted out of 10 sequential process steps with a total cycle time of at least 3 hours. Various bottlenecks and delays in the process were identified. Work standardization seemed to be lacking in certain parts of the process. In terms of waste the following types were identified: overproduction, waiting, motion, defects.

3. The (future state) value stream

The next step recommended by Ref. 14 is to map the future state value stream (Fig. 3). The future state is the blue print for the new process and will directly result in an implementation plan. It involves designing a new process where creating customer value and designing a waste free process is leading. The same group of people as those involved in the current state mapping were involved in creating a LEAN process. The participation of people that are currently working within the process is essential in two ways. Involving people from within the process during this stage is valuable because they often know best how a process works. In addition it stimulates acceptance of a new process because they have been involved creating it.

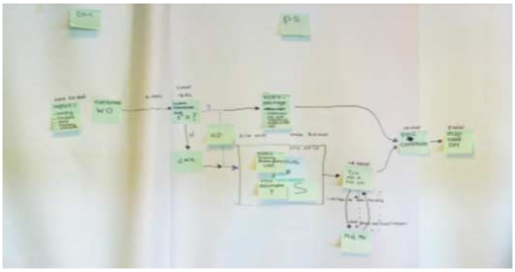

Figure 3. VSM (future state) work preparation

The future state process was designed with less than 5 sequential steps with a total theoretical cycle time of 40 minutes. Individual responsibilities were clearly defined and initial requirements (i.e. built in quality) for the work order were created, preventing unnecessary checks later in the process.

4. Implementation and trials

The difference between the current and future state value stream map results in a set of required actions necessary to operate with the newly designed process. Since the selected process was relatively small and manageable the newly designed process could be easily implemented without much investment. Students participated in a time trial study to verify the benefits of the new process. Trials showed that working the new process would lead to an estimated 80% improvement in cycle time compared to the current state process if it would be perfectly adhered to.

C. Analysis

LEAN principles were applied on a small scale within the JetSupport production support department. The application of Value Stream Mapping as LEAN tool resulted in a number of tangible and intangible improvements. The concept of value added and non-value added activities were introduced and built in quality was created to prevent needless quality inspections.

Not only can the cycle time for the work preparation process be reduced significantly, the staff was also stimulated to participate in problem solving and people could see LEAN working for them. Towards the end of the value stream session, staff members showed an active interest into improving their own processes. Value Stream Mapping allowed staff members to visualize and agree upon problem areas and it provided an instrument for continuous improvement.

When looking at the potential cycle time reduction one can see that a very significant reduction in cycle time was realized, but the theoretical cycle time was not achieved during the trial (Fig. 4). Because the work preparation process is so interwoven with the rest of the organization parts of the new process could not be executed and deviations from the ideal future state process were necessary.

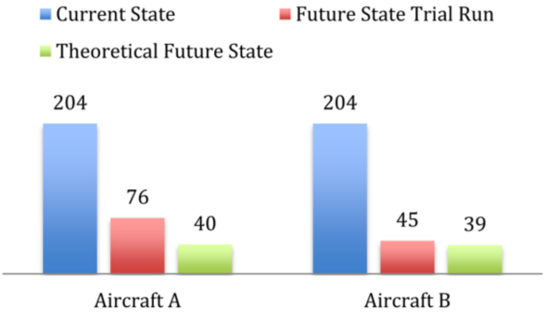

Figure 4. Cycle Time comparison (in minutes).

Another problem that surfaced was that a process improvement in one isolated area of the organization did not necessarily lead to a better overall (e.g. base maintenance) process. In other words, although applying LEAN on such as small scale could be manageable and good for LEAN acceptance, it might negatively affect other departments. For example it might be very interesting for product support to flow a work order thru the process as quick as possible, but it might create excess products (i.e. work packages) within the production department.

Although the main business process of JetSupport (i.e. aircraft maintenance) is unpredictable in nature, the supporting processes like those of production support seem to have great similarities with administrative processes seen in other industries. Value Stream Mapping therefore also seemed perfectly suitable in this environment. Experiments with more extensive LEAN tools such as kanban, 2-bin, flow and such were not performed at this stage. Instead the focus was more on creating process stability first.

D. Recommendations for further LEAN implementation

As presented, Value Stream Mapping was successfully used to achieve process improvement and proved to be a suitable tool for this environment. Significant cycle time reduction was achieved, but sub-optimization occurred. To prevent sub-optimization it is advised to perform a value stream analysis of an entire product or service family.[14] An example of such an analysis would be value stream mapping of the entire base maintenance process. This would involve departments such as sales, duty management, production support, production, material management and finance. Although door-to-door value stream mapping in a large organization is almost an impossible task, it would be feasible in the relative small size of JetSupport.

III. Conclusion

A successful initial application of LEAN was performed within the production preparation department of JetSupport. Value stream mapping showed to be a suitable tool within this environment to analyze and improve current processes. In addition to tangible cycle time reduction for the preparation of a work order, the technique stimulated staff participation in improving their processes. Principles such as waste, built-in-quality and customer value were applied and seemed suitable in this environment as well.

These initial results show that basic LEAN principles such as value stream mapping also apply in a small MRO environment. In terms of typical small business characteristics possible hindering a LEAN implementation we encountered a strong operational mindset and limited time available by project team members. Intensive external facilitation of the project by research students, especially in the startup phase of the project was necessary to ensure project continuation. The small business environment on the other hand allowed for staff from all levels of the organization to be present at value stream sessions, which increased LEAN awareness throughout the organization.

Value stream mapping was performed on a small scale. The high variation in product range and input which is typical for a small MRO facility, made it difficult to accurately estimate processing times. Even though this resulted in a lack of detail, the overall logic of the process could be easily optimized. Further experiments with more advanced LEAN tools such as one-piece-flow, strandard work, kaizen, visual management, 5S, kanban, and just-in-time are necessary to see if they are applicable in this environment.

In the mean time follow-up research at JetSupport focused on mapping of the total value stream as recommended. This includes the entire base maintenance process and all the previous mentioned departments. A future state is currently being finalized and implementation projects are underway. Additional, similar project are underway at other airframe MRO facilities in The Netherlands and Sweden. Thru these experimental LEAN research projects, LEAN tools and principles are being tested and implemented. The project gradually creates more knowledge on the suitability of LEAN within the small and medium MRO sector, while allowing for a gradual LEAN implementation at these facilities.

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Moonshine: employee-involved workplace innovation

An exploratory study

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Abstract

Moonshine is the practice of workplace innovation in which the end user plays a prominent role. The KLM Engineering & Maintenance moonshine program uses a prescriptive moonshine process model. This paper describes the development of a moonshine process model from practitioners' literature. The model is tested in twenty-three cases of employee involved workplace innovation at KLM Engineering & Maintenance. We found additional activities used in practice, and found activities depicted in the model but not used in the cases. The iterative and recursive nature of moonshine was observed. Variables affecting moonshine were found in the case study, which are used for constructing a research question for future research into moonshine.

Key words: moonshine, innovation, workplace innovation, teams, continuous improvement

I. Introduction

Toyota, Boeing, General Electric and KLM have adopted moonshine as part of their Lean strategy to continually improve their processes. Ever since its conception moonshine has proven to be successful in terms of quality improvement, shorter development time, better products[1], cost savings, waste reduction, efficiency increases, and reduction of the carbon footprint[2]. Apart from these hard organizational benefits, moonshine also contributes to improving intangibles like workers' satisfaction, morale[3,4], safety[1] and workers' pride[4]. This paper describes an exploratory study into a moonshine process model using cases from KLM Engineering & Maintenance. The study is also aimed at finding topics for new research into moonshine.

The KLM Engineering & Maintenance (E&M) moonshine program was introduced 'the moonshine way', i.e. using available resources in its broadest sense. Contrary to Boeing, where being a moonshiner on a full time basis is a prerogative for the most creative employee, the KLM E&M program was to be designed around part time availability of 'not-necessarily-the-most-creative' employees

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when workload would permit this. The next preliminary assumptions were made, each of which will be discussed below:
- Leading role of end user
- Involvement of all end users
- Part time availability of end user
- Everyone is creative
- Moonshine road map

The leading role of the end user in every stage of the moonshine process is vital for the acceptance and thus implementation of any solution. Better still, being involved in prototyping and subsequent continued development is the best way to ensure that the solution fits the end user's needs. Involvement of end users is required to obtain a high quality solution that will be accepted by all parties. Acceptance of a solution within one unit is a challenge in itself. Preceding it is the acceptance of a solution within a team of different end users, who will only accept each other's solutions if they understand each other's problems. This is achieved by sharing insights on the respective problems. Building on each other's solutions is imperative for reaching a solution with a high chance of being accepted by all parties involved. Part time availability of the end user is both a facilitator and inhibitor of moonshine. It increases the throughput time of a project and at the same time allows for time to contemplate and to incubate ideas. In addition, the part time nature of the moonshine activities ensures that team members don't get detached mentally and physically from their own working environment. Through continuous interaction with co-workers, feedback can be given first handedly and in a direct way, which leads to qualitatively better ideas. More importantly, employees accept a solution from a co-worker better than from an outsider. The moonshine manager believes that everyone is creative to a certain extent in a certain area[5, 6] and estimated that the challenge would not be in finding creative people but rather in unleashing the abundant creative power of the 5000+ KLM E&M employees. With substantial experience as a project leader and facilitator in different organizations, she realized that she would play a key role in coaching the inexperienced ad hoc teams and in managing the organizational environment. In order to manage the program and the teams, the program manager expressed the need for a 'moonshine road map'. More specifically, she required a moonshine process model and generic design principles.

In this paper, we first deal with the research objective and the research method of this paper, followed by the results of the literature research. We then describe the preliminary moonshine process model and test this in the cases. We conclude this paper with an answer on the research question and discussion of the limitations and roads for further research.

II. Research objective and method

No research has been done before into the field of moonshine and therefore we conducted an exploratory study to get acquainted with this relatively new practice. The primary objective of the research is to make a contribution to the body of knowledge of moonshine practitioners. An exploratory study showed that no moonshine models are available, so we decided to model the process. The main research question (RQ) therefore is:

RQ: How can the moonshine process be modeled?

In particular, the study aims at identifying the activities that comprise the moonshine process. In addition, the possible sequence of the activities and their interaction is researched. Furthermore, we want to identify topics that affect moonshine for future research. This paper describes the results of the study that comprised two parts each of which will be discussed below:

A. A literature review to model the moonshine process and its constituent activities
B. A case study in which:
    - the moonshine process model is tested (preliminary)
    - research topics are identified for future research

A. Literature review

The scholarly and 'real' practitioners literature make no mention of moonshine. For this exploratory study an Internet search was done using 'moonshine' and 'moonshining' as keywords. Results from the search were articles published in professional online magazines such as Boeing Frontiers online and Shipyard Log. The majority of the articles contained descriptions of real life experiences with moonshine, such as the activities pertaining to moonshine, the important topics that moonshine focused on and keywords that express the essence of moonshine. On reading the articles the word '3P' (Production Preparation Process) came up regularly. It is considered an addition to the normal way of moonshining[7, 1]. Therefore the literature review was extended to include articles on 3P, a product development practice in which design engineers work in tandem with manufacturing process engineers[8]. In addition to the Internet search, Boeing and KLM presentations were used to identify the same topics.

A database was built containing the worksheets 'key elements' and 'activities'. All articles were analyzed and individual words and parts of phrases were input in the corresponding worksheet together with a reference to the article they originated from. The 'key elements' worksheet contained words and phrases in seventy-three categories of which only those mentioned in more than five articles (6 in total) were used for composing a working definition for moonshine. The 'activities' worksheet contained all activities related to the moonshine process, totaling twenty-six.

B. Case study

The case study was performed in KLM E&M, whose core business consists of performing maintenance, repair and overhaul on aircraft, aircraft engines and aircraft components for mother airline KLM and third parties. Moonshine is focused on solving problems in the internal KLM E&M work environment and is not commercially driven, i.e. no external market demands drive the moonshine program.

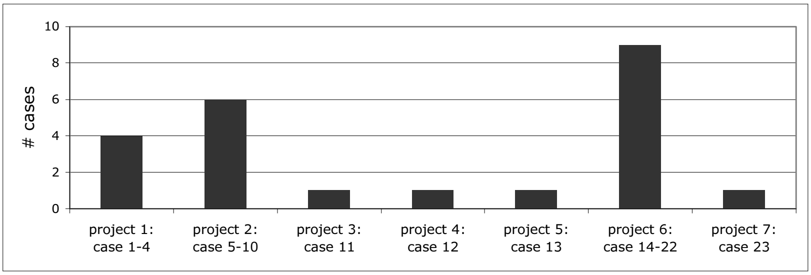

Figure 1: Seven moonshine projects comprising twenty-three cases

The moonshine process model was used in moonshine projects aimed at finding solutions for problems related to products and processes. Only cases that focus on product designs are part of this exploratory study. All moonshine projects were initiated at the specific request of

a unit manager who was also the problem owner. Projects consisted of several cases as can be seen in figure 1. Four of the seven projects consisted of one design case. High scorer project 6 contained a total of nine cases. For each case and each project, a similar structure was followed. After a short introduction of team members, the mutual goal was formulated and interpersonal team rules, including the 'building-on-each-other's-ideas' rule, were shared. The program manager provided for training in lean subjects that she considered relevant for the problem at hand and explained the moonshine process model and the generic design principles. To assess the applicability of the moonshine process model in real life situations, the model, its stages, and its activities have been evaluated during the case study on:

- Linearity of stages and activities
- Frequency of occurrence of stages and activities

- Ease of execution of an activity
- Interaction between stages and activities
- Completeness of stages and activities

III. A working definition of moonshine

No established definition for moonshine was found in available online practitioners' literature. Moonshine originally referred to the illegal alcohol production during the Prohibition in the USA. The term was later coined by Shingijutsu[9], formerly part of Toyota, to describe this 'exciting and innovative approach to creating something of value from spare and/or underutilized items'[10]. Boeing uses several descriptions of Moonshine, such as:

- a method of disruptive action, that occurs in secrecy, under and around organizational boundaries and procedures, producing order-of-magnitude improvement to any process[11]
- a lean manufacturing tool that uses fast and inexpensive prototyping to develop and prove a concept prior to its full implementation[11]
- the lean manufacturing practice of dedicating non production time and space to freewheeling problem solving[12]
- informal process development and improvement focusing on simple, reliable and safe solutions that promote lean manufacturing[13]

From current descriptions it remains unclear whether moonshine is applicable to products[10, 11], to processes[11, 13] or to both[12]. The inclusion of specific design features is remarkable when there is no specification of the underlying problem[13]. Descriptions are judgmental (exciting approach), vague (freewheeling problem solving) and they refer to order-of-magnitude improvements suggesting that small improvements cannot be the result of moonshine.

Literature reveals that creativity and innovation are key constituents of moonshine[7, 9, 12, 14, 15]. Creativity can be defined as the generation of ideas, problem solutions, or insights that are novel and appropriate[16]. Innovation on the other hand is the intentional introduction and application within a role, group or organization of ideas, processes, products or procedures, new to the relevant unit of adoption, designed to significantly benefit the individual, the group, the organization or wider society[17]. This definition of workplace related innovation corresponds to moonshine, since both refer to idea generation (creativity) and implementation.

Employee involvement is considered crucial for the success of the moonshine effort[2, 13, 18]. After all, the subject matter experts are the people who regularly perform the job and can offer the most innovative and effective ideas[2]. Both the end user and the internal manufacturer[1] are involved in the improvement process. The end user functions as the (internal) customer whose role varies between providing for input[19] to actively participating[13] during one or more activities of the moonshine process. The internal manufacturer builds or enhances prototypes and mock-ups of the innovation.

There is no agreement to whether moonshine should be considered an approach[10], a tool[20], a method[11], a practice[1, 12] or a philosophy[21]. We choose the term practice in concordance with the definition given by Dul & Hak (2008)[22]: 'a practice is the real life situation for which a moonshine practitioner has either a formal or an informal responsibility and in which he/she acts or must act'.

The distinguishing activity of moonshine is trystorming, a hands-on extension of traditional brainstorming taking it one step further in that an idea is mocked-up quickly so that it can be evaluated physically[8]. Trystorming includes activities such as prototyping, modeling, testing, simulating, and experimenting[23]. Thus, trystorming can be defined as the actual building and testing of mock-ups or prototypes of solutions that have been conceived during a brainstorm.

To prevent uncontrolled innovation and subsequent potential safety and legal issues retroengineering has been adopted as part of the moonshine process at KLM E&M. Retroengineering, or, engineering in retrospect, is the formalization of a 'design-by-trystorm' using traditional engineering techniques. Activities include technical drawing, structural analysis and certification of the design[24]. It can thus be defined as the formalization of a prototype that has been tested in real life situations to comply with technical, safety and legal requirements.

Considering the reflections on moonshine descriptions in literature including essential features and activities, we define moonshine as follows:

Moonshine is the Lean practice of employee-involved work related product and process innovation in which a solution is trystormed before formal implementation through retroengineering

IV. Preliminary moonshine process model

The moonshine model is built up of eight stages that are essentially linear[1, 7, 25]. Linearity does not imply an algorithmic approach to solving a problem, i.e. no fixed path is available that guarantees a solution. Literature describes iterations[19], circular loops and return paths[8]. We assume that iterations and circular loops refer to the same activity of repeating a process in which the results of a particular iteration are used as the starting point for the next iteration. It is not clear when and how often iterations and returns paths occur. Therefore they are not included in the preliminary moonshine process model and will be researched in the case study. Figure 2 shows a high level depiction of the moonshine process model.

Stage 1 focuses on defining and analyzing the problem thoroughly, including an observation and analysis of the process in which the problem occurs. Stage 2 aims to identify the essential function of the product in order to get the simplest solution possible. Stage 3 is dedicated to determining the evaluation criteria that are used to judge the solutions after the brainstorm. The early placement in the process allows end users to elaborate on their own evaluation criteria, i.e. reconsider or fine-tune them or add new ones. In addition, it allows different groups of end users to get a better understanding of each other's problems and evaluation criteria. This is especially important when (different) end users have conflicting requirements. Stage 4 is used for getting inspiration from everywhere including nature. Some moonshine practitioners include biomimicry, from the Greek bios (life) and mimesis (imitation), as part of their innovation process[1, 7, 26], since nature houses solutions that have been researched and developed during 3.8 billion years[27]. This relatively new science of which Janine Benyus is considered the pioneer[28], studies nature's models and then imitates or takes inspiration from these designs and processes to solve human problems[27]. Stage 5 is the brainstorm stage in which team members are required to come up with seven solutions and to build on each other's ideas. Why seven solutions? The insistence on seven is meant to expand the mind past individual preconceptions[26]. Stage 6 uses the evaluation criteria defined in stage 3 to select one or more solutions that will be trystormed. Stage 7, the trystorm stage is dedicated to building mock-ups and prototypes that are tested and improved until they satisfy the end user's needs. Stage 8 consists of the formalization of the prototype with drawings and a strength and risk analysis, in short: the 'traditional' or 'normal' engineering techniques to ensure a demonstrable safe use of a product before being put into service.

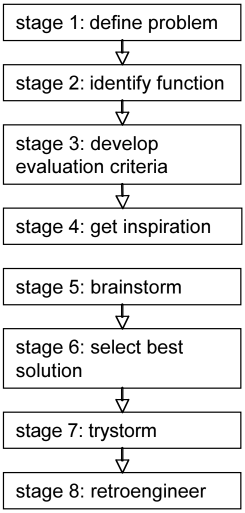

Figure 2: High level preliminary moonshine process model

In total twenty-six relevant activities were found in literature which described the moonshine process. They were allocated to eight clusters that were used to construct the preliminary 8-stage moonshine process model. The moonshine model is a prescriptive model implying that stages are to be applied in the given order. The activities do not have a prescribed order. The 8-stage moonshine process model with stages and activities is given in table 1.

The relatively low score of the initiating stage 1 (11 out of total 82) is surprising considering the importance of a thorough problem definition and analysis at the beginning of any improvement process. Retroengineering stage 8 has the lo17 average score suggesting that moonshine practitioners do not consider this stage part of the moonshine process. As can be expected the trystorm stage 7 with activities 17-21 scores highest (39 out of total 82). Within this stage, the activity 18 (building mock up or prototype) has the highest overall score (10), again as can be expected.

Table 1: 8-stage moonshine process model and its activities

Moonshine		Sources												
Stage	Activity	8	2	7	21	14	29	1	19	25	12	11	30	31
1	1. Map process												*	
	2. Visit workfloor			*										
	3. Find problem			*				*						
	4. Analyse problem			*				*						
	5. Find root causes			*				*						
	6. Scope						*			*			*	
2	7. Identify essential function						*	*		*			*	
3	8. Identify evaluation criteria						*			*			*	
	9. Operationalize moonshine criteria													
4	10. Find examples everywhere									*				
	11. Find examples in nature			*				*		*			*	
5	12. Brainstorm 7 solutions		*	*			*	*		*	*			*
	13. Sketch or describe solution							*		*				
	14. Build on conceived solutions													
6	15. Evaluate solutions									*				
	16. Choose solution			*			*			*			*	
7	17. Search for materials			*	*					*				
	18. Build mock up or prototype	*		*		*	*	*		*		*	*	*
	19. Test prototype	*		*		*	*	*		*		*		*
	20. Evaluate	*		*		*				*		*	*	*
	21. Continue development	*		*		*			*	*		*	*	*
8	22. Perform strength analysis			*										
	23. Determine material			*										
	24. Make drawings			*										
	25. Perform load test & risk analysis			*										
	26. Certify			*										

In addition to the activities found in literature two typical KLM E&M moonshine activities have been included in the model: 'operationalize moonshine criteria' and 'build on conceived solutions'. The first activity is a direct consequence of working with generic moonshine design principles that have to be 'translated' to specific evaluation criteria for the problem at hand. 'Building on conceived solutions' refers to the activity in which team members are required to add to others' solution. It is mentioned as a separate activity since it is explicitly stipulated when agreeing on the interpersonal team rules at the start of any team session.

V. Case study

The moonshine process model has been used in multiple moonshine cases for product and process related problems. Twenty-three product cases will be discussed, of which twenty-one in KLM E&M and two in two other KLM divisions. Table 2 gives an overview of the cases in which the products have been allocated to three different categories: components, tools and equipment. A tool is considered any handheld device used to perform or facilitate manual or mechanical work used during normal working conditions. Equipment is generally considered to include tools. For convenience, equipment in this study is regarded any non-handheld apparatus used to perform or facilitate manual or mechanical work. A component is anything that is not a tool or equipment.

As can be seen from table 2 almost half of the designs (11 of 23) were related to components two of which being redesigns of existing products. A redesign is here defined as a minor modification of an existing product to the extent that the basic function has not been altered.

A new design, even when containing elements of existing products, is build from scratch and cannot be traced back unambiguously to any existing products because of its inherently different functionality. Five tools and seven pieces of equipment were designed.

Table 2: Overview of 23 KLM E&M moonshine cases (* case outside E&M)

case nr	description	component	tool	equipment	succes? 1=y, 0=n	moonshine stage	final product	# produced
1	HarryÕs clamp	x			1	finished	external	2000
2	springclip	x			1	finished	external	500
3	removal tool upp hinge		x		1	finished	internal	2
4	set screw removal tool		x		tbd	trystorm	internal	1
5	stretcher bag	x			1	trystorm	external	13
6	text coding	x			1	finished	external	13
7	colour coding	x			tbd	trystorm	external	13
8	rings 3410	x			1	finished	internal	30
9	sicma	x			1	finished	internal	36
10	handle 3510	x			1	finished	internal	681
11	IDG tilter			x	0	finished	internal	1
12	foam comb		x		0	finished	internal	2
*13	visual bag ILV	x			tbd	trystorm	tbd	1
14	pulley puller		x		tbd	trystorm	internal	1
15	nose wheel cart			x	1	trystorm	internal	1
16	brake cradle			x	1	retroengineer	internal	1
17	wheel dolly			x	1	finished	internal	2
18	brake dolly			x	1	finished	internal	2
19	tool cart			x	1	trystorm	internal	1
20	torque extension tube		x		1	finished	internal	1
21	locking wire holder	x			tbd	trystorm	internal	4
22	multiservice cart			x	tbd	trystorm	tbd	1
*23	impact bumper	x			tbd	trystorm	tbd	1

Fourteen successful designs were reported, three of which are in the final phase of trystorming and at the verge of reaching the final design. Successes are found in all three categories: seven components, two tools and five pieces of equipment were a success. The latter category has the highest success rate with a relative score of 71% (5/7), followed by components (63%, 7/11), and ultimately tools (40%, 2/5).

Two designs are considered a failure and seven are to be evaluated yet, since they are in the beginning of the trystorm stage. The success of a design is determined as follows:

- for components a design is considered to be successful if the involved engineer decides it should be implemented
- for tools and equipment a design is considered to be successful if it is still in use half a year after its implementation

No failure has been observed in the component category. The five moonshine designs that were produced externally were all components that are used in the aircraft.

The twenty-three cases in which the 8-stage moonshine process model was tested are shown in table 3. An asterisk (*) indicates whether an activity has been performed and observed. They total 448 activities, corresponding to 75% of all 598 activities. This high score is not remarkable considering the prescriptive nature of the moonshine process model. Activities with the indication ‘u’ (31 in total) were done by individual team members or by an external supplier. No information is available to whether the activity was actually performed.

Table 3: Moonshine process model applied to 23 cases

Cases

Moonshine Stage	Activity	Harry's clamp 1	springclip 2	rem. tl upp. hinge 3	set screw rem. Tl 4	stretcher bag 5	text coding 6	colour coding 7	rings 3410 8	sicma 9	handle 3510 10	IDG tilter 11	foam comb 12	visual bag ILV 13	pulley puller 14	nose wheel cart 15	brake cradle 16	wheel dolly 17	brake dolly 18	tool cart 19	torque ext. tube 20	locking wire holder 21	multiservice cart 22	impact bumper 23
1	1. Map process					*	*	*				*		*										*
	2. Visit workfloor	*	*	*	*	*	*	*	*	*	*	*	*		*	*	*	*	*	*	*	*	*	
	3. Find problem	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
	4. Analyse problem	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
	5. Find root causes	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
	6. Scope	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*		*
2	7. Identify essential function	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*		*	*	*	*
3	8. Identify evaluation criteria	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
	9. Operationalize moonshine criteria	*	*	u	u	u	*	*	*	*	*	*	*	*	u	*	*	*	*	*	u	u	*	*
4	10. Find examples everywhere	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
	11. Find examples in nature																							
5	12. Brainstorm 7 solutions	*	*	u	u	u			*	*	*	*	u	*	*	*	*	*	u	*		u	*	*
	13. Sketch or describe solution	*	*	u	u	u	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	u	*	*
	14. Build on conceived solutions	*	*	u	u	u	*	*	*	*	*	*	u	*	*	*	*	*	u	*		u	*	*
6	15. Evaluate solutions	*	*	u	u	u	*	*	*	*	*	*	u	*	*	*	*	*	u	*		u	*	*
	16. Choose solution	*	*	*	*	u	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
7	17. Search for materials	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*		*	*	*	u	$\boxed{*}$	*
	18. Build mock up or prototype	*	*	*	$\boxed{*}$	*	*	$\boxed{*}$	*	*	*	*	*	*	*	*	*	*	*	*	*	*		$\boxed{*}$
	19. Test prototype	*	*	*		*	*	*	*	*	*	*	*	$\boxed{*}$	$\boxed{*}$	*	*	*	*	*	*	*		*
	20. Evaluate	*	*	*		*	*	*	*	*	*		*		*	*	*	*	*	*	*	$\boxed{*}$		*
	21. Continue development	*	*	*		$\boxed{*}$	*	*	*	*	*		*		*	$\boxed{*}$	*	*	*	$\boxed{*}$				*
8	22. Perform strength analysis	*	*	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	*	n/a					*	*	n/a	*	n/a		n/a
	23. Determine material	*	*	*	*	*	*	*	*	*	*	*	*		*		*	*	*		*			
	24. Make drawings	*	*	*	*	*	*	*	*	*	*	*	u		*		*	*	*		*			
	25. Perform load test & risk analysis	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	*	n/a		n/a	*	n/a	*	*		n/a	n/a		n/a
	26. Certify	$\boxed{*}$	$\boxed{*}$	$\boxed{*}$	*	n/a	$\boxed{*}$	*	$\boxed{*}$	$\boxed{*}$	$\boxed{*}$	$\boxed{*}$	$\boxed{*}$				$\boxed{*}$	$\boxed{*}$	$\boxed{*}$		$\boxed{*}$			

* = *done* = *not done* u = *unknown* n/a = *not applicable* ☐ = *current activity*

Performing a strength analysis is not always deemed necessary by the responsible engineer or it is not applicable to the product designed, indicated by the 'n/a' code (29 in total). A framed asterisk indicates the current status of a case.

VI. Evaluation of the case study

The failed designs of cases 11 and 12 show no directly observable difference in activities performed in comparison to the successful cases. Reversely, no evidence was found for activities conducive to the success of a moonshine design.

Linearity

The moonshine process model was used prescriptively, thus stages have been performed in the indicated order, starting with stage 1 and ending with stage 8. The program manager judged the moonshine process model useful for managing the innovation process. It proved to be the backbone of the moonshine design process and functioned as was intended: a moonshine roadmap. The activities are not linear, except for the brainstorm and trystorm stages where activities can be executed in only one order.

Frequency of occurrence

All stages were executed, in contrary to the constituent activities that show a different pattern. Mapping the process is not done very often (3 of 23), in contrary to the work floor visits done in almost all instances (21 of 23). In the non-E&M cases, no visit was paid to the work floor. Instead, pictures were made of the problem situation as a substitute for the work floor visit. Work floor is considered any working environment. Currently, biomimicry is slowly gaining interest from scholars and educators. Anecdotes are reported on the inclusion of biomimicry in moonshine. Still, the row of 'finding examples in nature' (activity 11) is completely blank: in not one instance has an explicit search been done to get inspiration from nature. This suggests that the practical application of biomimicry in KLM E&M is difficult for inexperienced moonshine design teams.

Ease of execution

Stage 1 was difficult to execute. The majority of the team members considered a thorough problem definition and analysis not always useful. In some cases, the trystorm stage and therefore the product design almost failed due to some misunderstandings about the nature of moonshine and the essence of trystorming. When regarding the activities; finding examples in nature was not done in any of the moonshine cases, as discussed before. Finally, the program manager judged the identification of the basic function of the 'to-be-moonshined' product cumbersome even though this stage 2-activity has been done in all instances.

Interaction between activities

Frequent going back and forth between stages and between activities within stages was observed in all design cases. For example, revisits of the work floor to study the actual process were done, as well as inclusion of new problems in stage 1 whereas the process was already in stage 3. Re-scoping, addition or deletion of evaluation criteria and sharing of insights obtained from an 'out-of-team' brainstorm were also observed.

The iterative character of the moonshine process in its entirety was recognized. In several cases, the moonshine process started again in stage 1 with an adjusted defect definition. The final design had already gone through the stage of retroengineering and showed one or more flaws.

Observations during the trystorm stage showed activities that at first sight looked like iterations. A thorough analysis of the sequence and characteristics of the activities in this stage revealed that rather than iteration another phenomenon took place, known as recursion. Additional problems that arose in the trystorm stage initiated a new moonshine process starting in stage 1. Said differently: the moonshine process started anew in the trystorm stage for a subproblem of the problem at hand. Meanwhile the main design process would come to a stand still and continue only after the recursive process had come to an end. Recursion is often used in computer science and can best be defined as the process of repeating items in a self-similar way.

Iteration and recursion are both repeating processes. Iteration is concerned with one problem while repeating the same process until a solution has been found and recursion contains levels of problems and subproblems that need to be solved in order to solve the main problem (adapted from Cornell, 1998). We choose to follow the definition above to discern between 'normal' iterations and recursions since they are intrinsically different processes.

Completeness

The application of the moonshine process model has revealed that activities were used in all cases that are not present in the preliminary moonshine process model. These activities include goal formulation, choice between discarding a prototype and continuing development, final product building, and administration of the new design.

VII. Conclusions

The exploratory research, consisting of a literature review and a case study has provided us with a first insight in the field of moonshine. At the outset of the exploratory study no definition was available for moonshine. A literature review revealed relevant information for composing a working definition of moonshine.

This study aimed at constructing a moonshine process model. A moonshine process model has been built using twenty-six activities identified in online available practitioners' literature. The activities are clustered into eight stages that are essentially linear. The model has been tested in a case study at KLM E&M. Some important activities were found missing from the model, although they had been performed in all cases. Reversely, some activities incorporated in the model were not used in the cases. The iterative and recursive nature of moonshine was observed in all cases and occurred between stages and between activities.

Limitations

In our exploratory study, we discovered that no models of moonshine existed in common practitioners' literature. We have constructed and tested a moonshine process model in real life situations. The applicability of the model has not been proven scientifically, which is the main limitation of our research.

Avenues for future research

Like any (work related) innovation, the success of moonshine is determined by an array of variables. It is imperative to have a thorough understanding of these variables in order to increase the chance of success of this employee-involved workplace innovation effort. Our future research will be aimed at better comprehending moonshine in order to build on existing knowledge, leading to our research question:

RQ: How can moonshine be modeled?

Considering the objective of the research the constituent subresearch questions are:
RQ1: Which variables influence moonshine?
RQ2: How does the influence take place?
RQ3: What is the interaction between the different variables?
RQ4: How can the variables in turn be influenced?

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New similarity metric for mixed production of aircraft assembly

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With the advancement of reconfigurable tooling and manufacturing systems, aerospace enterprises are looking for mixed production solutions to gain leading competitive edge. An accurate similarity metric will be necessary and crucial for making sound mix-production decisions. Most literatures studied similarity coefficients for grouping part families in cellular manufacturing systems; however they are not applicable to aircraft assemblies which involve large amount of manual work dealing with large heavy components and assemblies. This paper proposes a new similarity metric that incorporates both component level similarity and system level similarity of aircraft assemblies. The similarity in components level is modeled based on part-operation and operation-operation incidence matrices. The similarity in assembly level is modeled by similarity system theory associated with a newly proposed operation quota based weighting method. A digital manufacturing tool has been developed for the automated implementation of the new models. Both the models and the tool have been validated by six pairs of real life panel-assembly examples. Results showed that the new similarity index gives clear indication to the degree of commonality in panel assemblies, and the digital tool can generate the similarity results rapidly and accurately.

I. Introduction

Modern manufacturing companies need to produce products mix in a timely and cost effective way to meet customers' increasing demands on product variety. As different models of products require varied processing times and all products are mixed and produced in the same line, the assembly line design has become extremely complex. This creates a significant challenge for efficient utilization of labour and machinery. One fundamental question that always challenges operation manager is: "how to mix different products production to obtain the maximum gain?" Obviously, there is no simple answer to this question, and there is a need to propose new performance metrics for making the mixed production decisions. One of the key metric would be the similarity index which should represent not only the likeness of product shape but also the resemblance in manufacturing processes. This work is to propose a new similarity metric for making mixed production decisions for aircraft assemblies. Typically, aircraft assemblies are characterized by low volume, large work contents, labor intensive

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and immobile expensive equipments, and they are most produced by dedicated production lines. Today, with the advancement of reconfigurable systems, mixed production has become possible for such system.

Many literatures in the area of cellular manufacturing systems studied and applied similarity index based on their machining routes rather than assembly operations for grouping part families. Although several researchers started to incorporate the assembly aspects into the similarity analysis, their applications are limited to the cellular manufacturing systems for batch production of small-scale components, such as electronic devices, without taking account of the impacts on tooling and operators' learning, which are crucial in a large scale labour intensive production system. It is also pointed out by Jiao et al. [1] that product families need to be identified at every configuration level of products and manufacturing systems to optimize design, planning and production. However, most existing research only focused on the component level rather than sub-assembly and assembly levels. This work is to fill the gap by looking at the similarities at sub-assembly level of large-scale products, i.e. aircraft panel assemblies. Based on similarity system theory, part-operation and operation-operation incidence matrices, a new similarity metric is modeled by taking account of component types and geometry, operation types, operation amount and sequence, operation time, tools and fixtures. The effectiveness of the similarity index is validated through three real-life industrial examples, and the algorithm development in a digital environment is also presented. This paper is organized as follows. Section II introduces the literature. Section III presents the modeling method of the new similarity metric. Section IV introduces the digital tool for the automatic implementation of the new metric. Section V addresses the validation and application of the model and the tool. Section VI concludes the paper.

II. Literature Review

Group technology has become a management philosophy for modern enterprises to plan and control their production. Identifying process commonality of parts/products is one of the crucial step in successfully applying group technology. In literature, many researchers have introduced similarity or dissimilarity coefficients as a benchmark metric for making decisions [2-6]. Most of those metrics focused on cellular manufacturing system (CMS), where parts with similar manufacturing processes are categorized as a family and produced in one common workcell, so as to improve productivity. Many literatures introduced similarity coefficients between two parts to form part families based on a machine-part incidence matrix [3-6]. Some researchers resorted to the operation sequences to create similarity index between two parts for forming part families [7-9]. Garbie et al. [10] introduced a new similarity coefficient based on the processing requirements (processing time, production volume rate, demand, and number of operations) of a new part within an existing manufacturing cell. Zhou and Askin [11] proposed an operation based approach for forming manufacturing cells with consideration of tooling similarity. Seifoddini and Tjahana [12] used a similarity coefficient by taking production volume and batch size into account. Panchalavarapu and Chankong [13] accounted the assembly operations in the similarity coefficient derived from part-subassembly and part-machine matrices. Aryanezhad and Aliabadi [2] also considered assembly operations in designing CMSs with an objective to minimize the intercellular movements. Huang et al. [14] created a fast algorithm for assessing the similarity of manufacturing processes in mixed production related to capacity exchange.

Another area to apply similarity index lies in the newly proposed paradigm of reconfigurable manufacturing system (RMS), which aims to provide agile reconfigurability to cope with several parts/products families with different system configurations to achieve cost-effectiveness [15, 16, 17, 18]. The similarity index will be key to determine how to incorporate new parts/products into existing systems and when to change the configuration of the manufacturing system. The conventional methods to form part/product families in CMS need be restructured to achieve a comprehensive organization towards RMS. Galan et al. [15] gave a systematic approach for grouping products into families, which need to meet the requirements in reconfigurable manufacturing systems, including modularity, commonality, compatibility, reusability and product demand. Abdi and Labib [18] proposed a methodology for grouping products based on product types, operational similarity, product family efficiency, and product configurability, to achieve maximum machine utilization.

Most existing similarity measures are based on processing sequences for producing parts. But in the highly-skilled aircraft assembly industry, the process routes are not the key as a human operator will have enough flexibility to cope with various operation sequences. Hhowever, the operation types and steps will have a direct impact on operators' learning, so as to influence the processing time and production scheduling. Tooling and fixture is also key as the workstation is often jig based. If two assemblies cannot be mounted on the same jig, they are hard to be grouped into one family. This work will propose a new similarity metric for aircraft panel assemblies by taking into account all the above aspects, including component types, operation types and sequences, processing time, component geometry, jigs and fixtures, and component materials.

III. Similarity metric for aircraft assembly

Similarity system theory states that similarity exists between systems if they have common properties provided that they are not identical. Assume there are two systems A = {a_1, a_2 ... a_n} and B = {b_1, b_2 ... b_m}, in which a_i (1 <= i <= n) and b_j (1 <= j <= m) are constituent elements of A and B respectively. If a_i and b_j have common properties, then a_i and b_j are similar elements, and form a similar unit or pair u (a_i, b_j). There are l similar units in between systems A and B, denoted by u_1, u_2, …, u_l, and the weight of u_i (1<=i<= l) in the system is represented by e_i. Assume there are k similar properties in a_i and b_j, the weights of similar properties are (d_1, d_2, …, d_k) and the corresponding similarity values of similar properties are (c_1, c_2, …, c_k). Two formulas are firstly introduced in [19] to calculate the value of similar unit q(u_i) and the system similarity value Q(A, B) as follows.

$$\mathrm{q(u_i)} = \sum_{j=1}^{k} d_j * c_j \, , \tag{1}$$

and

$$\mathrm{Q(A,B)} = \frac{l}{n+m-l} \sum_{i=1}^{l} \mathrm{e_i q(u_i)} \, , \tag{2}$$

where $\mathrm{d_j} \in [0,1], \sum \mathrm{d_j} = 1, \;\; \mathrm{c_j} \in [0,1]$. Geng et al. [20] argued that the traditional formulae cannot well illustrate the key parts' importance and their engineering meaning, and a revised formula for calculating the similarity value Q(A, B) of BOM (Bill of materials) systems was introduced as follows.

$$Q(A,B) = \frac{\sum_{i=1}^{l}((\beta_{ai}+\beta_{bi})*q(u_i))}{(\sum_{j=1}^{n}\beta_{aj}+\sum_{k=1}^{m}\beta_{bk})} \, , \tag{3}$$

where β_{ai}(β_{bi}/ β_{aj}/ β_{bk}) is referred to as the weights of the i^{th}(i^{th}/j^{th}/k^{th}) element of system A(B/A/B). They are larger than 0, and can be set freely. Nevertheless,the resulting similarity value could be larger than 1 since the weights in these formulas are set freely and therefore there is a lack of engineering meaning. In order toobtain result within the range of [0, 1], further retune are needed. In the herein work, a new weighting method, which provides more engineering meaning, will be applied to equations (1) and (3) for assessing the system similarity of aircraft panel assemblies. In the following sections, the new similarity modeling method inclusive of both element and system properties for aircraft panel assemblies will be introduced for the first time.

A. Similarity model of element properties (cj)

A.1 Similarity of component type (c_1)

Component type is the most important property of the parts' similarity, as it is resulted from the component shape, location and function in the final products. If two components belong to the same category, they tend to be similar. So it is necessary to pair two components of identical type to form a similar unit. For aircraft assemblies, components are often clearly classified, such as wing, fuselage, panel, stringer, spar, etc. For determining the similar units between the two systems, the constituent elements of the two systems A and B are examined by paired comparison method with the following steps:

1. First, different groups are made according to component types, such as stringer and skin panel;
2. Then each element of A will be compared to the one element of the same type in B to form a similar unit;
3. Finally, if there is more than one constituent element of each system, the one with the most similar location in the final product will be preferred.

The similarity value for each similar unit can then be calculated as follows.

$$\mathrm{c_1(u_i(a_i, b_j))} = \begin{cases} 1, \textit{if } a_i \textit{ and } b_j \textit{ are similar} \\ 0, \textit{otherwise} \end{cases} \tag{4}$$

A.2 Similarity in operation types (c_2)

One of the key criteria of mixed production is to have as many repetitive operations as possible in the same workstation. Unlike the conventional machine based processes, the number of manual operation types will have a direct impact on the requirement of operators' skill level as well as their productivity. Therefore the similarity of operation types are crucial for making sound decisions of mixed production. Suppose the number of the operations required to produce the similar elements a_i and b_i is called v_{a_i,b_j} , the number of operations required for the element a_i but not required for the element b_j is defined as v_{a_i} , and the number of operations required for b_i but not required for a_i is named v_{b_i}. Then the value of similarity based on the operation type is calculated as follows:

$$c_2(\mathrm{u(a_i, bj)}) = \frac{v_{a_i,b_j}}{(v_{a_i,b_j}+v_{a_i}+v_{b_j})} \tag{5}$$

A.3 Similarity in operation sequences (c_3)

Operation sequence is also an important factor to be taken into account. Obviously, operation sequence has a direct impact on the layout of workstations. The present aircraft assembly practice shows that there are many operations in each workstation as the human operator have the flexibility and capability to cope with a wide range of tasks. It is worth pointing out that, operator learning, an important factor of efficiency, will be much influenced by operation sequences. For example, if two panel assemblies require identical assembly sequences, it will be easier for operators to master the processes quickly than coping with two assemblies associated with dissimilar operations. For computing the similarity value of operation sequences $c_3(u_i)$, the operation-operation incidence matrix method is used with the following steps.

1. Build an operation-operation matrix as follows:

Sequence of operations applied to a_i

Sequence of operations applied to bj

$$\begin{array}{cc} & \begin{array}{cccc} a_{i1} & a_{i2} & & a_{iz} \end{array} \\ \begin{array}{c} b_{j1} \\ b_{j2} \\ \\ b_{jz'} \end{array} & \begin{pmatrix} a_{i1}\, b_{j1} & a_{i2}\, b_{j1} & \dots & a_{iz}\, b_{j1} \\ a_{i1}\, b_{j2} & a_{i2}\, b_{j2} & \dots & a_{iz}\, b_{j2} \\ \dots & \dots & \dots & \dots \\ a_{i1}\, b_{jz'} & a_{i2}\, b_{jz'} & \dots & a_{iz}\, b_{jz'} \end{pmatrix} \end{array}$$

In the matrix the term z and z' represents the total number of operations applied to a_i and b_j respectively. The element value in the matrix will be 1 if the two operations are the same. Otherwise, its value is 0.

2. Compare the terms located in the same diagonal, and apply the next rule:
   - If $a_{it}b_{jt} = a_{i,\,t+1}b_{j,\,t+1} = 1$, the associated operations follow the same sequence.
   - If any part of the matix is formed by an identity matrix, all elements in the identity matrix except for its leading diagonal will be replaced by 0 instead of 1 as shown in Fig. 1, as the leading diagonal is enough to represent the similar sequence.
   - If $a_{it}b_{jt} = 1$ and the element (e.g. element (6, 6) in the matrix in Fig.1) belongs to the main diagonal, it is considered as same sequence although it is only one operation.

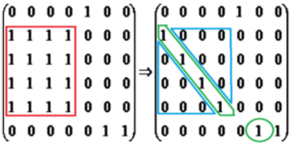


Fig. 1 How to update the matrix

3. The weight of each diagonal is based on a proportional rule with respect to the main diagonal, as shown in Fig. 2.

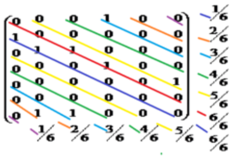


Fig. 2 Weights of each diagonal γ_λ

4. Calculate the value of similarity between the sequences of the common operations of both elements with the following equation.

$$c_3^{(a_i,b_j)} = \frac{\sum_{\lambda=1}^{\varepsilon}(F_\lambda * \gamma_\lambda)}{min\{z\ \ ,z'\ \ \}} \tag{6}$$

where F_λ is the number of operations realized in the same sequence in the λ^{th} diagonal, and ε as the number of sequences found in the matrix. γ_λ is referred to as the weight of the λ^{th} diagonal in the matrix.

A.4 Similarity in processing times in each workstation (c_4)

The commonality of process times is a good indicator of the workstation utilization from each similar elements, which can be helpful in minimizing the impact of production scheduling and rescheduling. In addition, the similarity of processing times is also an inevitable factor of operator learning. The closer the processing times for each element, the easier for it to be learned by one operator. The similarity score for similar elements a_i and b_j at the f^{th} workstation, can be calculated as follows:

$$s_f^{(a_i,b_j)} = \left(1 - \frac{\left| p_f^{a_i} - p_f^{bj} \right|}{\mathrm{Max}(p_f^{a_i}, p_f^{b_j})} \right) * 100\% \tag{8}$$

where $p_f^{a_i}$ and $p_f^{b_j}$ are referred to as the accumulated processing times for the similar elements a_i and b_j in the f^{th} workstation respectively. For each similarity unit, the similarity coefficient by which the scores from the step before are weighted is estimated based on corresponding workstation utilization, and this value is then summed for all workstations to obtain the degree of similarity.

$$c_4^{(a_i,b_j)} = \sum_{k=1}^{r} g_k * s_k^{(a_i,b_j)} \tag{9}$$

where the weight of the f^{th} workstation g_f is defined as $g_f = p_f / \sum_{f=1}^{r} p_f$, and $p_f = (p_f^{a_i} + p_f^{bj}) / p_f$ represents the load rate of element a_i and bj. With the pre-defined standard times associated with each standard operation, the processing time of each operation can be easily obtained [21],and so is the processing time of aircraft assemblies.

A.5 Similarity on geometry (c_5)

Component geometry also needs to considered, as it exerts an effect on the size of the jig and fixtures, on transportation tools and even the processing time. To work out the value of this property, similar elements of each similar unit are compared on length, width, depth and diameter (if applicable) in a proportional rule. The value can be determined with the following equation.

$$c_5^{(a_i,bj)} = \min\{\lambda_x, \lambda_y, \lambda_z, \lambda_d\} / \max\{\lambda_x, \lambda_y, \lambda_z, \lambda_d\} \tag{10}$$

where λ_x, λ_y, λ_z, λ_d represent the corresponding ratios of length, width, depth and diameter of two elements a_i and b_j.

A.6 Similarity on jigs and fixtures (c_6)

Jigs and fixtures are important factors to be considered in aerospace assembly. The high precision assembly processes are operated on one particular jig with a number of fixtures. If two assemblies cannot be deployed on one jig, it is impossible to put them together through the same workstation (jig). Although modular reconfigurable tools have been used in production to cope with the product family, certain components have to be changed or reconfigured in response to the product changes. The similarity of jigs and fixtures is still a useful indicator of the complexity of reconfiguration in between different models. In literature, similarity score method was used to evaluate the similarity of tools and fixtures [22, 23]. However, in the aerospace industry, most of operations are carried out on jigs. A jig is a type of fixture used to keep and hold the skin panels, hence allows the corresponding operations to be undertaken. For one model of aircraft, all the panel assemblies are made on the same jig, however for different models, the panel assemblies of each model are made in different jigs. On the other hand, if the models belong to the same series, for example, *CRJ series* (CRJ700, CRJ900, CRJ1000), their assembly operations can be made on the same jig. The reason being that the panel assemblies of different series of aircrafts have different curvatures, i.e., the diameters of them are different. And the curvature is determined by the skin panels, on which all other components are assembled. Due to the modular design of jigs, the length, width or depth sizes are irrelevant in the calculation of similarity on tools and fixtures. Therefore, the similarity on tools and fixtures is modelled as follows.

$$c_6^{(a_i,b_j)} = \frac{\min\{\varsigma_{ai}, \varsigma_{bj}\}}{\max\{\varsigma_{ai}, \varsigma_{bj}\}} \tag{11}$$

where ς_{ai} and ς_{bj} are the corresponding diameters of the skin panels of each system.

A.7 Similarity of component materials (c_7)

Component materials can be a decisive factor in mixed production, as different operations, tools and quality insurance methods may be required for the components of different materials. For example, the assembly processes of a composite panel will be quite different comparing to the processes used for metal panel. It is therefore of great interest to consider component materials in the calculation. The similarity can be calculated as follows.

$$c_7^{(a_i,b_j)} = \begin{cases} 1, \textit{if } a_i \textit{ and } b_j \textit{ are made from the same material} \\ 0, \textit{otherwise} \end{cases} \tag{12}$$

B. Weighting methods

For each similar unit, the similarity between any two elements are from their common properties, including types of components, operation types and sequences, processing times, component geometry, tools and fixtures, and materials. The weight of each property is dependent on the importance of each property on the production feasibility and productivity. In addition, certain properties may have the power to influence the other properties. For example, the type of components will have a direct effect on the operation types and sequences, and operation types will determine the corresponding processing times. Therefore, the weights of each property will depend on its importance, and can be decided by the production engineers or end-users. In this paper, fixed scoring method is used for assigning weights of each similar property based on their level of importance in the aerospace industry, see Table 1.

Table 1 Weights of similar properties

SIMILAR PROPERTY	**Weight d_k**
Type of components	0.250
Type of operations	0.170
Sequence of operations	0.170
Tooling and fixtures	0.160
Geometry of components	0.120
Processing time of operations	0.080
Material of components	0.050
Total	**1.000**

To determine the similarity value between two systems, the weight of every constituent element needs to be given depending on the importance of each element in the system. In aircraft assembly, the assembly processes generally follow a common procedure: locate, drill, countersink, disassemble, deburr, reassemble and rivet. The more operations applied to one component, the more weight of the component in the system. The same applies to the similar unit. Here, an operation quota method is proposed for weight assignment as follows.

$$\beta_{ai} = \frac{h_{ai}}{\sum_{i=1}^{L} h_{ai}} \tag{13}$$

$$\beta_{bi} = \frac{h_{bj}}{\sum_{i=1}^{L} h_{bj}} \tag{14}$$

Where h_{ai} (h_{bj}) represents the number of operations on component a_i (b_j), β_{ai} (β_{bj}) represents the ratio of the number of operations on component of a_i (b_j) to the total number of operations on all components of similar units in system A(B). This method is more exact than the fixed scoring method as the weight of each component is in proportional to the number of operations on it.

C. Algorithm development

Figure 3 shows the flow chart for calculating the similarity metric between two systems. The calculation starts from two systems with lists of constituent elements in each. Based on the types of constituent elements, the pair comparison method will be applied to form the similar units u_i. For each similar unit, the similarity values c_1 to c_7 will be evalued with the support information on operation types, sequences, and processing times of each constituent element, as well as the geometry and material information of componets, tools and fixuture requirement for each component. Once these similarity values have been obtained for all similar units, the weights of similar elements can be assigned by equations (13) and (14), and the similarity value between the two systems Q(A, B) can then be calculated using eqn.(3). It is worth noting that both EBOM and MBOM are required for generating the similarity value, which may involve many efforts from data collections and calculations. Therefore, an automated tool will be very useful to facilitate the calculation, and this will be introduced in the next section.

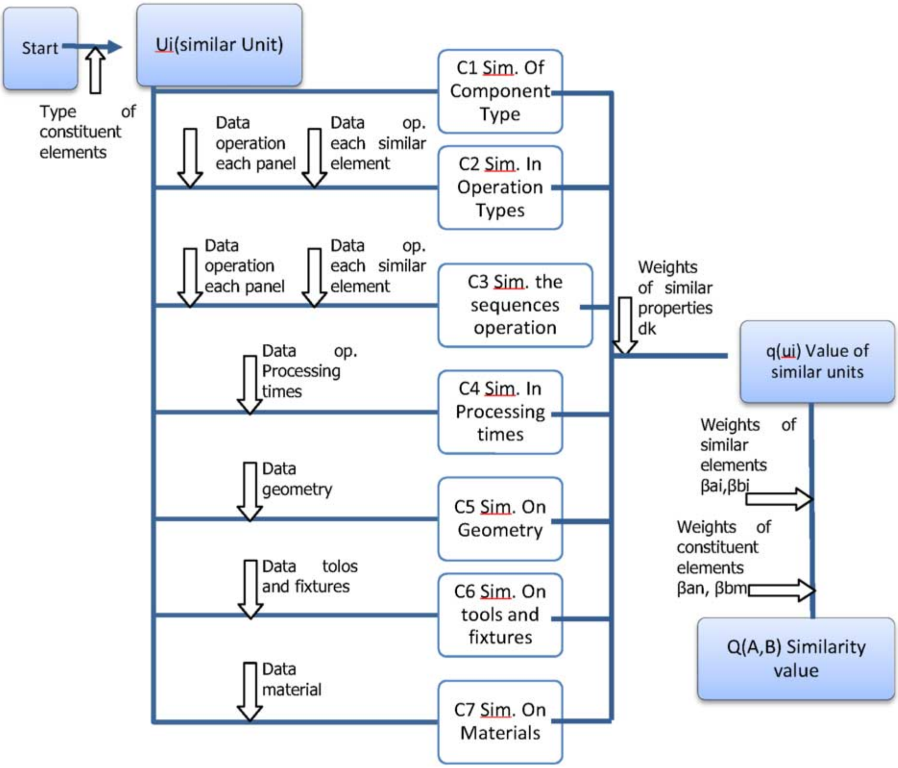
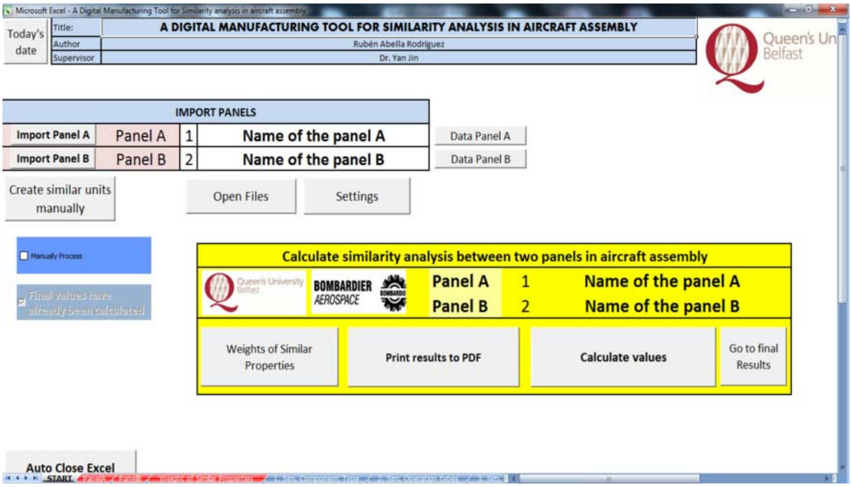


Fig. 3 Flow Chart for calculating similarity metric

IV. Automatic calculation of the metric

To achieve the similarity model automatically, a spreadsheet based digital tool has been developed with the programming language of Visual Basic for Automation in Microsoft Excel spreadsheet. A template with seven formatted spreadsheets was developed for storing all input data of each system, including constituent elements, operation types and sequence, processing time, component geometry, tools and fixtures and material information. A number of graphical user interfaces were also incorporated in the tool for visualizing the input data, paired elements and their properties, and final evaluation results. The main graphical user interface is shown in Fig. 4. In calculating the similarity of panel assemblies A and B, the data are firstly imported from the corresponding files by clicking the button ‘Import Panel A/B’, the computation of similarity value of A and B can then be triggered by clicking the button ‘Calculate Values’ provided the weights of similar properties are set. Figure 5 shows the graphical user interface of the final results. All other information used in the calculation is also generated in other spreadsheets, so that the user can trace all the values and detailed reports. Please refer to [24] for more details.



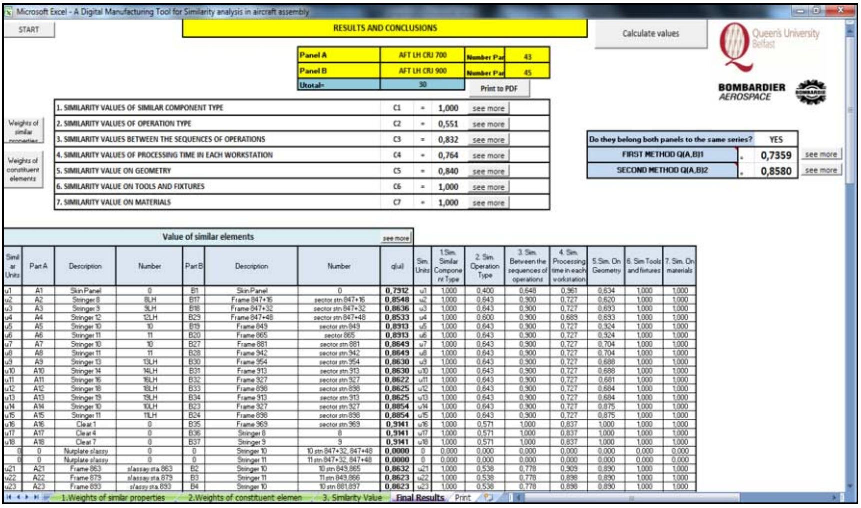
Title: A DIGITAL MANUFACTURING TOOL FOR SIMILARITY ANALYSIS IN AIRCRAFT ASSEMBLY
Author: Rubén Abella Rodriguez
Supervisor: Dr. Yan Jin

Panel A 1 Name of the panel A
Panel B 2 Name of the panel B

Calculate similarity analysis between two panels in aircraft assembly

Panel A 1 Name of the panel A
Panel B 2 Name of the panel B

Fig. 4 Main interface of the similarity evaluation tool



RESULTS AND CONCLUSIONS

Panel A	AFT LH CRJ 700	Number Par	43
Panel B	AFT LH CRJ 900	Number Par	45
Utotal=	30		

1. SIMILARITY VALUES OF SIMILAR COMPONENT TYPE	C1	=	1,000
2. SIMILARITY VALUES OF OPERATION TYPE	C2	=	0,551
3. SIMILARITY VALUES BETWEEN THE SEQUENCES OF OPERATIONS	C3	=	0,832
4. SIMILARITY VALUES OF PROCESSING TIME IN EACH WORKSTATION	C4	=	0,764
5. SIMILARITY VALUE ON GEOMETRY	C5	=	0,840
6. SIMILARITY VALUE ON TOOLS AND FIXTURES	C6	=	1,000
7. SIMILARITY VALUE ON MATERIALS	C7	=	1,000

Do they belong both panels to the same series?		YES
FIRST METHOD Q(A,B)1	=	0,7359
SECOND METHOD Q(A,B)2	=	0,8580

Value of similar elements

Similar Units	Part A	Description	Number	Part B	Description	Number	q(ui)	Sim. Units	1.Sim. Similar Component Type	2. Sim. Operation Type	3. Sim. Between the sequences of operations	4. Sim. Processing time in each workstation	5.Sim. On Geometry	6. Sim Tools and fixtures	7. Sim. On materials
u1	A1	Skin Panel	0	B1	Skin Panel	0	**0,7912**	u1	1,000	0,400	0,648	0,961	0,634	1,000	1,000
u2	A2	Stringer 8	8LH	B17	Frame 847+16	sector stn 847+16	**0,8548**	u2	1,000	0,643	0,900	0,727	0,620	1,000	1,000
u3	A3	Stringer 9	9LH	B18	Frame 847+32	sector stn 847+32	**0,8636**	u3	1,000	0,643	0,900	0,727	0,693	1,000	1,000
u4	A4	Stringer 12	12LH	B29	Frame 847+48	sector stn 847+48	**0,8533**	u4	1,000	0,600	0,900	0,689	0,693	1,000	1,000
u5	A5	Stringer 10	10	B19	Frame 849	sector stn 849	**0,8913**	u5	1,000	0,643	0,900	0,727	0,924	1,000	1,000
u6	A6	Stringer 11	11	B20	Frame 865	sector 865	**0,8913**	u6	1,000	0,643	0,900	0,727	0,924	1,000	1,000
u7	A7	Stringer 10	10	B27	Frame 881	sector stn 881	**0,8649**	u7	1,000	0,643	0,900	0,727	0,704	1,000	1,000
u8	A8	Stringer 11	11	B28	Frame 942	sector stn 942	**0,8649**	u8	1,000	0,643	0,900	0,727	0,704	1,000	1,000
u9	A9	Stringer 13	13LH	B30	Frame 954	sector stn 954	**0,8630**	u9	1,000	0,643	0,900	0,727	0,688	1,000	1,000
u10	A10	Stringer 14	14LH	B31	Frame 913	sector stn 913	**0,8630**	u10	1,000	0,643	0,900	0,727	0,688	1,000	1,000
u11	A11	Stringer 16	16LH	B32	Frame 927	sector stn 927	**0,8622**	u11	1,000	0,643	0,900	0,727	0,681	1,000	1,000
u12	A12	Stringer 18	18LH	B33	Frame 898	sector stn 898	**0,8625**	u12	1,000	0,643	0,900	0,727	0,684	1,000	1,000
u13	A13	Stringer 19	19LH	B34	Frame 913	sector stn 913	**0,8625**	u13	1,000	0,643	0,900	0,727	0,684	1,000	1,000
u14	A14	Stringer 10	10LH	B23	Frame 927	sector stn 927	**0,8854**	u14	1,000	0,643	0,900	0,727	0,875	1,000	1,000
u15	A15	Stringer 11	11LH	B24	Frame 898	sector stn 898	**0,8854**	u15	1,000	0,643	0,900	0,727	0,875	1,000	1,000
u16	A16	Cleat 1	0	B35	Frame 969	sector stn 969	**0,9141**	u16	1,000	0,571	1,000	0,837	1,000	1,000	1,000
u17	A17	Cleat 4	0	B36	Stringer 8	8	**0,9141**	u17	1,000	0,571	1,000	0,837	1,000	1,000	1,000
u18	A18	Cleat 7	0	B37	Stringer 9	9	**0,9141**	u18	1,000	0,571	1,000	0,837	1,000	1,000	1,000
0	0	Nutplate s/assy	0	0	Stringer 10	10 stn 847+32, 847+48	**0,0000**	0	0,000	0,000	0,000	0,000	0,000	0,000	0,000
0	0	Nutplate s/assy	0	0	Stringer 11	11 stn 847+32, 847+48	**0,0000**	0	0,000	0,000	0,000	0,000	0,000	0,000	0,000
u21	A21	Frame 863	s/assay sta 863	B2	Stringer 10	10 stn 849,865	**0,8632**	u21	1,000	0,538	0,778	0,909	0,890	1,000	1,000
u22	A22	Frame 879	s/assay sta 879	B3	Stringer 11	11 stn 849,866	**0,8623**	u22	1,000	0,538	0,778	0,898	0,890	1,000	1,000
u23	A23	Frame 893	s/assy sta 893	B4	Stringer 10	10 stn 881,897	**0,8623**	u23	1,000	0,538	0,778	0,898	0,890	1,000	1,000

Fig. 5 Interface to show the final results of similarity

V. Application and Validation

To validate the model and the newly developed tool, six panel assemblies of the Bombardier regional jets were taken as samples, and six pairs of panel assemblies were compared and the results are shown in Table 2 and Fig. 6. Each column of Table 2 is associated with one pair of panel assemblies. The degrees of commonality in both component level ($c_1 - c_7$) and assembly level (Q(A,B)) are clearly indicated by the value in the table. It can be clearly seen that the last column has the highest similarity value, i.e.,0.9965, as both the panel assemblies are from the same model of aircraft but in different position, and their major difference is from their processing time and component geometry as shown in Fig. 6. Panel assemblies AFT-LH-CRJ900 and Mid-BTM_RH-DASH8 have the least similarity (0.6915) because of their less likeliness in operation types, sequences, processing time, component geometry and tooling. The average computation time is about two minutes, which is acceptable for industrial engineers. These similarity results conform to the expectation of manufacturing engineers in the company, who totally agree that the similarity is a good indicator for making mix production decisions.

Table 2 Similarity evaluation results of panel assemblies

	AFT LH CRJ 700 & AFT LH CRJ 900	AFT LH CRJ 700 & MID BTM LH DASH8	AFT LH CRJ 700 & MID BTM RH DASH8	AFT LH CRJ 900 & MID BTM LH DASH8	AFT LH CRJ 900 & MID BTM RH DASH8	MID BTM LH DASH8 & MID BTM RH DASH 8
C1	1.000	1.000	1.000	1.000	1.000	1.000
C2	0.551	0.313	0.313	0.452	0.452	1.000
C3	0.832	0.474	0.474	0.560	0.560	1.000
C4	0.764	0.780	0.753	0.626	0.604	0.951
C5	0.840	0.500	0.501	0.538	0.539	0.999
C6	1.000	0.944	0.944	0.955	0.955	1.000
C7	1.000	1.000	1.000	1.000	1.000	1.000
Q(A,B)	0.8580	0.7098	0.7073	0.6934	0.6915	0.9965
Calculation time (s)	143	82	81	64	66	107

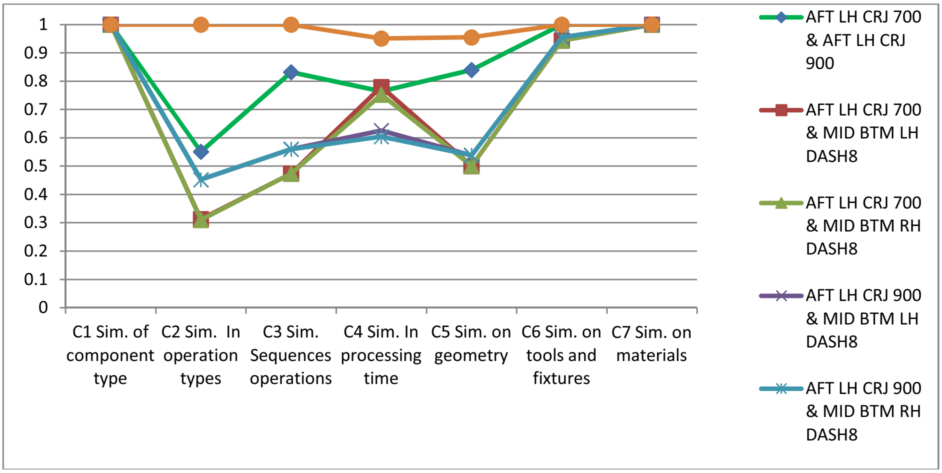


Figure 6 Similarity comparison of each pair of panels

Due to the space limitation, the computation processes is illustrated through only one pair of panel assemblies, i.e. CRJ700 and CRJ900 panel assemblies, as shown in the Appendix.

VI. Conclusion

Although similarity coefficient has been well studied in the literature, few of them considered assembly operations from a system perspective, and none of them can be applied to aerospace industry, where the production is still dominated by manual based dedicated production lines today. To fill the knowledge gap, this paper proposes a new similarity index which considers not only the EBOM but also MBOM for aircraft assemblies from a system perspective. Various similar properties of the constitute elements in the system are modeled based on several methods, including operation-operation matrix, part-operation metrix, and paired comparison method. The similarity at system level is modeled by using the similarity system theory. A digital manufacturing tool has been developed for automatic implementation of the new metric. Both the models and digital tools are validated through six real-life examples of panel assemblies. The results show that the similarity model can clearly indicated the degree of commonality (agreed by our industrial partner) and the automatic tool can generate the right results in a short time. The modeling method can be well applied to other labor-intensive industrial sectors such as rail-carriages and heavy machine assemblies. Our next step is to integrate this tool into the factory's digital manufacturing platform.

Appendix

Data for each panel

1. Components of each panel

Table 3 shows the systems (i.e. AFT LH Panel CRJ700 and AFT LH Panel CRJ900) and their constituent elements.

Table 3 Constituent elements of each panel

AFT LH PANEL CRJ700 (SYSTEM A)			AFT LH PANEL CRJ900 (SYSTEM B)		
Part	Qty	Description	Part	Qty	Description
a_{1}	1	Skin Panel	b_{1}	1	Skin Panel
a_{2}	1	Stringer 8LH	b_{2}	1	Frame sector stn 847+16
a_{3}	1	Stringer 9LH	b_{3}	1	Frame sector stn 847+32
a_{4}	1	Stringer 12LH	b_{4}	1	Frame sector stn 847+48
a_{5}	1	Stringer 10	b_{5}	1	Frame sector stn 849
a_{6}	1	Stringer 11	b_{6}	1	Frame sector 865
a_{7}	1	Stringer 10	b_{7}	1	Frame sector stn 881
a_{8}	1	Stringer 11	b_{8}	1	Frame sector stn 942
a_{9}	1	Stringer 13LH	b_{9}	1	Frame sector stn 954
a_{10}	1	Stringer 14LH	b_{10}	1	Frame sector stn 913
a_{11}	1	Stringer 16LH	b_{11}	1	Frame sector stn 927
a_{12}	1	Stringer 18LH	b_{12}	1	Frame sector stn 898
a_{13}	1	Stringer 19LH	b_{13}	1	Frame sector stn 913
a_{14}	1	Stringer 10LH	b_{14}	1	Frame sector stn 927
a_{15}	1	Stringer 11LH	b_{15}	1	Frame sector stn 898
a_{16}	24	Cleat	b_{16}	1	Frame sector stn 969
a_{17}	22	Cleat	b_{17}	1	Stringer 8
a_{18}	6	Cleat	b_{18}	1	Stringer 9
a_{19}	18	Nutplate s/assy	b_{19}	1	Stringer 10 , stn 847+32, 847+48
a_{20}	11	Nutplate s/assy	b_{20}	1	Stringer 11 , stn 847+32, 847+48
a_{21}	1	Frame s/assy sta.863	b_{21}	1	Stringer 10 , stn 849,865
a_{22}	1	Frame s/assy sta.879	b_{22}	1	Stringer 11 , stn 849,865
a_{23}	1	Frame s/assy sta.893	b_{23}	1	Stringer 10 , stn 881,897
a_{24}	1	Frame s/assy sta.909	b_{24}	1	Stringer 11 , stn 881,897
a_{25}	1	Frame s/assy sta.923	b_{25}	1	Stringer 10 , stn 913,927
a_{26}	1	Frame s/assy sta.939	b_{26}	1	Stringer 11 , stn 913,927
a_{27}	1	Frame s/assy sta.953	b_{27}	1	Stringer 10 , stn 942,954
a_{28}	1	Frame s/assy sta.969	b_{28}	1	Stringer 11 , stn 942,954
a_{29}	24	5/32" CSK Rivet	b_{29}	1	Stringer 12
a_{30}	353	5/32"CSK Rivet	b_{30}	1	Stringer 13
a_{31}	26	5/32"CSK Rivet	b_{31}	1	Stringer 14
a_{32}	76	5/32"UNI Rivet	b_{32}	1	Stringer 16
a_{33}	42	5/32 INIV Rivet	b_{33}	1	Stringer 18
a_{34}	31	5/32 INIV Rivet	b_{34}	1	Stringer 19
a_{35}	58	1/8" C/R 067395	b_{35}	4	Cleat (Type 1)
a_{36}	6	1/8" RIV 068461	b_{36}	63	Cleat (Type 4)
a_{37}	100	HI-LITE pin	b_{37}	6	Cleat (Type 7)
a_{38}	100	HI-LITE pin	b_{38}	7	Cleat (Type 4)
a_{39}	200	HI-LITE collar	b_{39}	1	MC. Ring Doubler
a_{40}	1	Window Coaming	b_{40}	1	Window Coaming
a_{41}	1	Window Coaming	b_{41}	1	Window Coaming
a_{42}	1	Window Coaming	b_{42}	1	Window Coaming
a_{43}	1	Window Coaming	b_{43}	1	Window Coaming
			b_{44}	1	Window Coaming
			b_{45}	1	Window Coaming

2. Operations applied to each panel

Tables 4 and 5 show a list of different operations and sub-operations applied to the two panel assemblies with their corresponding description.

Table 4 Operations Pre AR of Aft LH CRJ700 panel

AFT LH CRJ700 PRE AR (system A)			
Operation	Description	Sub-Op	Description
A.O$_1$	Load skin, frames, stringers	A.O$_{1.1}$	Locate skin panel
		A.O$_{1.2}$	Locate frames & stringers
		A.O$_{1.3}$	Locate cleats
		A.O$_{1.4}$	Locate & drill trapnuts
A.O$_2$	Transfer drill, open & countersink	A.O$_{2.1}$	Drill & countersink for frame to skin holes
		A.O$_{2.2}$	Drill & countersink for stringer to skin holes
		A.O$_{2.3}$	Drill of cleats
		A.O$_{2.4}$	Locate & drill cleats frames/stringers 863 & 869
		A.O$_{2.5}$	Open up holes thru stringer & cleats
		A.O$_{2.6}$	Open up holes thru cleats & frames
A.O$_3$	Dismantle, deburr & wet ass	A.O$_{3.1}$	Dismantle & deburr
		A.O$_{3.2}$	Wet assemble structure
A.O$_4$	Manual riveting	A.O$_{4.1}$	Rivet cleats
		A.O$_{4.2}$	Rivet cleats at frames 923&939, stringer 12
		A.O$_{4.3}$	Rivet complete frames & stringers
		A.O$_{4.4}$	Rivet cleat to stringers
		A.O$_{4.5}$	Wet assemble & rivet trapnut s/assy's
		A.O$_{4.6}$	Clean panel & remove excess sealant
A.O$_5$	Fitting, drilling and hi-liting of windows LH	A.O$_{5.1}$	Drill skin and windows to cold working size
		A.O$_{5.2}$	Drill skin and windows to cold working size
		A.O$_{5.3}$	Cold work holes in way of window coamings
		A.O$_{5.4}$	Cold work holes in way of window coamings
		A.O$_{5.5}$	Ream/countersink holes in way of window coamings
		A.O$_{5.6}$	Ream/countersink holes in way of window coamings
		A.O$_{5.7}$	Breakdown and deburr
		A.O$_{5.8}$	Surface preparation
		A.O$_{5.9}$	Wet assemble/fillet seal & install hi-lites

Table 5 Operations Pre AR of Aft LH CRJ900 panel

AFT LH CRJ900 PRE AR (system B)			
Operation	Description	Sub-operation	Description
B.O$_1$	Locate skin and frames	B.O$_{1.1}$	Locate skin and frames
B.O$_2$	Transfer drill 3/38" from frames	B.O$_{2.1}$	Transfer drill 3/38" from frames
B.O$_3$	Open holes & countersink from frames	B.O$_{3.1}$	Open holes from frames
		B.O$_{3.2}$	Holes from frames
B.O$_4$	Locate stringers & cleats, drill 3/32"	B.O$_{4.1}$	Locate stringers
		B.O$_{4.2}$	Locating cleats
		B.O$_{4.3}$	Transfer drill 3/38" holes thru cleats/stringers
		B.O$_{4.4}$	Drill from stringers to skin
B.O$_5$	Open holes in stringers & cleats full size & countersink	B.O$_{5.1}$	Open holes in & cleats full size
		B.O$_{5.2}$	Open & countersink from stringers to skin
B.O$_6$	Install machined doubler	B.O$_{6.1}$	Drill 2-off 3/32" dia holes, in way of aft fairing
B.O$_7$	Fit Window coamings & ream holes to pre cold work	B.O$_{7.1}$	Drill skin & windows to cold working size
B.O$_8$	Cold work window coamings, ream & deburr	B.O$_{8.1}$	Complete type II mandrel qualification test
		B.O$_{8.2}$	Complete type II mandrel qualification test
		B.O$_{8.3}$	Cold work holes in way of window coamings
		B.O$_{8.4}$	Cold work holes in way of window coamings
		B.O$_{8.5}$	Ream window holes final size & deburr
B.O$_9$	Hi-lite window coamings	B.O$_{9.1}$	Install hi-lites to window coamings
B.O$_{10}$	Dismantle & deburr panel assy	B.O$_{10.1}$	Dismantle & deburr
B.O$_{11}$	Wet assemble aft LH panel assy	B.O$_{11.1}$	Wet assemble

B.O$_{12}$	Rework frames in way of aft LH panel	B.O$_{12.1}$	Stage inspect sequence
B.O$_{13}$	Riveting of aft LH panel assy	B.O$_{13.1}$	Install rivets thru skin and frames
		B.O$_{13.2}$	Install rivets thru skin and stringers
		B.O$_{13.3}$	Install rivets thru cleat and stringers
		B.O$_{13.4}$	Install rivets in way of machined doubler
B.O$_{14}$	Unload aft LH panel from JIG	B.O$_{14.1}$	Unload panel from JIG

3. *Processing time of each panel*

The operating time of each of the sub-operations and operations applied to the panel assemblies, is calculated as the sum of run time and set up time, as shown in Tables 6 and 7. Due to confidential reasons, these data cannot be disclosed here.

Table 6 Processing time of Aft LH CRJ700 panel (system A)

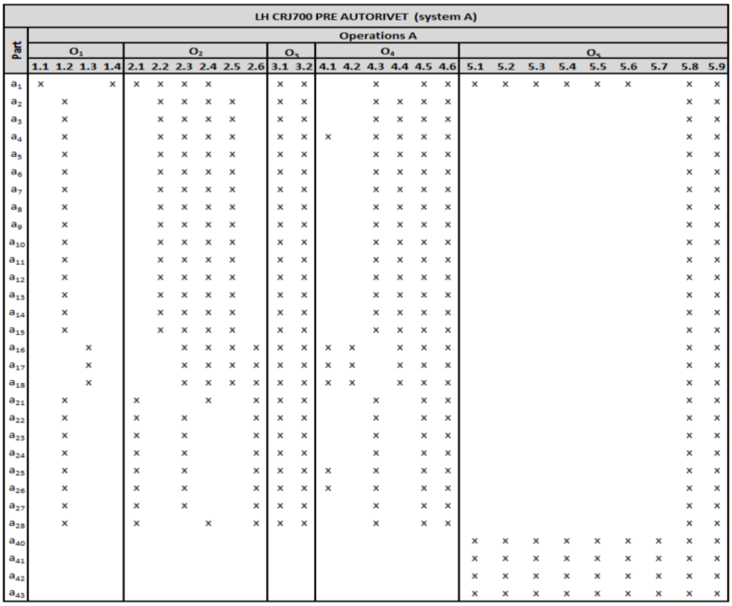
Op.	Run time	Set up time	Total time	Sub-op.	Run time	Set up time	Total time
A.O$_1$	x	x	x	A.O$_{1.1}$	x	x	x
				A.O$_{1.2}$	x	x	x
				A.O$_{1.3}$	x	x	x
				A.O$_{1.4}$	x	x	x
A.O$_2$	x	x	x	A.O$_{2.1}$	x	x	x
				A.O$_{2.2}$	x	x	x
				A.O$_{2.3}$	x	x	x
				A.O$_{2.4}$	x	x	x
				A.O$_{2.5}$	x	x	x
				A.O$_{2.6}$	x	x	x
A.O$_3$	x	x	x	A.O$_{3.1}$	x	x	x
				A.O$_{3.2}$	x	x	x
A.O$_4$	x	x	x	A.O$_{4.1}$	x	x	x
				A.O$_{4.2}$	x	x	x
				A.O$_{4.3}$	x	x	x
				A.O$_{4.4}$	x	x	x
				A.O$_{4.5}$	x	x	x
				A.O$_{4.6}$	x	x	x
A.O$_5$	x	x	x	A.O$_{5.1}$	x	x	x
				A.O$_{5.2}$	x	x	x
				A.O$_{5.3}$	x	x	x
				A.O$_{5.4}$	x	x	x
				A.O$_{5.5}$	x	x	x
				A.O$_{5.6}$	x	x	x
				A.O$_{5.7}$	x	x	x
				A.O$_{5.8}$	x	x	x
				A.O$_{5.9}$	x	x	x

Table 7 Processing time of Aft LH CRJ900 panel (system B)

Op.	**Run time**	**Set up time**	**Total time**	**Sub-op.**	**Run time**	**Set up time**	**Total time**
B.O$_1$	x	x	x	B.O$_{1.1}$	x	x	x
B.O$_2$	x	x	x	B.O$_{2.1}$	x	x	x
B.O$_3$	x	x	x	B.O$_{3.1}$	x	x	x
				B.O$_{3.2}$	x	x	x
B.O$_4$	x	x	x	B.O$_{4.1}$	x	x	x
				B.O$_{4.2}$	x	x	x
				B.O$_{4.3}$	x	x	x
				B.O$_{4.4}$	x	x	x
B.O$_5$	x	x	x	B.O$_{5.1}$	x	x	x
				B.O$_{5.2}$	x	x	x
B.O$_6$	x	x	x	B.O$_{6.1}$	x	x	x

B.O$_7$	x	x	x	B.O$_{7.1}$	x	x	x
B.O$_8$	x	x	x	B.O$_{8.1}$	x	x	x
				B.O$_{8.2}$	x	x	x
				B.O$_{8.3}$	x	x	x
				B.O$_{8.4}$	x	x	x
				B.O$_{8.5}$	x	x	x
B.O$_9$	x	x	x	B.O$_{9.1}$	x	x	x
B.O$_{10}$	x	x	x	B.O$_{10.1}$	x	x	x
B.O$_{11}$	x	x	x	B.O$_{11.1}$	x	x	x
B.O$_{12}$	x	x	x	B.O$_{12.1}$	x	x	x
B.O$_{13}$	x	x	x	B.O$_{13.1}$	x	x	x
				B.O$_{13.2}$	x	x	x
				B.O$_{13.3}$	x	x	x
				B.O$_{13.4}$	x	x	x
B.O$_{14}$	x	x	x	B.O$_{14.1}$	x	x	x

Table 8 Operations Pre AR of Aft LH CRJ700 panel applied to each similar element



LH CRJ700 PRE AUTORIVET (system A)																											
Part	Operations A																										
	O_1				O_2						O_3		O_4						O_5								
	1.1	1.2	1.3	1.4	2.1	2.2	2.3	2.4	2.5	2.6	3.1	3.2	4.1	4.2	4.3	4.4	4.5	4.6	5.1	5.2	5.3	5.4	5.5	5.6	5.7	5.8	5.9
a_1	x			x	x	x	x	x			x	x			x		x	x	x	x	x	x	x	x		x	x
a_2		x				x	x	x	x		x	x			x	x	x	x								x	x
a_3		x				x	x	x	x		x	x			x	x	x	x								x	x
a_4		x				x	x	x	x		x	x	x		x	x	x	x								x	x
a_5		x				x	x	x	x		x	x			x	x	x	x								x	x
a_6		x				x	x	x	x		x	x			x	x	x	x								x	x
a_7		x				x	x	x	x		x	x			x	x	x	x								x	x
a_8		x				x	x	x	x		x	x			x	x	x	x								x	x
a_9		x				x	x	x	x		x	x			x	x	x	x								x	x
a_{10}		x				x	x	x	x		x	x			x	x	x	x								x	x
a_{11}		x				x	x	x	x		x	x			x	x	x	x								x	x
a_{12}		x				x	x	x	x		x	x			x	x	x	x								x	x
a_{13}		x				x	x	x	x		x	x			x	x	x	x								x	x
a_{14}		x				x	x	x	x		x	x			x	x	x	x								x	x
a_{15}		x				x	x	x	x		x	x			x	x	x	x								x	x
a_{16}			x				x	x	x	x	x	x	x	x		x	x	x								x	x
a_{17}			x				x	x	x	x	x	x	x	x		x	x	x								x	x
a_{18}			x				x	x	x	x	x	x	x	x		x	x	x								x	x
a_{21}		x			x			x		x	x	x			x		x	x								x	x
a_{22}		x			x		x			x	x	x			x		x	x								x	x
a_{23}		x			x		x			x	x	x			x		x	x								x	x
a_{24}		x			x		x			x	x	x			x		x	x								x	x
a_{25}		x			x		x			x	x	x	x		x		x	x								x	x
a_{26}		x			x		x			x	x	x	x		x		x	x								x	x
a_{27}		x			x		x			x	x	x			x		x	x								x	x
a_{28}		x			x			x		x	x	x			x		x	x								x	x
a_{40}																			x	x	x	x	x	x	x	x	x
a_{41}																			x	x	x	x	x	x	x	x	x
a_{42}																			x	x	x	x	x	x	x	x	x
a_{43}																			x	x	x	x	x	x	x	x	x

Similarity values of similar properties

1 Similarity values of similar component type

Once all the components are known, it is possible to calculate the similarity value of similar component type by applying the corresponding algorithm discussed in Section III. The result is thirty similar elements of each system, and therefore thirty similar units whose relationship is shown below:

$u_1(a_1,b_1)$

$u_2(a_2,b_{17})$

$u_3(a_3,b_{18})$

$u_4(a_4,b_{29})$

$u_5(a_5,b_{19})$

$u_6(a_6,b_{20})$

$u_{11}(a_{11},b_{32})$

$u_{12}(a_{12},b_{33})$

$u_{13}(a_{13},b_{34})$

$u_{14}(a_{14},b_{23})$

$u_{15}(a_{15},b_{24})$

$u_{16}(a_{16},b_{35})$

$u_{21}(a_{23},b_4)$

$u_{22}(a_{24},b_5)$

$u_{23}(a_{25},b_{14})$

$u_{24}(a_{26},b_8)$

$u_{25}(a_{27},b_9)$

$u_{26}(a_{28},b_{16})$

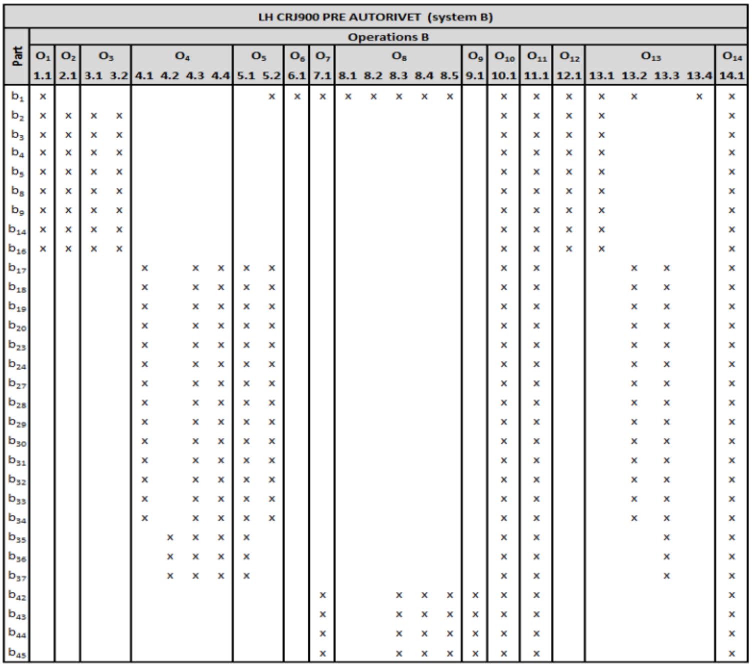
$u_7(a_7,b_{27})$	$u_{17}(a_{17},b_{36})$	$u_{27}(a_{40},b_{42})$
$u_8(a_8,b_{28})$	$u_{18}(a_{18},b_{37})$	$u_{28}(a_{41},b_{43})$
$u_9(a_9,b_{30})$	$u_{19}(a_{21},b_2)$	$u_{29}(a_{42},b_{44})$
$u_{10}(a_{10},b_{31})$	$u_{20}(a_{22},b_3)$	$u_{30}(a_{43},b_{45})$

2 Similarity values of operation type and of the sequences between operations

Once the operations applied on each panel are known, the next step is to indicate which operations are performed over each component. This process has produced data inTables 8 and 9 that indicate which component is associated with corresponding operations. Note that the operations are ordered according to their sequence in the process.

Tables 8 and 9 indicate the number of operations directly applied to each constituent element. To determine which of the operations performed in the system A are also executed in the system B, an operation-operation incidence matrix is constructed between the two systems based on the operation name. By applying eqn.(5), the similarity of operation type for each similar unit is obtained as shown in Table 10.

Table 9 Operations Pre AR of Aft LH CRJ900 panel applied to each similar element



LH CRJ900 PRE AUTORIVET (system B)																										
Part	Operations B																									
	O_1	O_2	O_3		O_4				O_5		O_6	O_7	O_8					O_9	O_{10}	O_{11}	O_{12}	O_{13}				O_{14}
	1.1	2.1	3.1	3.2	4.1	4.2	4.3	4.4	5.1	5.2	6.1	7.1	8.1	8.2	8.3	8.4	8.5	9.1	10.1	11.1	12.1	13.1	13.2	13.3	13.4	14.1
b_1	x									x	x	x	x	x	x	x	x		x	x	x	x	x		x	x
b_2	x	x	x	x															x	x	x	x				x
b_3	x	x	x	x															x	x	x	x				x
b_4	x	x	x	x															x	x	x	x				x
b_5	x	x	x	x															x	x	x	x				x
b_8	x	x	x	x															x	x	x	x				x
b_9	x	x	x	x															x	x	x	x				x
b_{14}	x	x	x	x															x	x	x	x				x
b_{16}	x	x	x	x															x	x	x	x				x
b_{17}					x		x	x	x	x									x	x			x	x		x
b_{18}					x		x	x	x	x									x	x			x	x		x
b_{19}					x		x	x	x	x									x	x			x	x		x
b_{20}					x		x	x	x	x									x	x			x	x		x
b_{23}					x		x	x	x	x									x	x			x	x		x
b_{24}					x		x	x	x	x									x	x			x	x		x
b_{27}					x		x	x	x	x									x	x			x	x		x
b_{28}					x		x	x	x	x									x	x			x	x		x
b_{29}					x		x	x	x	x									x	x			x	x		x
b_{30}					x		x	x	x	x									x	x			x	x		x
b_{31}					x		x	x	x	x									x	x			x	x		x
b_{32}					x		x	x	x	x									x	x			x	x		x
b_{33}					x		x	x	x	x									x	x			x	x		x
b_{34}					x		x	x	x	x									x	x			x	x		x
b_{35}						x	x	x	x										x	x				x		x
b_{36}						x	x	x	x										x	x				x		x
b_{37}						x	x	x	x										x	x				x		x
b_{42}												x			x	x	x	x	x	x						x
b_{43}												x			x	x	x	x	x	x						x
b_{44}												x			x	x	x	x	x	x						x
b_{45}												x			x	x	x	x	x	x						x

Table 10 Similarity values of operation type

SIMILAR UNITS	Number of operations applied to a_i	Number of operations applied to b_j	V_{ai}	V_{bj}	$V_{ai,bj}$	c_2^{ui}
$u_1(a_1,b_1)$	19	16	8	5	9	0.409
$u_2(a_2,b_{17})$	13	10	4	2	8	0.571
$u_3(a_3,b_{18})$	13	10	4	2	8	0.571
$u_4(a_4,b_{29})$	14	10	5	2	8	0.533
$u_5(a_5,b_{19})$	13	10	4	2	8	0.571

$u_6(a_6,b_{20})$	13	10	4	2	8	0.571
$u_7(a_7,b_{27})$	13	10	4	2	8	0.571
$u_8(a_8,b_{28})$	13	10	4	2	8	0.571
$u_9(a_9,b_{30})$	13	10	4	2	8	0.571
$u_{10}(a_{10},b_{31})$	13	10	4	2	8	0.571
$u_{11}(a_{11},b_{32})$	13	10	4	2	8	0.571
$u_{12}(a_{12},b_{33})$	13	10	4	2	8	0.571
$u_{13}(a_{13},b_{34})$	13	10	4	2	8	0.571
$u_{14}(a_{14},b_{23})$	13	10	4	2	8	0.571
$u_{15}(a_{15},b_{24})$	13	10	4	2	8	0.571
$u_{16}(a_{16},b_{35})$	14	8	8	3	5	0.313
$u_{17}(a_{17},b_{36})$	14	8	8	3	5	0.313
$u_{18}(a_{18},b_{37})$	14	8	8	3	5	0.313
$u_{19}(a_{21},b_2)$	11	9	4	2	7	0.538
$u_{20}(a_{22},b_3)$	11	9	4	2	7	0.538
$u_{21}(a_{23},b_4)$	11	9	4	2	7	0.538
$u_{22}(a_{24},b_5)$	11	9	4	2	7	0.538
$u_{23}(a_{25},b_{14})$	12	9	5	2	7	0.500
$u_{24}(a_{26},b_8)$	12	9	5	2	7	0.500
$u_{25}(a_{27},b_9)$	11	9	4	2	7	0.538
$u_{26}(a_{28},b_{16})$	11	9	4	2	7	0.538
$u_{27}(a_{40},b_{42})$	9	8	1	1	7	0.778
$u_{28}(a_{41},b_{43})$	9	8	1	1	7	0.778
$u_{29}(a_{42},b_{44})$	9	8	1	1	7	0.778
$u_{30}(a_{43},b_{45})$	9	8	1	1	7	0.778

Then by applying the method in Section III.A.3, the similarity in operation sequence for each similar unit is obtained as shown in Table 11.

Table 11 Similarity value of the sequences between operations

SIMILAR UNITS	Z = min{z_{ai},z_{bj}}		Number of diff. seq. 'ε'	Number of op. in the			Value of diagonals 'γ_i'			c_3^{ui}
	z_{ai}	z_{bi}		F_1	F_2	F_3	γ_1	γ_2	γ_3	
$u_1(a_1,b_1)$	11	9	3	3	1	4	0.556	1.000	0.778	0.642
$u_2(a_2,b_{17})$	9	8	2	1	5	x	1.000	1.000	x	0.750
$u_3(a_3,b_{18})$	9	8	2	1	5	x	1.000	1.000	x	0.750
$u_4(a_4,b_{29})$	9	8	2	1	5	x	1.000	1.000	x	0.750
$u_5(a_5,b_{19})$	9	8	2	1	5	x	1.000	1.000	x	0.750
$u_6(a_6,b_{20})$	9	8	2	1	5	x	1.000	1.000	x	0.750
$u_7(a_7,b_{27})$	9	8	2	1	5	x	1.000	1.000	x	0.750
$u_8(a_8,b_{28})$	9	8	2	1	5	x	1.000	1.000	x	0.750
$u_9(a_9,b_{30})$	9	8	2	1	5	x	1.000	1.000	x	0.750
$u_{10}(a_{10},b_{31})$	9	8	2	1	5	x	1.000	1.000	x	0.750
$u_{11}(a_{11},b_{32})$	9	8	2	1	5	x	1.000	1.000	x	0.750
$u_{12}(a_{12},b_{33})$	9	8	2	1	5	x	1.000	1.000	x	0.750
$u_{13}(a_{13},b_{34})$	9	8	2	1	5	x	1.000	1.000	x	0.750
$u_{14}(a_{14},b_{23})$	9	8	2	1	5	x	1.000	1.000	x	0.750
$u_{15}(a_{15},b_{24})$	9	8	2	1	5	x	1.000	1.000	x	0.750
$u_{16}(a_{16},b_{35})$	6	5	1	5	x	x	1.000	x	x	1.000
$u_{17}(a_{17},b_{36})$	6	5	1	5	x	x	1.000	x	x	1.000
$u_{18}(a_{18},b_{37})$	6	5	1	5	x	x	1.000	x	x	1.000
$u_{19}(a_{21},b_2)$	7	7	2	4	3	x	0.857	1.000	x	0.918
$u_{20}(a_{22},b_3)$	7	7	2	4	3	x	0.857	1.000	x	0.918
$u_{21}(a_{23},b_4)$	7	7	2	4	3	x	0.857	1.000	x	0.918
$u_{22}(a_{24},b_5)$	7	7	2	4	3	x	0.857	1.000	x	0.918
$u_{23}(a_{25},b_{14})$	7	7	2	4	3	x	0.857	1.000	x	0.918
$u_{24}(a_{26},b_8)$	7	7	2	4	3	x	0.857	1.000	x	0.918
$u_{25}(a_{27},b_9)$	7	7	2	4	3	x	0.857	1.000	x	0.918
$u_{26}(a_{28},b_{16})$	7	7	2	4	3	x	0.857	1.000	x	0.918

$u_{27}(a_{40},b_{42})$	8	7	3	1	4	2	1.000	1.000	1.000	1.000
$u_{28}(a_{41},b_{43})$	8	7	3	1	4	2	1.000	1.000	1.000	1.000
$u_{29}(a_{42},b_{44})$	8	7	3	1	4	2	1.000	1.000	1.000	1.000
$u_{30}(a_{43},b_{45})$	8	7	3	1	4	2	1.000	1.000	1.000	1.000

3 Similarity values of processing time in each workstation

The processing time is associated with each sub-operation, and the total processing time can be rolled up from the basic standard times of each sub-operation based on predefined rules by the company. Since all the Pre auto-riveter (AR) operations of both panels are made in only one workstation, the value of the weight factor of the utilization of the workstations is 1, and the results of the calculation are shown in the Table 12.

Table 12 Calculation of similarity values of processing time in each workstation

SIMILAR UNITS	P_i^{ai}		P_i^{bj}		$\Delta P_{22}^{(ai,bj)}$	ρ_{22}	$\Sigma\rho_{22}$	$w_{22}^{(ai,bj)}$	$d_{22}^{(ai,bj)}$	$đ_{22}^{(ai,bj)}$	s_{22}	c_4^{ui}
	P_{22}^{ai}	P_T^{ai}	P_{22}^{bj}	P_T^{bj}								
$u_1(a_1,b_1)$	28.243	28.243	27.150	27.150	1.195	0.731	0.731	1.000	1.093	28.243	0.961	0.961
$u_2(a_2,b_{17})$	18.950	18.950	13.769	13.769	26.843	0.432	0.432	1.000	5.181	18.950	0.727	0.727
$u_3(a_3,b_{18})$	18.950	18.950	13.769	13.769	26.843	0.432	0.432	1.000	5.181	18.950	0.727	0.727
$u_4(a_4,b_{29})$	19.990	19.990	13.769	13.769	38.701	0.445	0.445	1.000	6.221	19.990	0.689	0.689
$u_5(a_5,b_{19})$	18.950	18.950	13.769	13.769	26.843	0.432	0.432	1.000	5.181	18.950	0.727	0.727
$u_6(a_6,b_{20})$	18.950	18.950	13.769	13.769	26.843	0.432	0.432	1.000	5.181	18.950	0.727	0.727
$u_7(a_7,b_{27})$	18.950	18.950	13.769	13.769	26.843	0.432	0.432	1.000	5.181	18.950	0.727	0.727
$u_8(a_8,b_{28})$	18.950	18.950	13.769	13.769	26.843	0.432	0.432	1.000	5.181	18.950	0.727	0.727
$u_9(a_9,b_{30})$	18.950	18.950	13.769	13.769	26.843	0.432	0.432	1.000	5.181	18.950	0.727	0.727
$u_{10}(a_{10},b_{31})$	18.950	18.950	13.769	13.769	26.843	0.432	0.432	1.000	5.181	18.950	0.727	0.727
$u_{11}(a_{11},b_{32})$	18.950	18.950	13.769	13.769	26.843	0.432	0.432	1.000	5.181	18.950	0.727	0.727
$u_{12}(a_{12},b_{33})$	18.950	18.950	13.769	13.769	26.843	0.432	0.432	1.000	5.181	18.950	0.727	0.727
$u_{13}(a_{13},b_{34})$	18.950	18.950	13.769	13.769	26.843	0.432	0.432	1.000	5.181	18.950	0.727	0.727
$u_{14}(a_{14},b_{23})$	18.950	18.950	13.769	13.769	26.843	0.432	0.432	1.000	5.181	18.950	0.727	0.727
$u_{15}(a_{15},b_{24})$	18.950	18.950	13.769	13.769	26.843	0.432	0.432	1.000	5.181	18.950	0.727	0.727
$u_{16}(a_{16},b_{35})$	15.019	15.019	12.567	12.567	6.012	0.364	0.364	1.000	2.452	15.019	0.837	0.837
$u_{17}(a_{17},b_{36})$	15.019	15.019	12.567	12.567	6.012	0.364	0.364	1.000	2.452	15.019	0.837	0.837
$u_{18}(a_{18},b_{37})$	15.019	15.019	12.567	12.567	6.012	0.364	0.364	1.000	2.452	15.019	0.837	0.837
$u_{19}(a_{21},b_2)$	19.963	19.963	18.142	18.142	3.316	0.503	0.503	1.000	1.821	19.963	0.909	0.909
$u_{20}(a_{22},b_3)$	20.208	20.208	18.142	18.142	4.268	0.506	0.506	1.000	2.066	20.208	0.898	0.898
$u_{21}(a_{23},b_4)$	20.208	20.208	18.142	18.142	4.268	0.506	0.506	1.000	2.066	20.208	0.898	0.898
$u_{22}(a_{24},b_5)$	20.208	20.208	18.142	18.142	4.268	0.506	0.506	1.000	2.066	20.208	0.898	0.898
$u_{23}(a_{25},b_{14})$	21.248	21.248	18.142	18.142	9.647	0.520	0.520	1.000	3.106	21.248	0.854	0.854
$u_{24}(a_{26},b_8)$	21.248	21.248	18.142	18.142	9.647	0.520	0.520	1.000	3.106	21.248	0.854	0.854
$u_{25}(a_{27},b_9)$	20.208	20.208	18.142	18.142	4.268	0.506	0.506	1.000	2.066	20.208	0.898	0.898
$u_{26}(a_{28},b_{16})$	19.963	19.963	18.142	18.142	3.316	0.503	0.503	1.000	1.821	19.963	0.909	0.909
$u_{27}(a_{40},b_{42})$	11.933	11.933	21.742	21.742	96.216	0.444	0.444	1.000	9.809	21.742	0.549	0.549
$u_{28}(a_{41},b_{43})$	11.933	11.933	21.742	21.742	96.216	0.444	0.444	1.000	9.809	21.742	0.549	0.549
$u_{29}(a_{42},b_{44})$	11.933	11.933	21.742	21.742	96.216	0.444	0.444	1.000	9.809	21.742	0.549	0.549
$u_{30}(a_{43},b_{45})$	11.933	11.933	21.742	21.742	96.216	0.444	0.444	1.000	9.809	21.742	0.549	0.549

4 Similarity value on geometry

To calculate the similarity value on geometry, data are extracted from the drawings of both panels. As some of them are not listed, the calculation has been performed as precisely as possible with the available data. Due to its small size compared with the rest, the similarity value on geometry of some components, such as cleats, cannot be calculated because there are no measurements. The references in the drawings indicate that this is exactly the same type of components, so it is assumed that the similarity value on geometry is 1. The same applies to the window coamings. In this case, although their sizes are not as small as the cleats sizes, the number of reference confirms that they are the same for both panels, so their value is 1.

Table 13 shows the values of length, width and depth of most of the components. Through these values we can calculate the scale factor of each measure. With the algorithm addressed in Section III.A.5, the similarity value on geometry can be calculated, as shown in the last column in Table 13. All measures have been taken in unit of inches.

Table 13 Calculation of similarity value on geometry

SIMILAR UNITS	Length		λ_x	Width		λ_y	Depth		λ_z	c_5^{ui}
	a_i	b_j		a_i	b_j		a_i	b_j		
$u_1(a_1,b_1)$	115.130	177.600	0.648	78.774	77.050	1.022	0.186	0.186	1.000	0.634
$u_2(a_2,b_{17})$	111.310	161.700	0.688	1.000	0.900	1.111	0.820	0.820	1.000	0.620
$u_3(a_3,b_{18})$	112.110	161.700	0.693	0.800	1.000	0.800	0.820	0.820	1.000	0.693
$u_4(a_4,b_{29})$	112.110	161.700	0.693	0.800	0.800	1.000	0.820	0.820	1.000	0.693
$u_5(a_5,b_{19})$	12.800	13.850	0.924	0.800	0.800	1.000	0.820	0.820	1.000	0.924
$u_6(a_6,b_{20})$	12.800	13.850	0.924	0.800	0.800	1.000	0.820	0.820	1.000	0.924
$u_7(a_7,b_{27})$	12.800	10.300	1.243	0.700	0.800	0.875	0.820	0.820	1.000	0.704
$u_8(a_8,b_{28})$	12.800	10.300	1.243	0.700	0.800	0.875	0.820	0.820	1.000	0.704
$u_9(a_9,b_{30})$	111.310	161.700	0.688	0.800	0.800	1.000	0.820	0.820	1.000	0.688
$u_{10}(a_{10},b_{31})$	111.310	161.700	0.688	0.700	0.800	0.875	0.820	0.820	1.000	0.688
$u_{11}(a_{11},b_{32})$	110.170	161.700	0.681	0.700	1.000	0.700	0.820	0.820	1.000	0.681
$u_{12}(a_{12},b_{33})$	110.610	161.700	0.684	0.800	1.000	0.800	0.820	0.820	1.000	0.684
$u_{13}(a_{13},b_{34})$	110.610	161.700	0.684	0.700	1.000	0.700	0.820	0.820	1.000	0.684
$u_{14}(a_{14},b_{23})$	12.980	14.200	0.914	0.700	0.800	0.875	0.820	0.820	1.000	0.875
$u_{15}(a_{15},b_{24})$	12.980	14.200	0.914	0.700	0.800	0.875	0.820	0.820	1.000	0.875
$u_{16}(a_{16},b_{35})$	x	x	x	x	x	x	x	x	1.000	1.000
$u_{17}(a_{17},b_{36})$	x	x	x	x	x	x	x	x	1.000	1.000
$u_{18}(a_{18},b_{37})$	x	x	x	x	x	x	x	x	1.000	1.000
$u_{19}(a_{21},b_2)$	77.670	75.900	1.023	1.220	1.200	1.017	0.800	0.700	1.143	0.890
$u_{20}(a_{22},b_3)$	77.670	75.900	1.023	1.220	1.200	1.017	0.800	0.700	1.143	0.890
$u_{21}(a_{23},b_4)$	77.670	75.900	1.023	1.220	1.200	1.017	0.800	0.700	1.143	0.890
$u_{22}(a_{24},b_5)$	77.670	75.900	1.023	1.220	1.200	1.017	0.800	0.700	1.143	0.890
$u_{23}(a_{25},b_{14})$	77.670	75.900	1.023	1.220	1.200	1.017	0.800	0.700	1.143	0.890
$u_{24}(a_{26},b_8)$	77.670	75.900	1.023	1.220	1.200	1.017	0.800	0.700	1.143	0.890
$u_{25}(a_{27},b_9)$	77.670	75.900	1.023	1.220	1.200	1.017	0.800	0.700	1.143	0.890
$u_{26}(a_{28},b_{16})$	77.670	75.900	1.023	1.220	1.200	1.017	0.800	0.700	1.143	0.890
$u_{27}(a_{40},b_{42})$	x	x	x	x	x	x	x	x	1.000	1.000
$u_{28}(a_{41},b_{43})$	x	x	x	x	x	x	x	x	1.000	1.000
$u_{29}(a_{42},b_{44})$	x	x	x	x	x	x	x	x	1.000	1.000
$u_{30}(a_{43},b_{45})$	x	x	x	x	x	x	x	x	1.000	1.000

5 Similarity value on tools and fixtures

Table 14 Similarity value on tools and fixtures

Similar unit	ς_{ai}	ς_{bj}	c_6
$u(a_i,b_j)$	97.500	97.500	1.000

As the two panels of CRJ700 and CRJ900 have the same diameter as shown in Table 14, the similarity value in tooling is $c_6 = 1$.

6 Similarity value on materials

In cases that are being studied and applied to the aerospace industry, the materials of all components are almost the same, i.e., aluminium alloy. Therefore, the similarity on materials is $c_7 = 1$.

Value of similar units

Once determined, the information required to calculate the value of each similar unit, the similarity value of each similar unit can be obtained using eqn. (1). Table 16 shows the results.

Table 15 Calculation of the value of similar units

SIMILAR UNITS	$d_1{*}c_1^{ui}$	$d_2{*}c_2^{ui}$	$d_3{*}c_3^{ui}$	$d_4{*}c_4^{ui}$	$d_5{*}c_5^{ui}$	$d_6{*}c_6^{ui}$	$d_7{*}c_7^{ui}$	$q(u_i)$
$u_1(a_1,b_1)$	0.250	0.070	0.109	0.077	0.076	0.160	0.050	0.792
$u_2(a_2,b_{17})$	0.250	0.097	0.128	0.058	0.074	0.160	0.050	0.817
$u_3(a_3,b_{18})$	0.250	0.097	0.128	0.058	0.083	0.160	0.050	0.826
$u_4(a_4,b_{29})$	0.250	0.091	0.128	0.055	0.083	0.160	0.050	0.816

$u_5(a_5,b_{19})$	0.250	0.097	0.128	0.058	0.111	0.160	0.050	0.854
$u_6(a_6,b_{20})$	0.250	0.097	0.128	0.058	0.111	0.160	0.050	0.854
$u_7(a_7,b_{27})$	0.250	0.097	0.128	0.058	0.084	0.160	0.050	0.827
$u_8(a_8,b_{28})$	0.250	0.097	0.128	0.058	0.084	0.160	0.050	0.827
$u_9(a_9,b_{30})$	0.250	0.097	0.128	0.058	0.083	0.160	0.050	0.825
$u_{10}(a_{10},b_{31})$	0.250	0.097	0.128	0.058	0.083	0.160	0.050	0.825
$u_{11}(a_{11},b_{32})$	0.250	0.097	0.128	0.058	0.082	0.160	0.050	0.824
$u_{12}(a_{12},b_{33})$	0.250	0.097	0.128	0.058	0.082	0.160	0.050	0.825
$u_{13}(a_{13},b_{34})$	0.250	0.097	0.128	0.058	0.082	0.160	0.050	0.825
$u_{14}(a_{14},b_{23})$	0.250	0.097	0.128	0.058	0.105	0.160	0.050	0.848
$u_{15}(a_{15},b_{24})$	0.250	0.097	0.128	0.058	0.105	0.160	0.050	0.848
$u_{16}(a_{16},b_{35})$	0.250	0.053	0.170	0.067	0.120	0.160	0.050	0.870
$u_{17}(a_{17},b_{36})$	0.250	0.053	0.170	0.067	0.120	0.160	0.050	0.870
$u_{18}(a_{18},b_{37})$	0.250	0.053	0.170	0.067	0.120	0.160	0.050	0.870
$u_{19}(a_{21},b_2)$	0.250	0.091	0.156	0.073	0.107	0.160	0.050	0.887
$u_{20}(a_{22},b_3)$	0.250	0.091	0.156	0.072	0.107	0.160	0.050	0.886
$u_{21}(a_{23},b_4)$	0.250	0.091	0.156	0.072	0.107	0.160	0.050	0.886
$u_{22}(a_{24},b_5)$	0.250	0.091	0.156	0.072	0.107	0.160	0.050	0.886
$u_{23}(a_{25},b_{14})$	0.250	0.085	0.156	0.068	0.107	0.160	0.050	0.876
$u_{24}(a_{26},b_8)$	0.250	0.085	0.156	0.068	0.107	0.160	0.050	0.876
$u_{25}(a_{27},b_9)$	0.250	0.091	0.156	0.072	0.107	0.160	0.050	0.886
$u_{26}(a_{28},b_{16})$	0.250	0.091	0.156	0.073	0.107	0.160	0.050	0.887
$u_{27}(a_{40},b_{42})$	0.250	0.132	0.170	0.044	0.120	0.160	0.050	0.926
$u_{28}(a_{41},b_{43})$	0.250	0.132	0.170	0.044	0.120	0.160	0.050	0.926
$u_{29}(a_{42},b_{44})$	0.250	0.132	0.170	0.044	0.120	0.160	0.050	0.926
$u_{30}(a_{43},b_{45})$	0.250	0.132	0.170	0.044	0.120	0.160	0.050	0.926

It is confirmed that the similarity between the components is high. The first value obtained shows the similarity between the skin panels. This is the lowest value comparing to the other parts, because it is the component on which more operations are being performed, and it is the base element of each system. As more operations are performed on it, there is higher chance that the type of operations or the operation sequences will be different, which may lead to a lower similarity value. However, the obtained value is almost 0.8, which indicates that the two skin panels under study are quite similar, and the differences between them are largely in size. By referencing to the stringers and frames, all their value of similarity is greater than 0.8, in most of the cases even greater than 0.85. It shows a high level of similarity between this type of components. The similarity value of the cleats is 0.87. The cleats are from the same model, but they are different in the sequence, type, etc., of the operations. Nevertheless, the value obtained is higher, demonstrating a greater similarity on their properties inside the production process. Finally, the window coamings show the highest value, 0.926, since they are actually the same type for both models. The differences only lies in the type and the processing time of the operations. In general terms the most of the values in Table 15 are above 0.8, which indicates that the similarity units are made correctly, and likewise, the components that are considered similar within each similar unit, have been the right ones. This also determines the similarity between the panels as discussed later.

Weights of similar elements

By using the method described in Section III.B, the weight of each similar unites is obtained as shown in Table 16.

Table 16 Weights of similar elements 2

SIMILAR UNITS	Number of op. applied to a_i ,	Number of op. applied to b_j ,	β_{ai}	β_{bj}
$u_1(a_1,b_1)$	19	16	0.051	0.056
$u_2(a_2,b_{17})$	13	10	0.035	0.035
$u_3(a_3,b_{18})$	13	10	0.035	0.035
$u_4(a_4,b_{29})$	14	10	0.038	0.035
$u_5(a_5,b_{19})$	13	10	0.035	0.035
$u_6(a_6,b_{20})$	13	10	0.035	0.035
$u_7(a_7,b_{27})$	13	10	0.035	0.035
$u_8(a_8,b_{28})$	13	10	0.035	0.035
$u_9(a_9,b_{30})$	13	10	0.035	0.035
$u_{10}(a_{10},b_{31})$	13	10	0.035	0.035

$u_{11}(a_{11},b_{32})$	13	10	0.035	0.035
$u_{12}(a_{12},b_{33})$	13	10	0.035	0.035
$u_{13}(a_{13},b_{34})$	13	10	0.035	0.035
$u_{14}(a_{14},b_{23})$	13	10	0.035	0.035
$u_{15}(a_{15},b_{24})$	13	10	0.035	0.035
$u_{16}(a_{16},b_{35})$	14	8	0.038	0.028
$u_{17}(a_{17},b_{36})$	14	8	0.038	0.028
$u_{18}(a_{18},b_{37})$	14	8	0.038	0.028
$u_{19}(a_{21},b_{2})$	11	9	0.030	0.032
$u_{20}(a_{22},b_{3})$	11	9	0.030	0.032
$u_{21}(a_{23},b_{4})$	11	9	0.030	0.032
$u_{22}(a_{24},b_{5})$	11	9	0.030	0.032
$u_{23}(a_{25},b_{14})$	12	9	0.032	0.032
$u_{24}(a_{26},b_{8})$	12	9	0.032	0.032
$u_{25}(a_{27},b_{9})$	11	9	0.030	0.032
$u_{26}(a_{28},b_{16})$	11	9	0.030	0.032
$u_{27}(a_{40},b_{42})$	9	8	0.024	0.028
$u_{28}(a_{41},b_{43})$	9	8	0.024	0.028
$u_{29}(a_{42},b_{44})$	9	8	0.024	0.028
$u_{30}(a_{43},b_{45})$	9	8	0.024	0.028
	$\Sigma h_{ai}=370$	$\Sigma h_{bj}=284$		

Similarity value

Based on the similarity value of every similar unit (Table 15) and its associated weight (Table 16), the similarity of the two systems is calculated by eqn. (3) as follows.

$$Q(A,B) = 0.858$$

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Predicting Foreseeable Uncertainty Using a Value Driven Design Methodology

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Program overruns and delays have long been an issue within the aerospace industry. With so many external pressures from stakeholders and the continuously declining economy, aerospace manufacturers and developers are forced to concentrate effort to limit these overruns and delays. This paper introduces the development of a Value Driven Design inspired Capability Function (CF) that will ultimately be used to predict overrun and delay occurrence while also quantifying their economic impact on the program being developed. Within this paper specifically the inherent sub-variable reactions within the CF are explored and the most influential and design controllable variables identified. Upon identifying these variables an updated approximation of the CF is presented.

Keywords: Systems Engineering, Value-Driven Design, Cost, Uncertainty

Nomenclature

C_{DC} = Cost of delay and cancellation (of flight)
C_{Dev} = Cost of development
C_{Dis} = Cost of disposal
C_{Man} = Cost of Manufacture
C_{PF} = Cost per flight
$Disc_C$ = Customers discount factor
$Disc_P$ = Producers discount factor
E_{TPF} = Externality tax per flight
F_{Dcomp} = Uncertainty factor for design complexity
F_{Din} = Uncertainty factor for insufficient design
F_{Dr} = Uncertainty factor for design reliability
F_{PM} = Uncertainty factor for project management
F_{SC} = Uncertainty factor for supplier and contractors
F_{UC} = Uncertainty factor for uncontrollable uncertainties
MS = Market size
R_{PF} = Revenue per flight
UF = Uncertainty Factor
U_Z = Utilisation

I. Introduction

In a progressive world where technology is advancing rapidly, developing and producing new products has become a more complex process. Fuelling this advancement are groups of diverse stakeholders and customers all looking for the most robust product at the most competitive price.

When the current economic volatility is also considered the task of developing and producing a new product becomes a minefield of potential failure. With so many conditions to satisfy, the role of the designer has not

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only become more important but has become a role of greater responsibility. The success or failure of a product or program is now seen to rely predominately, if not solely on the decisions of designers as pointed to in past research[1] showing overruns occurring mainly due to design fault. Program problems such as cost and time overruns and product reliability through uncertain, inexperienced or negligent preliminary design decisions have resulted in program failure, company closure and industry instability.

The aerospace industry although growing is still suffering as a result of program cost overruns and delays. Companies are being forced to suspend programs such as Piper's Altaire program[2] and cancel initiatives such as GE's alternative F-35 engine program[3] due to uncertainty in developmental costs and schedules. This uncertainty has also lead to governments reconsidering their support of costly programs, and has prompted moves such as the defence bill being voted on by the US Senate that will see Lockheed "absorb the entire amount [of cost overrun] instead of splitting the increase with the US government."[4] Overruns are not new and even though methodologies are moving to address them, to date there has been no specific technique proposed that has the ability to predict potential overruns or in the very least, predict their impact.

Early engineering practices such as Systems Engineering (SE)[5], have ensured that the economic viability of programs is determined prior to development by calculating developmental, operational and disposal costs. This has been advanced with the introduction of Value Engineering (VE) and in particular Value-Driven Design (VDD)[6] which attempts to identify the program of greatest value to all stakeholders by performing unconstrained optimisations using value objective functions. However, as discussed in an assessment of the concepts in a study in 2011[1] existing methodologies and techniques are still incapable of reliably predicting the cost of aerospace programs due to the inadequate way in which they account for and manage uncertainty. Until uncertainty prediction and impact becomes a forefront and continuous consideration during product development, the accurate costing, value, robustness and ultimate success of a program cannot be determined.

The work and research that has been performed to date, which is presented in this paper, is aimed at advancing state of the art costing and valuation methodologies to allow for a program and design selection to be based not only on design merits but on how robust the design is against *foreseeable uncertainty*. Initially the phrase *foreseeable uncertainty* may seem counterintuitive owing to the fact that uncertainty in essence cannot be foreseen. In this context we define it as,

> *"obvious inherent uncertainty or variability of parameters within a design or pertaining to a circumstance about which assumptions or predictions can be made about their behaviour or contribution."*

It is the intention of this work to identify and automatically account for these foreseeable uncertainties when evaluating program or product cost and value. By way of achieving this aim a study of foreseeable uncertainties was performed[1], from which a new objective function for calculating realistic aircraft program value was determined. The function contained uncertainty coefficients relating to the foreseeable uncertainties bringing the current methodologies a step closer to automatic program uncertainty recognition and inclusion within calculations.

As summarised in the previous paragraph, the paper will begin by reviewing in more detail the research previously performed on the identification of cost and delay drivers and current costing methodologies. The developed Capability Function (CF), the end point of the previous work, will be reintroduced before discussing the most recent work. Results from an analysis of Surplus Value (SV) will be presented showing: the nature of the variables; stakeholder responsibility and control of the variables and the impact of the variables on SV and SV cost parameters. Given this analysis, the lowest level, independent and most influential variables will be identified. Uncertainty Factors (UFs) will be applied to these variables based on how the overrun drivers may affect them and as a result, a revised version of the CF will be presented.

II. Background and Work to Date

Program cost and time overruns are regrettably almost certain when new aircraft programs are developed. Cost and schedule are both determined within the early stages of the design development process, so it is reasonable to think that this stage should examine and plan for potential overruns. However, this does not seem to be the case with overruns tending to take developers by surprise. It is therefore important to gather a general understanding of where issues exist within the design process and identify why overruns are not anticipated.

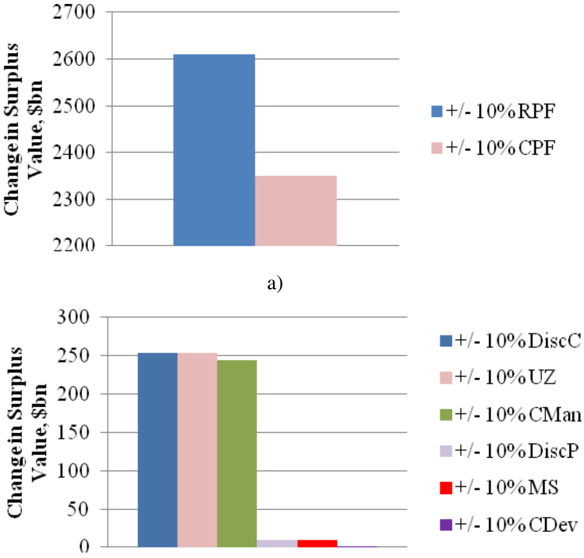
A study in March 2011[7] was initially performed on design strategies, assessing how they operated. Firstly Systems Engineering (SE) was investigated. It is no secret that historically, engineering and design often operated by an "over the wall" approach. This existed as a step by step process whereby the product was designed then ownership was handed to manufacturing, the next process. Unfortunately the concept behind SE functioned similarly with the lack of upfront "whole life" engineering and planning. Traditionally SE initially performs a requirements analysis followed by a functional analysis before generating a design. Processes such as manufacturing and maintenance are considered only after the function of the final design has satisfied customer requirements. It is understood that it is possible to offer feedback loops within the SE process to allow consideration of lifecycle stages but the ultimate decision will be based on whether or not the product satisfies the requirements. In addition to this, the SE process also relies heavily on the engineering experience of the designer and does not always ensure a repeatable process. Another issue with SE is the assumption that the design is correct, the consequent costing is accurate and the program will be completed correctly and in a timely manner. Of course 'what if' analysis can be performed but these are nothing more than blind sliding scales on parameters. Without knowing where the problems lie and their impact, it is impossible to determine the fragility of the program.

As a result of this, the theory behind VDD was examined in Fanthorpe et al.[7] and it was found that the methods involved encouraged "whole life" concurrent engineering, thus avoiding "over the wall" engineering. Using a value objective function that includes variables of interest to all stakeholders, the most valuable product in terms of economy, performance etc. is generated. A key to VDD is the maintaining of requirement flexibility, a theory not shared by SE advocators. Where SE seeks a product that first and foremost satisfies customer requirements, VDD seeks a high value product while allowing requirements to vary. However, as with SE, VDD still assumes complete program success. Again, only 'what-if' sensitivity studies aimed at approximating what could go wrong within the limitation of their formulated objective function can be performed when identifying issues.

Upon investigating SE and VDD methodologies work continued in beginning to develop a method through which overruns could be accounted for. Given the concurrent nature of VDD, it was seen that the theory offered a suitable platform from which addressing program overruns could be developed. In previous VDD studies[8] a formulation of the Surplus Value (SV) objective function was provided (Eq. 1). This formula used lifecycle attributes to calculate the total economic value of an aircraft program based loosely on Net Present Value (NPV).

$$SV = Disc_{P} \times MS \times [Disc_{C} \times U_{Z} \times (R_{PF} - C_{PF}) - C_{DC} - E_{TPF} - C_{Man}] - C_{Dev} \qquad (1)$$

The SV was calculated initially for a baseline case of a fleet of 150 passenger jet transport aircraft modelled to be travelling from Belfast International Airport to Paris Charles de Gaulle and resulted in a SV of $44.1bn. From this case, work began assessing sensitivities within the SV function to identify the most volatile parameters[9]. It was identified that when varied +/-10%, the parameters within the current SV objective function impacted SV as shown in Fig. 1.



a)

b)

Figure 1. Change in surplus value as a result of varying a) R_{PF}, C_{PF} and b) $Disc_C$, U_Z, C_{Man}, $Disc_P$, MS, C_{Dev}

It can be seen that the parameters with the greatest impact are revenue per flight (R_{PF}) and cost per flight (C_{PF}). Revenue is a function of ticket price, which is controlled by the airline and passenger load factor that is an almost uncontrollable variable. Cost per flight is a function: of fuel cost; externality taxes; airport fees; crew costs and maintenance, all of which that are controlled by various stakeholders. Although not ranking high, the variation in the development cost (C_{Dev}) parameter is still within the range of millions of dollars, a continual loss no company could sustain. It is important to note therefore that any uncertainty in the high impact parameters will have a detrimental impact on the value of the program. The analysis performed above, which can be performed for both SE and VDD, allows the user to see how SV is impacted by the parameters but not what variation the parameters are subject to when a new program begins or as it continues throughout its lifecycle. It will be the identification and inclusion of the uncertainties on the parameters that will offer a novel approach to overrun prediction and estimation.

The next step in this work looked at identifying the main issues identified in past programs (4 commercial and 5 military applications) that contributed to time and cost overruns[1]. It was anticipated that the cost drivers could be coupled with parameters in the SV function to allow program SV to be adjusted depending on the design decisions made. Fanthorpe et al.[1] researched and collated the main program cost and delay drivers for the selected programs and found that a range of conditions contributed to cost overruns. The work categorised the conditions into six clusters whose contribution varied depending on the aerospace application (Fig. 2 and Fig. 3). These categories fell closely in line with the major contributing factors identified in a study by the Deloitte Aerospace and Defence group.[10]

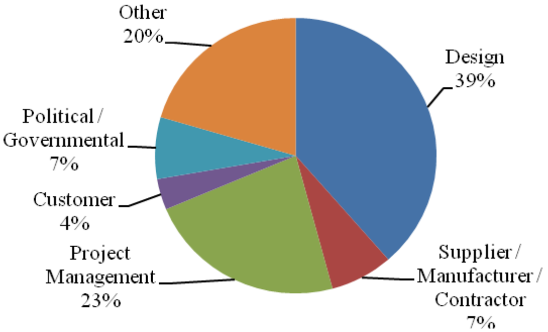


Figure 2. Military aircraft program issues for selected programs categorised into six main drivers and shown as percentages of total issues

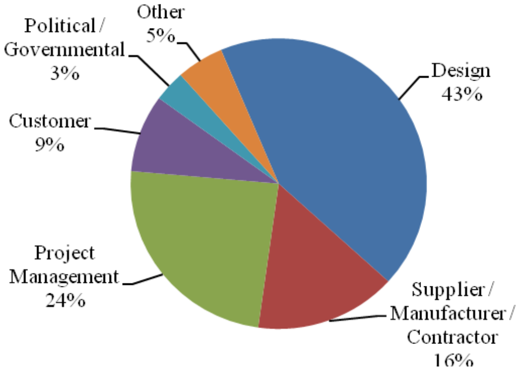


Figure 3. Commercial aircraft program issues for selected programs categorised into six main drivers and shown as percentages of total issues

The clusters seen in Fig. 2 and Fig. 3 are common to some extent among all new aircraft programs and it is from these six categories that the foreseeable uncertainty is determined. Based on design decisions, some aspect of the six cost driving clusters will impact aircraft programs so in effect we can predetermine this uncertainty, hence the use of foreseeable uncertainty.

Using the original SV function (Eq. 1) as a base, a new function was developed, known as the Capability Function (CF), shown in Eq. 2. The function has been adapted so that Uncertainty Factors (UFs) relating to the six cost driving clusters have been assigned to the appropriate SV parameter, allowing automatic consideration of design and decision uncertainty. As part of this work the original SV was rearranged so that E_{TPF} was included within the operating costs, a term relating to cost disposal (C_{Dis}) was added and C_{DC} was excluded since these eventualities are not a certainty and not within the control of the designer.

$$SV = F_{UC} \times \{ Disc_{P} \times MS \times [Disc_{C} \times (F_{D_r} \times U_{Z}) \times (R_{PF} - F_{D_r} \times C_{PF}) - \tag{2}$$

$$(F_{SC} \times F_{Dr} \times F_{D_{in}} \times F_{PM} \times C_{Man}) - C_{Dis}] - (F_{D_r} \times F_{D_{in}} \times F_{PM} \times F_{D_{comp}} \times C_{Dev}) \}$$

Given the current state of the CF it can be seen how much uncertainty affects the model and what type of cost driver impacts each top level parameter. What cannot be determined is how heavily the uncertainty can impact the parameter and in what manner. The initial form of the CF shown in Eq. 2 is the current state of the art in this approach. The next section of this paper will detail recent advancements in the development of the UFs relationships with the SV parameters, before arriving at a final approximation of the CF. Determination of UF percentage impact on aircraft programs will not be discussed in this paper but will follow in later work.

III. Inherent and Realistic Surplus Value Relationships

In previous work[1] a general assessment of cost drivers and their behaviour was performed. Before determining the UFs a similar study must now be performed for the variables within the SV function in order to determine:

- Relationships of the variables – how they are connected and fed through one another
- Nature of the variables – dependant or independent, controllable or uncontrollable, frequency of occurrence within SV
- Ownership of the variables – who determines what variable within the function and how much control over their variables do they have
- Behaviour of the variables – positive or negative impact on SV and costs within SV
- Magnitude of impact of the variables – Influential or irrelevant to SV and costs within SV

By generating the information above, it will be possible then to isolate those variables that can be controlled by the designer or manufacturer, variables that are independent and variables that have the biggest influence on program SV. Through focusing effort on these variables and the uncertainty associated with them, an immediate advancement in uncertainty management will be achieved, moving towards more realistic costing and SV methods.

Initially a diagrammatic hierarchy of the formulated SV function was produced in MS Office Visio 2007®. Using this hierarchy it was noted that there are 9 levels within the SV function and a total of 169 variables. Coupling a Matlab® formulation of the SV equation and the hierarchy, the nature of the variables are summarised in Fig. 4.

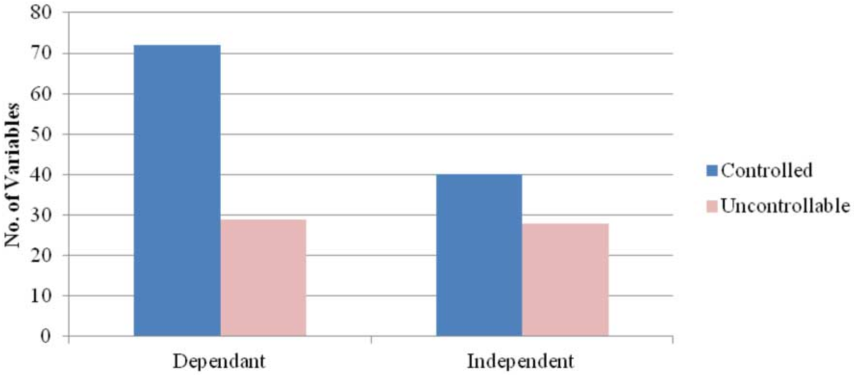


Figure 4. Surplus value variables grouped initially by dependency then grouped further by control

Figure 4 shows how the variables are categorised based on dependency and control. There are 101 dependant variables i.e. those generated though calculations based on the independent variables, and 68 independent variables which are user inputs. There are 112 controllable variables i.e. determined by customer, calculation or regulation etc, and 57 that are uncontrollable. Variables that are uncontrollable are noise factors such as salaries and finance factors, or those that tend to be consequential. Initially this program will look at the independent variables and will begin by applying UFs to the controlled variables. Given that there is a high quantity of uncontrollable variables effort will also be made to assess whether potential trends in these variables can be quantified. If some knowledge about their behaviour is known then there is a possibility that more accuracy can be built into any developed modelling techniques.

Now that the variables have been roughly defined, the next focus was to determine the group or stakeholders that determine each of the variables. Figure 5 shows a breakdown of the SV function and how each of the top level parameters can be broken down into stakeholders. In this instance stakeholders are defined as a group or department that is predominately associated with or responsible for the determination of the variables.

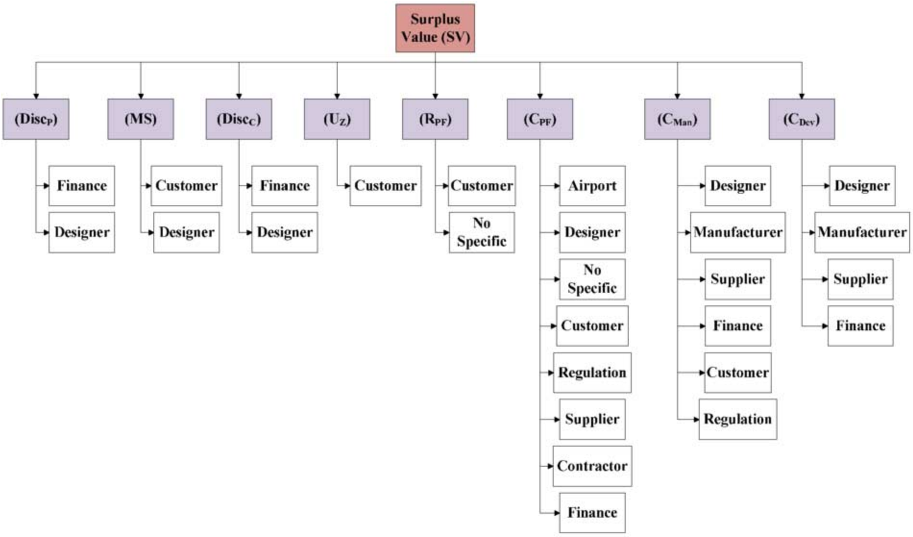


Figure 5. Surplus value hierarchy showing the associated stakeholder group for each of the parameters

Within the hierarchy there are nine groups. Up until this point the designer and manufacturer have been classed as individuals. Within industry the designer and manufacturers are combined within one enterprise e.g. Airbus and Boeing, so from this point forward the designer and manufacturer will be classified as one group, reducing the total number of stakeholder groups to eight. A description of each of the eight stakeholders is given below.

- ***Designer/Manu*** refers to any variable a designer or manufacturer determines or can have a direct impact on
- ***Regulation*** deals with variables determined by bodies such as governments, FAA or CAA
- ***Airport*** refers to variables determined by airport such as landing fees
- ***Supplier*** variables are those determined by part suppliers e.g. avionics, engine
- ***Contractors*** are variables relating to subcontractors for services such as maintenance (assuming the airline lease the maintenance).
- ***Customer*** variables are those determined by the purchasing airline
- ***Finance*** - banks, loans, financing, discount rates, cash flow
- ***No specific*** are variables without an immediately obvious or significant associated group with respect to the major stakeholder breakdown e.g. fuel density or salary premiums

Once the stakeholders and their influence on the SV function have been established, it is possible to determine how many variables they are responsible for and whether or not they have control over them. Having coupled the diagrammatic hierarchy of the SV function and Fig. 5, this information is shown in Fig. 6.

It is important to note that the information shown is only quantity of variables. It is possible that one stakeholder could be responsible for many variables but each with minimal impact. Quantity of variables does not necessarily equate to influence however, the information gained from this can still show useful interactions.

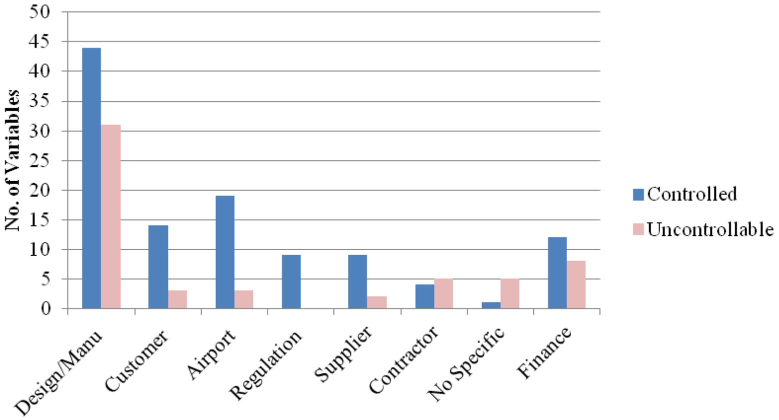


Figure 6. Surplus value variables grouped initially by associated or determining group and further by control

Using this information it is possible to establish groups with the greatest responsibility and if that responsibility is controlled. Both the customer and airport groups have high responsibility and control the majority of their associated variables. Regulation stakeholders control all their variables while the contractor group, for example, have more uncontrollable variables than controlled. It is clear from Fig. 6 that the designer and manufacturer (assumed to be one service like Airbus or Boeing) retain greatest responsibility relating to the SV formulation. However, it must be noted that there are many uncontrollable variables within this set. It is therefore as important to capture fluctuations in the uncontrollable variables as it is to capture it within the controlled. Failing to do so could cause a wash out in the benefits of performing overrun prediction.

The work continued by assessing specifically the variables controlled by the design and manufacturing group. Figure 7 categorises the "Design/Manu" variables initially by the design stage at which they are determined and then by whether or not the designer or manufacturer has control over them.

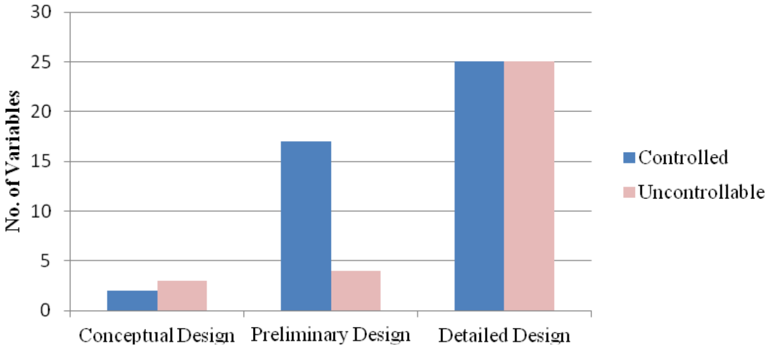


Figure 7. Design associated variables grouped initially by the design phase in which they are determined and further grouped by the control of the variable the design has at each phase

From the above graph it can be seen that irrespective of the continual request for concurrent engineering it is obvious that the vast number of design decisions are made in the later detailed design phase. Within the product lifecycle the majority of costs and commitments are locked down at the conceptual design stage. However, given the information in Fig. 7 it would seem that these costs are calculated and commitments made at a stage where very few variables have actually been decided on. With this in mind, it would be suggested that design decision making should be brought forward in the process, making as much information available at the earliest possible opportunity. Ideally it is envisaged that if design choices are made sooner and tested, then the chance of them causing issue at a later, critical lifecycle stage will be reduced. In some cases this is true however it is possible that making decisions sooner can lead to other less obvious issues. If a decision of high uncertainty is brought to an earlier design phase there is a chance that the effort in continual rework and testing will cancel out the benefit of moving it.

An alternative to this would be to calculate costs and make commitments later in the process; an unlikely case given the need for business proposals before programs commence.

Although the variable information has been generated using a simplified SV formulation it is possible to see the number of variables required. With the added complexity of aerospace systems, the required variables will increase dramatically, resulting in complexity becoming a potential driver of delays and cost overruns.

From Fig. 7 the ratio of controlled to uncontrollable variables is interesting. At the conceptual stage the uncontrollable variables are slightly higher than the controlled (3 and 2 variables respectively). In the preliminary design stage the controlled variables outnumber the uncontrollable (17 and 4 variables respectively) while at the detailed design phase the controlled and uncontrollable variables are equal (25 variables each). Again this trend encourages the analysis of the uncontrollable variables as much as the controlled if there is to be a significant improvement in SV and costing techniques when predicting overruns.

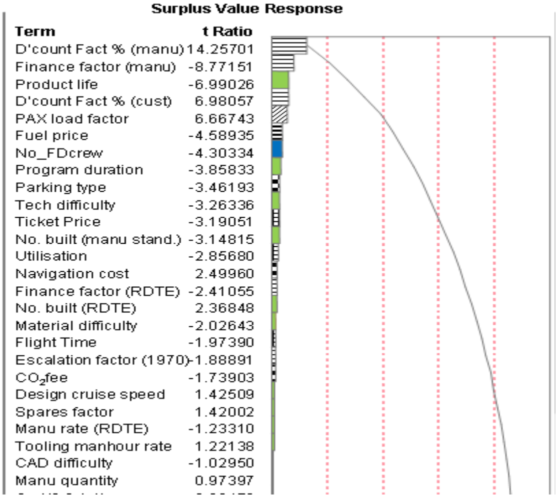
Upon assessing the SV sub-variables and the stakeholders responsible, the impact of the variables upon SV must be assessed. Until this point the focus has been on the quantity of variables and not their impact. In the following analysis the independent, variables both controlled and uncontrollable for all ownership groups were identified. Primarily this research is interested in the impact the variables have on cost and overall SV. It can be seen in Eq. 3 that SV is a function of three main costs; cost per flight (C_{PF}), cost of manufacture (C_{Man}) and cost of development (C_{Dev}).

$$SV = f\,(C_{PF,}\, C_{Man,}\, C_{Dev}) \tag{3}$$

Using the SV formulation, a fractional factorial DOE and screening effects test within JMP® was performed. From this data Pareto charts showing each of the variables impact on SV, were created (Fig. 8 and Fig. 9). The aim of this is to identify those variables with the greatest influence and those with little or no influence. Along with showing the response of each of the costs and SV to the variables, the bars have been coloured to identify the responsible stakeholder. Table 1 shows the stakeholder group colour coding.

Table 1. Colour coding for stakeholder identification in Pareto plots

Design/manu	🟩	Contractor	▥
Regulation	🟦	Customer	▦
Airport	▤	Finance	▤
Supplier	▧	No. specific	▨



Surplus Value Response

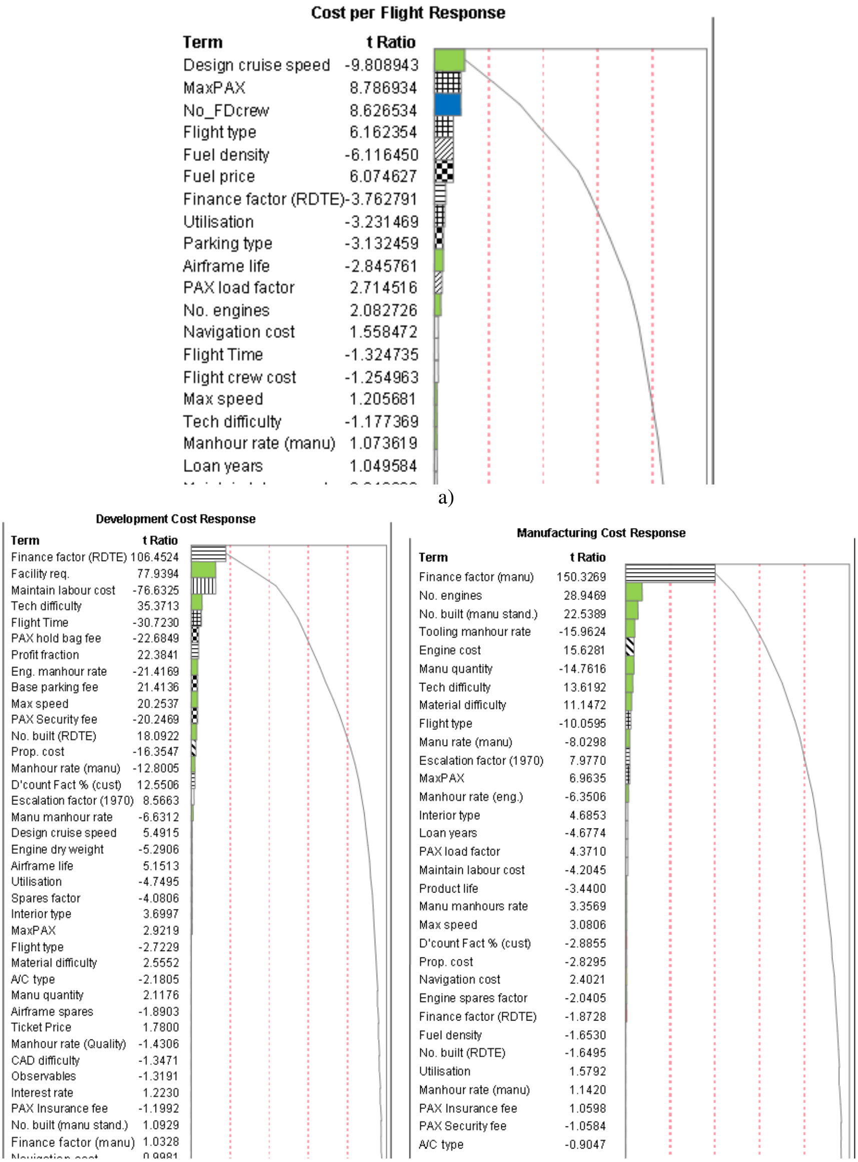
Term	t Ratio
D'count Fact % (manu)	14.25701
Finance factor (manu)	-8.77151
Product life	-6.99026
D'count Fact % (cust)	6.98057
PAX load factor	6.66743
Fuel price	-4.58935
No_FDcrew	-4.30334
Program duration	-3.85833
Parking type	-3.46193
Tech difficulty	-3.26336
Ticket Price	-3.19051
No. built (manu stand.)	-3.14815
Utilisation	-2.85680
Navigation cost	2.49960
Finance factor (RDTE)	-2.41055
No. built (RDTE)	2.36848
Material difficulty	-2.02643
Flight Time	-1.97390
Escalation factor (1970)	-1.88891
CO_2fee	-1.73903
Design cruise speed	1.42509
Spares factor	1.42002
Manu rate (RDTE)	-1.23310
Tooling manhour rate	1.22138
CAD difficulty	-1.02950
Manu quantity	0.97397

Figure 8. Surplus value response to +/-10% variation in variables with a t-ratio greater than 1

In Fig. 8 it can be seen that SV is not impacted greatly by any particular variable; rather, multiple variables have a similar impact. What can be noted from the Pareto is that within the top five, finance variables occur three times. The discount factors for producer and customer featuring high is no surprise but it is not immediately intuitive that the manufacturing finance factor would have a high impact. Along with finance stakeholder variables, design and manufacturing stakeholder variables appear frequently within the Pareto with varying impact on SV.

As with the SV response to variable variation, the cost per flight response does not have a major sensitivity to any one variable but a similar sensitivity to multiple. Design cruise speed, a design and manufacturing stakeholder variable, has the highest impact which is understandable since this would determine fuel usage; an assumed key variable in flight cost. However, it is surprising to see that even though it has a relatively high impact, fuel price has one third less impact on cost per flight than cruise speed. Within the cost per flight response analysis, the variables associated with the customer features most frequently, with two having significant impact.

Looking at the cost of development response to variation it can be seen that again a finance variable has the greatest influence. Design and manufacturing variables are the most frequently occurring variable. The impact of the maintenance variable associated with contractors is surprising in this case since it is primarily incorporated with the cost per flight parameter within SV and not within development.



a)

b)

c)

Figure 9. Response of a) cost per flight (C_{PF}), b) cost of development (C_{Dev}) and c) cost of manufacture (C_{Man}) as a result of +/- 10% variation in surplus value variables

From the manufacturing cost response to variable variation it is obvious that finance has a major impact in this case which is expected. It is no surprise that the design and manufacture variables appear most frequently however, even when their effects are combined, the impact is still less than the impact of the finance variable.

Previously, when assessing the stakeholders with the greatest variable count it was seen that the most responsible stakeholders, in rank order were: design; airport; finance and customer. However, it can be seen from this SV impact analysis that this order does not necessarily hold true with finance, for example, having a higher impact in most cases than design. This is different to the previous study showing that the quantity of variables controlled by the stakeholder does not necessarily mean they have the greatest impact. It is important to identify this information so that high impact variables are not overlooked when identifying cost overrun and delay drivers.

IV. Capability Function

Now that the relationships and impact of the variables within the applied SV formulation have been investigated, this information can be used to justify Uncertainty Factor (UF) allocation within the Capability Function (CF).

The initial approximation of the CF (Eq. 2) highlighted, at the highest level, where potential uncertainty arose relating to the researched cost and schedule overrun drivers (Fig. 2 & Fig. 3). Now that the most influential, independent variables within the SV calculation have been identified, the CF can be adjusted to specifically account for the uncertainty within these. Since the influential, independent variables appear in the lowest levels of the hierarchy, if UFs are applied there, it is believed that the effect of the UFs will translate upward through the function. An example of how this occurs is shown in Fig. 10.

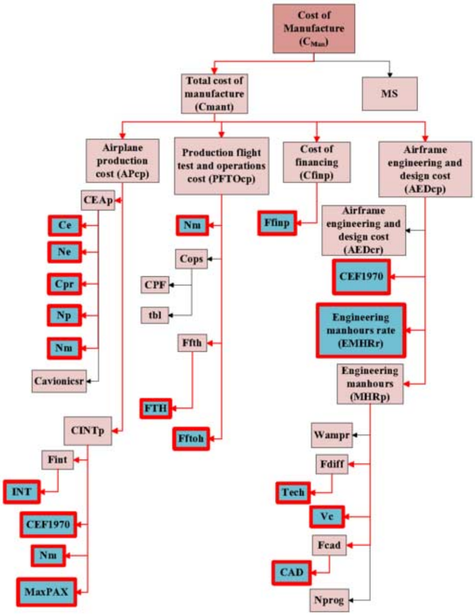


Figure 10. Section of SV breakdown showing an example of where uncertainty factors will be applied and how this will impact higher levels

The hierarchy above is a section of the manufacturing cost breakdown within the developed SV hierarchy. The lowest level variables highlighted above are a sample set of the influential, independent variables to which the UFs will be applied. The diagram does not explicitly show the UFs but represents their location and the flow of information up through the hierarchy.

Using the variable analysis above coupled with the SV hierarchy diagram, each of the 56 influential, independent variables are assigned UFs based on whether the variable could possibly be impacted by each of the researched overrun drivers. Assuming that the UFs are fed up through the hierarchy to the top level parameters, a second approximation of the CF has been produced below (Eq. 4).

$$SV = \alpha \mathrm{Disc}_{P} \times \alpha \mathrm{MS} \times [\beta \mathrm{Disc}_{C} \times \gamma U_{Z} \times (\alpha R_{PF} - \alpha C_{PF}) - \alpha C_{Man} - C_{Dis}] - \alpha C_{Dev} \tag{4}$$

Where:

$$\alpha = f(F_{SC}, F_{Dr}, F_{D_{in}}, F_{PM}, F_{UC}, F_{D_{comp}}) \tag{5}$$

$$\beta = f(F_{Dr}, F_{D_{in}}, F_{PM}, F_{UC}) \tag{6}$$

$$\gamma = f(F_{Dr}, F_{UC}) \tag{7}$$

It is clear from this improved adaptation of the CF that there is greater uncertainty within the original SV function and initial CF than first anticipated. The previous CF showed assumed uncertainty only associated with the top level parameters. However, on closer inspection of the variables, it is clear that there is more uncertainty within the sub-levels of the SV formulation. It is apparent therefore, that performing a top level sensitivity analysis is not sufficient in capturing all uncertainty; a possible reason behind current methodologies failing to accurately predict costs and issues. In Eq. 4 it can be seen that no UFs are assigned to the cost of disposal parameter (C_{Dis}). This parameter has not been evaluated as part of this work but once developed, the appropriate UFs will be assigned if necessary. Now that a greater appreciation of potential uncertainty has been developed, the research can proceed in quantifying the effects. This work provides the initial steps in predicting and *foreseeing* potential uncertainty and as a result, predicting and quantifying overruns.

Unlike the previous CF equation the parameters in Eq. 4 are described as being functions of the UFs. It must be noted that the UFs in each case could potentially differ depending on the variables with which they are associated. The value of and operators relating the UFs to the SV parameters cannot be determined until information on how the variables have behaved in past programs has been researched. This aspect will be developed in future work.

V. Conclusions

Given the previous research effort, this paper has provided the necessary knowledge required to make informed decisions on how best foreseeable uncertainty can be captured within VDD techniques.

Work completed to date has:

- Formulated the SV function and assessed its sensitivity to the top level parameters
- Identified the main cost and delay drivers from past aircraft programs
- Developed an approximation of the overrun predicting CF

This paper looks specifically at:

- Developing a hierarchical breakdown of the SV function
- Established where stakeholders fell within the SV function
- Identified the variables stakeholders are responsible for and whether they could control them
- Looked at where in the design process decisions about variables are made
- Developed Pareto plots showing the response of SV cost parameters and SV to variable variation
- Determined the most influential variables on cost parameters and SV
- Generated an improved version of the CF

The work performed to date on variable assessment will allow uncertainty to be captured within the most influential, lowest level design variables. By doing so, foreseeable uncertainty will effectively be built within a Value Driven Design framework allowing overruns and delays to be predicted.

VI. Future Work

Research within this area will continue by generating a database of extensive historical information regarding aircraft programs that have experienced overruns and delays. This information will be used to determine UF ranges and their operators within the CF.

To date overruns that have been included within the CF have only looked at directly mapping *cost* from design variables. Research will also be performed on how schedule shift impacts the developed CF and how this too can be built into the function to fully capture the effects of all overruns.

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Value Driven Design In The Presence Of Fuzzy Requirements

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As the demands and expectations of today's customers continue to rise, the designs required to fulfil these needs are becoming increasingly complex. More so, customers nowadays seek solutions that offer good value for money and satisfy both today's and tomorrow's needs. Recently, however, the cost and delay of developing these complex designs has been escalating out of control to the great dissatisfaction of both stakeholders and customers. Furthermore design teams are still struggling to effectively manage changing customer requirements at every stage of the design development without incurring expensive redesign charges. To address these concerns, this paper will introduce an innovative technique which infuses the inherent nature of System Engineering using fuzzy requirements with the evaluative framework of Value Driven Design. Benefits and limitations of the current methods will be reviewed, before outlining the steps of the proposed technique.

Keywords: System Engineering, Value Driven Design, Fuzzy Requirements, Design Methodology, Design Space, Robust Design

I. Introduction

To survive within today's high paced, dynamic and often unforgiving business environment, companies are constantly being forced to produce increasingly superior products for their customers. Demands and expectations from customers are continuing to rise[1], meaning that even once simple devices are now becoming increasingly complex. Take for example the everyday object of a simple car key. In the 1970's it was just a cut piece of metal used to open or lock a car door. Nowadays these devices incorporate not only keyless remote entry and locking, they also are used to disengage the immobilization of the engine and electronics, as well as store driver-specific settings and even music.

Additionally customers are now searching for products that last longer; to offset the initial high capital cost of purchasing[2]. Traditionally aeroplanes have been designed for an operation life of around 15-20 years after which they are retired, dismantled and recycled. However with customer budgets continually being reduced[3], due to the current economic climate, designs that either exceed or extend the service life of the product are becoming an increasingly attractive option. However it must be remembered that designing a product to last longer is not as simple as redesigning the components to withstand the extra wear and tear that it will receive. Instead the largest issue is ensuring that the design does not become obsolete before the service life of the product has passed[4,5]. To reduce the possibility of this occurring, designers commonly select a robust design, i.e. a design capable of operating in a range of scenarios with minimal performance loss. By "fuzzifying" the requirements however the expected range of scenarios are identified earlier and by the customer, allowing the designer to make better design choices.

Traditionally large complex systems such as spacecraft, submarines and weapon systems have been designed using the requirement based technique known as system engineering (SE)[6]. The methodology works by firstly identifying, then allocating requirements to all of the systems components and subsystems. Designers then

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endeavour towards meeting these requirements throughout all of the development stages and if a design is produced that meets all of them, it is deemed acceptable as it will have satisfied all of the customer needs[7].

However there are many recent, well documented, examples of over budget projects which use SE[8], it is clear that the SE methodology is not perfect. This occurs across industry sectors, even with decades of research into improved design methodologies and technological advancements. Worrying though this is not a new phenomenon, as Augustine's studies from the 1970's and 1980's show, complex systems regularly overran in cost and time[9].

Nevertheless in 2005 a new design process known as Value Driven Design (VDD) appeared which is trying to improve the inefficiencies of SE. This technique uses a value function to generate and then compare designs; in order to maximise value, as opposed to meeting requirements and then stopping. Although the procedure brings many advantages over the traditional SE approach, designers using this process are finding it very difficult to implement; as designing systems by maximising functions doesn't easily translate into whether the product will meet the needs of the customer or not[9, 10].

It has been known for some time that customers often only have a vague idea of what they want at the start of a project. These wants are generally high level, such as vehicle range, cruise speed and payload, but can also be subjective qualities like good fuel economy and low maintenance. In addition customer demands are often not fixed but instead change rapidly and sometimes without warning due to shifts in public opinion or through some technological advancement[11]. What is more this can occur at any stage of the systems development and can completely alter the customer's perceived need, ultimately leading to expensive overruns in both finance and time.

Therefore with the trend of customers expecting more, systems becoming increasingly complex and project costs rising, this paper proposes and outlines that a different design methodology is needed before these issues escalate out of control. A new approach will be presented that combines the benefits of both the SE and VDD methods, whilst addressing the limitations of both. This will be accomplished by adopting a fuzzy requirement formulation of the problem within a VDD evaluation framework.

II. Background

System Engineering (SE)

Traditionally the system engineering (SE) methodology has been used to find solutions in large complex systems, especially in the aerospace industry. Although created in the 1950's this requirement based approach is still being used today by many organisations because of its ability to systematically decompose and structure large complex systems into smaller more manageable problems[6]. It is because of this unique benefit that many companies employ this technique, with three predominate advocators of the SE approach being the International Council on System Engineering (INCOSE), the National Aeronautics and Space Administration (NASA) and the Defence Acquisition University (DAU)[12].

Normally the process begins by identifying the perceived customer needs either through market research or via a customer proposal, depending upon the industry[13]. After this information is acquired, stakeholders define a list of top level requirements to ensure that the product will meet expectations[10]. These requirements are used to assign parameters (also known as variables) and constraints to the component level to guarantee that only suitable designs are generated. A simplified breakdown structure of a military aircraft is shown in Fig. 1, however in reality a complex system such as this would have between seven to ten levels and thousands of components[9].

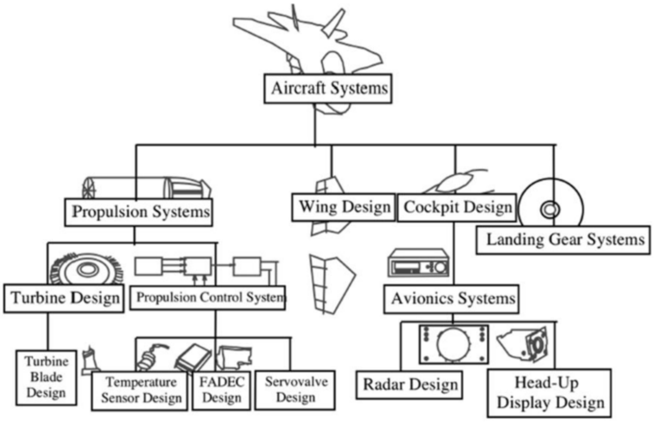


Figure 1 – Simplified Breakdown Structure Of A Military Aircraft[9]

Once the conceptual designs are generated they are then reviewed against the list of requirements defined at the beginning of the project. If successful, i.e. meets all requirements, and chosen by the customer, the conceptual design moves into the later stages of product development (i.e. detail design, prototype development, design critique and redesign) before finally entering final production[7].

Apart from the obvious benefit of being able to decompose and design large complex systems, the SE approach has many other advantages. The first and most important is that it focuses on producing products that meet the wants of customers whilst ensuring that the design complies with all the regulatory authorities. Another benefit is people inherently understand designing systems through budgetary and requirements constraints, along with the consequences that will occur if either is not met. Moreover the technique is well structured and simplistic as the design either meets requirements or not. Additionally the methodology provides management with a tool to manage project risk inherent within complex systems[14].

Although the SE methodology has helped many companies successfully design and create complex systems for more than the last half century, it is not without its limitations. The first and most obvious is that the requirements are defined at the beginning of the design phase when limited information is known about the customers use and/or expectation of the product. As a result the likelihood that costly redesigns will be required throughout the development process will have increased; as changing customer's needs and technological advances are difficult to incorporate into fixed designs. What is more these initial requirements are usually exact values, based on a specific mission, meaning that if the system were to be used for another mission the performance reduction could be significant as it won't be of optimal design[15,16].

Another major issue within the SE approach is that designs are only generated until an acceptable solution (one that meets all requirements) is found, meaning the identified design may not necessarily be the best solution. Furthermore when components/subsystems are subcontracted out due to their specialised nature (e.g. aircraft engines) there is no way to determine which design is better if two or more concepts fulfil all of the requirements[17]. To resolve this issue designers normally turn to design tools (e.g. alternative design matrix or the Pugh matrix) to identify the best design. These aids however should be used with caution as they are very subjective and highly dependent on the personnel involved, which can explain why different teams with the same information, choose different designs[18].

A further drawback of the SE procedure is that design teams become decoupled from the "big picture" and solely focus on meeting their requirements, which may lead to redesign issues later on. Additionally it can often be difficult to accurately define a design space using only requirements, as a significantly enhanced design may lie outside this region. What is more, the requirements themselves do not highlight or eradicate any "poor" design within the design space meaning that the customer could potentially still receive an inferior product[10].

Value Driven Design (VDD)

Value Driven Design has been a gradual evolution from SE with the primary focus shifting away from any design that meets requirements, to a design that provides the best value to the customer. Value is the benefit of the system compared to the cost to the company required to achieve it.

In 2005, the American Institute for Aeronautics and Astronautics (AIAA) founded a team to promote the application of Value Driven Design (VDD), a term first coined by James Struges. At the time, each founding member (Paul Collopy, James Struges and Fred Striz) chaired other technical committees within AIAA, and it was believed that any progress made by the group would be of mutual benefit to all parties involved[9].

VDD follows a cyclic iteration process (as shown in Fig. 2) with the sole aim of optimising the design to maximise an objective function with respect to cost. Additionally the VDD method places no requirements on the design meaning designers are no longer constrained to a certain area which may exclude the best design.

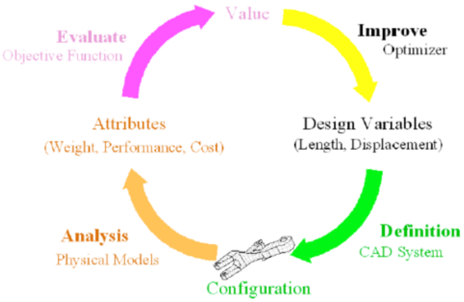


Figure 2 – VDD Process[16]

The VDD process begins just like the SE approach; by defining the customer's perceived need. Next the design team selects a point within the design space to identify all of the solutions design variables. After this is completed a detailed representation of the system can be created to facilitate the computer based predictive modelling that will occur in the analysis stage of design process. Typical simulations include Finite Element Analysis (FEA) and/or Computational Fluid Dynamics (CFD) models both of which are used to establish the attributes of the system. Based on the systems attributes, the systems objective function can be constructed which will enable the stakeholder to determine the "value" of each design, at which point a scalar score will be given. The configuration with the highest score offers the best value to the stakeholder. At this point the design team either accepts the design or if budget permits, repeats the process in search of a better design[16].

Collopy and Hollingworth[9] discuss the advantages of the VDD approach. A major advantage of the VDD method is that it encourages design optimisation to take place throughout the entire design development and at every level. Furthermore the use of the objective function not only theoretically eradicates personal opinion from the design process; it also prevents dead loss trade combinations occurring which can reduce the overall value of large projects by tens of percent. Take for example two design teams working on the same project trying to improve their individual component design. One team may sacrifice great cost ($10,000) to achieve a small reduction in weight (50 lb) whereas the other team may sacrifice far more weight (125 lb) to gain a small reduction in cost ($4,000). Although both teams believe they are improving the overall design, the net effect of their decisions is negative, as the design now weighs and costs more, i.e. a dead loss trade. Another benefit of VDD technique is that it can help managers mitigate risk as short falls in materials properties or technologies can be quantified and not subjectively described i.e. "poor", "bad" etc. And again by removing the requirements from the design process, designers are no longer constrained to a particular design space but instead are free to explore outside this region for more valuable design.

However there are two major difficulties with the VDD technique. The first is designing a system without requirements and the second is the creation of the objective function. People intuitively understand requirements, the effects they have on the design and when an acceptable design has been generated, i.e. all the requirements have been met. Unfortunately the same cannot be said for designing a system via an objective function, as the effect of modifying a design variable does not easily translate into how it will affect the system's ability to meet user needs. The development of the objective function is another concern, yet vital to the success of the project, as it is used to optimise the system. The objective function is created at the beginning of the design phase when limited information is known about the customers use and/or expectation of the product meaning it is liable to change; forcing designers to revise previous work. Also the meaning of the term "value" is highly subjective, leading to some debate within the field, thus making it more difficult to accurately define the objective function[10]. For example customers at high latitudes would see heated car seats as adding value to the vehicle, whereas customers in the topics would see the opposite.

Robust Design

Ever since business around the world adopted the Taguchi technique in late 1980's, to produce products that are capable of operating in a range of scenarios, designers have shifted their focus from finding the optimal solution to a solution that is robust[19]. Take for example the design of a simple power tool that is dispatched worldwide. Customers of this product would expect the tool to perform in the same way under a range of conditions, no matter which country the tool was shipped from. Therefore a design can be considered to be robust if the system's performance is insensitive to variation from variables beyond the control of designers. These uncontrollable variables are usually termed "noise" and come from many different sources; such as customers alternating the product's working environment and/or use the deterioration of components due to operational wear and deviation arising from component manufacture[11].

Robust design is advantageous as designers focus on improving the overall reliability and quality of the product, giving the system a major advantage, in terms of overall performance and longevity, over designs that were developed for specific mission. Additionally a robust design is less vulnerable to a reduction in performance, when used in a variety of situations. To illustrate this, Fig. 3 compares the two designs.

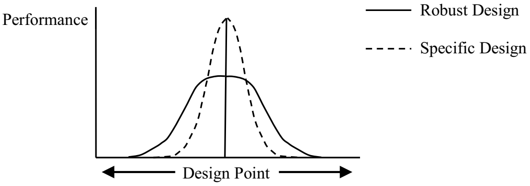


Figure 3 – Robust Design vs. Specific Design

As expected the specific design outperforms the robust design when operated at the conditions it was designed for. However as the system is operated away from the design point, the performance of the specific design system radically reduces, whereas the robust design performance remains relatively constant, increasing the customer's overall product satisfaction.

Fuzzy Logic

Fuzzy logic was first proposed by Professor Lotfi Zadeh in 1965 and is seen as a practical addition to traditional logarithms as it can mathematically represent classes of numbers, such as A or B, which do not belong to a defined numerical set[20]. In other words, fuzzy logic has the ability to deal with subjective and vague information in a rational way. It achieves this by placing a varying degree of membership on objects ranging between 0 and 1, whereas traditional Boolean logic states that the membership should be either 0 or 1[1]. To illustrate this difference, Fig. 4 is simple example of how the different theories define various room temperatures.

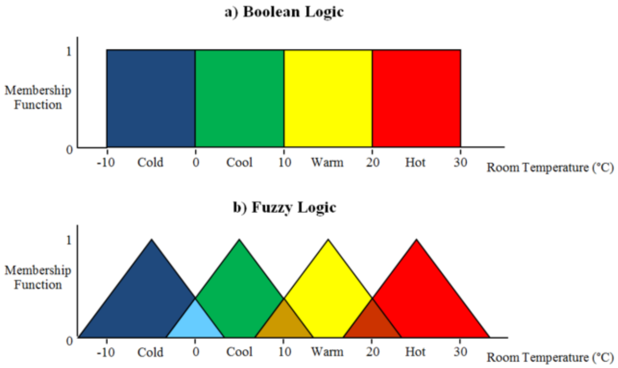


Figure 4 – Room Temperature Characterised Through Different Logic[22]

The major advantage therefore of using fuzzy logic is that it replicates human thinking/decision making much more closely, as it captures the transition between the various subjective quantities. Although traditionally used in control applications[21], fuzzy logics unique ability to capture and process imprecise information in a rational way makes it an ideal choice to manage customer needs and ensures that the design space remains open, giving designers more freedom to explore for feasible designs. Furthermore fuzzy logic also removes the burden from designers to precisely convert subjective descriptions (through their own interpretation) into numerical values, which enables them to be processed via conventional logarithms.

III. Proposed Methodology

After reviewing the current SE and VDD methodologies, it is clear that neither approach offers the perfect framework to design complex systems. It is therefore proposed that a new design approach is presented that combines the benefits of both the SE and VDD methods, whilst addressing the limitations of both. Additionally by including fuzzy logic requirements, this design approach will allow for changing customer needs without over restricting designers.

The proposed methodology is compared in Fig. 5 to the existing SE and VDD approaches. (SE and VDD flowcharts modified from Ref. 14 & 23.) Like the current techniques the proposed method begins by defining the perceived customer needs to ensure that the product will meets the customer's expectations. Additionally at this point, the systems stakeholders and their definition of value are determined to enable the systems value to be established. However, unlike the traditional methods, this is a cyclic process which can begin and end at any point due to the dependency each step has upon each other. To clarify, a stakeholder is defined as a person, group or even an organisation that has stake in the company and is affected by the company's actions, objectives or policies. Examples include shareholders, employees, suppliers and, in some cases, a government. Furthermore it is important that these people are selected carefully, as they will determine how to calculate the product's "value". Also different stakeholders will have different ideas/definitions of value, for example some stakeholders may feel that value is all about maximising profits whereas others may believe it is maximising the product's performance.

Next, the list of requirements can be specified by using the same techniques employed in the traditional SE approach. Once this is complete, a review with the customer should be performed to determine the acceptable degree of flexibility of each requirement. For example the desired cruise speed of a new commercial aircraft may be 0.75 Mach; however in reality the customer may be willing to accept any value between 0.72 and 0.8 Mach. This degree of flexibility or fuzzifying of the requirement gives the designer more details of the "true" product the customer desires and ensures the final design does not unnecessary exceed the customer's need by adding unwanted features at the expense of a cost increase or worse, a performance reduction.

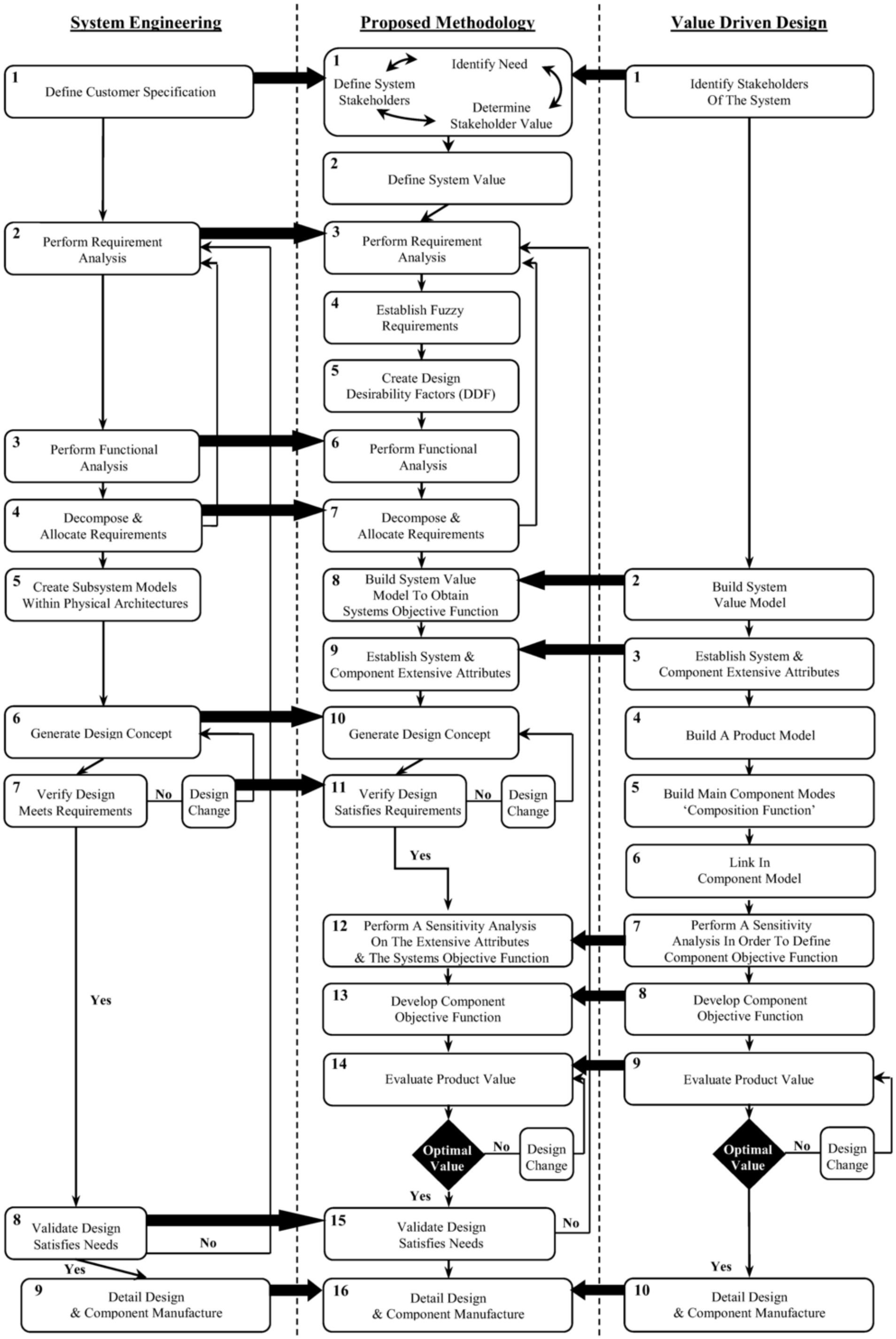


Figure 5 – Comparison Of Current And Proposed Methodologies For Designing Complex Systems

Another benefit of fuzzifying the requirements can be seen in Fig. 6 which compares the feasible design space identified through the SE and proposed method. Although the design space for the SE technique is larger and includes more designs; it appears that most of these designs are just not feasible, such as the design that meets the range requirement but weights zero. On the other hand the design space identified by the proposed method is more densely populated with feasible designs which meet the customer's needs. Furthermore by defining a range to each parameter, plausible technologies can be identified early, which can then be feedback to the stakeholders to mitigate risk. Although this process will undoubtedly increase the cost, time and effort required to complete the task, the advantages gained through this technique significantly outweighs the initial penalty.

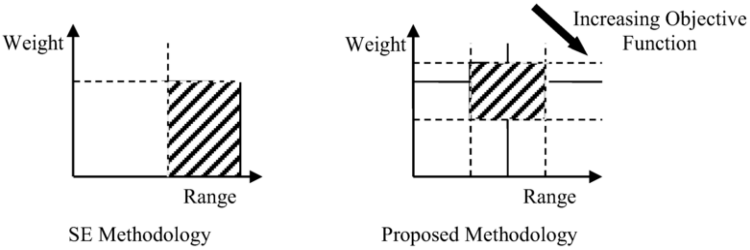
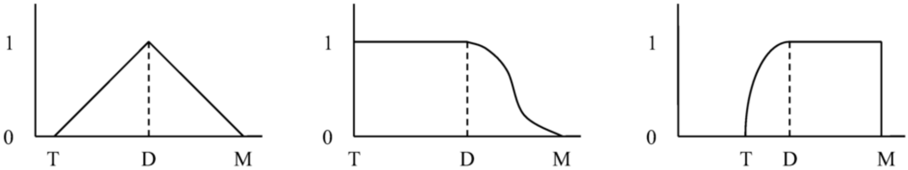


Figure 6 – Comparing Design Space Of SE And Proposed Method

The next step in the procedure is to create the design desirability factors (DDF) from the fuzzy array. The DDF is an innovative new feature required to ensure that designers endeavour to meet the customers' expectations and will be used within the objective function to show how close the chosen design is to the customer's needs. Take for example a customer's desire for a new aircraft to have a range of 3000 NM. Using fuzzy requirements it is identified that an aircraft with a range between 2800 NM and 3100 NM would be acceptable. If no incentive therefore was placed on the designer to meet the customer initial desire (i.e. 3000 NM), the designer will automatically stop when a value has been achieved in the acceptable range. This may leave the customer feeling displeased as it may cost more to operate a longer range aircraft and some routes may have to be revised or stopped if the aircraft range is reduced.

Studying Fig. 7 it is clear that the desirable value always has a factor of 1, whereas the values beyond the threshold and maximum, have a factor of 0 to indicate a non-satisfactory requirement. The factors between these two values will be defined by a mathematical function, formulated by the design team and approved by the stakeholders. Furthermore DDFs do not necessarily have to be a straight line or symmetric about the desired requirement as shown in Fig. 7.



(a) e.g. Range (b) e.g. Weight (c) e.g. Speed

Figure 7 – Visualisation Of Design Desirability Factors

Next a functional analysis is performed to transform the systems requirements into functional requirements to ensure that the system has the desired behaviour. Once the top level functions have been identified the requirements are then decomposed into sub functions until they are completely defined. Although similar to the traditional SE approach, the proposed method uses a fuzzy array and not a limit; therefore, design managers can place lenient constraints on components, which have previously required significant redesigns and thereby possibly avoid budget overruns and delays. Steps 3-7 should then be repeated until the system requirements are refined, as each step in the process may highlight a requirement change, due to the increasing level of detail coming from each step.

A detailed system value model or overall object function is then created, based on the systems attributes to output a system score. System attributes in this case include anything which affects the operating or manufacturing costs of the product as well as the system's ability to generate revenue. The value model and the DDFs are then combined to formulate an overall design function, so designers can impartially establish each concept's "value" and customer desirability. By knowing this information early and before any concepts are generated, designers will be able to differentiate between different designs and not waste time optimising a poor design.

The design team will now begin generating concepts with successful designs i.e. ones which meets all requirements, moving onto the next stage. Upon these concepts a sensitivity analysis will be performed, to determine how minor changes in the design affect the system's performance. This information is then used to develop the components objective function. Designers use these functions to search for the optimal designs until the budget permits or the design team accepts the design because the return from resources does not justify the expense, i.e. value is only marginally increasing (e.g. less than 3%).

Designs with high values are then chosen by the design team to be optimised via the value model. Following this task the top designs are presented to customer to obtain feedback. If at this stage the customer is content with a design, it will move through to the detail design stage for a more in-depth analysis. The product will then be manufactured and put to market, finalizing the design methodology. If not, a report is sent to each member on the design team to inform them of the customer's feedback and necessary changes, to further mitigate risk. Subsequently the objective function is updated (to incorporate these alterations), and then the design is re-evaluated to determine its new value.

Although the proposed methodology is still within the conceptual stage, with some areas needing further refinement, work has already begun on developing a simplified test case to verify the viability of the approach. The results of this model will then be compared to designs obtained through SE and VDD to identify any variation between the different techniques. Once this is complete the methodology will then be scaled and tested against a more complex design.

IV. Future Work

The work discussed throughout this paper focuses primarily on a proposing a new design method capable of not only designing complex systems within budget but also effectively managing changing customer demands. The aim therefore for the future is to firstly refine and verify the technique using a simple motorised vehicle (go-kart) before using the procedure to design a more complex system. By validating the design in this way it is believed that any shortcomings in the design process will be identified quicker and more easily. Additionally to compare the results of the new approach the go-kart will also be produced via the SE and VDD methods to highlight any variation in the designs produced. A breakdown of the proposed future work is shown in Fig. 8.

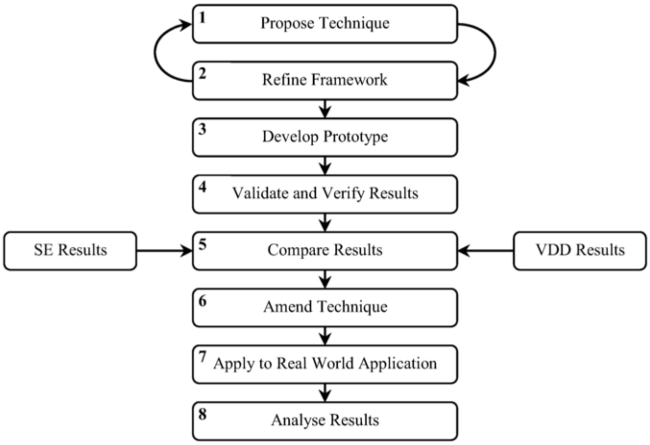


Figure 8 – Breakdown of Future Work

V. Conclusion

In this paper an advanced design method was proposed which infused the advantages of both the traditional SE approach and the new VDD technique. Additionally by incorporating fuzzy logic into the decision making process, it is believed that designers will be able to make better informed choices capable of effectively managing changing customer requirements. It was also suggested that the new unproven methodology would be first trialled on a small motorised vehicle (go-kart) to refine the procedure before undertaking a more difficult challenge such as the design of a small commercial aircraft or the design of a city car. Once these steps are completed and verified, it is envisaged that designing via this new technique will:

- ➢ Provide designers with a process of managing changing customer requirements
- ➢ Ensure that designed systems not only provide "value" but also meet customer requests
- ➢ Produce rational, clear and traceable decision choices
- ➢ Reduce project risk and hence budgetary overruns

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Development of a Surplus Value Parameter for Use in Initial Aircraft Conceptual Design

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Simple constraints analysis, as taught to most aerospace engineering students gives little guidance as to exactly which design point should be selected. There is a recent body of work that attempts to solve this for initial designs, without having to fully size the new aircraft concept. The best of these focuses on maximizing a 'Range Parameter' which leads to minimizing gross weight for transport aircraft. However, this is not guaranteed to maximize the value of the new design. This paper presents a corresponding surplus value parameter which is design to provide just that capability. Furthermore, it shows that in at least some cases the resulting optimum design point will shift from that suggested by the range parameter.

Nomenclature

C_i = Cost
CP_i = Cost parameter
D_i = Discount multiplier
H_i = Hours
M_{max} = Maximum Mach number
N_{Eng} = Number of engines
N_{market} = Annual Market Size
Q = Total number of aircraft
R = Range/Rate/Revenue
RP = Range parameter
SV = Surplus value
SVP = Surplus value parameter
T_{Block} = Block time
T_{max} = Maximum thrust, per engine
t_i = Programme duration or product life
$\left.\frac{T}{W}\right|_{SL,0}$ = Thrust to weight ratio, sea-level, static
U = Annual utilization
V = Maximum velocity/Velocity
W_i = Weight
$\left.\frac{W}{S}\right|_{0}$ = Wing-loading, max gross weight
$_{0}$ = Max gross, beginning of mission
$_{AF}$ = airframe
$_{c}$ = customer
$_{crew}$ = crew
$_{D}$ = development support
$_{dev}$ = development
$_{E}$ = Engineering
$_{e}$ = empty
$_{Eng}$ = engine

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F = Fuel/Flight test support
f = fuel, per gallon
$flight$ = per flight
$Fuel$ = Fuel, per flight
man = manufacturing
$matl$ = materials
mtc = maintenance
p = producer
PL = payload
QC = quality control
T = tooling
α = Thrust lapse
β = Mission weight fraction
$\alpha_{0/1}$ = Empty weight multiplier
β_0 = Empty weight exponent
σ_i = discount rate

I. Introduction

The use of a thrust-to-weight vs. wing-loading constraints diagram is a standard way for aircraft conceptual design explorations to be launched. Historically, this has been attempted to assist in getting a good initial condition via which an aircraft can be sized and synthesised. One of the issues with the standard constraint analysis is that any measure of goodness is inherently crude, minimise T/W and maximise W/S. Further, it is nearly impossible to select and initial design point for some aircraft types as no trade between T/W and W/S can be determined from the information contained. One solution to this is to periodically revisit the constraint diagram after actually sizing the aircraft, producing contours or thumbprints on the constraint diagram or a similar Thrust vs. MTOW chart[1,2]. McDonald[3] identified a significant problem with this in that one has to actually size the aircraft to produce these charts. As such this requires some level of parametric sizing capability such as that provided by programs such as NASA's FLOPS[4,5]. In order to alleviate this issue some authors have proposed using L/D[6] and M(L/D)[3,6] as a surrogate for the sized aircraft. However, these only consider the aerodynamic performance of the aircraft. McDonald[3] further proposes the use of either a Range Parameter (RP) and/or Endurance Parameter (EP).

The RP approach, which also includes that ability to estimate the optimum cruise speed and altitude. This approach is typically based upon selecting a simple and straightforward weight fraction for the cruise, McDonald used 0.8[3]. However, while this may make sense for simple sizing to minimize MTOW at a maximum range and payload it does not represent the reality of how aircraft are typically operated, in shorter range and payload conditions[7]. This means that for many operations the applicable cruise weight fraction may actually be a fair bit lower.

Further, while the RP and EP measures may lead to aircraft that have the lowest possible MTOW for the design, they do not guarantee the best possible value to either the operator or manufacturer. To ensure this it is necessary to use a more 'sophisticated', value-driven approach[8–11]. The value approach looks at both the traditional performance of the aircraft and the actual operating environment, including maintenance, manufacturing and design and development considerations into account.

II. Background

The development of a surplus value parameter for use in very early conceptual design is based upon the prior work of developing a range parameter, plus the principles behind conceptual cost modelling and surplus value. In order to progress further it is necessary to identify and understand each of these.

A. Range Parameter

McDonald[3] defined the Range Parameter (RP) in terms of the different characteristics of the conceptual aircraft. Normally, performance codes use the Specfic Range (SR), shown in Eq. 1, to illustrate the instantaneous efficiency of the entire flight vehicle as a specific flight condition. While the SR is quite useful, the appropriate flight conditions are not always something that is known a-priori in the conceptual phase.

$$SR \equiv \frac{V}{C_T D} \quad (1)$$

What is more often known, at least for the unconstrained cruise operations, in conceptual design is the thrust specific fuel consumption (c_T) and the cruise lift-to-drag ratio (L/D). Expanding from the range equation, see Eq. 2, it is possible to pull out the performance parameters in the form of the RP, Eq. 3.

$$R = \frac{V}{c_T}\frac{L}{D} ln\left(1 + \frac{W_f}{W_p + W_e}\right) \quad (2)$$

$$RP \equiv \frac{V}{c_T}\frac{L}{D} \quad (3)$$

The units of the range parameter are in terms of pure distance, i.e. that is how far the aircraft can be flown for the natural log of the inverse of the weight fraction.

In addition to the range parameter McDonald[3] also proposed an equivalent formulation for endurance, the Endurance Parameter (EP). This is shown in Eq. 4.

$$EP \equiv \frac{1}{c_T}\frac{L}{D} \quad (4)$$

McDonald fully investigates the different uses and permutations of the range and endurance parameters, most of which while useful, are beyond the scope of this paper. This paper will restrict the use of range parameter to the case where Mach and altitude can be optimally chosen at all times.

B. Surplus Value

Surplus value (SV) has been well defined by several previous authors. This paper uses the same basic form first described by Collopy[12] and formalised by Hollingsworth[11]. This form is given in Eq. 5.

$$SV = D_P N_{market}\left[D_C U\left(R_{flight} - C_{flight}\right) - C_{Man}\right] - C_{Dev} \quad (5)$$

Hollingsworth[11] goes into detail regarding the calculations of discount multipliers, D_P & D_C. However, the simplest form of the discount multipliers is given in Eq. 6.

$$D_i = \frac{1}{\sigma_i} - \frac{1}{\sigma_i (1+\sigma_i)^{t_i}} \quad (6)$$

The beauty of the SV formulation is that it allows for a relatively simple ranking of different engineering options on a financial basis without having to perform detailed future forecasts. If models for estimating costs based on extensive engineering attributes exist then it is relatively straightforward to link these attributes to the SV function. The only one of the SV inputs that cannot be easily given to engineers or determined by engineering analysis is the revenue per flight. However, most design choices being considered, especially rubber designs are not going to significantly affect the revenue generated. Consequently, since we are more interested in the rank order it is possible to leave out the revenue entirely. This gives Eq. 3.

$$SV_{cost} = D_P N_{market}\left[D_C U\left(C_{flight}\right) - C_{Man}\right] - C_{Dev} \quad (7)$$

It must be noted that for the cases where revenue changes for different conceptual designs, e.g. those described by Sutcliffe and Hollingsworth[10], then this simplification cannot be made.

C. Cost Modelling

In order to capture the potential surplus value of a product it is necessary to model the costs. While there are a number of cost models available, for the purposes of this paper the authors propose that a simple, weight regressed cost approach be used. The reasons for this are multiple. One, it is not always possible to full understand the actual activities involved in the construction of a new design at the conceptual/constraint analysis phase. Two, different organisations have different approaches and regression factors for their cost models. Regardless, it is relatively straightforward to demonstrate the approach with a published approach and alter it as necessary to fit a new model. The model used for this research is the DAPCA IV model developed by RAND[13–15] and modified by Raymer[1]. It consists of estimators for the manufacturing cost and development and testing. These are given in Eqs. 8-19.

$$H_E = 4.86\, W_e^{0.777}\, V^{0.894} Q^{0.163} \quad (8)$$

$$H_T = 5.99 W_e^{0.777}\, V^{0.696}\, Q^{0.263} \quad (9)$$

$$H_M = 7.37 W_e^{0.82}\, Q^{0.641} \quad (10)$$

$$H_{QC} = 0.133H_M \tag{11}$$

$$C_D=89.10W_e^{0.630}V^{1.3} \tag{12}$$

$$C_F = 2438.452W_e^{0.325}V^{0.822}\,FTA^{1.21} \tag{13}$$

$$C_{matl} = 21.58W_e^{0.921}V^{0.621}Q^{0.799} \tag{14}$$

$$C_{ENG} = 3644.05[0.043T_{Max} + 243.25M_{Max} - 2228] \tag{15}$$

$$C_{Avionics} = 0.20 \times Final\ aircraft\ cost \tag{16}$$

$$C_{Dev} = C_D + C_F \tag{17}$$

$$C_{Man,Total} = H_E R_E + H_T R_T + H_M R_M + H_{QC} R_{QC} + C_{matl} + C_{ENG} N + C_{AVIONICS} \tag{18}$$

$$C_{Man} = \frac{C_{Man,Total}}{Q} \tag{19}$$

The quantity (Q), empty weight (W_e), maximum velocity (V) and Mach number (M_{Max}), and engine maximum thrust (T_{Max}) are the basic contributors to these costs. Quantity is also directly related to the market size, i.e. it is the sum of all the aircraft produced and sold over the course of the programme plus any prototypes that are not sold. Meanwhile, thrust and empty weight are directly related to both the constraints diagram and the sizing of the aircraft.

Operating costs are typically split into direct and indirect operating costs. These can be computed on either a per-hour or per-flight basis. Depending on which method is used, the specific value of utilization in the SV equation is either flights per annum or hours per annum. The indirect costs are generally insensitive to the design of the aircraft. As a consequence they only serve to shift the SV up or down as a constant and are not necessary to rank order different designs. As such, the indirect costs are excluded from the method presented in this paper. Regardless of the specific form of estimation, there are four basic direct costs: fuel, crew, maintenance and fees. Using models developed by Liebeck et al.[16], the basic fuel, crew and maintenance costs are given in Eqs 20-31.

$$T_{Block} = (0.0021 \times Distance + 0.94) \tag{20}$$

$$C_{Fuel} = \frac{W_f}{\rho_f} C_f \tag{21}$$

where: $\rho_f = 6.7 \frac{lb}{gallon}$

$$C_{Crew,Flight} = 3.08\left(440 + 0.590(\frac{W_0}{1000})\right) T_{Block} \tag{22}$$

$$C_{Crew,Cabin} = 38.62\ \left[2 + \left(\frac{(N_{Seats})-100}{50}\right)\right] T_{Block} \tag{23}$$

$$C_{crew} = C_{Crew,Flight} + C_{Crew,Cabin} \tag{24}$$

$$C_{Mtc,AF,Labour} = \\ 38.62\ \Big\{\Big[1.26 + 1.774\left(\frac{W_{Airframe}}{10^5}\right) - 0.1071\ \left(\frac{W_{Airframe}}{10^5}\right)^2\Big] T_{Block}U + \Big[1.614 + 0.7227\left(\frac{W_{Airframe}}{10^5}\right) + \\ \mathit{0.1204WAirframe1052} \tag{25}$$

$$C_{Mtc,AF,Matl} = \\ 1.54\Big[\Big(12.39 + 29.8\left(\frac{W_{Airframe}}{10^5}\right) + 0.1806\left(\frac{W_{Airframe}}{10^5}\right)^2\Big) T_{Block}U + \Big(15.2 + 97.33\left(\frac{W_{Airframe}}{10^5}\right) - \\ \mathit{2.862WAirframe1052} \tag{26}$$

$$C_{Mtc,AF} = {\left(C_{Mtc,AF,Labour} + C_{Mtc,AF,Matl}\right)}\Big/_{U} \tag{27}$$

$$C_{Mtc,Eng,Labour} = 38.62\left(0.645 + \left(\frac{0.05 \times T_{\mathrm{Max}}}{N_{Eng} \times 10^4}\right)\ \left(0.566 + \frac{0.434}{T_{Block}Ut_c}\right)\right) T_{Block}UN_{eng} \tag{28}$$

$$C_{Mtc,Eng,Matl} = 1.54\left(25 + \left(\frac{0.05 \times T_{\mathrm{Max}}}{N_{Eng} \times\ 10^4}\right)\left(0.62 + \frac{0.38}{T_{Block}Ut_c}\right)\right) T_{Block}UN_{eng} \tag{29}$$

$$C_{Mtc,Eng} = {\left(C_{Mtc,Eng,Labour} + C_{Mtc,Eng,Labour}\right)}\Big/_{U} \tag{30}$$

$$C_{mtc} = C_{Mtc,AF} + C_{Mtc,Eng} \tag{31}$$

The fees themselves are strictly a function of maximum gross weight (W_0) and are given in Eqs. 32 to 34.

$$C_{Ldg} = 6.25 \times (W_0/1000) \tag{32}$$

$$C_{nav} = 0.20 \times 500 \times \sqrt{\frac{W_0}{1000}} \tag{33}$$

$$C_{fee} = C_{Ldg} + C_{nav} \tag{34}$$

with the resulting cost per flight shown in Eq. 35.

$$C_{flight} = C_{Fuel} + C_{crew} + C_{mtc} + C_{fee} \tag{35}$$

III. SV Model in Constraint Analysis

Like the RP approach it is necessary to capture the essence of an aircraft design, in a surplus value approach, without having to size and design for the entire mission. Unfortunately, given the results in Eq. it is not strictly possible to produce a single value for SV without sizing an aircraft. What can be done is to look at the factors that affect the surplus value and eliminate those that are less significant for the typical aircraft programme. Revisiting Eqs. 6 & 7 we see that the primary effectors of SV are the number sold, the utilization, programmatic factors such as discount rates and expected durations and the individual cost components. The individual cost components, in the simplified models, are all functions of a combination of W_0, W_e, W_f, or T plus a series of other parameters that are a function of operating speeds, payload and market size. Keeping in mind that the max take-off weight is a function of these variables, shown in Eq 36, it is possible to define W_0 and consequently $\frac{W_0}{S}$ as a function of these.

$$W_0 = W_f + W_e + W_{pl} \tag{36}$$

Combining Eqs. 2, 3 & 26 we get the take-off weight as a function of the range parameter, shown in Eq. 37.

$$W_0 = \left(W_{pl} + W_e\right) e^{\frac{R}{RP}} \tag{37}$$

This can be combined with Eq. 38[17], which gives a simple relationship between empty weight and gross weight to form Eq. 39.

$$W_e = \alpha_0 W_0^{1+\beta_0} \tag{38}$$

$$W_0 = \frac{W_p e^{\frac{R}{RP}}}{1-\alpha_0 W_0^{1-\beta_0} e^{\frac{R}{RP}}} \tag{39}$$

Obviously, the problem here is that in this formulation $W_0 = f(W_0)$, this means an iteration must be performed. However, it is possible, to determine ahead of time a rough order for $W_e = f(W_0)$. This can be refined as the actual sizing takes place. Replacing Eq. 36 with a form that is purely a fraction of W_0, Eq. 40, allows Eq 39 to be recast as Eq 41.

$$W_e \cong \alpha_1 W_e \tag{40}$$

$$W_0 \cong \frac{W_p e^{\frac{R}{RP}}}{1-\alpha_1 e^{\frac{R}{RP}}} \tag{41}$$

or in terms of $\left.\frac{W}{S}\right|_0$ as shown in Eq. 42.

$$\left.\frac{W}{S}\right|_0 \cong \frac{W_p}{S} \frac{e^{\frac{R}{RP}}}{1-\alpha_1 e^{\frac{R}{RP}}} \tag{42}$$

This shows us that as a first order the take-off wing loading is a function of the payload loading and range parameter. Returning to Eqs. 8-14 & 16-19 it is self evident that the airframe cost is primarily a function of W_0. Engine cost on the other hand is a function of installed thrust. The development cost can be represented as a function of $\left.\frac{W}{S}\right|_0$ as shown in Eq. 43.

$$\frac{C_{Dev}}{S} = 89.10 \left(\alpha_1 \frac{W_0}{S}\right)^{0.630} V^{1.3} + 2438.452 \left(\alpha_1 \frac{W_0}{S}\right)^{0.325} V^{0.822}\, FTA^{1.21} \tag{43}$$

A quick review indicates that the first portion of Eq 43 is dominant (C_D), producing values that are typically an order of magnitude or more greater than (C_F), see Figure 1. This gives a development cost parameter (CP_{Dev}) that is solely a function of the wing loading. This is shown in Eq. 44.

$$CP_{Dev} = 100 \left(\alpha_1 \frac{W_0}{S}\right)^{0.7} \tag{44}$$

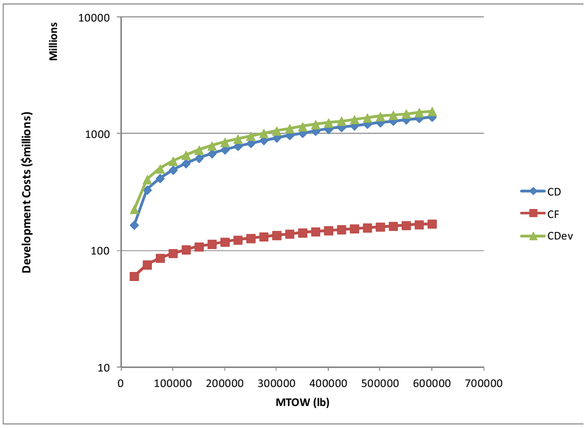


Figure 1: Comparison of Development and Flight Test Costs as a function of MTOW, where $\alpha_1 = 0.48$, $V = 498\,kts$ and $FTA = 4$

A similar activity can be undertaken with the manufacturing cost. Equation 19 can be rewritten as

$$C_{Man,AF} = 4.86\,W_e^{0.777}\,V^{0.894}Q^{-0.837}R_E + 5.99W_e^{0.777}\,V^{0.696}\,Q^{-0.737}R_T + 7.37W_e^{0.82}\,Q^{-0.359}R_M + 0.980W_e^{0.82}\,Q^{-0.359}R_{QC} + 21.58W_e^{0.921}V^{0.621}Q^{-0.201} \qquad (45)$$

or

$$\frac{C_{Man,AF}}{S} = 4.86\left(\alpha_1\frac{W_0}{S}\right)^{0.777}V^{0.894}Q^{-0.837}R_E + 5.99\left(\alpha_1\frac{W_0}{S}\right)^{0.777}V^{0.696}\,Q^{-0.737}R_T + 7.37\left(\alpha_1\frac{W_0}{S}\right)^{0.82}Q^{-0.359}R_M + 0.980\left(\alpha_1\frac{W_0}{S}\right)^{0.82}Q^{-0.359}R_{QC} + 21.58\left(\alpha_1\frac{W_0}{S}\right)^{0.921}V^{0.621}Q^{-0.201} \qquad (46)$$

Again, one or a few components of the cost tends to dominate, for smaller production size this is the engineering and tooling along with materials cost, see Figure 2.

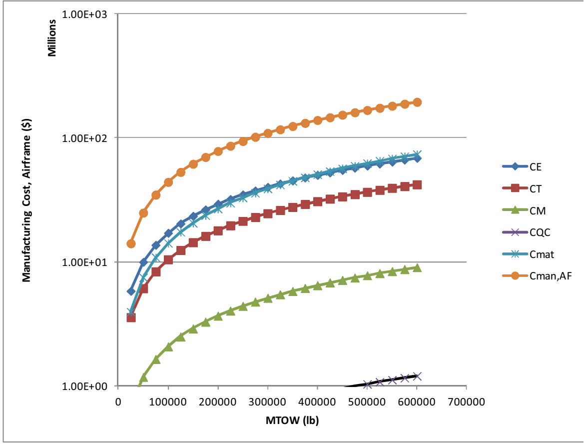


Figure 2: Comparison of Airframe Manufacturing Costs as a function of MTOW, where $\alpha_1 = 0.48$, $V = 498\,kts$ and $Q = 1200$

For larger runs, the materials dominate. As such an airframe cost parameter can be approximated in Eq 47.

$$CP_{Man,AF} = 20\left(\alpha_1\frac{W_0}{S}\right)^{1.0}V^{0.9}Q^{-0.36} \qquad (47)$$

The engine manufacturing cost can also be approximated using a similar cost parameter, Eq. 48.

$$CP_{Man,Eng} = 160\left(\frac{T}{W}\right)_{SL,0} + Constant \qquad (48)$$

While the development and manufacturing costs are directly related to either the wing loading or the thrust to weight ratio the operating costs are proportional to the mission being flown. The fuel consumed, and hence the fuel cost is proportional to e raised to the inverse of the range parameter.

$$C_{fuel} = \frac{W_f}{\rho_f} C_f \propto e^{\frac{1}{RP}} \tag{49}$$

The key is to know how C_{fuel} relates to other costs. In this case a typical mission weight fraction needs to be calculated. Using Eqs. 2, 36 & 37 it is possible to estimate the W_f for a mission, shown in Eq. 50.

$$W_f = \left(W_0 - \frac{W_0}{e^{\frac{R}{RP}}} \right) = \left(1 - \frac{1}{e^{\frac{R}{RP}}} \right) W_0 \tag{50}$$

A cost parameter for fuel would take the form of:

$$CP_{fuel} = \frac{C_f}{\rho_f} \left(1 - \frac{1}{e^{\frac{R}{RP}}} \right) \left(\frac{W}{S} \right)_0 \tag{51}$$

The crew costs conversely scales with block time, and has no direct relation to the range parameter. This can be represented by a crew cost parameter.

$$CP_{Crew} = 3.08 \left(440 + \frac{0.590}{1000} \left(\frac{W}{S} \right)_0 \right) T_{Block} \tag{52}$$

Note, the cabin crew cost is also a relative constant, not directly affected by the $\frac{T}{W}$ or $\frac{W}{S}$ as such, like the revenue it can be excluded.

The final set of costs are the maintenance costs. A review of Eqs. 25 & 26 and 28 & 29 indicate that they are dominated by the reocurring costs per flight instead of the fixed costs. As such a cost parameter for both the airframe and the engine will be developed that contain only the reoccurring costs. These are given in Eqs. 53 and 54.

$$CP_{mtc,AF} = \left\{ 1.54 \left[\frac{29.8}{10^5} \left(\alpha_1 \left. \frac{W}{S} \right|_0 \right) + \frac{0.1806}{10^5} \left(\alpha_1 \left. \frac{W}{S} \right|_0 \right)^2 \right] + 36.82 \left[\frac{1.77}{10^5} \left(\alpha_1 \left. \frac{W}{S} \right|_0 \right) - \frac{1.07}{10^5} \left(\alpha_1 \left. \frac{W}{S} \right|_0 \right)^2 \right] \right\} T_{block} \tag{53}$$

$$CP_{mtc,Eng} = \left\{ 38.62 \left(0.645 + \frac{0.028}{10^4} \left(\frac{T}{W} \right)_{SL,0} \right) + 1.54 \left(25 + \frac{0.031}{10^4} \left(\frac{T}{W} \right)_{SL,0} \right) \right\} T_{block} \tag{54}$$

Consequently a surplus value parameter (SVP) can be developed from Eq. 7 and Eqs. 44, 47, 48 and 51-54. This is given in Eq. 55.

$$SVP = D_p N_{market} \left[D_C U \left(-CP_{fuel} - CP_{crew} - CP_{mtc,AF} - CP_{mtc,Eng} \right) - CP_{man,AF} - CP_{man,Eng} \right] - CP_{Dev} \tag{55}$$

The result is that ideal thrust to weight and wing loading is dependent on the range parameter and the thrust to weight and wing loadings.

In order to determine the appropriate surplus value parameter response for a given aircraft the following procedure should be used:

1. Determine Constrains as appropriate, this paper uses the Mattingly's[17] method
2. Calculate Range Parameter using McDonald's method[3]
3. Calculate Surplus Value Parameter using Eqs. 44, 47, 48 and 51-55

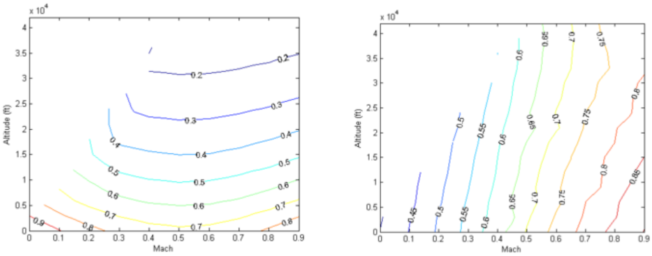
IV. Example

In order to demonstrate the concept of an SV parameter in initial conceptual design it is necessary to use an example of an early conceptual design process. Further, to demonstrate the applicability the results will be compared to both the typical methods taught to engineering students and McDonald's range parameter[3]. For the purposes of this study a simple, current technology 150 passenger class aircraft will be used. The basic engine and aerodynamic decks are obtained from FLOPS internal routines[4]. This allows aerodynamic and propulsion data that is slightly more sophisticated than simple $\frac{L}{D}, TSFC = constant$, approaches. A further simplification from McDonald[3] is that this example only investigates the case where the aircraft cruises at optimum altitude and Mach number. While this does not typically replicate the reality of operations it is sufficient for this example. Additionally the aircraft will be subject to four simple constraints. These are given in Table 1.

Table 1: Basic Aircraft Constraints

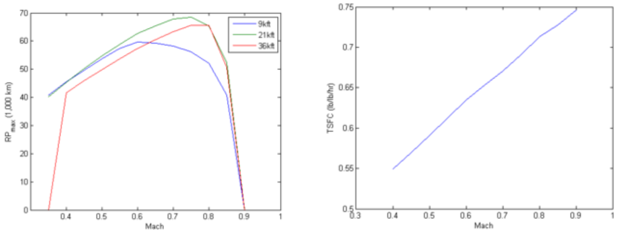
Constraint	Value
Service Ceiling	36,000 ft at $\beta = 0.80$
Take-off Ground Roll	4,000 ft
Second Segment Climb, one engine inop	1.4°
Approach Speed	130 kts, $\beta = 0.75$

Figure 3 contains the aerodynamic and engine performance for the aircraft



(a) $\alpha_{\max}$ for the engine

(b) TSFC min at 80% Throttle



(c) Maximum RP

(d) Max thrustTSFC at Tropopause

Figure 3: Aerodynamic and Engine Performance for the Notional 150 Passenger Aircraft

This results in a simple constraints diagram as shown in Figure 4. The problem with this style constraints diagram is that, as most students are taught, it is impossible to select a starting design point. Each point along the Take-off constraint, between the cruise ceiling and approach speed constraints is equally valid. This isn't a problem if the user is completely indifferent to the different points, in which case the designer can choose any one of the points that lies along these lines.

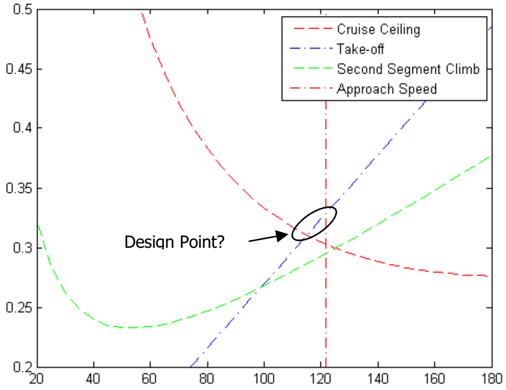


Figure 4: Basic Constraint Analysis for Notional 150 Passenger Aircraft

What happens if the designer wants to minimize the weight of the aircraft? McDonald[3] has shown that maximizing the Range Parameter approximates the minimum gross weight. For the notional aircraft the maximum range parameter point, shown in Figure 5, is generally at a high wing loading and low thrust to weight ratio.

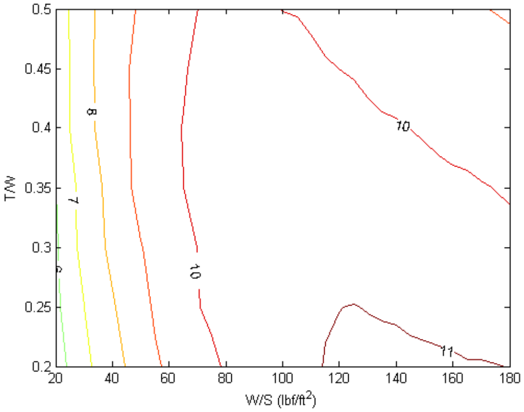


Figure 5: Range Parameter Contours for Notional 150 Passenger Aircraft (1000 nmi)

However, while the general trend holds the specific contours are more complex, forming closed boundaries and not just simple lines. The key is to try and find a point on the constraints boundary that is nearly parallel to one of the range parameter contours. This is shown in Figure 6. In this case the notional design point, one that minimizes gross weight, shifts to the intersection of the take-off and cruise ceiling constraints as this is essentially parallel to the local range parameter contour. The reader should note that while this specific contour holds true for the notional 150 passenger aircraft, it is not guaranteed for every design and the user should actually use the appropriate values.

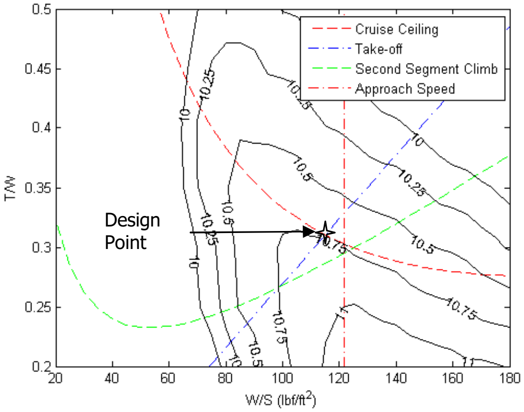


Figure 6: Range Parameter Contours and Constraints for Notional 150 Passenger Aircraft (1000 nmi)

This result is useful for the cases where the goal is purely to minimize gross weight. However, as Collopy and Hollingsworth[8] have shown this is not necessarily the best design for the firms producing and operating the aircraft.

Moving a step beyond the range parameter to the surplus value parameter it is necessary to define a few more properties of the aircraft and its market. These are given in Table 2, with the resulting surplus value parameter contours shown in Figure 7.

Table 2: Surplus Value Parameter Calculation Market and Business Case Properties

Property	**Value**
Producer Discount Rate (σ_p)	12.5%
Customer Discount Rate (σ_c)	25%
Programme Duration (t_p)	15 years
Aircraft Life (t_{cp})	20 years
Market Size (Q, N_{market})	3000 aircraft (200/year)
Annual Utilization (U)	1200 flights

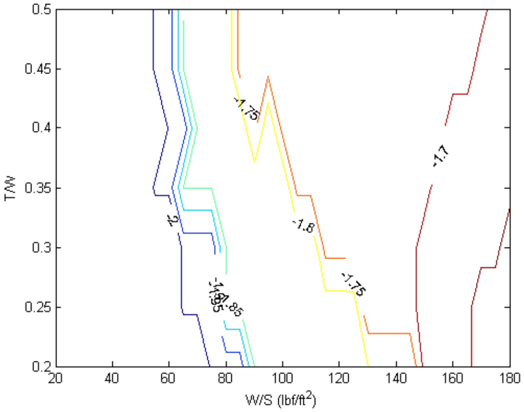


Figure 7: Surplus Value Parameter Contours for Notional 150 Passenger Aircraft (1x10^{10}\$ ft^{-2})

The results are highly negative, which is a consequence of the removal of the revenue term in Eq. 7. It is straight forward to adjust these values by a simple constant if the designer feels that this is more useful. The reason for this is that we are only trading amongst different designs and not deciding on whether or not we will proceed with a programme. In this case the user wants to maximize the surplus value parameter. While in general the trend is toward higher wing loadings, it is not as sensitive to thrust-to-weight as the range parameter.

Again, in order to select the best starting design point, with respect to a first order assessment of surplus value, it is necessary to superimpose the constraint analysis on the surplus value parameter contours. Once this is done, the user seeks out the point on the constraints that is nearly parallel to the surplus value parameter contours. This is shown in Figure 8.

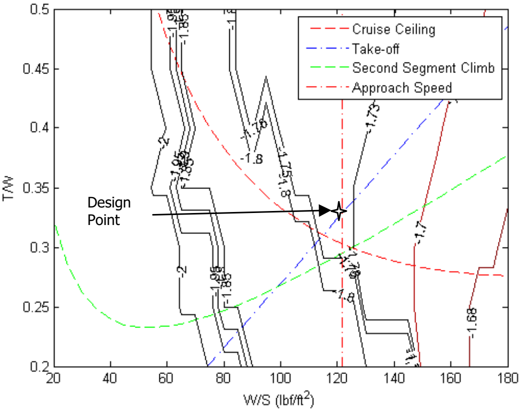


Figure 8: Surplus Value Parameter Contours and Constrains for Notional 150 Passenger Aircraft (1x10^{10}$ ft^{-2})

Again the design point has shifted, unlike the range parameter maximizing point, which is at the intersection of the take-off and cruise constraint. The surplus value maximizing parameter is located at the intersection of take-off and approach speed constraints.

V. Conclusion

It is possible to develop an equivalent to the range parameter for maximizing the surplus value of a commercial transport. Instead of minimizing gross weight this parameter maximizes the potential return for an early conceptual design. Further, the design point suggested by this parameter does not always lie at the same point as the one that minimizes gross weight. Because of this the use of the surplus value parameter has the potential to produce a better starting point than either classic constraints analysis alone or constraints analysis plus range parameter. However, the result is just that a starting point for a fully constrained rubberised design. It is a quick what to gauge where an initial guess at thrust-to-weight and wing-loading should be placed. From this point, it is necessary to begin developing a more detailed model of the aircraft, improving both the engineering and value estimates. Furthermore, it is useful to relax or remove the constraints and further design and optimize the aircraft to maximize its value.

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Part II

IMAPP

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A Maintenance Packaging and Scheduling Optimization Method for Future Aircraft

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This paper proposes an optimization method for aircraft maintenance tasks packaging and scheduling integrated in an aircraft lifecycle simulation. It is demonstrated that the developed methods are feasible to model a prognosis-based maintenance concept. Such maintenance concepts are a prerequisite for a profitable application of prognostics and health management systems in future aircraft. The applicability of the method is analyzed and economically assessed over an aircraft lifecycle considering aircraft operation. The analysis shows that a variation of the maintenance opportunities frequency for a short-range aircraft, provided in the aircraft rotation plan, can have a significant influence on the operator's net present value (NPV). A benefit of up to 2.8 million USD, representing 1.2% of the operator's NPV, can be realized, when maintenance opportunities are provided every 3 instead of every 7 days, while aircraft utilization is assumed to be constant. Compared to a traditional block check concept the presented method leads to higher maintenance costs, under the condition that the same volume of maintenance work has to be carried out.

Nomenclature

AIRMAP = Aircraft Maintenance Planning
AirTOBS = Aircraft Technology and Operations Benchmark System
C = cost [USD]
C_0 = initial investment [USD]
C_i = cash flow in the i-th year [USD]
DMC = direct maintenance cost [USD]
DOC = direct operating cost [USD]
FC = flight cycle
FH = flight hour
FSB = flight schedule builder
LC2B = life cycle cost-benefit model
LCC = life cycle cost [USD]
LRU = line replaceable unit
MH = man-hour
MEL = minimum equipment list
MRO = maintenance, repair, and overhaul
MSB = maintenance schedule builder
MTBUR = mean time between unscheduled removals [FH]
MTTR = mean time to repair [h]
NPV = net present value [USD]
PHM = prognostics and health management
r = required rate of return
RUL = remaining useful life [FH]
t = time

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I. Introduction

THE aircraft operators are under great pressure to increase aircraft availability and operability in the future and continue to reduce the cost of aircraft operation. Reductions of maintenance downtimes and the prevention of operational interruptions can help to achieve these objectives. Therefore aircraft manufacturers are aiming for a drastic reduction of the scheduled maintenance programs for future aircraft. In the ideal case – even though it will probably never be reached – there will be no more scheduled maintenance programs. This means a complete shift away from a preventive to a condition- or prognosis-based maintenance strategy. It enables an optimal utilization of the remaining useful lifetimes of aircraft components and (in theory) the minimization of ground times and maintenance events.

Technical and organizational requirements must be met in order to achieve a widely prognosis-based maintenance. The aircraft must be equipped with diagnostic and prognostic systems, which are able to monitor the state of health of components and systems, and to announce impending failures in time. Prognostics and Health Management (PHM) systems may help to reduce both, operational interruptions due to unscheduled maintenance events, and maintenance downtimes due to (unnecessary) preventive maintenance.[1] Industrial an academic research is working on PHM systems for many years and has announced significant advances. But several challenges have still to be resolved for the onboard deployment of an aircraft-wide system.[2]

A. Future maintenance concepts and technologies

PHM technologies installed in future aircraft could help to reduce scheduled and unscheduled maintenance and consequently increase the aircraft availability and operability. Significant shares of today's scheduled maintenance tasks are related to inspections, which may become obsolete in future aircraft when equipped with PHM systems. In many cases safety critical items have hard times today. If a PHM system can ensure a reliable detection of an imminent fault of this item, its useful lifetime can extend substantially.

Unscheduled maintenance events and no-fault-founds (NFF) can be prevented, when an efficient PHM system reports imminent failures and localizes failure root-causes. The mentioned effects can lead to significant reductions in maintenance downtime and costs.[3]

Individual loads and production tolerances lead to different component degeneration, which finally results in an individual remaining useful life (RUL) of component or a system. PHM technology is able to estimate the RUL of an item based on the individual state of health and (estimated) future degeneration processes. A successful failure prognosis enables a repair or replacement of the degraded item before the critical failure occurs.[4]

A single-task-oriented and condition-based maintenance concept is required, when aiming for high utilizations of component's RULs. In the following we call such a concept a prognosis-based maintenance. On the organizational side, a fully prognosis-based maintenance leads to great challenges. Today´s maintenance programs are characterized by preventive and corrective tasks. While preventive tasks with fixed intervals are foreseeable and easy to plan, time and effort for corrective work is more difficult to plan as they arise from the results of (preventive) inspections. A wider use of prognostics can lower the portion of preventive tasks and thereby reduce the predictability of future maintenance work. With prognostics, many preventive inspections may become obsolete, while prognosis-based tasks have to be planned and carried out with (potentially) short warning times. Predicted RULs are not fixed but deviate depending on further component degradation trends. This leads to the necessity of more flexible maintenance planning processes in order to support prognostic systems in an optimal way. Maintenance activities have to be grouped together ("packaging") and performed at the right point in time ("scheduling") depending on estimated remaining useful life (RUL).[5] It is be the goal to minimize aircraft maintenance downtime and costs while aircraft rotation planning and limited maintenance capacities are considered.

II. Methodology

The approach presented in this paper is based on a branch-and-bound algorithm for maintenance planning and a discrete-event simulation of aircraft operation. The results are evaluated with a life cycle cost-benefit analysis. An overall architecture containing these models has been established for the intended analysis.

A. Lifecycle Approach

The three major commercial stakeholders in the air transportation system – aircraft manufacturer, airlines and MROs – have conflictive goals, since all striving for profit maximization. New technologies for the air transportation system must therefore not only lead to technical improvements, but have to show economic advantages compared to the current system.

Direct operating cost (DOC) is an established metric to perform economic valuation of existing aircraft or future aircraft concepts.[6,7] Standard DOC methods account for crew expenses, landing and navigation charges, maintenance cost, fuel cost, depreciation, insurance cost, and interest. DOC formulae use global technical, operational, and economic parameters to come up with an average DOC value on a flight-cycle or flight-hour basis.

When assessing technologies and processes with impacts on the air transportation system level, all phases of the life cycle and interdependencies with other system elements have to be considered. New maintenance concepts influence maintenance cost and aircraft availability. To capture time and cost aspects, the lifecycle cost-benefit model AirTOBS (Aircraft Technology and Operations Benchmark System) was developed.

It models all economic relevant parameters along the aircraft life cycle. The aircraft operational lifecycle is initiated by the acquisition of an aircraft and ends with the decommissioning. The model includes aircraft specific parameters, operational aspects, e.g. route network or maintenance concepts, as well as global boundary conditions, e.g. fuel price trend. AirTOBS focuses on the perspective of an airline and includes methods to account for costs and revenues.

An overview of AirTOBS is shown in Fig. 1. It consists of three main modules. The Flight Schedule Builder (FSB) generates a generic aircraft lifecycle flight schedule based on airline route data. Routes are considered based on the aircraft cycle time including flight time, taxi and runway operation times, and turnaround time.

This provisional flight schedule serves as the fundament for the Maintenance Schedule Builder (MSB). The MSB executes a simulation run of the flight operation and maintenance events over the aircraft lifecycle. The MSB uses input data from maintenance databases for the modeling of scheduled and unscheduled maintenance events, including airframe, engine and component maintenance. Scheduled maintenance is considered depending on discrete, interval-based events. Intervals are specified by flight hours (FH), flight cycles (FC), and time (years, months, days). Each event has a specific ground time, during which the flight schedule is adjusted while producing time discrete costs to the airline. To account for operating experience and maturity effects in maintenance, maturity curves are provided within the model. The maintenance schedule created by the MSB follows a traditional block check concepts for line and base maintenance.

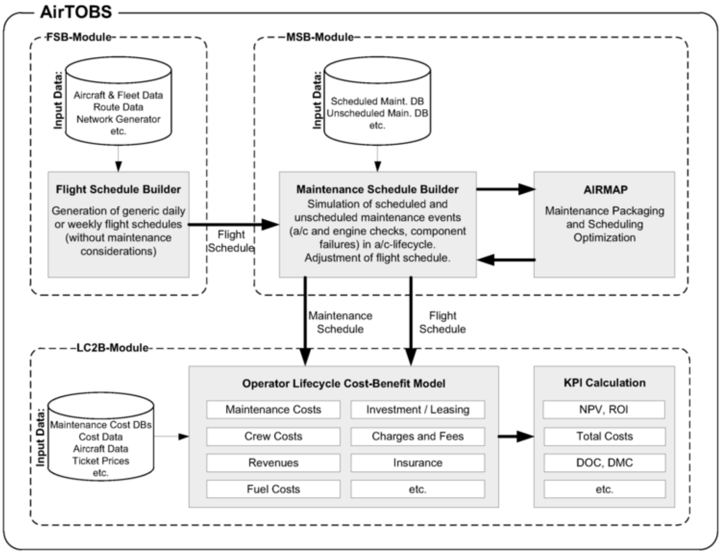

Figure 1: Overview of aircraft lifecycle cost-benefit model with integrated Maintenance Packaging and Scheduling Optimizer

To analyze new maintenance concepts, like a prognosis-based maintenance in combination with PHM-use in this study, the Aircraft Maintenance Planning (AIRMAP) Optimizer module can be linked to the MSB. AIRMAP produces an optimized maintenance schedule based on intermediate results from the MSB. The methodology used in AIRMAP is described in section B.

After the optimized maintenance schedule and the adjusted flight schedule are generated, the results are passed on to the Operator Lifecycle Cost-Benefit Model (LC2B), where costs and revenues are calculated (as shown in Fig. 1). Revenues are modeled using statistics with consideration of flight distances, seating classes, seat numbers and mean load factors. The actual time of occurrence of the cost and revenue elements is captured to account for the time value of money. All values are escalated over the aircraft lifecycle to account for inflation, before they can be summarized as net present value (NPV). The NPV is a common metric to quantify a project's net-contribution to wealth[8] for a certain period of time, while accounting for the time value of money and the opportunity cost of capital. It can be calculated as given in Eq. (1), where C_0 is the initial investment (i.e. aircraft price) and C_i is the cash-flow in the i-th year. The discount rate r represents the rate of return that could be achieved with a similar risky investment.

$$NPV = C_0 + \sum_i \frac{C_i}{(1+r)^i} \tag{1}$$

Unscheduled maintenance is considered on an accumulated ATA-Chapter level or by a provided component database. Using the modeled lifetime flight schedule, unscheduled events can be simulated based on mean times between unscheduled removals (MTBUR) or component failure distribution functions, aircraft related mean times to repair (MTTR), e.g. time needed for a component or line replaceable unit (LRU) replacement. Component failures produce costs for labor and material. Furthermore they can result in flight delays or cancellations depending on the minimum equipment list (MEL), the MTTR, and the planned aircraft turnaround time. Delays are modeled as a reduction in aircraft availability and a cost element that covers passenger compensations and accommodation.

The weekly availability is based on seven 24 hour days and is reduced by night curfews at airports. The resulting availability is further reduced by taking the flight schedule into account, including turnaround and block times. From this flight schedule line maintenance events are derived, assuming no influence on the flight schedule while accounting for cost.

To consider the influences of maintenance strategies and component reliabilities on spare part provisioning, related inventory costs are modeled. Overall LRU inventory costs are modeled based on estimated component quantities to meet a desired service level and the total carrying cost (capital and inventory cost). The estimated component quantities are calculated based on the aircraft utilization, quantities per aircraft, MTBURs, repair turnaround times and fleet size.[9]

B. Maintenance Planning Optimizer

The planning of aircraft maintenance is the allocation of maintenance tasks (i.e. objects) to be performed on specific aircrafts to maintenance capacities (i.e. bins). Combinatorial problems of this character are of higher complexity and are very similar to the elementary bin packing problem[10,11]. Since the aircraft maintenance planning, as discussed in this paper, considers more variables and constraints as the 'simple' bin packing problem, it is very likely to be NP-hard[*]. NP-hard problems can be solved heuristically in polynomial time with branch-and-bound algorithms.[12]

The algorithm described below, as used in AIRMAP, is able to solve the previously formulated NP-hard AIRMAP-Model[13] in polynomial time. The AIRMAP-Optimizer can be characterized as a depth-first-search branch-and-bound algorithm.

As specified in section I, aircraft operators and manufacturers strive to shift away from a scheduled (i.e. hard-time) to a prognosis-based maintenance. Prognosis-based tasks have to be planned and scheduled in a way that leads to an economic optimum.

The optimizer can function as a planning interface between flight and ground operations of future aircraft equipped with PHM-technology. It uses data inputs from flight and maintenance operations as shown in Fig. 2. Based on the aircraft rotation defined by flight operations and considering restrictions of the maintenance organization (capacities and capabilities), the optimizer creates a maintenance schedule at minimized total costs. This maintenance planning process can be executed for a single aircraft or an entire fleet of aircraft with different aircraft types for any finite planning horizon.

The optimizer follows a single-task-oriented approach. Each ground time of an aircraft (turnaround times and overnight stays) is regarded as a maintenance opportunity. The goal is to avoid additional maintenance downtimes and to utilize existing maintenance opportunities efficiently. This can be done by appropriate clustering of maintenance tasks, while considering technical (maintenance intervals or RULs reported by a PHM-system) and organizational restrictions.

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[*] NP-hard (non-deterministic polynomial-time hard) problems cannot be efficiently solved in polynomial time. By using adequate heuristic algorithms it is possible to efficiently verify integer optimization problems.

The RUL estimate is a major input parameter for AIRMAP. The duration of maintenance tasks and costs can be derived from maintenance documents in combination with MRO's experience. The aircraft rotation plan provides the optimizer with the aircraft location at a specific time, the aircraft type, and the tail sign.

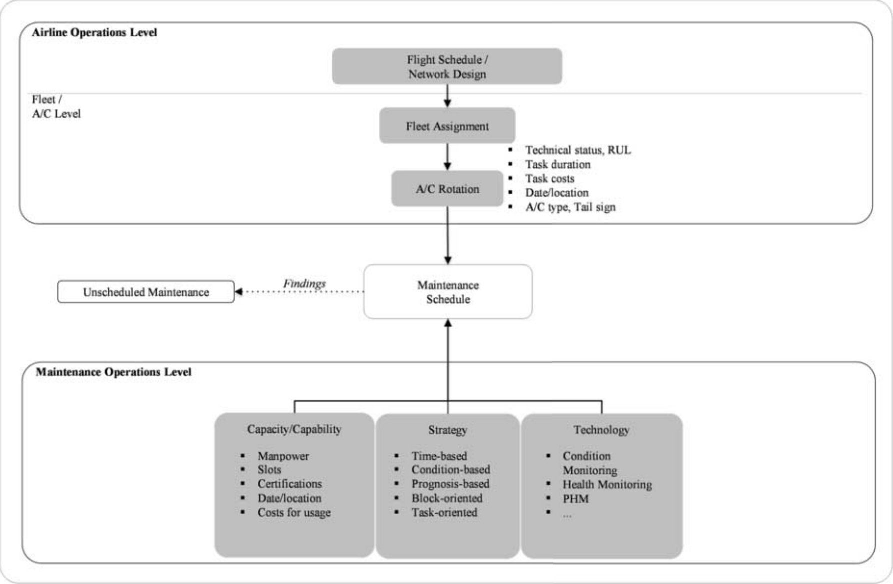

Figure 2: Airline Optimization Model

The main variables and restrictions regarding maintenance operations are those in the block 'Capacity/Capability' in Fig. 2. A maintenance schedule is valid, if

- the available manpower is sufficient to execute the allocated tasks,
- enough free maintenance slots are available (e.g. for tasks to be performed in hangar environment),
- required certifications for the aircraft type are available at specific maintenance location,
- and the aircraft ground time is sufficient to execute the allocated tasks at the selected maintenance location.

The optimizer charges costs for usage of a maintenance opportunity in order to minimize additional fix costs that can be expected for a maintenance event.

Optimizer program flow

In Fig. 3 the optimizer program flow is shown. After read-in of relevant input data (1.) from airline (*Tasks*) and maintenance operations (*Opps*), the algorithm is configured with the following parameters (2.):

1. *Usage factor* (from 0 to 1) – regulates the minimum share of the RUL that must be used before a maintenance task may performed.
2. *iMax* – determines the number of iterations.
3. *1st Bound* – feeds the branch-and-bound algorithm with a first reference, which must be a great value (e.g. 10^{10}).

In the first branch (3.) the optimizer tries to find at least one proper opportunity for each task. In case of one or more unallocated tasks, the algorithm stops, because no valid maintenance schedule can be created. The user can see from the output values, which tasks have not been allocated due to a lack of maintenance capacities.

When sufficient maintenance opportunities exist, the complete list of tasks to be performed is sorted in the next step (4.). Both, allocating the task with the highest priority first (i.e. the one with the smallest RUL) or allocating the task with the highest cost can be reasonable. However, our tests have shown that better results can be achieved when sorting the tasks by cost in descending order. Since the optimizer considers costs for waste of life, it is beneficial when the most expensive task (with potentially high costs for waste of life) can be allocated to a maintenance opportunity short before the predicted failure occurs. The wasted life variable is calculated for each task for all proper maintenance opportunities with Eq. (2). When new problems or optimizations with changed parameters should be solved, it is recommended to test both sorting methods in order to reach the best results. The sorting process represents the branching strategy.

$$Cost\ of\ wasted\ life = \frac{Lifetime - RUL\ at\ maintenance\ date}{Lifetime} \cdot Task\ Cost \tag{2}$$

In the next step, the first task in the list is selected and a proper opportunity is searched (5.). If there is no remaining match, the current iteration quits and the optimizer tries to find another maintenance schedule. If there is a match with several maintenance opportunities, the cheapest one is selected. This whole loop is repeated until each task is allocated to its cheapest maintenance opportunity (6.). When all tasks have been allocated, the total costs of the current plan are calculated (7.). A new best plan is found, if the total costs are below the costs of the previously found best plan. This procedure is repeated as long as the iteration limit *iMax* is not reached. The final result of the optimizer is the maintenance schedule with the lowest overall costs, which could be found.

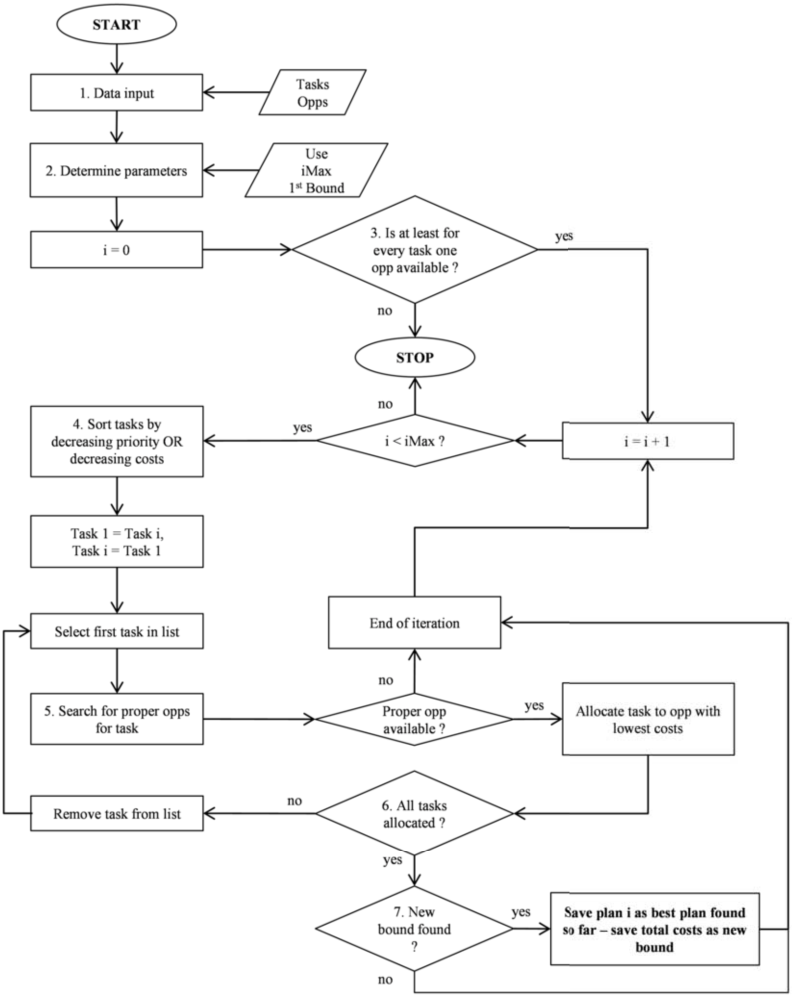

Figure 3: AIRMAP-Optimizer program flow

Optimizer characteristics

In general, the optimizer prefers late maintenance opportunities in order to minimize the waste of life. Nevertheless, earlier maintenance resulting in higher waste of life can lead to lower overall costs. This is the case, when fixed costs of an additional maintenance event including loss of production costs are higher than the waste of life cost. By modification of the input variables RUL, task duration and task costs the influence on maintenance packaging, scheduling and costs can be evaluated. Controlling these three variables it is possible to simulate alternative aircraft maintenance strategies with tasks resulting from different health managing technologies applied to an aircraft.

C. Integration of AIRMAP-Optimizer in AirTOBS-Model

The lifecycle cost-benefit analysis of the prognosis-based maintenance concept in AirTOBS is limited to a single aircraft. Therefore the following calculations in AIRMAP are limited on a single aircraft either, although the optimizer is able to handle a fleet of aircraft.

For a global analysis of the impact of a prognosis-based maintenance concept on aircraft operator's NPV it is necessary to integrate the AIRMAP model into AirTOBS and to establish appropriate data interfaces (Fig. 4).

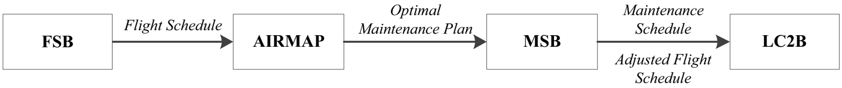

Figure 4: Model integration and interface definition

Based on the flight schedule prepared by the FSB a maintenance opportunities table for a two month long planning period is produced by AIRMAP. The optimizer allocates the maintenance tasks to the opportunities in the current planning period. Tasks with due-dates outside the current period are shifted to the next period. After completion of all planning periods in the aircraft lifecycle the resulting maintenance plan is transferred to the MSB. Then all events included in the maintenance plan are integrated into the aircraft lifecycle simulation. Finally, the resulting maintenance and flight schedule is delivered to the LC2B, where the airline's cash flows are calculated.

III. Analysis and Results

A simulation of a 150-seat short-range aircraft, followed by a lifecycle cost-benefit analysis will show the potential advantages of a prognosis-based maintenance concept. Furthermore it will provide information on economical, technical, and organizational requirements to be met for a future implementation of the concept.

A. Input data and assumptions

Since data availability for future aircraft is extremely limited, we selected an Airbus A320 type of aircraft for demonstrating the maintenance optimization approach together with the assessment framework. An operating lifecycle of 25 years is assumed.

The aircraft's maintenance program is based on today's scheduled maintenance programs as shown in Table 1. The aircraft in this study is equipped with a PHM system, which allows performing former preventive maintenance tasks on a prognosis basis. Unscheduled maintenance events and its consequences like flight delays or cancellations are neglected in this paper. A list of tasks to be allocated by the maintenance optimizer has been derived from the mentioned scheduled maintenance program. Only maintenance man-hours from Weekly, A-, and C-Checks have been extracted as AIRMAP-input. The selected block-checks have been split up into small work packages of 4 to 9 hours which can be handled during regular aircraft ground times. Costs have been equally distributed over the work packages.

Table 1: Scheduled maintenance data of A320-family aircraft[14]

Name	Downtime *[h]*	Intervals				Man-hours	Material cost *[USD]*
		Flight hours *[h]*	Flight cycles	Days	Months		
Weekly	-	-	-	7	-	10	700
A-Check	24	600	-	-	-	80	5,500
C-Check	138	-	-	-	18	2,000	28,500
IL-Check	336	-	-	-	72	14,300	380,000
D-Check	672	-	-	-	144	20,000	1,500,000

In this paper we assume that heavy maintenance checks (former IL- and D-Check) will still be necessary for future aircraft, because many detailed inspections and overhaul actions cannot be divided into smaller work packages. Although a reduction of heavy maintenance expenditure through the use of new materials (e.g. CFRP) can be expected, it is assumed as unchanged in the following analysis.

The aircraft operation follows a typical aircraft rotation on short-range with a network carrier resulting in a daily utilization of 7.5 flight hours and a total daily cycle time (i.e. sum of flight hours, taxi-times, and turn-around-times) of 13.8 hours. The remaining 10.2 hours per day function as a maintenance opportunity, when the aircraft is located at a maintenance station.

B. Analysis

A flight schedule with daily utilizations, maintenance opportunities (including frequencies, ground times, and available manpower) and event cost have been defined for four different scenarios as shown in Table 2.

Table 2: Aircraft operation and maintenance opportunities

		Baseline	Low	Medium	High
Daily utilization		7.5 FH / 13.8 CH	7.5 FH / 13.8 CH	7.5 FH / 13.8 CH	7.5 FH / 13.8 CH
Maintenance opportunities	*Frequency*	Block check program	Every 7 days (6 in 2 month)	Every 5 days (9 in 2 month)	Every 3 days (20 in 2 month)
	Ground time		10.2 h	10.2h	10.2 h
	Manpower		20	20	20
Fixed maintenance event cost		-	2,000 USD	2,000 USD	2,000 USD

The 'Baseline' scenario acts as the reference of today's maintenance programs, while the three remaining vary in their frequency of maintenance opportunities. The aircraft rotation in the "Low" scenario provides a maintenance opportunity every seven days, in case of the "Medium" and "High" scenario every 5 and 3 days respectively. More infrequent opportunities preclude the finding of feasible maintenance plans while more frequent opportunities allow better solutions but more stringent constraints for the aircraft rotation planning process. The length of the ground-time and the number of available mechanics ("*Manpower"*) is assumed to be equal for all scenarios. In addition to the variable maintenance event costs, an additional fixed cost rate ("*Fixed maintenance event cost*") of USD 2,000 will be charged for the use of a maintenance opportunity.

C. Results

The analysis results reflect the characteristics of the AIRMAP optimizer described in section B. It can be seen from Fig. 5 that the optimizer uses more maintenance opportunities, when more opportunities are available. An extension of opportunities functions as a relaxation of constraints in the optimization problem and consequently enables better solution.

Figure 6 shows the delta NPV curves of three scenarios with "Low-frequency opportunities" as reference. The provision of more maintenance opportunities lead to an increased NPV of 2.1 million USD (0.9%) in case of scenario "Medium" and 2.8 million USD (1.2%) in case of scenario "High" compared to the scenario "Low".

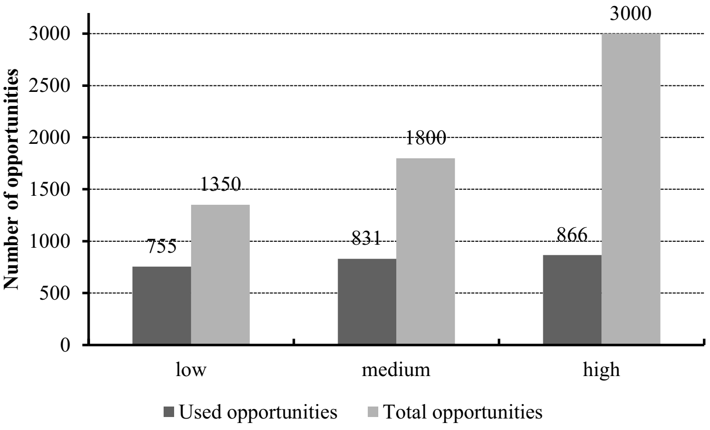

Figure 5: Opportunities used for maintenance

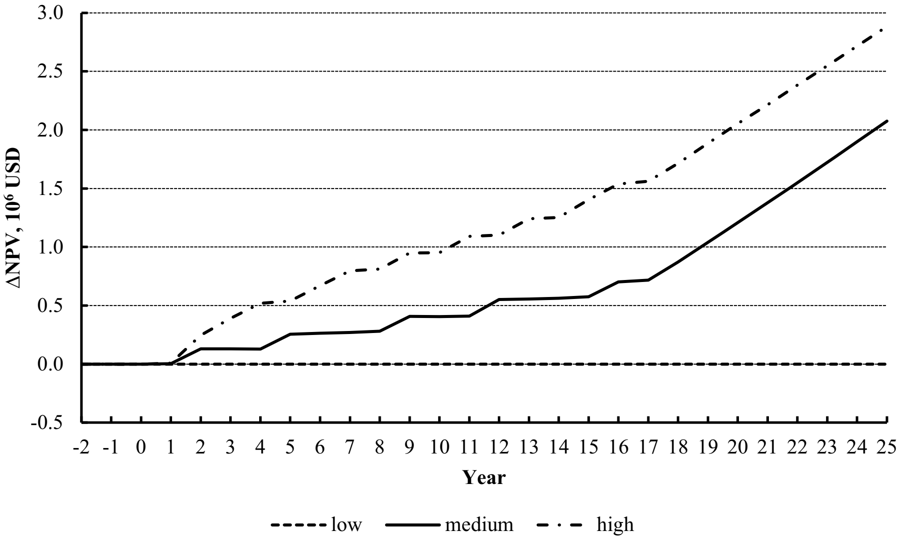

Figure 6: Delta NPV curves for maintenance opportunity scenarios

When comparing the “Medium” scenario with the “Baseline” (Fig. 8), it becomes obvious that the NPV of “Medium” at the end of operating life is significantly lower than the NPV of the reference. All three AIRMAP scenarios produce an economic result that is between 7.7 and 10.6 million USD lower than the reference. This fact is surprising because the reduced maintenance downtimes resulting from the breakup of A- and C-Checks should lead to increasing aircraft utilizations and ticket revenues. The reason is located in the maintenance packaging and scheduling which seems to deliver results that are inefficient compared to a traditional block check concept. Repeated selections of earlier than necessary maintenance opportunities lead to large increases in maintenance cost, when the waste of life results in additional maintenance events over the lifecycle.

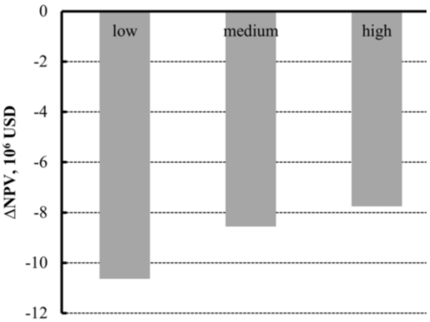

Figure 7: NPV of the three scenarios compared to reference

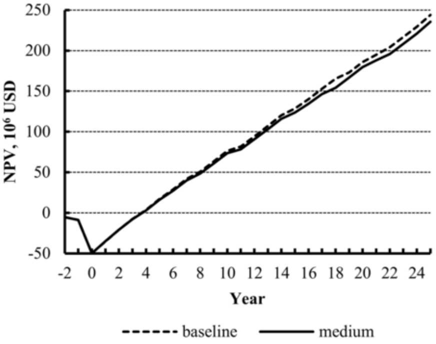

Figure 8: Comparison of 'Baseline' and 'Medium' scenario

We expect that significant improvements in efficiency are possible with further studies of the optimal parameter settings in AIRMAP. It is the goal of this study to focus on the effects of a prognosis-based maintenance concept without mixing it up with the benefits of a PHM technology. When the extension of useful life of components and the omission of many inspections due to the implementation of PHM are included in an analysis, the prognosis-based maintenance concept might be very beneficial. Detailed data of resulting useful lifetimes and of maintenance tasks – while considering the reliability of the PHM systems – are required to provide a profound assessment in future studies.

IV. Conclusion

In this paper we have presented an approach to model a prognosis-based maintenance concept for future aircraft and to analyze its economic impact on a lifecycle level. The study indicates that the method chosen in AIRMAP is feasible to conduct the maintenance scheduling and packaging process for future aircraft. Improvements are necessary to achieve a sufficient efficiency in the lifecycle. Therefore more detailed analysis of optimization results and adjustments of optimizer parameters are planned.

The integration of AIRMAP and AirTOBS allows the economic assessment of maintenance concepts on a lifecycle level. It can deliver valuable requirements for the future development of condition- and prognosis-based maintenance concepts and its consequences for operators and MROs. The consideration of extended and varying lifetimes through the use of PHM would be reasonable for comprehensive comparisons to current maintenance concepts.

An extension of AirTOBS on a fleet-level basis would allow using the complete functional range of AIRMAP – scheduling maintenance tasks and planning capacities for a fleet of different aircraft types on an airline's network. In further studies we intend to analyze the effects of varying daily aircraft utilizations in order to investigate the applicability of the approach for different airline business models (e.g. network or low-cost carrier).

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NFF- Who is to be Blamed?

Unravelling the Mysteries of NFF

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This paper outlines the rationale, contents, and application of the ARINC 672 Guideline. It follows an integrated approach towards understanding the issues at stake when considering the No Fault Found (NFF) phenomenon, to purposefully work towards an NFF-reduction solution. And for this purpose the outline is structured along the following topics, i.e.: Introducing the situational context, Presenting some underlying principles, Describing an integrated process, Concluding with an appraisal. The objective is to highlight the fundamental "back to the basics" approach followed for ARINC 672 thus qualifying it as a suitable baseline treatment of the NFF-topic and document on which any future refinements can be based. It also outlines the application of the guideline which is sufficiently general for an appropriate tailoring and customisation in the aviation and for that matter also many other industry branches.

Nomenclature

A/C = Aircraft
AEEC = Airlines Electronic Engineering Committee
AMC = Avionics Maintenance Conference
ARINC = Aeronautical Radio Incorporated
BIT = Built-In Testing
BITE = Built-In Test Equipment
EASA = European Aviation Safety Agency
FCM = Future Concepts for Maintenance
IEC = International Electrotechnical Commission
LRU = Line Replaceable Unit
NFF = No Fault Found
OEM = Original Equipment Manufacturer
OMS = On-Board Maintenance System
RTS = Return to Service
SRU = Shop Replaceable Unit

I. Introduction

The ARINC 672 "Guidelines for the Reduction of No Fault Found"[2] is the result of a combined effort of several persons that were directly or indirectly involved with the miseries of NFF in the aviation industry. It is an age-old phenomenon that strangely enough has not yet been entirely successfully solved. In 2005 a dedicated workgroup was established within the ambit of the Future Concepts for Maintenance (FCM) Task Group 111, which is a joint activity of the AEEC and AMC. The guideline was ultimately published in June 2008.

In an interview with Aviation Week[3] Axel Müller, chairman of the ARINC 672 Workgroup, said the following regarding intend and purpose of the workgroup:

> "Our purpose was to help the industry understand the nature of NFF and to develop conclusions that each individual organization could use to help it address and solve the problem," he said. "It doesn't provide a set of hard and fast

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[2] Refer to Reference [1]

[3] Refer to Reference [3]

> directions, but it does help see the big picture, and to develop an adequate approach to NFF. The paper addressed technical, documentation and training issues, as well as [the impact of] insufficient information to isolate NFF on the aircraft, that often results in perfectly good units being removed. Whenever healthy units are removed, you are creating an NFF."
>
> As Müller pointed out, the ARINC 672 Working Group looked at NFF by focusing on the complete lifecycle of avionics equipment, from the initial design through usage and maintenance - at both line and shop level. "Other papers published on NFF focused on maintenance issues only and have never closed the loop back to the design of the equipment," he remarked.

This paper intends to give an outline of its salient contents and a first round of introduction towards a possible customised application of the proposed NFF-reduction process. Several initiatives have been undertaken in the past and most certainly will be initiated in future. An outstanding feature of the ARINC 672 guideline is the approach to cover a 2-dimnsional space of, firstly, different aviation levels of abstractions, and, secondly, the entire aircraft life cycle. It therefore covers activities and role-players/ stake-holder from initial concept through development, production, integration and the all the way up to operation and support. And, simultaneously, also covers the hierarchical spectrum of abstraction levels, i.e. fleet, aircraft, system and equipment. Another unique feature is the closing of the loop from operation and support back to design and production.

II. Some Underlying Principles

Any NFF-reduction effort requires an understanding of the essential underlying principles that determine the NFF-phenomenon. This section presents some of those underlying principles that are required to understand the rationale of the ARINC 672 approach that was followed.

A. Some NFF Definitions

For the present purpose of mutual understanding some of the NFF relevant terms are defined as follows:

A **Failure** is the termination of the ability of an item to perform a required function. [Source: International Electrotechnical Commission (IEC)].

A **Malfunction** is the termination of the ability of some software to perform a required function. It is sometimes used to distinguish between software and hardware related inability to function. [Adapted from IEC definition].

A **Fault** is the state of an item characterized by the inability to perform, excluding inabilities due to preventive maintenance, other planned actions, or lack of external resources. [Source: International Electrotechnical Commission (IEC)].

A **No Fault Found** (NFF) is the result of testing when a unit removed as faulty at one level of maintenance is found to be fault free when tested at the next lower level of maintenance. [Source ARINC 672].

This presentation often refers to stake-holders and/or role-players, which, for the present purpose are distinguished as follows:

> A **Stake-holder** is understood to influence decisions, have some or other benefit to gain, and/or cost to pay with regard to NFF issues.
>
> A **Role-player** is understood to be an actor, who is actively involved in day to day operations and NFF caused problems

B. NFF in a System Life Cycle Context

Figure 1 depicts a schematic illustration of a generic “Hierarchical System Life Cycle”, with particular reference to the aviation environment. It shows a 2-dimensional space of Hierarchy versus Time[4]. The time dimension shows two major phases, i.e. Design/ Production and Operation/ Support. And the hierarchy dimension shows 4 generic levels of abstraction, i.e. Fleet, Aircraft, System, and Component. This presentation aims at facilitating an understanding of the complexity within which the NFF phenomenon occurs. Any serious NFF-treatment must start at the beginning/ origin of the subject under consideration, e.g. air vehicle, and cover its entire life time.

Firstly, the major **Design/ Production** phase serves the purpose of **Air Vehicle Realisation**, which comprises two sub-phases, i.e. **Define/ Develop** and **Integrate/ Validate**. In Figure 1 the so-called V-Model is superimposed on the hierarchy dimension, to emphasise the fact that an aircraft/ air vehicle is a complex entity that comprises different levels of abstraction. This is a convenient way to get a grip on air vehicle complexity.

Secondly, the major **Operation/ Support** phase spans the longest time of the air vehicle life cycle, and comprises two sub-phases that run concurrently, i.e. **Deploy** and **Utilise** the air vehicle. This major phase serves

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[4] This is an extract from Reference [2]

a dual purpose, i.e. **Air Vehicle Maintenance** and **Maintenance Support,** and which thus enables air vehicle deployment and utilisation.

To comprehend the complexity of NFF with its possible sources/ causes and associated possible solutions, the entire air vehicle life cycle must be considered in the context of its many facets, as well as role-players and stake-holders. This is a typical systems viewpoint, i.e. “from cradle to grave”.

During Design/ Production the ground work is laid for the future air vehicle operation, performance, and for that matter also its maintenance and support. The V-model depicts the iterative, top-down and subsequent bottom-up systems engineering process.

During the Design/ Develop sub-phase this process defines the fleet, aircraft, system, and component requirements at each successive level of abstraction. And, similarly, it develops the corresponding solution(s) for each of these levels of abstraction.

During the Integrate/ Validate sub-phase the different solutions developed for each of the different levels of abstraction are aggregated/ integrated into successively larger complexes until finally the entire air vehicle is ready for its subsequent operation and support.

It is therefore readily understood that all the inherent design characteristics of the air vehicle have their origin in the initial Design/ Production major phase. And this includes, amongst others, such decisive/ significant characteristics as failure/ fault behaviour, built-in testing (BIT), diagnosis (BITE), trouble shooting, etc., just to mention a few of the essential maintenance performance drivers.

During the later Operation/ Support major phase the air vehicle maintenance and corresponding maintenance support are the central activities that ensure air vehicle availability to the Airline/ Operator. Figure 1 shows these two activity groupings that are identified for purposes of a structured understanding.

Air Vehicle Maintenance occurs over all the hierarchical levels. Similarly, Maintenance Support also occurs over all these hierarchical levels. It is very important to comprehend this “big picture”, because air vehicle performance and thus operational availability is the result of a successful integration and orchestration of all these individual efforts. Non-performance is usually a combination of one or several causes at various abstraction levels and not only at Component (LRU) level as is commonly implied. Also, non-performance may have its root cause at one or several of the phases/ stages of air vehicle design/ production and/or operation/ support.

Air Vehicle Maintenance involves the day-to-day maintenance effort that aims to satisfy Airline/ Operator requirements for operational availability. Maintenance Support on the other hand is mainly provided from the Airframer and Supplier environment, to assist the air vehicle maintenance where, when and how required. Figure 1 also shows examples of the different role-players/ stake-holders that are involved with both these objectives of air vehicle maintenance, as well as maintenance support. The implication of this interaction complexity with regard to understanding and reducing NFFs becomes apparent. This interaction complexity is further discussed in the following Section II.C.

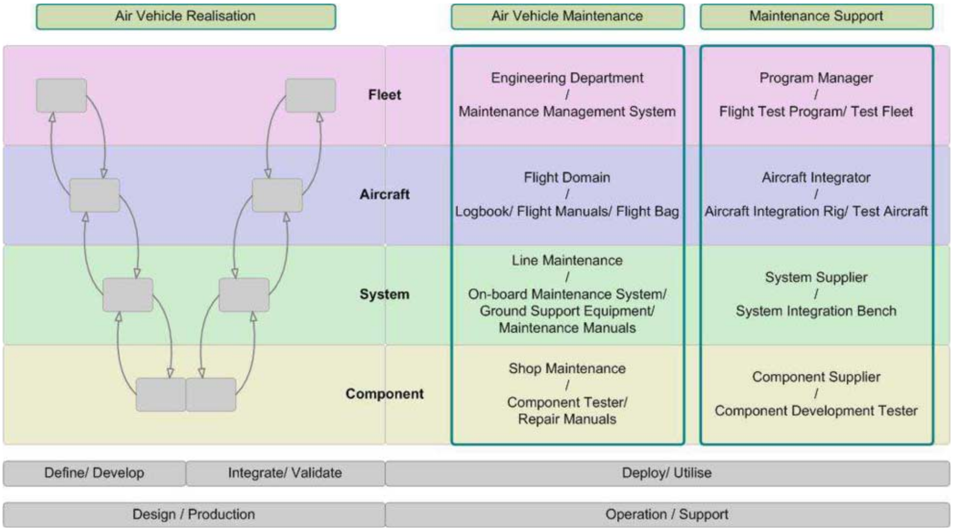

Figure 1 Schematic Presentation of a Generic “Hierarchical System Life Cycle”, e.g. Aviation

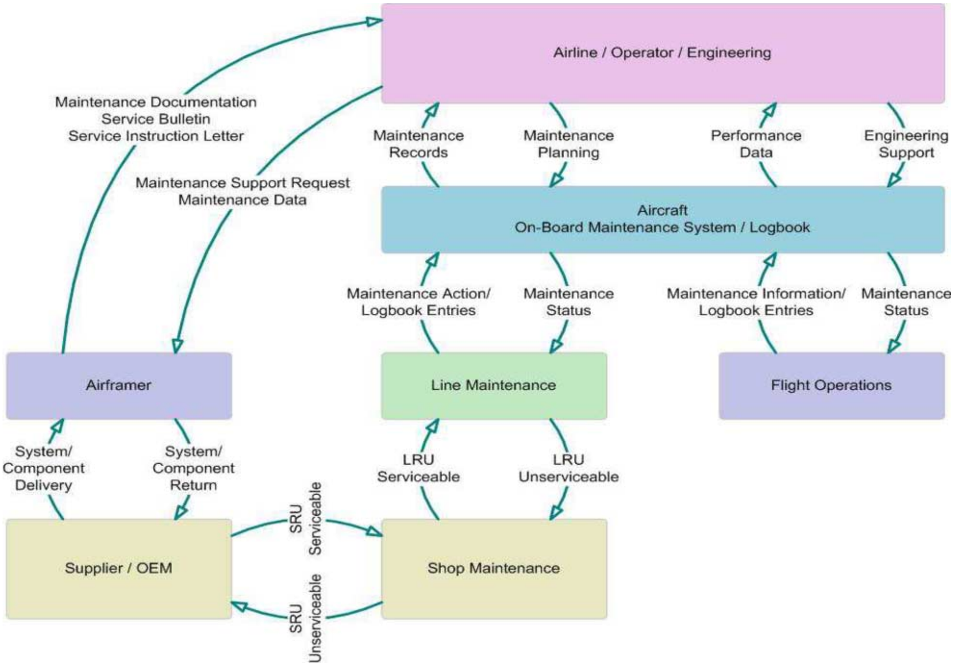

Figure 2 Schematic Presentation of Role-players/ Stake-holders and their Mutual Interaction During the Operation/ Support Phase of the Life Cycle

C. NFF in an Operational Context

Figure 2 is a schematic presentation of the mutual interactions of the different role-players/ stake-holders during the Operation/ Support phase (see Figure 1) of the air vehicle. It is not meant to be in any way comprehensive and/or all-inclusive. However, it aims to depict the complexity of the interactions that exist and thus the inherent potential for possible non-performance problems. In addition to the hierarchical view depicted in Figure 1, the interactions between the various role-players/ stake-holders at the different abstraction levels are considered here.

The **Aircraft** is the subject of consideration, which is, amongst others, usually equipped with some form of **On-Board Maintenance System (OMS)**, **Logbook** and technical documentation, etc.

The **Airline/ Operator** receives ***Maintenance Records*** from the aircraft via the **OMS** and/or **Logbook**. In return the **Airline/ Operator Engineering** performs the ***Maintenance Planning*** and provides this in some suitable format to the **OMS** and/or **Logbook** on board the aircraft. **Engineering** receives ***Performance Data*** from the aircraft and provides ***Engineering Support*** when and if required.

Flight Operations receives, amongst others, ***Maintenance Status*** information from the **Aircraft** via the **OMS/ Logbook**, and provides ***Maintenance Information/ Logbook Entries*** via the **Logbook** to the **Aircraft** and thus also to **Line Maintenance**.

Line Maintenance receives ***Maintenance Status*** information from the **Aircraft** via the **Logbook** and performs corresponding ***Maintenance Actions*** on the **Aircraft** and makes corresponding ***Logbook Entries***, to document the Return to Service (RTS) status.

Shop Maintenance receives amongst others, ***Unserviceable LRUs*** from **Line Maintenance** for testing, calibration, repair, upgrade, update, etc., and in exchange it provides ***Serviceable LRUs*** for replacement.

Shop Maintenance delivers ***Unserviceable SRUs*** to the **Supplier/ OEM** of that equipment for testing, calibration, repair, upgrade, update, etc., and in exchange it receives ***Serviceable SRUs*** from the **Supplier/ OEM**.

The **Airframer**, in addition to initial design/ production and delivery of the aircraft to the **Airline/ Operator**, performs an important design authority, as well as maintenance support role. It provides ***Maintenance***

Documentation, Service Bulletins (SB), Service Instruction Letters (SIL), etc., to the **Airline/ Operator**. The **Airframer** may receive a ***Maintenance Support Request*** from the **Airline/ Operator** and may also request/ receive ***Maintenance Data*** from the **Airline/ Operator**.

The **Supplier/ OEM**, delivers ***Systems/ Components*** to the **Airframer** for initial aircraft production, and may also sometimes receive unserviceable/ unsuitable ***Systems/ Components*** back from the **Airframer**. In a similar way the **Supplier/ OEM** supports the **Shop Maintenance** through replacing ***Unserviceable SRUs*** with ***Serviceable SRUs***. ***Unserviceable SRUs*** may undergo testing, calibration, repair, upgrade, update, etc., and may, in certain cases, even be disposed if repair is not warranted.

D. Some Considerations Regarding the ARINC 672 Approach

ARINC 672 explicitly states that it does not intend to provide a “quick fix recipe” or “5 Easy Steps of How to…” approach. It is rather intended to provide a guideline that enables tailoring of the basic NFF-reduction process so as to customise it for a specific operations environment. An important key in applying it is therefore to understand the particular approach that is followed. Although an NFF-problem is usually observed at the shop maintenance level it is by no means an isolated shop issue. It rather relies on a well-integrated and well-orchestrated approach that includes role-players and stake-holders at the various abstraction levels and over the entire life cycle. This principle was outline in the previous two sections (see Sections II.B and II.C above).

From field experience and observations it appears that there are several ways in which to categorise and/or group the NFF-phenomenon. In general the following major groupings can be observed, i.e.

- Aircraft Related
  - System/ Component/ Equipment failures/ faults (malfunctions) leading to undefined/ unwanted (loss, erroneous, uncommanded, etc.) function behaviour
  - Software content and complexity has been, and still is, increasing tremendously, and thus causing similar malfunctions leading to undefined (loss, erroneous, uncommanded, etc.) function behaviour
  - Cabling/ Wiring/ Connector failures/ faults (malfunctions) leading to intermittent function behaviour
- Skill Related
  - Training
  - Communication
- Support Related
  - On-Board Maintenance System (OMS)
  - BIT and BITE for system/ components
  - Test equipment
  - Documentation

When developing the ARINC 672 Guideline a decision had to be taken on the viewpoint from which the process would be considered. Several viewpoints are possible each one leading to a different/ particular approach.

A further reduction in complexity was accomplished through selecting a two dimensional matrix of Domains versus Categories. Thus a framework is created that further narrows down complexity to something more manageable. In particular for the ARINC 672 Guideline the following selection was made:

- Domains
  - Design/ Production
  - Flight Operations
  - Line Maintenance Operations
  - Shop Maintenance Operations
- Categories
  - Documentation
  - Communication
  - Training
  - Testing
  - Systems and Components

III. NFF-Process Outline

This Section presents an outline of the ARINC 672 NFF-Process[5]. It is a direct, verbatim copy of certain parts from this ARINC Guideline. This information will be used as a basis for a short description regarding an understanding and subsequent application of the proposed ARINC NFF-reduction process. Although it is not intended to present a detailed NFF-Process description here, it should be sufficient to understand an application of the guideline.

A. Concise Description of the ARINC NFF-Reduction Process

Following is a copy of Section 2.0 and Section 3.0 from the ARINC 672 Guideline document. Note that ARINC 672 Figure- and Table-number are referenced in the Figure- and Table-captions below, for ease of relating to the ARINC 672 document. Therefore, the Figure- and/ or Table-numbers used in the ARINC 672 Guideline will differ from those followed in this presentation. It should, however, be possible to easily relate to the appropriate Figure- and/or Table-reference.

OVERVIEW

This section provides two tables to support NFF identification and potential solutions:

- ARINC 672, Table 2-1 presents possible NFF-sources
- ARINC 672, Table 2-2 presents the recommended NFF-reduction actions

Overview of NFF Sources

Refer to Table 1 below for a schematic presentation of the ARINC 672 table arrangement.

ARINC 672, Table 2-1 depicts a cross listing of domains and categories involved in the resolution of an NFF-issue. The table should be interpreted as a check list for reviewing items within the

- Domain named in the columns, i.e. Design/ Production, Flight Operations, Line Operations, Shop Operations, and the
- Category named in the rows, i.e. Documentation, Communication, Training, Testing, and System/ Components.

Each domain can involve several different role-players. The list of role-players is not exhaustive and can be appended for a particular situation, e.g. field engineers, fleet engineering, reliability engineering, etc.

Each bullet represents possible source(s)/ causes(s) that a particular role-player may experience within a particular category and domain. Detailed descriptions of the table entries are presented in Appendix A of the ARINC 672 document. The table does not represent a solution. Recommended actions are summarized in ARINC 672, Table 2-2.

ARINC 672, Table 2-1: Summary of NFF-Sources/Causes for Domain versus Category Matrix

Refer to ARINC 672, Appendix A for a more detailed description of the NFF-Sources/ Causes summarised in the schematic table below.

Overview of Recommended Action

Refer to Table 1 below for a schematic presentation of the ARINC 672 table arrangement.

ARINC 672, Table 2-2 depicts the cross listing of recommended actions within a given domain in the columns and a particular category in the rows for resolving the NFF-instance.

This table contains recommended solutions to the issues identified in ARINC 672, Table 2-1. It should be interpreted as a proposed list for recommended action items within a particular category.

ARINC 672, Appendix B describes the contents of ARINC 672, Table 2-2 in more detail.

ARINC 672, Table 2-2: Summary of Recommended Action for Domain versus Category Matrix

Refer to ARINC 672, Appendix B for a more detailed description of the recommended actions summarised in the schematic Table 1 (ARINC 672, Table 2-2) below.

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[5] See Reference [1], for a detailed treatment

Table 1 A Schematic Presentation of the 2-dimensional Domain vs. Category View (Source ARINC 672, Table 2-1 and Table 2-2)

		Domain			
		Design/Production	Flight Operations	Line Operations	Shop Operations
Category	Documentation	Table 2-1: NFF Sources/ Causes	Table 2-1: NFF Sources/ Causes	Table 2-1: NFF Sources/ Causes	Table 2-1: NFF Sources/ Causes
		Table 2-2: Recommended Action	Table 2-2: Recommended Action	Table 2-2: Recommended Action	Table 2-2: Recommended Action
	Communication	Table 2-1: NFF Sources/ Causes			
		Table 2-2: Recommended Action			
	Training	Table 2-1: NFF Sources/ Causes			
		Table 2-2: Recommended Action			
	Testing	Table 2-1: NFF Sources/ Causes			
		Table 2-2: Recommended Action			
	System/ Components	Table 2-1: NFF Sources/ Causes			
		Table 2-2: Recommended Action			

NFF REDUCTION PROCESS

This section describes the shop perspective since this domain determines when a maintenance event will be classified as NFF.

This section only defines the functions and objects that are expected to be relevant to an NFF-reduction program. Specific contents will be tailored for a specific organization/ instance/ application. The action defined does not intend to define a comprehensive process but only indicates the relevant functions and objects.

Figure 3 below (ARINC 672, Figure 3-1) depicts the underlying basic NFF-reduction process in the context of the aviation environment.

Establish Potential NFF Candidate

Maintenance Event Data

This comprises the data related to a maintenance event, e.g.

- Event data
  - Pilot report
  - Logbook entry
  - Post Flight Report for A/C equipped with an OMS
  - A/C configuration and flight phase at time of occurrence
  - Event/context snap-shot information from flight deck
  - etc.
- Maintenance data
  - Removed LRU
  - Reason for removal
  - etc.

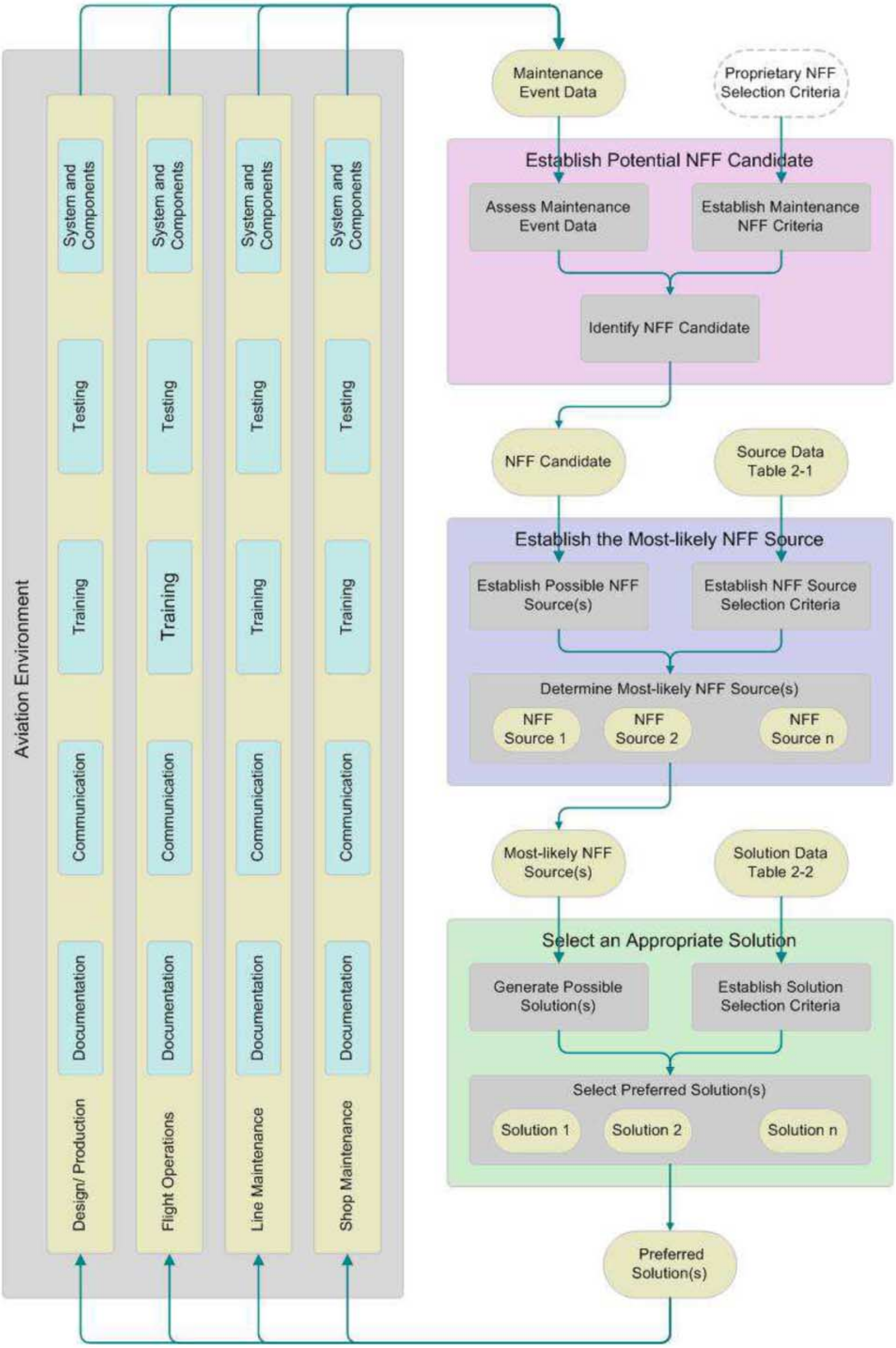

Figure 3 Schematic Presentation of the NFF-Reduction Process (Source ARINC 672, Figure 3-1)

Establish Maintenance NFF Criteria

The process requires a set of selection criteria. Define a set of parameters that are to be used as selection criteria by the organization that implements the NFF-reduction program.

This list may include, but is not limited to, the following, e.g.

- LRU Part Number and Cage Code
- LRU serial number
- A/C tail number removed from
- Station where LRU was removed
- Repetitive low time removal
- If LRU removal solved problem on aircraft
- Economical criteria/ pain factor/ financial impact
- Operational impact (service interruption)
- Unscheduled removal rate
- Period over which occurrences have been observed
- etc.

Assess Maintenance Event Data

Analyze the maintenance event data received from Line Operations and possible other domains to assess the reason for removal.

- Analyze collected failure data
- Assess failure history
- Determine whether there are repetitions with respect to Serial Number, A/C Number, etc.
- Determine the persons involved
- Analyze context/ situational information
- Clarify maintenance data received where necessary
- etc.

Identify NFF Candidate

Determine from the removed LRU data that is collected and assessed, whether and how this fits the criteria of an NFF-candidate as defined for a particular organization.

- Identify repetitive units
- Assess test results from on-board testing
- etc.

NFF-Candidate

An NFF-candidate is an item that fits the NFF selection criteria.

Establish the Most-likely NFF Source

Establish NFF Source/ Cause Selection Criteria

Using ARINC 672, Table 2-1, select the most appropriate category and domain combination as the most likely NFF-source/ cause.

Establish Possible NFF Source/ Cause for NFF Candidate

Using ARINC 672, Table 2-1 correlate the observed behaviour of the selected NFF-Candidate for comparison with the most likely category and domain combination.

Determine Most-likely NFF Source(s)

Compare the correlated behaviour with the selection criteria to determine the major NFF-driver, i.e., Category/ Domain combination.

Most-likely NFF Source(s)

Resulting from the correlation of the different possible Sources with the Source Criteria a most likely source(s)/ cause is determined.

Select an Appropriate Solution

Establish Solution Selection Criteria

Using ARINC 672, Table 2-2 select the possible recommended solutions that correspond to the particular category and domain NFF-source/ cause combination identified in the previous step.

Generate Possible Solution(s)

Using ARINC 672, Table 2-2 correlate the most likely NFF-Source identified in the previous step for comparison with the most likely category and domain combination.

Select Preferred Solution(s)

Compare the correlated solution with the selection criteria to determine the preferred solution(s) for the particular category/ domain combination,

Preferred Solution(s)

This is the result from the selection of the preferred solution and should be the action implemented for the particular category/ domain combination determined.

Implement Preferred Solution(s)

Figure 3 (ARINC 672, Figure 3-1) above depicts a "closure of the loop" where the preferred solution can involve:

- A single domain and any one or a combination of different categories listed in ARINC 672, Table 2-1 and Table 2-2.
- A combination of domains and any one or a combination of several categories listed in ARINC 672, Table 2-1 and Table 2-2.

The implemented solution(s) should now have an effect on the "Maintenance Event Data" observed/ recorded for the new situation. In this way the effectiveness/ success/ appropriateness of the implemented solution(s) can be evaluated.

B. Concise Description of Applying the ARINC NFF-Reduction Process

Figure 4 (ARINC 672, Figure 3-2) below is a schematic presentation that illustrates applying the ARINC 672 NFF-reduction process. It combines various elements from the guideline in such a way to present an overall time sequential view of the process.

The NFF-reduction process depicted in ARINC 672, Figure 3-1 is the outline of the approach to be followed. It comprises the 3 stages that are described in Section III.A above, i.e.

Stage 1: Establish a Potential NFF Candidate

ARINC 672 leaves the detail of this stage to each individual user/ application, since it is highly individualised for different Airlines/ Operators. It assumes that the NFF selection stage has already revealed a potential NFF-candidate for a particular NFF-problem that is being experienced.

Stage 2: Establish the Most-likely NFF Source

At this stage it is assumed that an NFF-problem has been observed and a possible candidate selected. Then ARINC 672, Table 2-1 is scanned in a left-to-right and top-down sequence to determine if the observed situation is covered by the entries in one or more cells of the matrix. Refer also to Figure 4 below which indicates this link between NFF-reduction process and the summary of possible sources/ causes listed in ARINC 672, Table 2-1. The process requires now to select the most likely source(s)/ cause(s).

ARINC 672, Table 2-1 is a summary and if more detail is required then ARINC 672, Appendix A is consulted. This table provides a more detailed description for each one of the causes in ARINC 672, Table 2-1, which helps to narrow down the selection process. See also the arrows in Figure 4 below that indicate this linking of tables.

Stage 3: Establish the Most-likely NFF Source

Once the source(s)/ cause(s) have been established the next stage assists to select an appropriate solution. Jumping from a particular cell in ARINC 672, Table 2-1 to the corresponding cell in ARINC 672, Table 2-2 provides some recommended action(s) that should help mitigating the identified source/ cause. Refer also to Figure 4 below which indicates this link between the NFF-reduction process and the summary of possible solutions listed in ARINC 672, Table 2-2. Again, this can lead to one or more possible solutions and the process requires a narrowing down to select the most appropriate/ preferred solution.

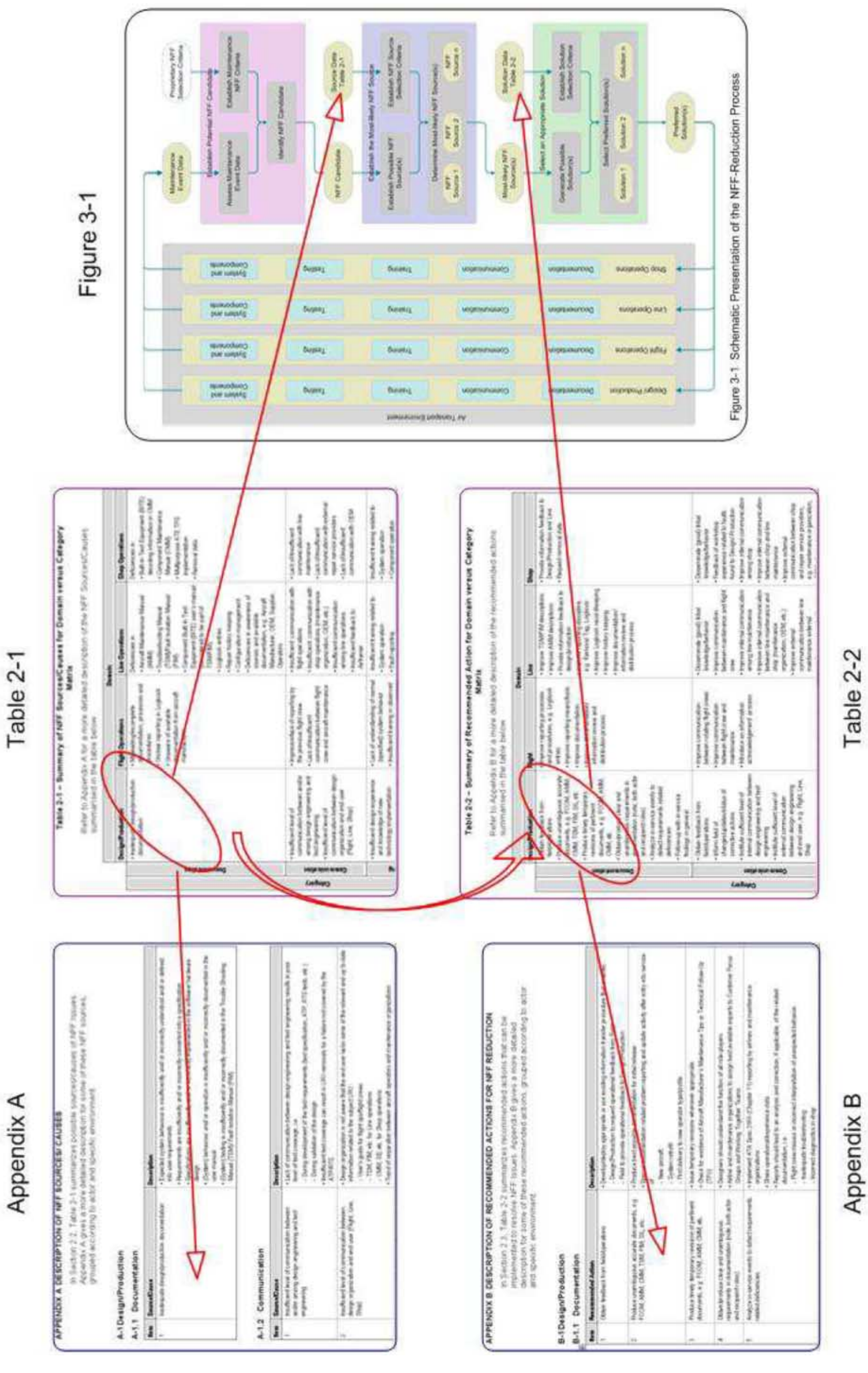

Figure 4 Schematic Presentation of Applying the NFF-Reduction Process (Source ARINC 672)

ARINC 672, Table 2-2 is a summary of solutions and if more detail is required then ARINC 672, Appendix B is consulted. This table provides a more detailed description of each one of the solutions in ARINC 672, Table 2-2, which helps to narrow down the selection process. See also the arrows in Figure 4 above that indicate this linking of tables.

IV. Appraisal

In the introduction an initial objective was set to present an outline of the salient features that the ARINC 672 guideline offers. And now in conclusion some closing observations are appropriate, i.e. ARINC 672 Guideline for the Reduction of No Fault Found offers:

1) A well-structured approach that helps with understanding the essential underlying principles, mechanisms, relationships, interactions, etc. of an NFF-situation.
2) A comprehensive process with optimal mix of detail/ complexity versus content/ understanding that enables gaining a thorough understanding of the NFF-Arena.
3) A fundamental NFF-reduction framework that is tailorable for application to a wide variety of specific/ customised implementations.
4) An integrated, orchestrated approach covering an aircraft in both the dimensions of life cycle - from design/ production through to operation/ support, as well as hierarchy - and from fleet level down to component level. And in addition closing the loop from operation/ support back to design/ production.
5) A sound base foundation with scope for possible improvements/ elaborations based on future experience gained from actual NFF-reduction implementations and any additional needs that may arise with this.

It is strongly recommended to put the ARINC 672 Guidelines to test and use them as a starting foundation for any future enhancements that will improve its value and applicability.

Acknowledgements

The Author would like to acknowledge the efforts of the ARINC 672 Workgroup. The content of this "Guideline for the Reduction of No Fault Found" is the result of many hours of dedicated commitment and active participation. It is only through a team effort of this magnitude that many years of hands-on experience can be mustered to extract and concentrate the essentials of such a far reaching topic for the aviation industry. And most certainly these ideas and concepts will further develop and mature as time goes by. May this fundamental ground work serve as a solid foundation on which future efforts can be added on to.

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An attempt to quantitatively underpin the rationality of maintenance support

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Professional maintenance support is generally seen as a sacrifice to achieve benefits. The societal expenses on maintenance resources are significant and they may be justified by some benefits obtained from an ability to timely respond to maintenance requests. This paper comments on an approach from Smith & Knezevic and Dinesh Kumar & Knezevic (Ref.1, Ref.2) to quantitatively relate benefits with avoiding delays in maintenance support. This paper argues for an improved approach.

Nomenclature

Av = Steady state operational availability
Av_x = Point availability at a time x
L = A Bernoulli variable that decides about the presence of a delay
$MTBF$ = Mean Time Between Failure
$MTTR$ = Mean Time To Repair
$MTTS$ = Mean Time To Support
Q = A variable that genuinely reflects common sense of benefits
S = A variable that genuinely reflects common sense of an ability to provide maintenance support in time
Y = A Bernoulli variable that decides about benefits

I. Introduction

A. Statement of problem

This paper presupposes that organizations invest in maintenance resources like tools, facilities, spares, people and so on in order to timely respond to requests for maintenance support. These investments are rational iff benefits exceed sacrifices at last. Generally, providing maintenance support is seen as a sacrifice. So, if it can be deferred till infinity without loss of benefits, expenses on maintenance resources are irrational. Hence delays should necessarily cause some losses to justify some requested service rate of a maintenance organization. Although societal expenses on maintenance support are significant, attempts to quantitatively underpin the rationality of its timely delivery are scarce. This paper reviews an attempt from Ref.1 and Ref.2 on its ability to justify rational decisions to provide maintenance support in time.

B. Literature

Although some may enjoy the process of restoring as such, the idea that providing maintenance support is generally seen as a sacrifice does not seem controversial. Many authors see maintenance support as a contributor to an equipment's life-cycle costs to preserve quality. Among others Ref.3, Ref.4, Ref.5, Ref.6 and Ref.7 refer to some cost-effectiveness criterion that balances an equipment's life-cycle costs with some long term benefits. In their view, an investment in maintenance support is rational iff it increases cost-effectiveness. Although some authors see performance measures on the logistics of a maintenance support organisation as leading indicators and (financial) benefits as a consequence, to my limited knowledge Ref.1 and Ref.2 are quite unique in their attempt to

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quantitatively relate benefits with providing maintenance support in time. This paper has therefore been dedicated to an equation from Ref.1 and Ref.2 that relates a mean time to support (MTTS) to a quality measure (Operational Availability, $\overline{Av}$) as depicted in Equation 1.

$$\overline{Av} = \frac{MTBF}{(MTTS + MTTR) + MTBF}$$

Equation 1

Ref.1 and Ref.2 pose that Equation 1's terms should converge to limiting values as time approaches infinity. At first glance, Equation 1 seems to claim that providing maintenance support in time is rational. It appears evident that delays in providing maintenance support increases MTTS which is one of the factors that determine a benefit quantified by $\overline{Av}$. This paper omits some remarks on the choice for MTTS and $\overline{Av}$ as quantifiers for supportability and benefit respectively since this has already been done in Ref.8. The problems addressed in this paper are entirely related to the composition of Equation 1 itself.

Although Ref.1 and Ref.2 present some simulated cases, I am unaware of publications that test Equation 1 with field data from industry. My naive attempt to test Equation 1 was problematic. This exploration may be helpful in a quest for an improved approach.

C. Research question

This paper questions whether Equation 1 implies the rationality of a timely response to maintenance requests, given an enumerable amount of evidence.

II. A necessary condition for rational maintenance support

Let Q be some variable that genuinely quantifies common sense of benefits and let S be some variable that genuinely quantifies common sense of an ability to provide maintenance support in time. Then, a desire to control S is rational iff it contributes to Q. So, a dependency of Q on S is a necessary condition for a rational decision to sacrifice for S to achieve Q. A causal dependency of Q on S may follow from a deductive Argument 1.

1	$S_t = s_t$	$\exists S_t$	Let a variable S take a value s at some time t
2	$(S_t = s_t) \rightarrow (Q_{t+x} = q_{t+x})$	$\forall t, \exists x$	Universal claim that S at any time t implies Q at t+x
3	$\therefore Q_{t+x} = q_{t+x}$	$\exists Q_{t+x}$	Follows from 1,2 by modus ponens

Argument 1

Argument 1 claims that q_{t+x} is uniquely determined by s_t. Of course an increased q_{t+x} may not outweigh the sacrifice to achieve s_t but any sacrifice to achieve s_t that does not imply any effect on some q_{t+x}, is irrational.

For a rational decision to timely provide maintenance support, a dependency of Q on S may also be uncertain. This may be illustrated by Argument 2.

4	$S_t = s_t$	$\exists S_t$	Let a variable S take a value s at some time t
5	$Pr(Q_{t+x} = q_{t+x} \mid S_t = s_t)$ $\neq Pr(Q_{t+x} = q_{t+x})$	$\forall t, \exists x$	Universal claim that S=s at any time t is relevant knowledge for the probability that Q takes a value q at t+x
6	$\therefore Q_{t+x} = q_{t+x}$	$\exists Q_{t+x}$	Does not follow from 4,5. However, knowledge of line 4 matters for one's belief in line 6. It may therefore suffice for a rational decision.

Argument 2

Although Argument 2 is not a valid deductive argument, it may still justifiably claim rationality of sacrificing for s_t. A decision maker's control over s_t influences the degree of certainty of obtaining q_{t+x}. This may be worth the sacrifice for steering S_t to a value s_t.

Having introduced the necessity of some dependency of Q on S as a necessary condition to make sacrifices for control over S rational, it may be interesting to analyze Equation 1's claim from this perspective. Let an equipment be either beneficial or not beneficial. So, the benefits may be represented by Equation 2's Bernoulli variable (Y).

$$Y = \begin{cases} 1 \ If\ \ insufficient\ benefits \\ 0 \ If\ sufficient\ benefits \end{cases}$$

Equation 2

An equipment's point availability (Av_x) may be defined as the probability of $Y_x=0$ as shown in Equation 3.

$$Av_x = 1 - E[Y_x] = 1 - \left(p_{Y_x}(0) \times 0 + p_{Y_x}(1) \times 1\right) = 1 - p_{Y_x}(1) = p_{Y_x}(0) = \Pr(Y_x = 0)$$

Equation 3

Equation 3 shows that an equipment's point availability (Av_x) and the expected value $E[Y_x]$ are related. For a time interval that approaches infinity, the mean of the point availabilities may converge to a steady state value.

$$\overline{Av} = \lim_{t\to\infty} \frac{1}{t} \sum_{x=1}^{t} Av_x = 1 - \lim_{t\to\infty} \frac{1}{t} \sum_{x=1}^{t} E[Y_x] = \bar{q}$$

Equation 4

Ref.1 and Ref.2 explain that $\overline{Av}$ in Equation 1 refers to a steady state value. Ref.9, Ref.10 and Ref.11 explain that a steady state availability may be estimated from observed frequencies of some Bernoulli variable (Y) that distinguishes a state of failure from a state of functioning as shown in Equation 4. Equation 1 however, seems to approach $\overline{Av}$ somewhat different. Equation 1 partitions the points of time in three classes: MTBF, MTTS and MTTR. Without being very explicit about whether MTBF, MTTS and MTTR should be understood as a property of a queuing system or as a property of an equipment, Ref.1 and Ref.2 seem to estimate some expected values by observed frequencies. Let L_x be a Bernoulli variable that decides whether a delay in maintenance support occurs at a time x or not.

$$L_x = \begin{cases} 1 \ If\ maintenance\ support\ is\ in\ delay\ at\ t \\ 0 \ If\ maintenance\ support\ is\ not\ in\ delay\ at\ t \end{cases}$$

Equation 5

Equation 5 shows that for all times x where $L_x=0$, no delays in providing maintenance support occurred. In this way, MTTS may be seen as the fraction of a time interval where a delay in providing maintenance support occurred as shown in Equation 6.

$$MTTS = \lim_{t\to\infty} \frac{1}{t} \sum_{L_t \mid L_t = 1} L_t = \bar{s}$$

Equation 6

Having a finite life, a researcher may only collect an enumerable amount of evidence for a tentative test of Equation 1. Therefore, Equation 4, Equation 6 and the other terms of Equation 1 cannot pertinently be assessed. Argument 3 shows that Equation 1 does not compel $s_{[1,u]}$ to imply $q_{[1,u]}$.

7	$S_{[1,u]}=s_{[1,u]}$	$\exists S_{[1,u]}$	Let variables $S_1,\ldots,S_u$ take value $s_1,\ldots,s_u$. u is a finite number that refers to the limited amount of evidence available to a researcher.
8	$\bar{q} = \dfrac{mtbf}{(\bar{s} + mttr) + mtbf}$		Equation 1's universal claim
9	$\therefore Q_{[1,u]}=q_{[1,u]}$	$\exists Q_{[1,u]}$	Does not follow from 7,8

Argument 3

Argument 3 reveals two concerns about Equation 1. Firstly, line 8 only relates S to Q if time approaches infinity. So, a finite sequence of $q_{[1,u]}$ is not bound by line 7,8. Of course this similarly applies when estimating probabilities by observed frequencies. So, Argument 2 may neither be testable due to this first concern. However, one may hope that frequencies converge rapidly enough for an approximation of a probability at some degree of certainty. A prayer for rapidly converging means may similarly rescue Argument 3 from my first concern. Secondly, Equation 1 entails four terms. Equation 7 may illustrate my second concern since all Equation 1's variables whose values and mutual dependencies are undetermined, have been replaced by a question mark. Clearly, knowledge of $\bar{s}$ in Equation 7 does not prohibit any $\bar{q}$. So, Equation 1 also allows for the special case where $\bar{q}$ is independent of $\bar{s}$. Therefore, Equation 1 does not suffice to claim that providing maintenance support in time is rational.

$$\bar{q} = \frac{"?"}{(\bar{s} + "?") + "?"}$$

Equation 7

Ref.1 and Ref.2 acknowledged my second concern by showing the influence of various probability functions whose expected values have been stated in Equation 1. Ref.1 and Ref.2 however do not explicitly mention that Equation 1 also allows for cases where $\overline{Av} = f(MTTS)$is an increasing function. Since all cases from Ref.1 and Ref.2 seem to present $\overline{Av} = f(MTTS)$as a strictly decreasing function, they are in my view just limiting cases of what Equation 1 asserts. As a result, Equation 1 lacks the precision to claim that providing maintenance support in time is rational.

III. An additional premise

Apparently, Ref.1 and Ref.2 implicitly add an additional premise to Argument 3 to claim the importance of S for Q within a finite time interval. This section attempts to articulate this additional premise explicitly. Loosely phrased, Ref.1 and Ref.2 follow the convention of a steady state availability in their cases. MTTS and MTTR clearly refer to a state of failure where an equipment is not beneficial (Y=1) and MTBF refers to a state of functioning where an equipment is beneficial (Y=0). In this way, Equation 1 may actually be seen as observed frequencies of some Y.

However, Ref.1 and Ref.2 enrich the semantics of MTBF, MTTS and MTTR by associating them with states of maintenance support in a queuing system. It seems that MTBF refers to a state of idling, MTTR to a state of busying and MTTS to a state of queuing. Hence, Ref.1 and Ref.2 claim an equivalence between logistics and benefits in their cases. Then, the presence of a delay at a time x (L_x=1) implies that ($E[Y_x]$=1). With this additional premise, Argument 4 can be constructed.

10	$E[Y_x]=[0,1]$	$\forall E[Y_x]$	Y_x Defined in Equation 2
11	$L_x=\{0,1\}$	$\forall L_x$	Defined in Equation 5
12	$L_x=l_x$	$\exists L_x$	Let some L take a value l at a time x
13	$L_x=1 \rightarrow E[Y_x]=1$	$\forall L_x \forall E[Y_x]$	Additional Premise
14	$\therefore E[Y_x]=1$	$\exists E[Y_x]$	Follows from 12,13 by modus ponens when l_x=1. Does not follow from 12,13 when l_x=0

Argument 4

Line 13 allows for any value of $E[Y_x]$ in [0,1], given L_x=0 but it asserts that $E[Y_x|L_x=1]=1$. Therefore, for any time x Equation 8's inequality holds.

$$L_x \leq E[Y_x]$$

Equation 8

Equation 8's result may be generalized to any time interval that eventually approaches infinity as shown in Equation 9.

$$\lim_{t\to\infty}\frac{1}{t}\sum_{L_t|L_t=1} L_t \leq \lim_{t\to\infty}\frac{1}{t}\sum_{x=1}^{t} E[Y_t]$$

Equation 9

So, due to line 13, Equation 9 relates the terms of Equation 4 and Equation 6. In this way, Equation 10's dependency of $\bar{q}$ on $\bar{s}$ has been asserted. The illustrative cases from Ref.1 and Ref.2

use this dependency to show the effects of delays in maintenance support. Due to Equation 8, this dependency even holds at finite time intervals.

$$\bar{q} \leq 1 - \bar{s}$$

Equation 10

Equation 10 makes that $\bar{q}$ converges to zero when delays approach infinity but $\bar{q}$ is not bound upon the elimination of delays $(\bar{s} = 0)$. Therefore, Equation 10 does not claim that eliminating delays is necessarily rational. So, one may argue for another additional premise that claims the irrationality of equipment that does not bring any benefits. The effort to conceive, design and construct of an equipment is conventionally posed as a sacrifice that would not take place without significant benefits. For brevity, $\bar{q} > 0$ has been omitted from Argument 4.

Although Equation 8 may function as a necessary condition to claim a dependency of $\bar{q}$ on $\bar{s}$, it should be confirmed by empirical evidence. Ref.1 and Ref.2 do not seem to utilize field data for their case studies, so I have naively asked some organizations for their maintenance support records and some indicators of benefits. Then it turned out that these organization's common sense of maintenance support easily refutes Equation 8. Many delays where found while the equipment was still performing satisfactorily.

To conclude, the additional premise of Argument 4's Line 13 confines the applicability of Equation 1 to an extent that many common sense maintenance support becomes inadmissible.

IV. Conclusion

This paper explained that a dependency of benefits perceived (Q) on providing maintenance support in time (S) is a necessary condition for the rationality of maintenance support. Attempts to quantitatively confirm this dependency are scarce. This paper reviewed a solution from Ref.1 and Ref.2.

In section II, it has been explained that this solution does not suffice to claim a dependency of Q on S since Equation 1 lacks precision. Section III presents an additional premise that Ref.1 and Ref.2 implicitly used for their case studies. Although, this additional premise restores a dependency of Q on S, it seems easily be refuted by empirical evidence. So, Equation 8 confines the applicability of Equation 1 to an extent that it seems to prohibit the vast majority of common sense maintenance support to be admissible. So, Equation 8 refutes the vast majority of empirical cases as genuine cases. This paper therefore argues for an improved approach to quantitatively underpin the rationality of timely providing maintenance support.

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Cost-Benefit Evaluation of Aircraft Maintenance Base-Check Downtime and Cost

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This paper analyzes the impact of varying downtime and cost of base maintenance checks for aircraft and gives an economic cost-benefit assessment. The reduction of downtimes for scheduled base maintenance checks is complex in terms of technical and logistical aspects. Therefore, the net benefit of such efforts is evaluated to optimize maintenance cost and aircraft availability from an aircraft operator point of view. For this purpose, the cost-benefit model AirTOBS (Aircraft Technology & Operations Benchmark System) is set up. The model is able to capture all economically relevant impacts on aircraft operations and maintenance over the life cycle. AirTOBS follows a discrete event simulation approach for aircraft operation and maintenance to capture time effects. An operator life cycle cost-benefit analysis accounts for costs and benefits. A use case of an Airbus A320 similar aircraft is conducted to show the potential of maintenance downtime reductions in terms of time and cost aspects. It is shown that the potential of a C-Check downtime reduction by 12.5% is worth a C-check cost increase of 10%, depending on various operational and maintenance aspects. Further, a set of ISO curves for constant net-present values of an airline is provided to show the cost increase potential of decreasing C-check downtimes.

Nomenclature

AirTOBS = Aircraft Technology & Operations Benchmark System
BC = business class
C = cost [USD]
C_0 = initial investment [USD]
C_i = cash flow in the *i*-th year [USD]
DB = database
DMC = direct maintenance cost [USD]
DOC = direct operating cost [USD]
DoT = US Department of Transportation
EC = economy class
EIA = US Energy Information Administration
EIS = entry into service
EU = European Union
FSB = flight schedule builder
IOC = indirect operating cost [USD]
KPI = key performance indicator
LC2B = life cycle cost-benefit model
LCC = life cycle cost [USD]
MH = man-hour
MIDT = Marketing Information Data Tapes
MRO = maintenance, repair and overhaul
MSB = maintenance schedule builder
MTOW = Maximum take-off weight [kg]
MTTR = mean time to repair [h]
NPV = net present value [USD]
r = discount rate
ROI = return on invest
t = time
WACC = weighted average cost of capital

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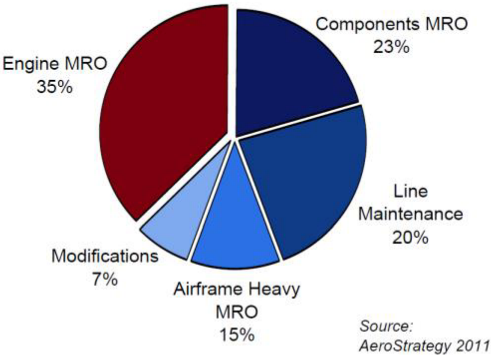
I. Introduction

THE market for passenger and freight air transportation has grown significantly over the last few decades, and it will continue in the future[1,2]. The operation of aircraft is a capital intensive business in a competitive market environment. Airlines need to constantly identify cost saving potentials and ways to improve efficiency, for example in support processes. This objective is strongly related to the evaluation of new technologies and processes to reduce costs for owning and operating aircraft throughout its life cycle.

A significant share of these life cycle costs (LCC) are expenditures for maintenance, repair, and overhaul (MRO) of the aircraft. MRO expenditures making up 13% to 20% of aircraft direct operating costs (DOC)[3]. MRO processes additional influence multiple elements of aircraft operation. One major maintenance element is the base or hangar maintenance, including airframe and parts of the component maintenance and modifications. Therefore, the base maintenance has a share of about 20% of direct maintenance cost (DMC) (see Figure 1)[3]. Additionally, the base maintenance checks cause aircraft downtimes of up to several weeks. Aircraft produce no revenues during this time.

Maintenance assessment can be separated into quality and cost-time aspects[4]. This paper focuses on the cost-time aspects *availability* and *costs*. Various methods for the estimation of aircraft DOC exist. Newer methods were developed by Roskam[6] (1990), Liebeck[7] (1995), Scholz[8] (1998), and Harris[22] (2005). These models are less suitable for comprehensive life cycle considerations, as they lack the prediction of the point in time of the occurring of the costs. The models do not consider the impact of maintenance downtime and revenues to account for the benefit of an aircraft, either. The methodology of AirTOBS is based on a life cycle cost benefit approach. The approach simulates lifetime flight- and maintenance schedules as well as revenues. The AirTOBS model is not aiming at forecasting absolute costs, revenues and utilization, but rather intends to reflect the general influence of certain factors and the resulting relative changes to economic key performance indicators (KPI), relative to a reference case.



Source: AeroStrategy 2011

Figure 1: Aircraft MRO cost overview

In this study AirTOBS is applied to assess the net-benefit of reduced downtimes of maintenance C-checks. An Airbus A320 similar aircraft operated by a network carrier is analyzed. It is assumed that a reduction of base maintenance downtime has no influence on the volume of work that has to be performed during the check. Therefore, maintenance check expenditures stay constant or increase due to higher organizational, logistical and technical complexity resulting from the base-check speed-up.[9]

II. Methodology

The methodology proposed in this paper uses a life cycle cost-benefit analysis based on a discrete-event simulation of aircraft operation and maintenance. All relevant impacts of varying maintenance downtimes and costs of future or legacy aircrafts are captured from airline- and MRO-perspective. An overview of the aircraft life cycle cost-benefit model AirTOBS is shown in Figure 2. The flight schedule builder (FSB) generates aircraft life cycle flight schedules based on specified route and operational data. The following input is required for the FSB:

- flight time
- turnaround time
- taxi-in- and taxi-out-times
- aircraft lifetime for which the schedule should be generated
- operation-days per week
- curfew hours per day.

The computed flight schedule contains daily flight cycles, flight hours, and block hours for one or multiple routes.

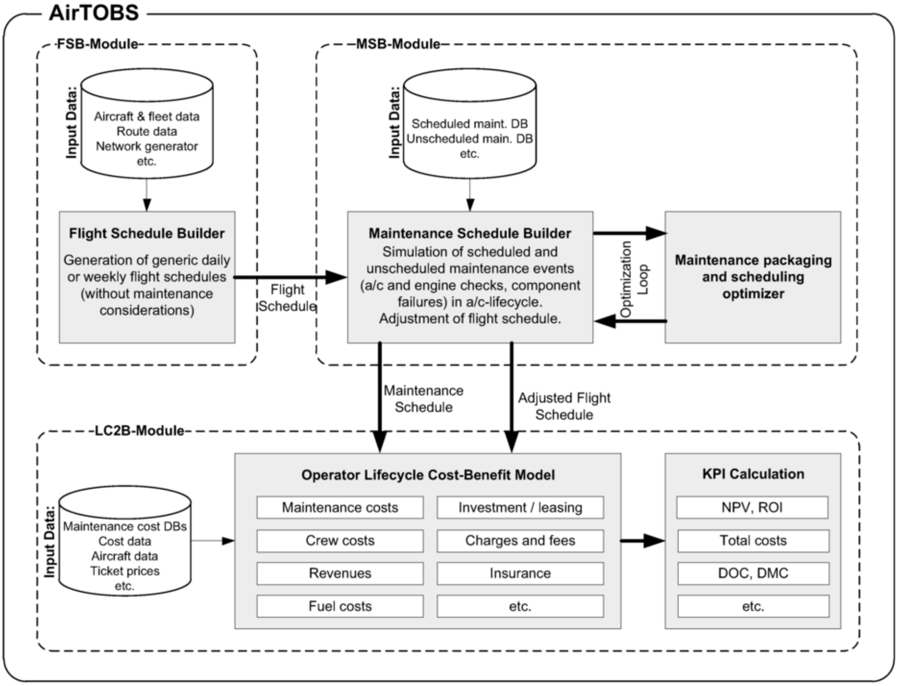


Figure 2: Overview of aircraft life cycle cost-benefit analysis

The flight schedules serve as the fundament for the Maintenance Schedule Builder (MSB), which simulates maintenance events over the aircraft life cycle. The MSB uses input data for line, base and engine checks as well as for components and heavy components. These checks and components are described basically by the induced downtime, interval (flight hours, flight cycles, and calendar time), man-hours, and material and fix cost. The MSB adjusts the flight schedule according to the time of occurrence and duration of maintenance downtimes. The method of the FSB and the MSB is depicted for a weekly based flight schedule in Figure 3. The maximum theoretical time for operation per week is 7 days times 24 hours, less curfew hours. The maximum theoretic utilization equals the maximum number of flights including turnaround times which can be fitted into this time period. Based on this schedule, the maintenance events are modeled as discrete events in time. According to the provided downtime of a maintenance event flights are canceled.

The generated schedule for line, base, engine, and component maintenance and the adjusted flight schedule are passed on to the operator life cycle cost-benefit model (LC2B), where costs and revenues are modeled and assigned to the discrete events. The DOC included in the LC2B are fuel cost, crew cost, navigation and airport charges, insurance cost, aircraft acquisition costs, and direct maintenance cost (DMC). The actual time of occurrence *(t)* of the cost and revenue elements *(C)* is captured to account for the time value of money. All values are escalated over the aircraft life cycle to account for inflation, before they can be summarized as net present value (NPV). The NPV is a common metric to quantify a project's net-contribution to capital[10] for a certain period of time, while accounting for the time value of money and the opportunity cost of capital. The NPV can be calculated as given in Eq. 1, where C_0 is the initial investment (i.e. aircraft price) and C_i is the cash-flow in the i-th year. The discount rate r represents the rate of return that could be achieved with a similar risky investment.

$$NPV = -C_0 + \sum_{t=1}^{T} \frac{C_t}{\left(1+r\right)^t} \tag{1}$$

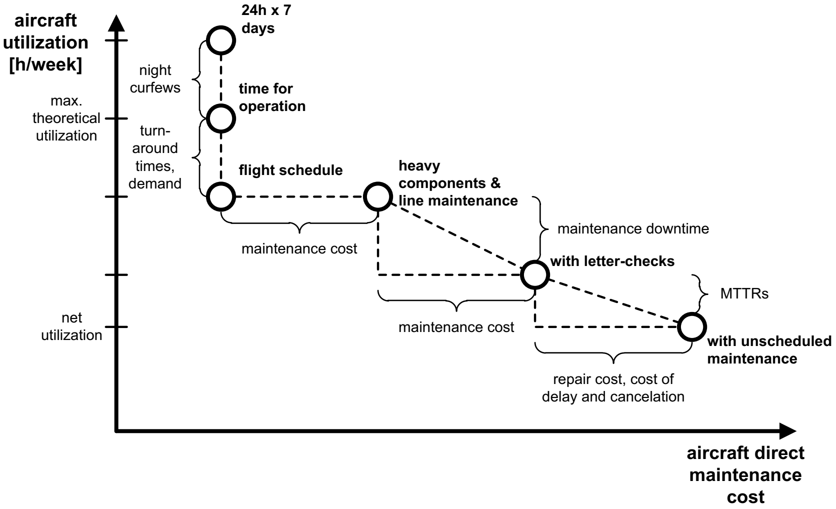


Figure 3: Aircraft utilization method as used in AirTOBS

A. Reference aircraft and input data

The analysis in this study is based on a 25-years life cycle of a 150-seat short range aircraft. Economic values not specifically mentioned refer to current public available values. For the input of the FSB, the utilization data of the Lufthansa A320-family fleet is extracted from Ascend[11]. A reference route with a flight time of 1.25 h and an average utilization of 1972 flight cycles per year was chosen. An analysis of the taxi times at Frankfurt, Munich and Hamburg (Germany) with data by Eurocontrol[12-15] provide average taxi-in times of 5.3 minutes and taxi-out times of 11.6 minutes. This results in a block time of 1.53 h.

Line, base, heavy component, and engine maintenance data is extracted from Aircraft Commerce[16]. An overview of the base maintenance checks applied in this study is presented in Table 1. A labor-rate of 70 USD/MH is adapted from an analysis of the worldwide MRO labor-rates[17]. Maturity effects are considered by provided maturity curves as published by Ali[18] (see Figure 4).

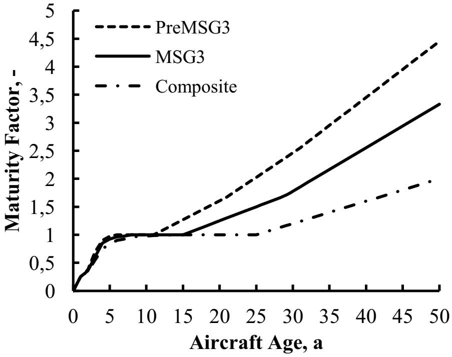


Figure 4: Maintenance aging adjustment of maintenance costs[18]

Table 1: Base maintenance data of A320-family aircraft[16]

Name	Downtime [h]	Intervals Flight Hours	Flight Cycles	Days	Months	Man-hours	Material Cost [USD]
A-Check	24	600	-	-	-	80	5,500
C-Check	138	-	-	-	18	2,000	38,000
IL-Check	336	-	-	-	72	14,300	380,000
D-Check	672	-	-	-	144	20,000	1,500,000

The price of the aircraft and engines is assumed to be paid in advance to the entry-into-service (EIS) of the aircraft. Based on Marx[19], a three year down payment period is used. During this period a total of 30% of the price is paid and 70% will be paid as a delivery payment. The price for this study is assumed to be the current aircraft and engines list price minus a discount of 30%, as proposed by Pfaender[20]. The implemented crew cost model is adapted from a study by Eurocontrol[21]. This method estimates the cockpit and cabin crew size as well as the labor-rates depending on the type of aircraft and airlines service standards. The fuel cost calculation module uses the provided fuel consumption for the selected reference route. The historical Jet-A prices as well as a trend scenario for future Jet-A prices are adopted from the US Energy Information Administration (EIA)[22]. Insurance cost is assumed to be 0.5% per year of the total aircraft price referring to Harris[23] and Liebeck[24]. Navigation charges are calculated with Eq. 2 as published by Eurocontrol[25]. An analysis of the unit rates within Europe in the years 2010 and 2011 result in an average of 128.5 USD/nm.

$$Charge_{en-route} = \sqrt{\frac{MTOW[t]}{50}} \cdot \frac{distance[nm]}{100} \cdot unitRate \tag{2}$$

The examination of the landing charges at the airports of Frankfurt, Munich and Hamburg in 2011 results in an average of 3085 USD based on an Airbus A320 and a seat load factor of 80%.[26-28] For the estimation of the indirect operating cost Form 41 data by the US Department of Transportation (DoT)[29] from the years of 2000 to 2010 is analyzed. With an underlying confidence interval of 80% the IOC to DOC rate is about 1.2.

The revenue model is based on MIDT[30] (Marketing Information Data Tapes, MIDT), which includes historical booking and ticket data. For the year of 2009 the routes flown by Lufthansa and the achieved ticket prices are available. For an 80% confidence interval the results from a regression analysis are shown in Eq. 3 for the economy class (EC) and in Eq. 4 for the business class (BC).

$$TP_{EC} = 0.822 \cdot (0.239 \cdot distance[nm] + 17.4984) \tag{3}$$

$$TP_{BC} = 2.467 \cdot (0.239 \cdot distance[nm] + 17.4984) \tag{4}$$

To account for the time-dependent value of money and to adjust monetary input values of different years the results within AirTOBS are adjusted by historical inflation values and trend assumptions. The average inflation value during the years 1990 to 2011 of 1.94% in the European Union (EU)[31] is used. As the discount rate *r* for the NPV calculation (see Eq. 1) the weighted average cost of capital (WACC) from the Lufthansa financial report[32] of the years 2006 to 2010 of 7.9% is applied. The NPV reference year is 2012.

B. Reference AirTOBS output

For the following case study a simulation with AirTOBS based on the previously presented input values serves as a reference. The reference case's direct operating costs during the aircraft life cycle from EIS in 1995 to 2020 are shown in Figure 5. The characteristic of the DMC is caused by the simulation of the high value base and engine maintenance checks. The fuel cost characteristic is a function of the provided fuel cost trend curve and respectively historic data and the aircraft utilization.

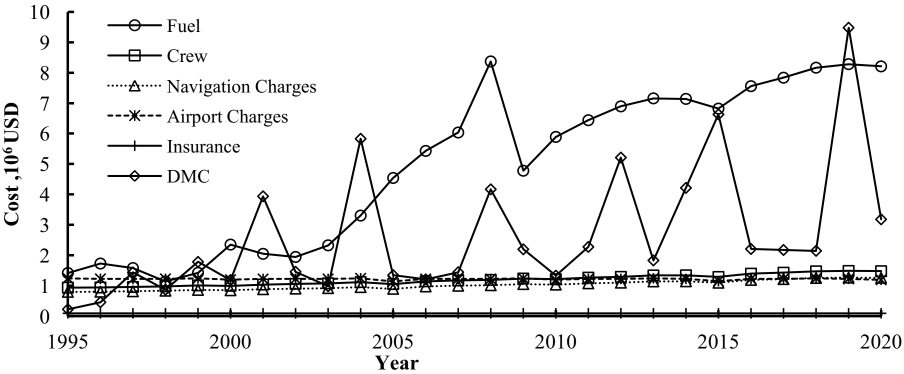


Figure 5: AirTOBS modeled direct operating cost (excluding acquisition cost) of the reference case

Figure 6 shows the reference NPV as a function of the TOC and the revenues. The NPV shows a negative trend before the EIS, because the aircraft acquisition cost is paid partly in advance, while no revenues are generated. During years with major maintenance events, a drop in revenues is caused by maintenance downtimes of several weeks. The model was compared and calibrated with available data from Aircraft Commerce[16] and DoT[29] and results seem to be in the right order.

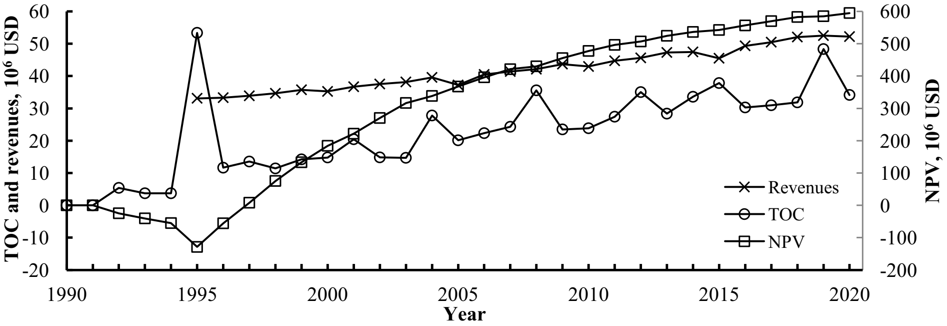


Figure 6: AirTOBS modeled TOC, revenues, and NPV of the reference case

III. Analysis

With the presented methodology of AirTOBS, a cost-benefit analysis of a maintenance C-check downtime variation is performed as a case study. In the following section the analytical steps and the results of the study are presented and discussed.

A. Analytical steps of maintenance downtime case study

The analytical steps of the parameter variation are based on the presented reference case and data. To determine the monetary value of the C-checks downtime, the parameters *check cost* (consisting of labor and material cost) and *downtime* of the C-check is varied as listed in Table 2.

Table 2: Parameters and values used for case study

Parameter	Reference value	Minimum variation value (absolute)	Maximum variation value (absolute)	Minimum variation value (relative)	Maximum variation value (relative)
Downtime	138 h	103.5 h	172.5 h	75%	125%
Man-hours	2,000 MH	1,500 MH	2,500 MH	75%	125%
Material cost	$ 38,000	$ 28,500	$ 47,500	75%	125%

B. Analysis results for the evaluation of the net-benefit of maintenance downtime

The conducted analysis shows the potential monetary value of a downtime reduction for a maintenance C-check. The evaluation focuses on the NPV as a KPI of the evaluation. Figure 7 shows the relative change in NPV by the relative downtime variation for a variation of the check cost. As expected, a reduction in downtime positively affects the NPV of the aircraft, while an increase in costs has a negative effect. It can be seen, that a reduction of the check costs by 25% is comparable to a reduction of the checks downtime by about 14%, since both equal a rise in NPV of about 0.2% in respect to the reference case.

Figure 8 shows the relative C-check downtime by the relative C-check cost in respect to the reference case. The plotted ISO curve ΔNPV = 0 shows the results for an NPV equal to the one of the reference case. In this case a downtime reduction of 12.5% (87.5% of the reference value) would be compensated by a cost increase of the C-check of about 10%. An increase in downtime by 8% requires a cost decrease of 2.5% for a constant NPV. From aircraft operators point of view, staying left of the ISO curve ΔNPV=0 is beneficial based on the assumptions of this use case. The reduction of the downtime of 25% results in a 159 additional flight cycles over the life cycle of 25 years. These flight cycles result in a revenue increase of about 0.29%. Due to the downtime reduction the NPV increases by 0.44%. For an increase in downtime by 25% the number of flight cycles decreases by 96 resulting in a revenue decrease of 0.17%. The increased downtime affects the NPV by a 0.27% decrease. Aiming at a higher net-benefit for the aircraft operator, an increase of the ΔNPV by 0.1% can be archived by a downtime decrease of about 12.7%, a cost decrease of about 11% or a combination of both influence factors described by the corresponding ISO curve ΔNPV +0.1%.

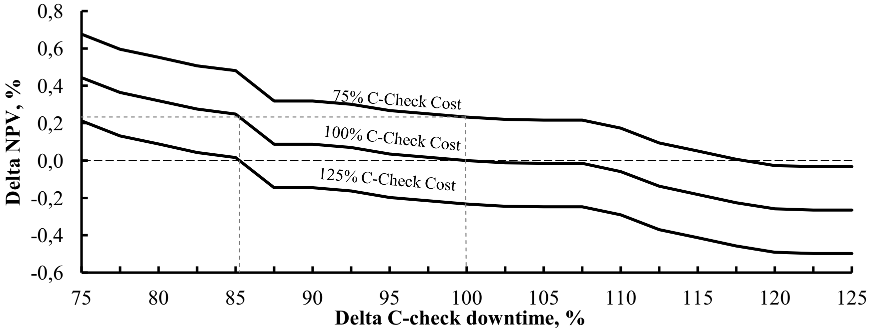


Figure 7: Delta NPV curves for variation of C-check downtime and cost

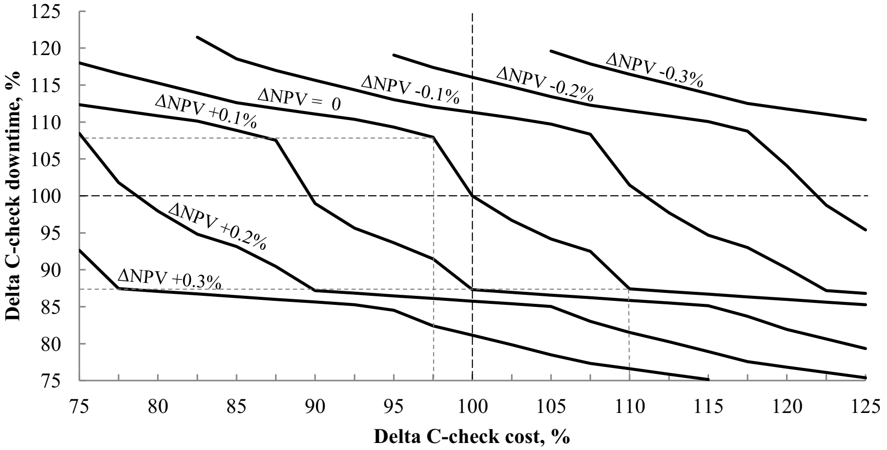


Figure 8: ISO curves for C-check cost variation by downtime variation

IV. Conclusion and Outlook

The presented study assesses changes in downtime compared to cost changes. The methodology is transferred to the tool AirTOBS, enabling economic life cycle analyses. The results of the study show the profitability of downtime reductions by accounting for the impact on the aircraft utilization. The variation of one base check on a single aircraft can produce significant economic benefits for an airline. The study should be expanded to all relevant maintenance checks to estimate the overall impact and potential of maintenance downtime optimization for one aircraft. The presented methodology is able to give fundamental requirements for changes in maintenance downtime or cost in order to generate a profit improvement of an airline.

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Development of a Maintenance Decision Model to Optimize for Technical Reliability – A component based approach

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The impact of unscheduled removals of components on an airline's operational availability is a known and recurrent problem. This paper describes the development of a generic model that forms a prognostic decision tool, which generates a component-based optimization for an airline's maintenance program. The suggested solutions range from assessing the quality of repairs (e.g. No Fault Found), to the development of a new specific maintenance action. The model's goal is to provide enhancement possibilities at an operational/financial level without endangering the airworthiness or safety of the aircraft. The optimization is designed in cooperation with a regional airline, VLM Airlines N.V., resulting in a practical approach to the problem.

Nomenclature

AMM = Aircraft Maintenance Manual
A_{Avg} = Average service life seen of the component, i.e. average TBO
A_{Max} = Maximum age of the investigated component
B_{AOC} = Extra budget provided by the airline
B_{Avb} = Available budget
$B_{Avb\text{-}MX}$ = Available budget for maintenance action, after subtraction of research cost
C_{Acq} = Acquisition cost of a new component
C_{Can} = Average cost of one cancellation
$C_{Cor\text{-}HT}$ = Cost of correcting for the unscheduled removal of a component, for a hard time action
$C_{D/C}$ = Cost of delays and cancellations
C_{Del} = Average cost of one delay
C_{HT} = Total cost of Hard Time action
C_{Ins} = Cost for installing a new component
C_{MH} = Cost of Men Hour
C_{Out} = Average cost for using the facilities at an outstation (hangar space + test run)
$C_{Pre\text{-}HT}$ = Cost of preventively removing components for a hard time action
C_{Rem} = Cost for removing a failed component
C_{Rep} = Average repair cost of a failed component

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C_{SM} = Cost of performing scheduled maintenance on a component
C_{Scr} = Cost for scrapping an old component
Can_{Red} = Reduction in cancellations per year
Can_{UR} = Number of cancellations per Unscheduled Removal
CDF = Cumulative Distribution Function
COC = Component Operating Cost
COC_{Sav} = Budget generated by reducing the Component Operating Cost
Del_{Red} = Reduction in delays per year
Del_{UR} = Number of delays per unscheduled removal
FC = Flight Cycles
FH = Flight Hours
HIL = Hold Item List
HT = Hard Time
L = Load factor of the aircraft
LRU = Line Replacement Unit
MEL = Minimum Equipment List
MFOP = Maintenance Free Operating Period
MH = Man Hours
MH_{Req} = Man Hours required for a maintenance action
MOD = Modification
MSG-3 = Maintenance Steering Group 3
$N_{A/C}$ = Number of aircraft in service
N_{Che} = Number of checks
N_{Com} = Total number of active components
N_{MA} = Number of Maintenance Actions per year
NFF = No Fault Found
OEM = Original Equipment Manufacturer
PDF = Probability Density Function
P_{Aff} = Number of affected passengers due to operational disturbance
P_{Max} = Maximum number of passengers on the aircraft
PH = Planning Horizon
R_{AL} = Reliability at Alert Level
R_{Int} = Reliability increase/decrease between two actions
R_{PH} = Reliability at the end of the planning horizon
RCM = Reliability Centered Maintenance
S = Percentage of failed components after a certain time
TBO = Time Between Overhaul
TDR = Technical Dispatch Reliability
TC = Type Certificate
TLOC = Total Lifetime Operating Cost
TSN = Time Since New
TSLSV = Time Since Last Shop Visit
t = One year, expressed in FH, FC, or Days
t_{Int-HT} = Interval of the Hard Time
t_{Int-MA} = Interval of the Maintenance Action
Δt = Time difference
UR = Unscheduled Removal
U = Number of Unscheduled Removals per year

I. Introduction

Aircraft maintenance has a large impact on safety, dispatch reliability, schedule integrity and preservation of aircraft residual values[1]. It has a function in satisfying regulatory requirements, and has its role in the asset management of an airline as well. Where the supporting activity used to be considered as an unnecessary burden, it is now regarded as a value creating activity, i.e. next to the direct cost generated to perform the maintenance activities, there is also an indirect cost due to the downtime of a system: a loss of revenue. Because of the latter, there is a future trend in the maintenance industry towards measuring maintenance performance[2], but also in creating distinct periods of operating time and downtime: creating Maintenance Free Operating Periods (MFOP)[3].

While the monitoring of the technical reliability of their Fokker 50 fleet, the engineering department at VLM Airlines N.V., a wet-lease operator for Cityjet Ltd., noticed that the unscheduled removals of certain components, more than others, had a larger impact on the availability of their aircraft.

In this light, it was decided to construct a theoretical model to predict the number of failures of these components and determine their impact, both operational (delays and cancellations), and financially (the change in Total Lifetime Operating Cost (TLOC)). This model would lead to a new Reliability Centered Maintenance (RCM) strategy within the company, that should lead to *a reduction in the number of technical delays and cancellations*.

The presented problem is an example of a common difficulty encountered with the current aviation maintenance strategy, Maintenance Steering Group 3 (MSG-3), which is the aviation variant and predecessor of the main-stream maintenance philosophy, RCM. Reliability Centered Maintenance is defined by Ref. 4 as:

> A specific process used to identify the policies which must be implemented to manage the failure modes which could cause the functional failure of any physical asset in a given operational context.

The RCM logic focuses on determining the best actions to prevent functional failures, by looking at the impact failures have on safety, the environment and finally at an operational/ economical level. MSG-3 however puts the emphasis on safety and continued airworthiness. By doing so, it often neglects the optimization for costs of failures with an operational effect[5].

The model developed in this paper aims to fill the gap left by the MSG-3 strategy. It forms an addition to the current maintenance program of an airline, that reduces the operational and economical impact of a functional failure of a component.

A. Research goal

In cooperation with VLM Airlines N.V. the research goal is set up. The goal is to reduce the number of delays and cancellations due to unscheduled removals (UR's) of components on the Fokker 50 and in this way increase revenue/reduce costs and improve the technical reliability of the aircraft without compromising the airworthiness and safety. The result should be a component based, generic optimization model. Which forms a prognostic/ decision tool, that gives a quantitative indication of the improvement or deterioration on an operational and financial level.

B. Constraints and assumptions

Some constraints and assumptions are made to reduce the complexity of the model. The most important ones are found below.

1) The model concentrates on finding operational improvements, not on redesigning the component. As a result, no technical changes are allowed on the component. Only the implementation of existing modifications are permitted.
2) The model is applicable for all component categories: rotables, repairables and consumables.
3) Only delays and cancellations caused by the unscheduled removal of components are considered.
4) The consequential delays and cancellations that may occur due to a component malfunction are neglected.
5) The failure behavior is modeled on a component level, not on failure mode level. Components have several failure modes, to have an exact optimization, each failure mode should be considered separately. However this amount of detail falls beyond the scope of the model.

II. Model

The structure of the developed model is shown in the flowchart in Fig. 1. The required inputs range from the fleet characteristics and maintenance program data, to the component's failure behavior. These are necessary parameters for the optimization process. The first part in the actual process is to determine the yearly cost generated by the selected component. The resulting value will be used for comparison with the different solutions. The second part is to follow a four step path to find the best improvement areas: (1) Looking if the No Fault Found (NFF) phenomenon is an issue for the selected component. (2) Investigating if a Modification (MOD) is available that can have a positive impact on the reliability. (3) Calculating whether a Hard Time (HT) can be instated and finally (4) Researching if the development of a new maintenance action can have a beneficial effect. The result of these four actions are summarized in a component performance improvement report.

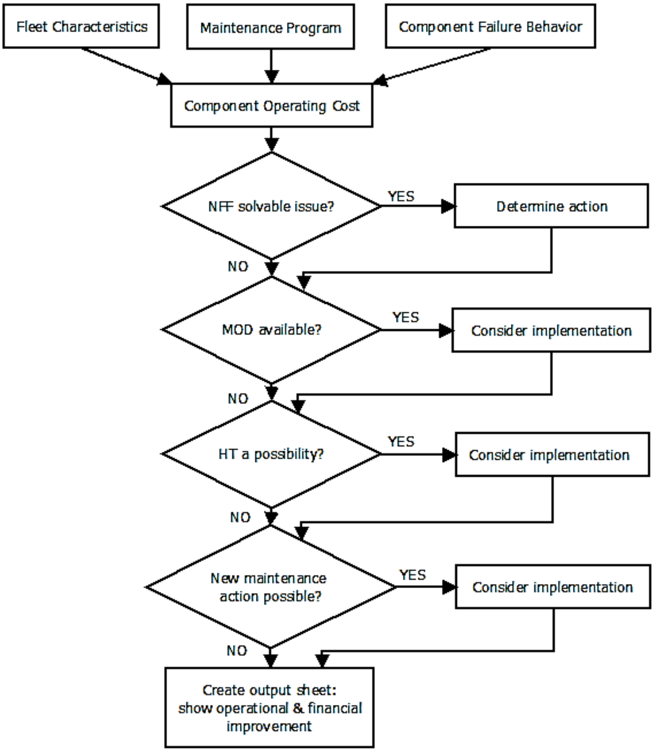

Figure 1. Flowchart of the developed model

A. Inputs

The first input are several fleet characteristics. Both operational and financial information about the fleet is necessary. Table 1 shows the data that is used in the model. Most of the information like daily utilization, Flight Hour (FH)/ Flight Cycle (FC) ratio and Technical Dispatch Reliability (TDR), can be obtained from the monthly reliability reports. Other values are less easy to attain, especially the delay and cancellations costs. There are many different variables involved (direct costs: e.g. crew costs, airport charges,… and indirect costs: e.g. loss of revenue or loss of customer satisfaction), which allows the value to be defined in several ways.

Table 1. Fleet characteristics used for input (averages)

Input parameters	
Aircraft in service	Scheduled flights/year
Route length	Technical Dispatch Reliability
Passenger capacity	Technical delays/year
Occupation rate	Delay length
Flight Hours/year	Delay cost
Flight Hours/Flight Cycles	Technical cancellations/year
Daily Utilization	Cancellation cost

The second necessary input are maintenance costs, more specifically: Man Hours (MH) costs and maintenance outstation costs (C_{Out}). The latter includes costs for the rental of hangar space and test runs (if necessary).

The last input contains all the component-specific information, of which the following details are required:

- Failure modes and effects: from the shop visit reports it is possible to extract the failure effects, the different failure modes and their frequencies.
- Failure consequences: i.e. can the components be put in the Hold-Item List (HIL) in accordance with the Minimum Equipment List (MEL)?
- Operational impact: the number of delays and cancellations caused by the component per year and per UR.
- NFF data: the shop visit reports also allow to define the percentage of repairs that can be classified as NFF.
- Failure data: to model the failure behavior of the component, Time Since New (TSN) and Time Between Overhaul (TBO) or Time Since Last Shop Visit (TSLSV) data is necessary.

After filtering the failure data and establishing its statistical relevance, it is possible to start modeling the failure behavior of the component. To select the appropriate model, the flowchart[6,7] in Fig. 2 is used.

It is first necessary to know if the component under investigation is repairable or non-repairable (consumable). For the consumable component statistical distribution fitting can be used to find the corresponding failure behavior. For the repairable components on the other hand, one first has to find the trend in the maintenance data. This can be done by visual or analytical methods. The model proposed herein uses both. For the visual trend tests, scatter plots and cumulative failure plots are used to observe whether a trend is present. From the different analytical trend tests available, it only uses the Mann Test, the Laplace Test, and the Military Handbook test[6].

After the selection of the most suitable model, one then can determine the associated Probability Density Function (PDF), Cumulative Distribution Function (CDF), or Reliability Function.

It is now possible to feed the information to the model and obtain the best possible improvement actions for the selected component.

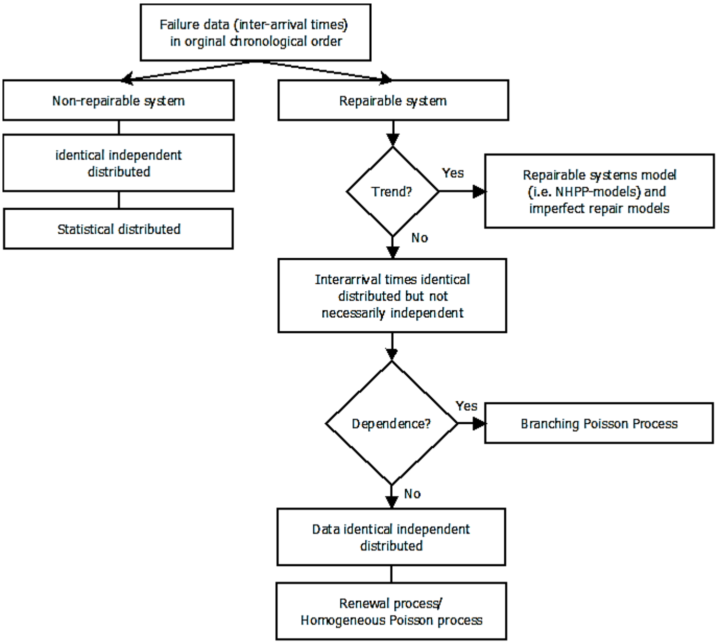

Figure 2. Model Identification Framework

B. Component Operating Cost

The Component Operating Cost (COC) is the cost generated by the component in one year time, and it is expressed in €/year. The calculation in the model uses only direct operating costs, the full equation is shown in Eq. (1).

$$COC = C_{Acq} + C_{Scr} + U * \left(C_{Ins} + C_{Rem} + C_{Rep} + C_{Out}\right) + C_{SM} + C_{D/C} \tag{1}$$

The first element in the cost calculation is the average amount of components that have to be bought new each year (including transportation costs), C_{Acq}. The scrap costs, $C_{Scr,}$ are the expenses made for the number of components scrapped per year. The third part of the equation covers the losses generated on a component level due to a number of unscheduled removals per year, i.e. the MH cost for installing a new component and removing the failed one, respectively C_{Ins} and C_{Rem}. But also the average repair costs, C_{Rep}, of the component (including transportation costs to and from the repair shop). And finally the additional budget necessary to support a component change in an outstation, C_{Out}. The fourth element, is the scheduled maintenance cost, which is calculated by the time spent, in MH, on a number of standard maintenance actions performed on the component. These values are obtained from the Aircraft Maintenance Manual (AMM), and can be confirmed by licensed engineers that the specified MH values are realistic. The full equation is shown in Eq. (2).

$$C_{SM} = N_{MA} * MH_{Req} * C_{MH} * N_{A/C} \tag{2}$$

The final part of the COC calculation are the costs of the delays and calculations generated by an unscheduled removal, the associated equation is shown in Eq. (3).

$$C_{D/C} = \left(Del_{UR} * U * C_{Del}\right) + \left(Can_{UR} * U * C_{Can}\right) \tag{3}$$

This sum gives the most important direct operating costs for one component for the operator in one year time. A more detailed calculation could include e.g. transportation cost of components and certifying staff to the location of the grounded aircraft, or income lost due to the faulty removal (e.g. inefficient troubleshooting).

C. No Fault Found

After creating the starting point of the model, the first optimization step is taken: looking at the No Fault Found behavior of the investigated unit. This is the first step because defining whether NFF is an issue, is one of the most straight-forward actions that can be done to start improving reliability. Moreover, NFF is a problem with a high cost and with a self-sustaining effect (rogue units), therefore it cannot be neglected in a reliability research.

In general the NFF problem is caused by, either the repair shop, the operator, or by a lack of communication between the two parties. It could be that the repair shop is not able to accurately simulate the operating environment, or they use inappropriate test equipment (human or non-human). The operator on the other hand, can apply poor troubleshooting techniques, or have wrong use of built-in-tests. NFF is a complex and elaborate problem and determining the exact cause varies for each system, hence it requires a dedicated research per component.

During the model development a flowchart was constructed in an attempt to locate the source of the NFF. Fig. 3 presents the logic followed. The outcome of the decision tree is not to provide the exact source of NFF, it merely serves as an indicator that narrows the search scope.

The starting point is comparing the percentage NFF of the component seen at the airline, to the average ratio NFF of all operators, as seen by the shop. If the item is below average, this is a good situation, and depending on the trend and its prediction for next year, an appropriate action is determined. In the case where the current value is acceptable, but the trend is deteriorating, one needs to consider whether an increase in NFF is financially justifiable, e.g. the new selected repair shop shows a higher NFF return rate, but is lower in repair cost. Is this better than the old shop which was more expensive but with a lower NFF ratio?

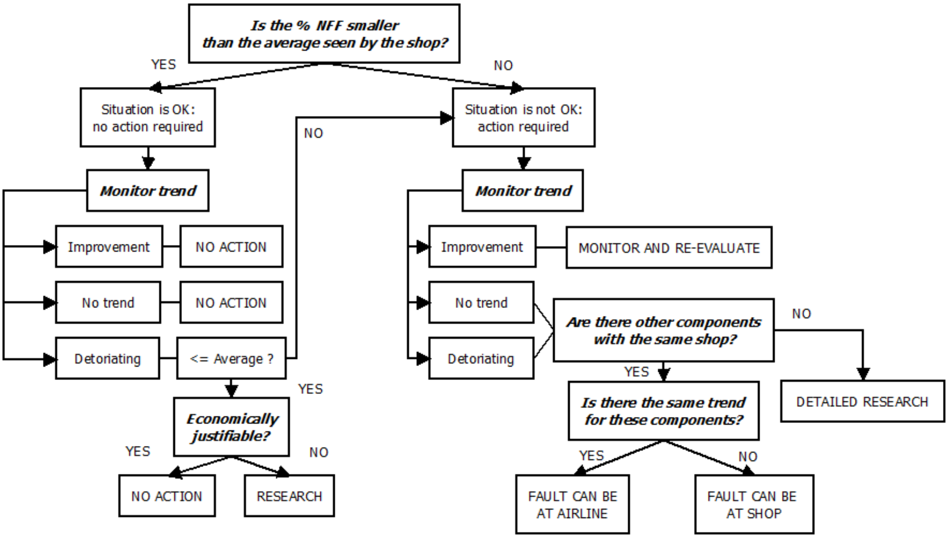

Figure 3. Logic to determine the origin of the NFF problem

However, if the observed NFF rate is, or will be, above the average of the shop, another approach is required. This is the logic on the right side of Fig.3. Now it is necessary to compare the investigated unit with other units that are going to the same repair shop (if there are any). In the case where all components show an increasing NFF trend, the conditions in the shop environment may have changed (e.g. new management, new techniques,…) that influences the repair quality. If only one component shows this behavior, it could be that troubleshooting of a certain defect is ineffective, and that the unit is often unnecessarily removed, which indicates action should be taken at the airline's side.

Nevertheless, it needs to be kept in mind, that during the set-up of this flowchart, not all variables were included, and this flowchart is intended for orientation purpose only. The exact reason for NFF always requires detailed, individualized research.

D. Modification

Implementing an existing modification is the only technical change that is allowed by the model. For the component under investigation, research has to be done, to know which modifications are available, how much the total installation cost is, and which failure mode will be reduced by the modification. Even more, one would like to know which percentage of the UR could be reduced. This number is very hard to quantify. During the development it was revealed that neither the Type Certificate (TC) holder, nor the Original Equipment Manufacturers (OEM) could quantify the expected improvement. The most realistic estimation was established by investigating the shop visit reports. From these reports the frequencies of the different failure modes can be found, and these can be used as an upper limit for the possible improvement.

By using this possible reduction in UR in the COC equation, as seen in Eq.1, a new total COC prediction is calculated. It is now possible for an operator to compare the cost and operational improvement against the initial investment costs.

E. Hard Time

The third step in the optimization process is considering the implementation of a hard time limit on the component. By using the failure behavior of the component, one tries to find if there is an optimal point in time to replace the unit, so that the total maintenance cost is at a minimum. Secondly one tries to find a point where the cost of the new scheduled maintenance balances the cost saved by preventing delays and cancellations. Is there a break-even point?

The possible intervals range from zero up to the maximum identified age of the component, expressed in FH. After each interval a percentage of components installed in the fleet will have failed and an amount will have survived. At the end of that interval all components will be replaced by new ones, i.e. each component is modeled as a consumable. This is an important assumption. The calculation does not take in to account the usage of repaired units, which have a different chance on failure as compared to new components. Hence the results are only representative for consumables. For repairables and rotables adjustments are still required.

Eq. (4) shows the calculation for the total hard time cost, Eq. (5) indicates how the preventive maintenance cost is determined, Eq. (6) does this for the corrective maintenance cost.

$$C_{HT} = N_{Com} * \frac{A_{Max}}{t_{Int-HT}} * (C_{\ Pre-HT} + C_{Cor-HT}) \tag{4}$$

The total hard time cost in Eq. (4) reveals how much the total cost would be between 0 FH and the maximum age seen for the researched component. For example, if an interval would be chosen equal to the maximum age, maybe only one component would have survived until the end of the interval. The total hard time cost will be the sum of the costs made by having only one component scheduled removed ($C_{Pre\text{-}HT}$) and the rest of the pool that unscheduled removed and replaced by new components ($C_{Cor\text{-}HT}$).

The cost of the preventive maintenance exists out of the budget spend on replacing the amount of components that survived, S. This covers installing, removing and repairing the old one, but also including the loss of value by removing the component from the system before it has reached its full potential.

$$C_{Pre-HT} = S * \left(C_{Ins} + C_{Rem} + C_{Rep} + (A_{Max} - t_{Int-HT})\frac{C_{Acq}}{A_{Avg}}\right) \tag{5}$$

When performing corrective maintenance, money is spend on replacing and repairing the number of components that will have been removed unscheduled, and on the costs made by their operational impact, i.e. delays and cancellations.

$$C_{Cor-HT} = (1 - S) * \left(C_{Ins} + C_{Rem} + C_{Rep} + C_{Out} + (C_{Del} * Del_{UR} + C_{Can} * Can_{UR})\right) \tag{6}$$

Next to the total minimum cost, one would also want to know at which point the costs made by performing preventive maintenance, would equal the cost made by the unscheduled removal. This is the point where Eq. (5) equals Eq. (6) for an equal amount of removals, hence in Eq. (6), (1-S) is replaced by S. The result is written down in Eq. (7). After rewriting, it states that for the action to break-even, the cost due to the usable life lost, should equal the sum of the cost of an UR at an outstation and its operational impact, see Eq. (8).

$$C_{Pre-HT} = S \ * \left(C_{Ins} + C_{Rem} + C_{Rep} + C_{Out} + (C_{Del} * Del_{UR} + C_{Can} * Can_{UR})\right) \tag{7}$$

$$(A_{Max} - t_{Int-HT}) * \frac{C_{Acq}}{A_{Avg}} = C_{Out} + C_{Del} * Del_{UR} + C_{Can} * Can_{UR} \tag{8}$$

In the last part of the HT section a sensitivity analysis is performed. The value of the independent variables are changed up to +/- 75% with steps of 25%, by each time calculating C_{HT}, so that the most influential variables are known. The independent variables considered are shown in table 2.

Table 2. Independent variables in the HT calculation

Independent Variables		
C_{Ins}	$t_{Int\text{-}HT}$	Del_{UR}
C_{Rem}	C_{New}	C_{Can}
C_{Rep}	A_{Avg}	Can_{UR}
A_{Max}	C_{Del}	

F. Maintenance Action

The final action performed by the model, is studying the possibility of a new maintenance action. The steps taken to find an efficient and cost-effective action are presented in the flowchart in Fig.4.

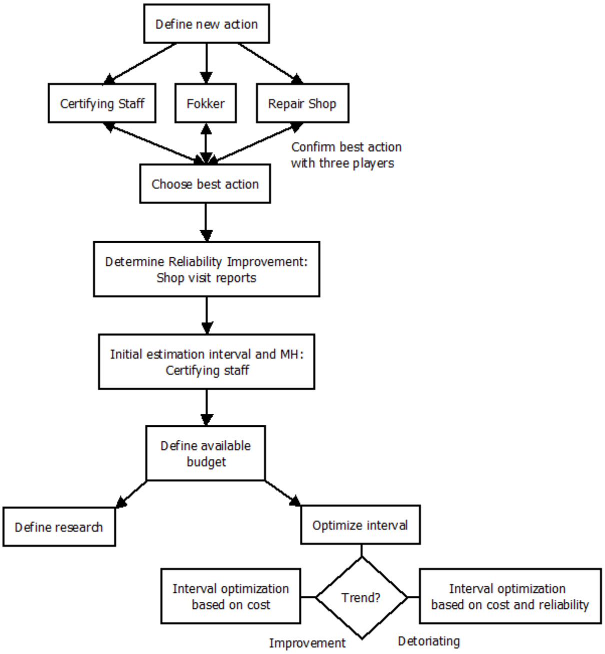

Figure 4. Selection and optimization process of new maintenance actions

The development of the new action is done by three parties. The certifying staff, or licensed engineers, which have the most operational experience with the component. The TC holder, Fokker, who designed the whole system and has a specialist available for each system. And finally the repair shops, which have thorough knowledge of the components functioning and failure modes.

Each of the three parties are given a list of the most regular failure modes seen by the components, and are asked the following questions:

- What possible maintenance actions could you think of, that would improve the reliability of the component, based on the failure modes seen?
- What is your estimation on the reliability improvement possible for that action?

From the different replies the most feasible action is discussed within the engineering department, and the chosen option is proposed and confirmed with the three parties involved.

As with determining the improvement for a modification, it is difficult to estimate the percentage improvement for the selected action. Once again the shop visit reports are the tool to determine this value, on a comparison basis, before and after the action has been implemented.

The following step is to obtain an initial guess for the time necessary to perform the action and the interval at which it should occur. For this step, the knowledge and experience is used of the licensed engineers. This is the final step in setting up the new action. The second part is making sure that it is cost-effective, i.e. one wants to be sure that the benefits of performing the action outweigh the cost made by that action. To find the benefits of the new maintenance activity, the decrease in UR is used in Eq.1, to find the new COC. This forms one part of the available budget for the new maintenance. The other part may be provided by the airline, which make extra money available, a start-up budget. This is the maximum available budget, see Eq. (9).

$$B_{Avb} = COC_{Sav} + B_{AOC} \tag{9}$$

The available budget is used for the actual maintenance action, and for some extra research. It may be possible that the new maintenance action has a risk on a large number of initial findings, which would imply a large start-up risk. Or it could be that the TC holder needs to validate and approve the suggested maintenance. These are factors that require extra attention. From the available budget in Eq.9, the research costs need to be deducted to know the actual sum available for the maintenance action.

With the available resources, two different scenarios are possible. The first one is when in the failure behavior an improvement trend is noticed. In this case, cost will be the dominating variable. The interval and duration of the suggested action is checked with the available budget. If the action is financially supportable, it is approved. If the budget is overrun, a new interval is selected by applying Eq. (10).

$$t_{Int-MA} = \frac{t}{\frac{B_{Avb-Mx}}{N_{A/C} * MH_{Req} * C_{MH}}} \tag{10}$$

The other scenario is when the failure behavior of the component is deteriorating. If this occurs, the interval is constructed, based on reliability. The first step is the same as for an improvement trend, namely checking whether the suggested interval size and action duration is financially feasible. If this is not the case, the number of checks are adjusted. The second step is calculating the estimated reliability decrease from a preset alert level until the end of the planning horizon, giving the workable reliability range. The preset alert level is determined by engineering and should be approved by senior management. This range is divided by the possible number of checks, so that between each maintenance action there is an equal reliability decrease, see Eq.11. As a result from this action, the intervals show a decrease in size.

$$R_{Int} = \frac{R_{PH} - R_{AL}}{N_{Che}} \tag{11}$$

Fig. 5 gives a qualitative example of the decreasing interval size for an increased failure rate. The green bar at 1500 FH indicates the reaching of the preset alert level, at this moment the first action is performed. The different red lines indicate when the next maintenance actions are done, in this example the second action takes places at 2000 FH, the third at 2400 FH, the fourth at 2700 FH. So the interval is decreasing from Δt = 500 FH to Δt = 300 FH.

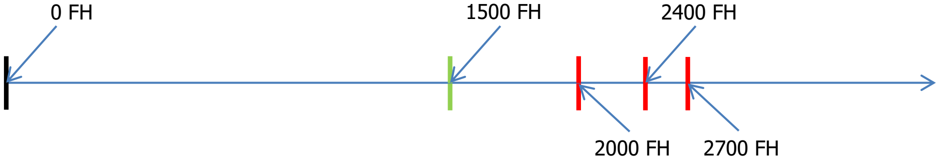

Figure 5. Example of decreasing interval size

III. Results and Validation

A. Results

The model was tested for three different components of the Fokker 50. The first step was obtaining the necessary fleet characteristics. Although most information was available in the monthly reliability reports, the delay and cancellation costs were harder to determine. The financial department at VLM Airlines N.V. was not able to provide these values. The required values were found from reports of two institutes. The University of Westminster[8] performed an elaborate research on the true cost of a ground and airborne delay; for an aircraft like the Fokker 50 with an average delay length of 53 minutes, the cost of ground delay including network effect would be about €1500. The second source used was EUROCONTROL. They utilize standard inputs for their cost-benefit analyses. In this report the SESAR evaluation team calculated that a cancellation of 50 seat narrow-body aircraft costs about €3400. The values from these reports were run by the financial department. These confirmed that the costs were in of the right order of magnitude. Table 3 contains the overview of the essential parameters.

Table 3. Fleet characteristics for the Fokker 50 fleet of VLM Airlines N.V.

Parameter	Value	Parameter	Value
Aircraft in service	14	Scheduled flights/year	19607
Average route length	385 km	TDR	99.4092%
Passenger capacity	50	Technical delays/ year	86
Occupation rate	49%	Average delay length	53 min
FH/year	1258 FH	Average delay cost	€1500
FH/FC	0.96	Technical cancellations/year	30
Daily Utilisation	3.44 FH	Average cancellation cost	€3400

The next input is the relevant maintenance cost. The maintenance program and its associated costs are not provided in this paper due to confidentiality reasons.

The last required input, is failure data from the components. From the list of components, of which the UR caused most delays and cancellations, three items were selected to serve as a test-case. These are: the Flight Idle Stop Solenoid (FISS), Engine-Driven hydraulic Pump (EDP) and the Attitude and Heading Reference Unit (AHRU). These are all classified as rotables, but they show large differences in many areas. The acquisition, repair and transportation costs are very different, e.g. the acquisition costs range from €1000 until €55000, while the repair cost go from €500 up to €15000. This is partly due to the large difference in technical complexity, but also in size. The third difference is in the delay and cancellation rate per UR. Table 4 shows the impact of the components on the flight schedule.

Table 4. Operational impact of investigated components

	FISS	EDP	AHRU
Delay/UR	0.058	0.143	0.200
Delays/year	0.5	1.5	2.5
Cancellation/UR	0.110	0.063	0.081
Cancellations/year	1	1	1

The next challenge encountered was finding sufficient and usable data. The Computerized Maintenance Management System at VLM Airlines N.V. was only implemented recently and not all history was available. Therefore it was chosen to select a limited timeframe from which data would be collected, namely from 01/01/2007 until 31/12/2010. In cooperation with Fokker, the airlines: KLM Cityhopper and Amapola Flyg AB, and the repair shops. By this data pooling, the risk exists that the failure behavior is not representative anymore for the VLM Airlines N.V. fleet. Due to insufficient initial data, this risk had to be accepted. By doing so, sufficient data was available (with a reasonable error margin) to generate meaningful results.

By applying the visual and analytical trend test, the best failure modeling technique was chosen, which led to the values shown in table 5.

Table 5. Failure data analysis of the investigated components

Component	Trend test	Model	CDF
FISS	Decreasing failure rate	RP	$1.112\text{-}1.057\cdot e^{(-t/4166.66)}$
EDP	Decreasing failure rate	NHHP	$0.136\cdot t^{0.686}$
AHRU	Decreasing failure rate	NHHP	$2.456\cdot t^{0.417}$

The received inputs are provided to the model, and the results are shown in table 6.

Table 6. Final model results, when applied to the FISS, EDP and AHRU

Parameter	FISS	EDP	AHRU
COC	€3605.21	€3818.48	€6596.88
NFF	No action	No action	No action
Modification	Not available	Not available	Not available
Hard Time	At max. age	At max. age	At max. age
UR reduction/ year	0.48%	8.25%	1.50%
Maintenance Action	Lubrication	Operational check	Operational check
Action duration – Interval	0.5 MH – 1258 FH	0.3 MH – 650 FH	0.75 MH – 350 FH
UR reduction/ year	8%	8.25%	1.50%
Delay reduction/ year	0.02	0.34	0.22
Cancellation reduction/ year	0.04	0.19	0.07
TDR Improvement	0.0003%	0.0027%	0.0015%
Total cost	€518.88	€-802.03	€-5195.63

For all three components NFF proved not to be an issue, and no special action is necessary. The second step, investigating whether a modification is possible, was unsuccessful. No modifications were available for these components. The first successful action is setting a Hard Time. For the three components this is set at the maximum age, resulting in an UR reduction of a few percent. Finally for all components a new maintenance action could be found. The sensitivity analysis revealed that A_{Max} and C_{Acg} are the most influential variables on $t_{HT\text{-}Int}$, and that A_{Max}, C_{Del} and C_{Can} have the most effect on the C_{HT}.

Combining the improvements on all three components means an absolute delay reduction of 0.58 per year and a cancellation reduction of 0.30 per year, against a collective cost reduction of €-5478.78. The FISS is the only component that actually requires an investment. In this case the cost reduction from the new maintenance action is too low to support the action, the airline would need to invest to support the action.

The total cost reduction is rather low. This is partly due to the low costs of a delay and cancellation, respectively €1500 and €3400. Also the impact on the operational disturbances is not that significant, however, the effect it has on customer satisfaction cannot be neglected. The value lost by unsatisfied passengers can be much larger. The exact influence operational disturbances have on customer satisfaction requires a separate study. To get an indication, the number of persons affected can be calculated by Eq.(12). This equation calculates the average number of passengers affected per flight ($P_{Max}\cdot L$), for the improvement over the planning horizon ($(Del_{Red}+Can_{Red})\cdot PH$). Inserting the values for VLM Airlines N.V. for a planning horizon (PH) of five year, results in about 107 less passengers affected.

$$P_{Aff} = P_{Max} * L * (Del_{Red} + Can_{Red}) * PH \tag{12}$$

B. Validation

The final step to complete is validation. The NFF result was confirmed by the three repair shops, who agreed that the current component under investigation did not show alerting trends, and that the percentage NFF is below average and no immediate action is required. The logic in the flowchart Fig. 3 will need to be validated further by using more and different components that actually show alerting NFF trends or have a higher percentage.

The validation of the second part, modification, shows another problem. First of all, no modifications were available. And secondly, not enough time and data was available to check the improvement from past modifications, to verify if the results from shop visit reports are usable as an estimation.

For the HT action, sufficient historical data was available to validate. The HT interval suggested by the model was applied on the datasets from 2007-2010, and the relevant improvement was compared to the one calculated by the model. For the FISS this prediction was quite accurate, it was estimated that the HT could bring a 0.48% UR reduction per year, while actually it would have been 0.59%. For the EDP and the AHRU on the other hand, the real values dropped from, respectively 1.47% to 0.63% and from 8.25% to 0.82%. The large difference seen with the latter two components can be explained due to (1) the relative small data sets and the associated larger error margin for the failure behavior. (2) a lack of data, which influences the maximum age seen, and thus the hard time interval. (3) And finally by not including the reparability effects in the model the outcome may be more optimistic.

The validation of the last part, the introduction of new maintenance action, could not be done. The true outcome of a new physical action can only be seen by actually doing the action. Only after a trial-period it will be possible to compare the effects with the best estimation made by Fokker, repair shops, staff and shop visit reports.

IV. Conclusion and Recommendations

A. Conclusion

The developed model complies with the requirements set by the research goal. It is a generic tool that optimizes the maintenance strategy on a component level.

It is able to model the component's failure behavior and provide a prognosis for the future. And, it shows the impact that an unscheduled removal has on the airline, in terms of: delays and cancellations, component operating costs and passengers. The optimization suggested is developed in cooperation with people in-the-field, yielding a very practical approach to the problem. The four different steps in the optimization process each work on a different level to find the best improvement, i.e.:

- Step 1: Is NFF a problem with the airline or shop? (Quality)
- Step 2: Is a technical solution available and applicable? (Technical)
- Step 3: Is age a factor that can be ignored? (Age)
- Step 4: Can a new maintenance action be more effective? (Operational)

Each solution is compared to the current situation, and per component a performance improvement report is generated.

When applying the model on three components of a Fokker 50, the model shows that by applying only two actions, a hard time and developing a new maintenance action, an improvement of 0.58 delays and 0.30 cancellation per year is possible. Which will generate a total cost reduction of €5478.78 per year. Or over a five year period a reduction of €27393.90 and 107 less passengers affected. These results prove that by using historical data, the introduction of a hard time interval can have a financial benefit, although it may not be required by the aircraft maintenance program. Also it is an example that by cooperating with different parties, i.e. certifying staff, OEM and repair shops, new maintenance actions can be developed. And even though these developments require time and money, the generated benefits outweigh the initial investments necessary.

If the model would be applied to more components and with more accurate data the long term benefits are considerable.

Most importantly, the developed model is a practical example of how the current MSG-3 strategy can be used as basis to add the operational and economic effects of functional failures, without effecting the airworthiness or safety.

B. Recommendations

During the construction of the model some difficulties were encountered, that required awareness for operators, OEM and repair shops.

- *Model*: the validation of the model requires some additional work. More historical data needs to be collected to validate whether using the shop visit reports are a good tool to estimate the possible enhancements. The validation of the maintenance action requires some test-cases, as it is not possible to theoretically validate these.
- *Delay and cancellations cost*: the exact cost of a delay and a cancellation is difficult to determine. Although it is suggested that an airline calculates a practical value for themselves. This value should also include the effects on customer satisfaction, as this parameter cannot be underestimated. Knowing what the impact is of an operational disturbance and the value lost, will aid in making decisions.
- *Component lifetime information*: having much and detailed information about the failure behavior of assets is the key for making accurate predictions and determining the best possible maintenance actions. Keeping track of TSN, TBO and TSLSV together with the failure modes and effects of the shop visit reports will lead to correct understanding of the failure behavior of the component.
- *Communication (external)*: during the design of the model, scarceness of data was a recurring issue. Even more, the need for additional information was not only seen with the operator. For further product improvement, also the OEM and repair shops have a continuous need for input. This stresses the importance of having good communication and cooperation between all three parties. The experience and knowledge available can only be used effectively and efficiently if it is brought together. Only in this way a clear picture of the components behavior can be constructed and actual changes can be made.
- *Communication (internal)*: the need for communication is also present on a lower level, within the airline itself. Cost data, reliability information, historical information, and past researches, all data should be centralized and be easily made available for all departments. Only by creating a common data pool and using the different expertise's, constructive solutions can be found and the right decisions can be made.

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Modification and Certification of Research Aircraft

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In this paper strategies for substantiation of airworthiness for modified type certificated standard aircraft are discussed. Modifications shown include complex external structures like a flying wind tunnel, ring antennas, wing stores, and noseboms. An equivalent level of safety compared to the original certification specification is maintained by structural testing and limitations to the aircraft's flight envelope. Hence aircraft modification and certification involves different technical fields; prerequisites for collaboration between specialized Design Organizations are explored.

Nomenclature

Re = Reynolds number
S = Strouhal number
f = frequency of elastic eigenmode
D = mean diameter of noseboom
v_P = airspeed perpendicular to noseboom axis
v_N = airspeed air speed in direction of boom axis
ν = kinematic viscosity of air
h = lifetime
GVT = Ground Vibration Test
DLR = German Aerospace Center
AWI = Alfred Wegener Institute
HALO = High Altitude and LOng Range Research Aircraft
ATRA = Advanced Technology Research Aircraft
EASA = European Aviation Safety Agency
CS = Certification Specification
ELOS = Equivalent Level of Safety
CFD = Computational Fluid Dynamics
ATTAS = Advanced Technologies Testing Aircraft System
PMS = Particle Measurement System
CFRP = Carbon Fiber Reinforced Plastics
DOA = Design Organization Approval
HoOA = Head of the Office of Airworthiness
SoW = Statement of Work

I. Introduction

Industry and research organizations use type certificated standard aircraft for research purposes by fitting wing stores, nose booms, belly pods or additional cabin equipment to an individual aircraft of a specific aircraft model. Regulatory requirements call for an additional certification effort to re-establish airworthiness of the modified airplane.

Examples of airplane modifications such as a modified glider employed as a flying wind tunnel, ring antennas mounted under a Dornier DO 228 wing, wing stores for a Part 25 aircraft and noseboom for glider and DLR ATRA A320 research aircraft will be shown. The planning process to

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meet airworthiness requirements for operations with scientists as passengers, operational needs and, last but not least, budget goals includes a multi disciplinary approach.

Simplified procedures for substantiation of structural safety and load limitations are outlined along with the operational consequences for the flight envelope of the modified aircraft.

For smaller companies, which hold an approval as Design organization in specific fields, collaboration with other Design Organizations with complementing scope can open a chance for handling of complex projects. Standard procedures in place within the Design Organization of Leichtwerk AG will be presented

A. Certification Process

Modification of research aircraft are sometimes very challenging tasks, beyond the original purpose of the basic certification specifications. The basic certification specification, which requirements were fulfilled at time of Type Certification, defined a basic level of safety for the design and operation of the aircraft. However, this equivalent level of safety (ELOS), has to be substantiated also for the modified aircraft.

B. Examples of Modified Aircraft

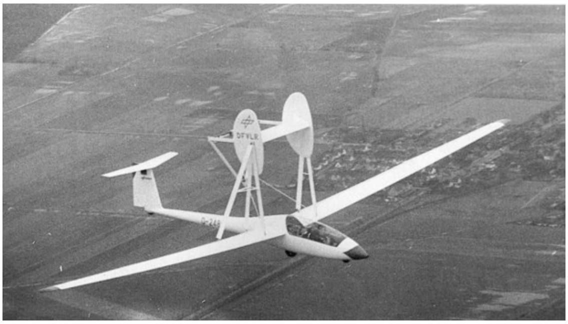

Figure 1. Flying wind tunnel Janus, DLR [1].

Simplified certification can involve limitations to the operational envelope of the specific aircraft, e.g. the Flying Wind tunnel Janus of DLR Braunschweig.

For 2D airfoil measurements, a test wing with adjustable angle of incidence is mounted between two vertical wall plates. The airfoil pressure distribution and the drag are measured with pressure transducers and a rake.

The aircraft fulfills static strength and flutter criteria. The operational envelope is limited in terms of max. speed and allowable side slip angle.

For in flight measuring of sea ice thickness an antenna system was mounted to the wing hard points of the DO 228 aircraft of Alfred Wegener Institute Bremerhaven [2]. Substantiation was shown for the flight loads, static strength by load testing and flutter.

Aerodynamic load analysis was done with a 3D vortice lattice code simulating the wing of the aircraft and the antenna together. This analysis showed conservative results compared to handbook data derived from Hoerner [5].

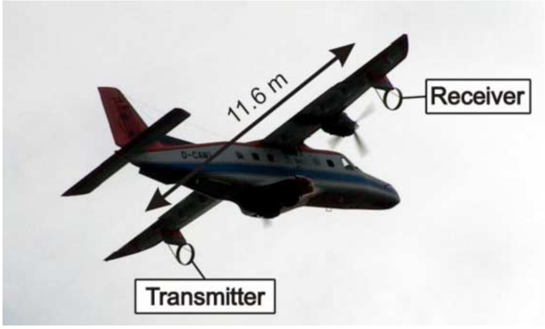

Figure 2. Antennas at Do228 wing, AWI [2].

The flying prototype antennas were qualified with a static strength test up to Ultimate Load. Prior to flight testing eigenmodes of the antennas were measured in a Ground Vibration Test (GVT) and a theoretical flutter prediction was performed.

The research aircraft HALO of DLR, a modified Gulfstream G-550, will be operated worldwide, e.g. for meteorological scientific campaigns. The modifications to this aircraft includes belly pod and ventral fin, wing stores and various hardpoints, viewports and sensors along the fuselage. Preliminary substantiation for development flight testing is shown mainly by structural testing and flutter analysis.

Figure 3. HALO (G-550) with wing stores, DLR [3].

Initial limitations to the allowed lifetime and to the flight envelope, like no flights into icing and lightning conditions, allow for early flight testing of the modifications with qualified test pilots as a *proof of concept.* Opening the envelope during flight test included instrumented flutter investigations. After development flight testing a more complete and therefore complex, expensive and time consuming substantiation will allow to operate the aircraft without restrictions.

A 18m wingspan glider is used by DLR as a research platform for aerodynamic performance and flight mechanics measurements. The aircraft is equipped with an optimized noseboom to minimize adverse effects on the aerodynamic characteristics of the base aircraft. The minimum first eigenfrequency was measured with 13 Hz and was verified to be sufficient during flight tests.

Figure 4. Discus 2c with noseboom, DLR [4].

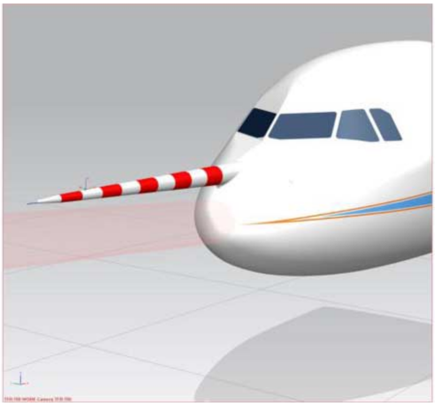

Figure 5. DLR ATRA (A320) research aircraft with noseboom.

The ATRA Airbus A 320 research aircraft of DLR will be equipped with a noseboom to provide a sensor platform in undisturbed airflow.

Substantiation shall be as complete as necessary to avoid limitations to normal operational procedures and the use of the weather radar. It is also required to operate the aircraft without the noseboom installation.

C. Certification Strategies

For substantiation of an aircraft's airworthiness certification specifications are issued by the aviation authorities. Depending on the class of aircraft, mainly separated by the maximum take off mass, each specification represents requirements to maintain a certain level of safety. E.g. the specification for gliders (EASA CS 22) allows for more simple means of compliance than the specification for large transport aircraft (CS 25).

The certification process starts with a project description, where the purpose of the intended modification is defined. In the next step, the certification program identifies the technical fields involved in the substantiation process and describes the substantiation strategy.

It is often necessary to define a simplified substantiation process to meet time and budgetary requirements.

II. Simplified Certification Strategies

Substantiation of individual modified aircraft can be simplified as long as the equivalent level of safety can be maintained.

D. Loads

Aerodynamic load calculation can be performed by handbook techniques, e.g. Hoerner [5]. Drag and lift coefficients may be considered as maximum feasible values. Maintaining ELOS typically means to make an assumption on the safe side.

Care has to be taken to avoid neglecting important influences, e.g. at transonic speed local shocks may require more detailed CFD analysis.

The upper wing smoke generator used on the VFW 614 ATTAS research aircraft is an example for local shocks at relative low speed Ma=0.65.

Figure 6. VFW 614, ATTAS upper wing smoke generator, DLR.

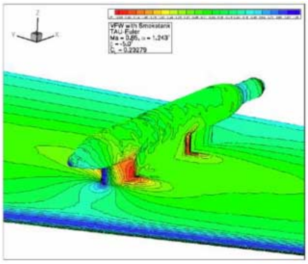

Figure 7. Tau-Euler analysis of VFW 614 smoke generator, DLR.

E. Structure

In general, structural analysis can be distinguished in design, when the structure is defined, and in substantiation, when it is shown that it is airworthy. To achieve the first goal, all adequate techniques have to be applied to arrive with a fully functional structure. For showing its compliance with airworthiness specifications a more simplified approach might be useful.

For only one flying prototype it is often sufficient to show structural integrity by static load testing. With a simple test, the overall structural reliability of sometimes complex structures can be demonstrated.

For the DLR HALO research aircraft (Fig. 3), structural substantiation of the wing stores for meteorological probes (Particle Measurement System, PMS-Carrier) was done by a static test up to 1.15 time Limit Load.

The wing store was made mainly from carbon fiber reinforced (CFRP) structure, and was considered as secondary structure with a safe life design approach. The stress strain curve of CFRP is typical linear elastic until fracture; there is not necessarily an indication of approaching fracture. Therefore it is necessary to show a certain margin above Limit Load. For metallic structure it is often sufficient to show strength up to Limit Load, given that the test article suffered no permanent deformation during the test. Then the plastic region of the material provides some additional margin.

Figure 8. HALO Setup for static load test for DLR HALO PMS-Carrier.

The load test for the PMS-Carrier was manual operated with three winches and ropes with load cells connected to the structure.

Appropriate instruction for continued airworthiness were issued with inspection programs to maintain airworthiness throughout the planned lifetime.

The advantage of this process is a relative straight and slender strategy to enter flight test for verifying the overall design. To maintain the required ELOS, there are some operational limitations connected to this approach.

1) Limited lifetime of 500 - 1000h
2) The prototype can be tested without validation of drawings and other production and quality assurance documentation. In this case it is not possible to fly a duplicated part without performing a new strength test.

In this particular case - the base aircraft is certified according to FAR 25 - additional analysis was done for substantiation of flutter safety, icing and lightning strike protection as well as bird strikes.

F. Prototyping Techniques

The antenna system for the DO 228 (Fig. 2) was built as a single prototype with *out of autoclave techniques* mainly from glass fiber reinforced plastics (GFRP) with hand layup techniques. With the white colored surface substantiation for a max. service temperature of 72°C was sufficient and prevented the need for a high temperature matrix system.

The production in low cost milled negative moulds and the simplified certification process allowed for a fast eight months process from start to final substantiation.

Figure 9. Antenna system mounted to DO228 wing.

Figure 10. Antenna system before finishing.

Ground vibration testing and theoretical flutter analysis was performed prior to maiden flight.

Structural substantiation was done by Ultimate Load testing with winches and the antennas mounted to the wing hardpoints. The applied load was controlled with load cells and deformation were measured with LVDT-sensors.

G. Noseboons

Mounting a noseboom to a glider could be considered as a simple task. If the aerodynamic performance of the aircraft must not be spoiled and specified elastic eigenmodes of the boom have to be met, it is more a design than a certification driven process to meet the requested parameters.

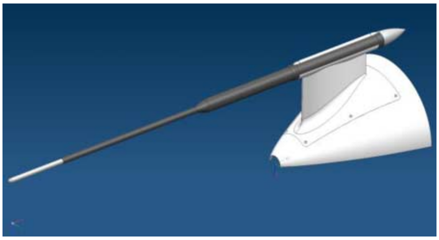

Figure 11. Noseboom Discus 2c.

The aerodynamic shape was optimized by mounting the boom on top of a pylon to avoid interference with the aircraft's aerodynamic characteristics. The requested stiffness and eigenfrequency of the boom minimized vibration effects which could affect the precision of the tip mounted 5-hole probe.

The overall eigenmodes of the aircraft and the boom were measured in a Ground VibrationTest.

Static strength was substantiated by loading the boom with appropriate masses.

The planned noseboom (Fig. 5) for the DLR ATRA (A 320) research aircraft is a much more challenging task. As it is a secondary structure which is part of a large transport aircraft, a more detailed substantiation is required.

The design is driven by the requirement for the lowest first eigenfrequency of the boom. This is derived from the aircraft's structural eigenmodes and the frequency of the von Karmann vortex street behind the circular section of the boom from the velocity component normal to the cylinder axis.

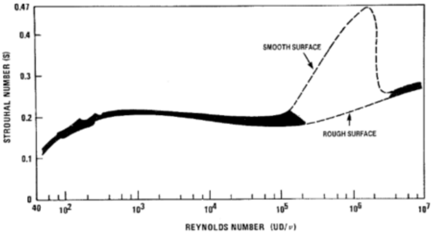

Figure 12. Strouhal number vs. Reynolds number for a circular cylinder in 2D flow [6].

A region of turbulent vortex streets with significant periodic structure exists in the range of Re = $3{\cdot}10^2$ up to $3{\cdot}10^5$, see Ref. [6]. The corresponding Strouhal number is approximately S=0.2.

Assuming a nose boom frequency of f=15 Hz and a mean diameter of D = 169 mm, a critical air speed v_P perpendicular to the boom axis of

$$v_P = \frac{f \cdot D}{S} = 12.7 \frac{m}{s}$$

Concerning the Reynolds number, the speed range in boom axes direction v_N = Re·v/D is between 0.03 m/s (Re = 3·102) and 25.93 m/s (Re =3·105) at sea level (kinematic viscosity v = 1.4607·10-5). The corresponding angles of attack are above 60° and clearly outside the flight envelope.

The preliminary design shows the noseboom structurally integrated in the radome. This avoids complex structural modifications to the forward pressure bulkhead and allows removal of the noseboom installation by changing the radome. The position of the boom above the weather radar allows for normal radar operation up to antenna inclinations of around 4° upward.

Structural substantiation will be made for material properties including damage tolerance effects, lightning strike protection, bird strike and fatigue loading.

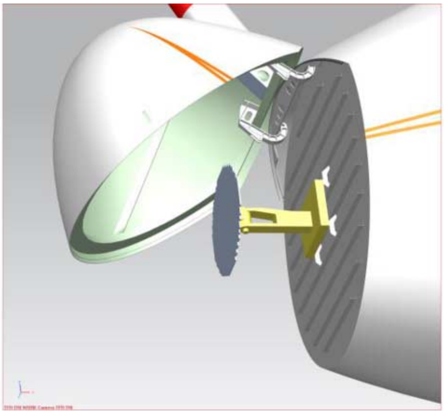

Figure 13. Integration of noseboom in radome structure.

H. Collaboration of Design Organizations

Aircraft certification requires expertise in several technical fields. Smaller companies can handle more complex projects with arrangements between different Design Organizations (DOA).

In that case DOA 1 shall hold the full responsibility for the type investigation and all supporting documents under its EASA approval. The competences of DOA2 complement the scope of work of DOA 1. Within the framework of their own DOA, DOA 2 staff is qualified, trained and capable.

DOA2 shall support DOA 1 with regards to design related activities and any other subject as defined in a DO/DO Arrangement and a project specific Statement of Work (SoW) to be signed by the Head of the Office of Airworthiness (HoOA).

DOA2 shall produce design data and compliance documents as specified in the SoW. Deliverables shall be compiled and released by DOA2. Design data produced by DOA2 and listed as deliverables to be supplied in the SoW will be incorporated in the identification and configuration system of DOA 1 to maintain configuration control.

The compliance documents compiled and released by DOA2 will be incorporated in the DOA 1 type investigation system by means of a cover sheet signed by the authorized signatories and project specific Certification Verification Engineers (CVE).

III. Conclusion

The effort for substantiation of modification to research aircraft can be optimized depending on the certification specification applicable and strategies to show an ELOS for simplified substantiation and production techniques. This can be achieved with limitations to the scope of the required certification. These can be operational limitations but also limitations to only certify one single part without the chance for reproduction.

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Upgrading a multi-mission research aircraft

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National Aerospace Laboratory NLR and Delft University of Technology, Faculty of Aerospace Engineering together operate a special aircraft for research purposes. Unlike other Special Purpose Aircraft, PH-LAB is truly a multi-mission aircraft, engaged in a wide variety of R&D in-flight research projects and often specially modified for each project. For this aircraft a significant upgrade of the aircraft avionics and data acquisition suite was designed, certified and implemented.

Nomenclature

SPA = Special Purpose Aircraft
STC = Supplemental Type Certificate

I. Introduction

SPECIAL Purpose Aircraft (SPA) are flying platforms with applications in addition to commercial air transport. When related to SPA in R&D environments, examples of SPA can be found in several fields, such as remote sensing, atmospheric research, avionics development, micro-gravity research, and the application of the SPA as flying classroom for instructional purposes.

For some R&D applications the SPA is the carrying vehicle of specific sensors: the aircraft in itself is not the research objective. These sensors need to be developed and maintained. Integration of these sensors will typically involve changes to the type certificate of the aircraft through a Supplemental Type Certificate (STC) or other means.

Operating a SPA is a demanding task in an economically challenging environment for several reasons. All expenses related to owning and operating an aircraft apply: not only direct operating costs such as fuel and landing fees, but also depreciation, insurance, maintenance, flight crew and administrative costs related to the continued airworthiness of the aircraft. Operators of a SPA will normally have a very small fleet of one or a few aircraft, so these recurring costs must be carried by a few airframes. In addition, these aircraft will normally not fly the number of hours that a passenger-carrying aircraft will make, increasing the break-even hourly rate further.

An operator of a SPA can be a small business with a very low cost structure, working with long-term contracts for a few large customers. For example in aerial survey and flight inspection of navigation aids such companies can be found. Another possibility is that a SPA is operated as a flight division inside a larger commercial company such as an avionics manufacturer, or as part of a semi-governmental institute, such as a national Meteorological Office.

Since the early Nineties the Dutch National Aerospace Laboratory NLR and Delft University of Technology Faculty of Aerospace Engineering have been operating a SPA using yet another business model by adapting a Cessna Citation II to serve as a *Multi Mission* SPA. This aircraft, call-sign PH-LAB is engaged in a wide variety of R&D in-flight research projects and often specially modified for each project. Although this means that the aircraft is often modified and adapted, the dependency on one

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or two larger contracts is not an Achilles' heel in the economic viability of such an operation. Examples of earlier deployments of the aircraft span a wide range of special missions, including Remote Sensing missions, operation as a Flying Classroom, measurement of take-off performance on contaminated runways, Sense- & Avoid technology development missions, wake vortex encounter measurements, Flight Inspection flights, implementation of a Fly-By-Wire system, volcanic ash measurement flights, and many more.

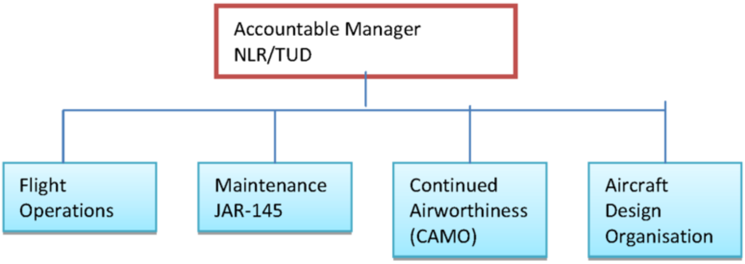
As with every research facility, the operator faced an assessment if this aircraft still meets the requirements for continued operation in its present role, or perhaps a mid-life upgrade or even a replacement was required. A business case was developed, based on the very broad and versatile mission spectrum, for the continued use of the aircraft until 2020 and beyond. Based on this business case a significant upgrade of the aircraft avionics and data acquisition suite was designed, certified and implemented in 2011.

The paper will elaborate on the modification capability applied in designing and implementing aircraft modifications in support of its multi-mission role. A broad range of missions that this SPA is involved in, as well as on some mission-specific modifications that were designed for this aircraft, will be discussed. Furthermore, the development of the Business Case for the mid-life upgrade will be explained, as well as a description of the implemented improvements to the aircraft avionics and data acquisition system.

II. Operations and Design and implementation of aircraft modifications

As a *multi-mission* SPA, the aircraft is deployed on various missions during the year, often requiring multiple modifications over the period of a number of weeks. Due to this need for frequent modifications, NLR and TUD have an agreement with the Dutch Civil Aviation Authorities (CAA-NL) where limited authority is delegated to NLR-employed approved inspectors to certify smaller modifications. When a new project requires modification or instrumentation of the aircraft, the request for this modification is forwarded to the Research Aircraft Design Organisation (RADO), a department of NLR that is capable of designing the modification. Here a judgement is made on the scope of the modification and whether it should be judged as a major, minor change. Minor changes can be approved and certified by the RADO, after which the NLR Part-145 organisation can perform the modification on the aircraft. Major changes will follow the route of a Supplemental Type Certificate (STC) via the CAA-NL. All the examples treated in this paper were designed in-house.

For every project, the flight test operations department is involved in a very early phase, even before the design of the modification starts. Generally one of the research test pilots is dedicated to the project as project pilot. He then becomes responsible for drafting the flight test schedule and functions as a consultant to the project engineers.



III. Examples of PH-LAB Special Missions

A. Integration of optical sensors

Within the framework of the European DANIELA and NESLIE research projects PH-LAB was modified to accommodate an innovative optical air data system. This system applies a LiDAR to measure the air speed vector of the aircraft. This system was evaluated during flight tests in polar, moderate and tropical regions[1].

Measuring airspeed, α and β using and optical technique works by using four laser beams, focused on a very small volume just outside the aircraft fuselage (See Figure 1). Part of the emitted laser energy is backscattered to the system's receiver by particles in the airflow, like aerosols, water and ice particles. The shifted frequency (Doppler shift) in these four returned signals is a measure for the air speeds along each of the four axes. With three out of the four axes, the aircraft's air speed vector (magnitude and direction) can be determined. A fourth axis is used to determine a consistency parameter.

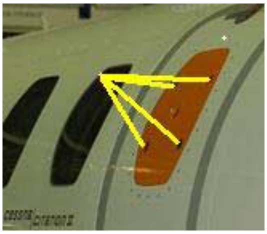


Figure 1. Alignment of four LiDAR beams for air data measurements.

To install this system the location of the existing emergency escape hatch was chosen as pass-through for the laser beams. The existing window was replaced with a aluminum plate housing four optical grade glasses. The plate was manufactured and certified at NLR and included provisions for additional stiffness as well as a system for anti-icing and defogging of the windows.

Avionics boxes for the optical system and data recording were developed and attached to the existing seat tracks in the cabin.

For this configuration the classification of the emergency hatch and cabin modifications were such that certification of it was performed internally by NLR's approved inspectors.

An extended version of this set-up was required for research into forward looking LiDAR applications, such as wake vortex or Clear Air Turbulence (CAT) detection. Within the IWAKE and DELICAT EU programs an outward protruding extension was developed to house a mirror assembly that enables the laser beam to point in the direction of flight.

As can be seen in figure 2, this extension could potentially influence the air flow into the engine and could affect aircraft handling and performance. A more extensive certification path was required that included CFD analysis and flight tests, leading to a STC for this configuration.

Figure 2. External mirror assembly for forward-looking LiDAR applications.

B. Flight Inspection

A common application of SPA is flight inspection activities for the calibration of radio navigation aids according to ICAO guidelines. NLR/TUD is responsible for flight checking all ILS, VOR, DME and TACAN facilities for Air Traffic Control The Netherlands (LVNL) and the Royal Dutch Airforce (RNLAF).

For this purpose the aircraft is equipped with an Aerodata Flight Inspection System (FIS), with specially calibrated antennas for the reception of radio signals, using a Differential GPS system as a reference. Inside the cabin a Flight Inspection console is fitted as the working position of the Flight Inspector.

Flight Inspection is a recurring activity for NLR/TUD, often performed ad-hoc or in-between research programs. For this reason the aircraft configuration is changed regularly to a flight inspection configuration and back.

Figure 3. Flight Inspector console fitted in the cabin.

C. Take-off and landing performance on contaminated runways

Following a review of accidents involving commercial jets during take-off and landing, aviation authorities in the early 1990s identified the need to update existing regulations and flight manuals. The aim of the CONTAMRUNWAY study[4] was to support legislation in reviewing the validity of the existing requirements for operation on runways contaminated by rain/snow/ice for small and commuter aircraft. This was done by measuring contaminated runway drag and the aquaplanning speed of wheels free to roll (no braking), identifying the most important parameters acting on the total drag and assess the validity of AMJ 25.1591 "Supplementary Performance information for take-off from wet runways and for operation on runways contaminated by standing water, slush, loose snow, compacted snow or ice". To do this, the aircraft was instrumented with accelerometers and wheel speed sensors and a number of take-offs, landings and ground runs were performed in standing water, dry snow and on compacted snow. Flight trials were performed at Cranfield (UK) and Skavska (Sweden).

Figure 4. Take-off and landing trials on wet and contaminated runways.

This project demonstrated that flight test activities are not restricted to the carriage of sensors, but the aircraft itself can be the object of research. It also shows that Medium and High risk flight testing is part of the activities. For this purpose, NLR/TUD apply a Flight Test Operating Manual[5], providing a regime for the preparation and execution of flight tests, including a rigorous safety assessment as part or the preparation phase.

D. Flying Classroom

Delft University has a long history of incorporating test flights in the aerospace engineering curriculum. When TU Delft and NLR acquired PH-LAB, one of the first projects was the development of the flying classroom. A central data-acquisition system was built that logs data from various sources and distributes this data via an on-board Ethernet. Touch-screen displays were installed in the seat head rests with the seats in a forward facing commuter configuration, so that six student observers can view the displays and interact with the system. A coordinator station was installed behind the cockpit divider to control the system. All bachelor students make one or two test flights during the curriculum and perform measurements on performance and flying qualities of the aircraft.

E. Fly-By-Wire testbed

In 2006, TU Delft research on developing a method to objectively and quantifiably asses the extent to which a flight simulator supports real-flight pilot behavior reached the stage where in-flight measurements became necessary. An essential part of this research was to obtain a database of multimodal, i.e., visual-vestibular pilot models in real flight.

A fly-by-wire control system including a sidestick was designed, built and certified that made it possible to fly automatic flight maneuvers and fly the aircraft with computer generated flight control signals. By introducing this fly-by-wire control system it was possible to set the conditions to properly estimate these

Figure 5. FBW controls (below glareshield), side-stick and experimental display.

pilot models.

To limit the time and expense involved with certifying FBW-control actuators, use was made of the existing autopilot control actuators. The experimental system breaks in on the existing autopilot channels. This way, it was possible to certify the experimental FBW system, without the actuators. The system can be connected to the onboard experimental computer, which allows for a very flexible setup, where different control laws can be selected during flight. Different controllers can be connected to the experimental computers, such as the side stick depicted in Figure 5.

IV. Aircraft upgrade

A. The need for a mid-life upgrade

In the previous section it was demonstrated that the business model for this SPA is based on multi-mission engagements, with the aircraft frequently undergoing (major) modifications. Approaching 20 years in service, several avionics components, such as CRT tubes, analog symbol generators and electro-mechanical instruments, were approaching the Mean Time To Repair (MTTR). In addition, new CNS requirements for the operation in European airspace were being published by Eurocontrol and others, for example the requirement for the carriage of ModeS transponders with Extended Squitter, the introduction of Performance Based Navigation and the upcoming introduction of CPDLC. Meeting these requirements meant that the existing avionics needed to be replaced to continue operations in the longer term.

Also, NLR has been selected as Associate Partner for SESAR. To be able to support future ATM related research its flying testbed should ideally be equipped with state-of-the-art avionics.

Based on these considerations and through a market analysis a Business Case was developed where it was demonstrated that the investment in a major avionics upgrade made economical sense[2].

B. Design of the new flight deck avionics and data acquisition system

Rather than simply replacing the existing avionics, a more extensive program was developed that also increased the aircraft capabilities, preparing the aircraft for a future role of ATM testbed. The following elements were incorporated in the design:

1. Replacement of the existing CRTs and electro-mechanical instruments by LCD displays. The option is created to replace the cockpit displays with experimental displays fed by workstations in the cabin;
2. Replacement of the FMS with a new UNS 1Fw SBAS enabled FMS with a Multi Mission Management System (MMMS), an ARINC-739 compliant MCDU and new ModeS transponders. This meant that the aircraft is now compliant with all present and foreseen CNS requirements;
3. Introduction of a server platform for non-essential applications, such as paperless cockpit applications, synthetic vision, ASAS and datalink applications;
4. An Integrated Avionics Processor System (IAPS) provides single-point access to all parameters on the ARINC-429 databus. This means a significant simplification of the data acquisition system.
5. Replacement of attitude gyros by a dual Attitude Heading Reference System (AHRS). For many flight tests an Inertial Navigation System (INS) is fitted in the cabin as reference for attitude information. These instrument grade INSes are expensive to maintain and are approaching their end-of-life cycle. When required, accurate attitude information can now be derived from the AHRS.

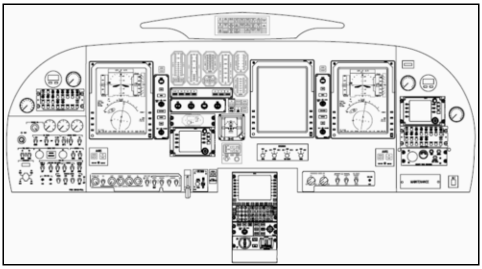


Figure 5. Schematic overview of modified flight deck.

6. Replacement of existing communication and navigation equipment, Radio Control Units, Weather Radar, TAWS, TCAS, Air Data Computers, CVR and Standby Instruments.

One special point of attention had to be given to the requirement to prepare the aircraft for possible research projects with experimental displays fitted in the aircraft. The design was chosen to accommodate possible experimental displays on the right hand side of the aircraft, replacing the number 2 and 3 screens. To meet dispatch requirements an Integrated Standby Instrument System (ISIS) was added to the design, and a third independent attitude indicator was retained. This enables the aircraft to be dispatched with only the pilot flight display. Because it was envisaged that external (test)pilots will be invited for the evaluation of such displays this meant that possibly a non-typerated pilot must be accomodated. As the C550 is certified as a two-pilot aircraft, a Single Pilot waiver was sought for possible test flights with an external pilot occupying the right seat.

C. Certification

For the modification use was made of an existing Transport Canada STC. This STC was then subsequently changed to meet NLR/TUD requirements, such as the Single Pilot requirement and a change in flight deck instruments lay-out. This STC was submitted to EASA for transfer.

In addition, a second STC was developed as PH-LAB is not a standard C550. Several minor structural and wiring differences existed that were addressed in a separate STC that was submitted to CAA-NL.

For both the transfer of the existing STC as for the national STC a certification program was required that included ground- and flight tests. Also, for the operational approval for Single Pilot operations a flight test schedule was performed.

The certification effort was initiated well in advance of the actual modification and spanned almost one calendar year, the total downtime of the aircraft was approximately 3 months.

V. Conclusion

Operating a SPA can be done using different business models. NLR/TUD have chosen to adapt a modus operandus where the aircraft serves as a Multi Mission SPA. As a consequence the aircraft is modified frequently, changing the configuration of the aircraft on a regular basis. These modifications can be limited to changes in the instrumentation, but can also require obtaining an STC for the modified configuration and thus requiring a substantial certification effort. To support the aircraft in this multi-mission role, an operational, maintenance, continued airworthiness and design organisation is required.

For this aircraft and its specific role it was possible to develop a business case for the development of a new flight deck and data acquisition system based on an integrated design. Preparing the aircraft for future ATM research was a focal point of the design. Almost all avionics were replaced and the aircraft was prepared for Single Pilot operations with experimental displays. A bundle of EASA and national STCs, together with additional Operational Approvals, was required to continue operating this aircraft in its role as Multi Mission SPA.

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Part III

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Modelling of Human Performance-Related Hazards in ATM

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Existing approach towards agent-based safety risk analysis in Air Traffic Management (ATM) covers hazards that may potentially occur within air traffic operations along two ways. One way is to cover hazards through agent-based model constructs. The second way is to cover hazards through bias and uncertainty analysis in combination with sensitivity analysis of the agent-based model. The disadvantage of the latter approach is that it is more limited in capturing potential emergent behaviour that could be caused by unmodelled hazards. The research presented in this paper explores to what extent agent-based model constructs that have been developed for other purposes, are capable to model more hazards in ATM through the agent-based framework. The focus is on model constructs developed by VU Amsterdam, mainly addressing human factors and interaction between multiple (human and computer) agents within teams. Inspired by a large data base of ATM hazards analysed earlier, a number of VU model constructs are identified that have the potential to model remaining hazards. These model constructs are described at a conceptual level, and analysed with respect to the extent at which they increase the percentage of modelled hazards in ATM.

I. Introduction

ATM is a joint cognitive system in which a large variety of human and technical agents interact with each other[22]. Thanks to these interactions, they jointly cope in an intelligent manner with the various disturbances that may be caused by the environment. For example, an unexpected weather front or thunderstorm may trigger a sequence of activities that ripples through several agents in the joint cognitive system, all with the aim to establish an effective and safe re-organisation of the air traffic.

The scientific discipline which studies the design of such intelligent joint cognitive systems is known under the name Resilience Engineering[21,23]. Resilience indicates that operations and organisations are able to resist a wide variety of demands within their domains and thus should be able to recover from any condition in their domains that may disturb the stability of the operation or organisation. This implies that resilience engineering aims to address a wide range of nominal and non-nominal conditions. Resilience engineering has some common grounds with safety analyses, where non-nominal conditions often are referred to as hazards. In spite of this commonality between resilience engineering and traditional safety analysis, there also are two significant differences:

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1. Resilience engineering emphasises much more the potential ways human agents in the joint cognitive system can respond in a flexible way to the various nominal and non-nominal conditions, rather than quantifying safety risks of various non-nominal conditions.
2. Focus of traditional safety analysis (e.g., Ref. 13) is on hazards that can be analysed using linear causation mechanisms (e.g. fault/event trees); the consequence of which is that a significant part of nominal and non-nominal conditions tend to fall out of sight.

The flexibility of human responses is especially important to respond well when the air traffic situation evolves into a condition for which the procedures are no longer unambiguous. From a resilience engineering perspective this means that we should find out what these kind of non-nominal conditions are and how humans anticipate upon their potential evolution from a nominal condition into a non-nominal condition.

For a joint cognitive system as complex as ATM is, resilience engineering is at an early stage of development. During recent years novel psychological model constructs have been studied in capturing human cognition and its interaction with other joint cognitive system entities[21,23]. The results currently obtained also demonstrate that there are non-psychological challenges when it comes to a systematic analysis of the combinatorially many potential behaviours that may stem from external and internal events and the subsequent interactions between the various entities in the joint cognitive system.

To support a more systematic analysis, the MAREA (Mathematical Approach towards Resilience Engineering in ATM) project aims to develop a mathematical modelling and analysis approach for resilience engineering in ATM. As a first step, in a previous phase of the project, a large data base of hazards in ATM has been identified, including ways that pilots and controllers deal with them. In addition, a systematic analysis has been performed to assess which hazards from the set are and which are not modelled by existing multi-agent model constructs of the TOPAZ (Traffic Organization and Perturbation AnalyZer) safety assessment methodology[1,2]. This analysis[37] indicates that 58% of the hazards in the ATM Hazard Database are modelled well, 11% are partly modelled, and 30% of the hazards are not modelled. Although the TOPAZ approach evaluates the unmodelled hazards through bias and uncertainty analysis[14], this limits the capability in identifying emergent behaviour that would be due to unmodelled hazards.

In the next phase of the project, which is the main topic of the current paper, the analysis mentioned above is used as input for a follow-up analysis. The main goal of this second analysis is to explore whether the percentage of hazards from the database that are modelled can be (substantially) increased by taking other agent-based model constructs into account that have been developed outside the air transport safety analysis domain. The focus in this analysis is on model constructs that have been (co-)developed by the Agent Systems research group at VU University Amsterdam and are based on a large body of literature in the areas of human factors and agent-based modelling. In total, in this paper 11 novel model constructs are identified, which address human factors topics such as trust, visual attention, and handling confusing information in maintaining situation awareness and decision making. For each model construct, a high level description is provided of the concepts that play a role in the model as well as the functioning of the model. Moreover, by an informal comparison, the 11 model constructs are matched against all hazards in the database. During this comparison, for each hazard-model construct combination, the nature of the hazard in question is studied and by performing 'mental simulation' (i.e., imagining that the model construct in question is actually executed) the analyst assesses whether this 'simulation' is able to reproduce the hazard.

This paper is structured as follows. Section 2 provides a brief, high level description for all of the existing VU-model constructs that are identified as being relevant for agent-based modelling of remaining hazards. Section 3 presents an analysis of the extent to which the TOPAZ and VU-model constructs are capable of modelling the hazards from the database. Section 4 concludes the paper with a discussion and an overview of follow-up research.

II. Overview of VU-Model Constructs

The focus of the analysis described in this paper is on model constructs that have been developed according to the multi-agent modelling and analysis approach used by the Agent Systems research group at VU University Amsterdam[4,5]. This choice is motivated by the fact that the VU approach is well in line with the multi-agent view for safety analysis that is advocated in the MAREA project[37], which is reflected in the earlier phase of the project (in which a list of model constructs was identified that follow the multi-agent DRM modelling paradigm of the TOPAZ methodology[1,2]). Similar to multi-agent DRM modelling, the VU approach also takes an agent-based perspective, where an agent may represent any autonomous entity (i.e., both a human and a technical system) that is able to make decisions and interact with its environment by communication, observation and actions. The approach attempts to describe the dynamics of agent systems by sequences of states of the world over time, and expresses the basic mechanisms that lead to those sequences as causal/temporal relations in some formal language (see below for more details). Furthermore, the VU Agent Systems research group has extensive experience in developing dynamical computational models for human-related processes that play a role within socio-technical systems (including ATM), such as decision making, situational awareness, and visual attention. These computational models are based on a large body of literature in the areas of human factors and agent-based modelling. For this reason, the focus of the current work package is on model constructs developed by this research group.

In this section, existing model constructs (co-)developed by VU that were identified as being applicable in the current project, are described at a conceptual level. Note that, although the model constructs are only presented in an informal notation here, each of them has a precise formal definition, which can be found in the corresponding paper(s). In principle, all of the presented models have been developed on the basis of a standard methodology developed by the Agent Systems group at VU Amsterdam. This methodology is inspired by the assumption that real world processes can be described by sequences of states of the world over time, and that the basic mechanisms that lead to those sequences can be expressed as causal/temporal relations in some formal language. To this end, to formalise the model constructs, the generic modelling language (and software environment) TTL[4] (Temporal Trace Language) and its executable sublanguage LEADSTO[5] (Language and Environment for Analysis of Dynamics by SimulaTiOn) are often used. These languages are hybrid in the sense that they combine logical/qualitative aspects (e.g., as in rule-based systems) with mathematical/quantitative aspects (e.g., as in dynamical systems/differential equation modelling). They also allow the modeller to represent probabilistic aspects. In the following paragraphs, these formal details have been left out, since their main aim is to provide a high-level overview of the concepts and relationships that play a role in the selected model constructs. For more technical details of the languages TTL and LEADSTO, see Ref. 4 and 5, respectively.

In the following sub-sections, model constructs are presented for 11 processes related to human behaviour in ATM that were considered useful within MAREA.

A. Bottom-up Attention

This model construct[8] describes the development of a human's state of attention over time. The model construct has been developed in the context of operators that have to perform demanding tasks in dynamic environments. The human's 'state of attention', which roughly refers to all objects in the environment that are in the person's working memory at a certain time point, is defined as a distribution of values over different locations in the environment. The model continuously calculates this state of attention based on a number of factors, including the person's gaze direction, the locations of the objects involved, and the characteristics of these objects (such as their brightness and size). More precisely, the extent to which a location attracts attention is calculated as the weighted sum of the attention-drawing characteristics of all objects at the location divided by the Euclidean distance between the location and the point of gaze. Next, for each location, this level of attraction is combined with the old level of attention, in order to determine the new level of attention for that location. In addition, a decay mechanism ensures that attention gradually decreases over time for locations that are not observed.

B. Experienced-Based Decision Making

For the process of experience-based decision making, two model constructs have been identified, which are described in Ref. 34 and 36 respectively.

The first model construct[34] is based on the Expectancy Theory by Vroom, as described in Ref. 31. According to this theory, when a human evaluates alternative possibilities to act, he or she explicitly or implicitly makes estimations for the following factors: *valence* V{i}, *expectancy* E{i,j} and *instrumentality* I{i,j,k}. The estimation consists of: first determining the outcomes of an action alternative, and then evaluating how desirable are these outcomes for the agent (i.e., evaluation w.r.t. the agent's goals). For example, reporting of a safety incident may lead to the team's approval, which is desired by the agent.

Expectancy refers to the individual's belief about the likelihood that a particular act will be followed by a particular outcome (called a first-level outcome). Its value varies between 0 and 1. Instrumentality is a belief concerning the likelihood of a first level outcome resulting into a particular second level outcome; its value varies between -1 and +1. Instrumentality takes negative values when a second-level outcome has a negative correlation with a first-level outcome. A second level outcome represents a desired (or avoided) state of affairs that is reflected in the agent's needs. In the proposed approach the original expectancy model is refined by considering specific types of individual needs described above. Valence refers to the strength of the individual's desire for an outcome or state of affairs; it is also an indication of the priority of needs. Values of expectancies, instrumentalities and valences change over time, in particular due to individual and organisational learning.

The second model construct[36] is based on the *simulation hypothesis* proposed by Hesslow[17]. Hesslow argues that emotions may reinforce or punish simulated actions, which may transfer to overt actions, or serve as discriminative stimuli. To realise this idea, Damasio's *Somatic Marker Hypothesis*[11] was adopted. This hypothesis provides a central role in decision making to emotions felt. Within a given context, each represented decision option induces (via an emotional response) a feeling which is used to mark the option. For example, a strongly negative somatic marker linked to a particular option occurs as a strongly negative feeling for that option. Similarly, a positive somatic marker occurs as a positive feeling for that option. To realise the somatic marker hypothesis in behavioural chains, emotional influences on the preparation state for an action are defined. Through these connections emotions influence the agent's readiness to choose the option. From a neurological perspective, the impact of a sensory state to an action preparation state via the connection between them in a behavioural chain will depend on how the consequences of the action are felt emotionally.

C. Operator Functional State

The operator functional state (OFS) model construct[3] has also been developed in the context of operators that have to perform demanding tasks in dynamic environments. The model determines a person's *functional state* as a function of task properties and personal characteristics. The model is based on two different theories: (1) the cognitive energetic framework[19], which states that effort regulation is based on human recourses and determines human performance in dynamic conditions, and (2) the idea, that when performing sports, a person's generated power can continue on a *critical power* level without becoming more exhausted[18]. The FS of a human represents a dynamical state of the person. In the model, this is defined by a combination of factors, including exhaustion, motivation and experienced pressure, but also the amount of generated and provided effort. All of these factors are represented as a real number between 0 and 1, and their mutual influences are represented by a set of differential equations. For a more detailed description, see Ref. 1.

D. Information Presentation

This model construct[30] consists of two interacting dynamical models, one to determine the human's functional state and one to determine the effects of the chosen type and form of information presentation. The dynamic model for the functional state used was adopted from Ref. 1 and is described in the previous section. The interaction from the model for information presentation to this model for functional state takes place by affecting the task demands: *processing demand* in the information presentation model has input to *task demands* in the functional state model.

The general paradigm of the relations within the presentation model is partially based on existing models on workload that consider the fit between individual factors, such as coping capacity, effort, motivation, on one side and work demands on the other side. One example of such a model can be found in Ref. 29. This paradigm has been applied to the fit between the effort that a human is willing to invest while performing a task and demand. Effort is determined by internal and external factors while demand is imposed externally.

Presentation format aspects can be seen as a part of task demands that are imposed on a person because a form of a presentation may change processing demands. On the other hand, some presentation aspects, for example, background colour and luminance, can be seen as available resources that help a person to perform a task. Luminance is regarded both as a part of demands and as a part of resources in this model. All types of aspects converge into two more global internal factors that influence the task performance: physiological state of *alertness* and mental *information processing* state of an operator. Among these concepts a distinction is made between the states of available and used resources of alertness and information processing, *alertness utilisation* and *available effort* respectively, and the states of demand for alertness and information processing, *alertness demand* and *processing demand*. The fit between the usage of these capacities and the demands determines the functioning of a human while performing a task, the *functioning fit*. Two specific types of fit are considered: *alertness fit* and *processing fit*.

If the usage of capacities and demands are at the same level, the fits will be high. If the levels of capacities and demands differ much, then the fits will be low. If both *alertness fit* and *processing fit* are high, then the *functioning fit* will be high. The absolute difference between capacities and demands is evaluated, and there is no distinction between the situations of high capacity and low demand vs. low capacity and high demand, because in the context of the given model both situations are not efficient with respect to the usage of resources and correspond to poor fit.

E. **Safety Culture**

The model construct for safety culture is extensive and can be found in detail in Ref. 35. In this paper, an application of the model to an occurrence reporting cycle is presented in the context of an existing air navigation service provider. The main purpose of modelling was to establish how safety culture described by a set of safety culture indicators related to safety occurrence reporting emerges from the organisational structures and processes. The organisational model was specified using the framework described in Section 2H below. It includes national culture aspects based on the cultural framework by Hofstede[20], in particular, *individualism* (IDV) - the degree to which individuals are integrated into groups; *power distance index* (PDI) - the extent to which the less powerful members of an organisation accept that power is distributed unequally; and *uncertainty avoidance index* (UAI) dealing with individual's tolerance for uncertainty and ambiguity.

One of the important internal states considered in the model is the agent's commitment to safety. Commitment to safety is determined largely by the agent's maturity degree and the agent's tasks. In the theory of situational leadership[16] the agent's maturity w.r.t. to a task is defined as an aggregate of the agent's experience, willingness and ability to take responsibility for the task. The agent's willingness to perform a task is determined by the agent's confidence and commitment, which are necessary for the air traffic control (ATC) task execution. The ability of an agent to perform a task is determined by its knowledge and skills. The maturity value changes over time as a result of gaining new knowledge and skills, and changing self-confidence of a controller.

In the model, the adequacy of the mental models for the ATC tasks depends on the sufficiency and timeliness of training provided to the controller and the adequacy of knowledge about safety-related issues. Such knowledge is contained in reports that resulted from safety-related activities: final occurrence assessment reports resulted from occurrence investigations and monthly safety overview reports.

The agent's commitment to safety is also influenced by the perceived commitment to safety of other team members and the management. An agent evaluates the management's commitment to safety by considering factors that reflect the management's effort in contribution to safety (investment in personnel and technical systems, training, safety arrangements). The perception of an agent of the average commitment to safety of its team is based on the perception of commitment to safety of the team supervisor and of other team members.

In such a way, the commitment value is calculated based on a feedback loop: the agent's commitment influences the team commitment, but also the commitment of the team members and of the management influence the agent's commitment.

F. **Situation Awareness**

The model construct for situation awareness[26] (SA) consists of four main components. Three components are in line with the model of Endsley[12], which includes the perception of cues, the comprehension and integration of information, and the projection of information for future events. In addition, the model extends the model presented in Ref. 12 by incorporating some sophisticated AI-based inference algorithms based on mental models, as well as the notion of aggregated complex beliefs.

The model functions as follows. Initially, the agent starts to observe within the world, and obtains the results of these observations. These results are forwarded to the component responsible for the formation of beliefs about the current situation. In this component, two types of beliefs are distinguished, namely *simple beliefs*, and *complex beliefs*. The simple beliefs concern simple statements about the current situation that have a one-to-one mapping to observations, or have a one to one mapping to another simple belief (e.g., I believe that an aircraft is ready for takeoff based upon my observed communication about this). The complex beliefs are aggregations of multiple beliefs and describe the situation in a composed manner. Both types of beliefs are represented in a hybrid language, including both qualitative information (namely the information that the belief is about) and quantitative information (namely a real number representing the time point to which the belief refers, and a real number representing the strength of the *activity* of the belief in the mind of the agent). Using the knowledge stored in the mental model (represented in terms of causal/temporal relationships, see Ref. 26 for technical details), the component first of all derives simple beliefs about the situation. Thereafter, the complex beliefs are derived from the simple beliefs, again using the knowledge stored in the mental models. In case a complex belief is composed of multiple beliefs that are in conflict, this complex belief will have a lower activation value (i.e., the agent is less certain about it). In order to project the complex beliefs to the future situation, they are forwarded to the component belief formation on future situation. Herein, again a mental model is used to make the predictions. The judgment of the future situation that then follows is used to direct the observations of the agent.

G. Trust

For the concept of trust, five closely related model constructs have been identified. Trust is based on a number of factors, an important one being the agent's own experiences with the subject of trust; e.g., another agent. All five models in this section are based on this notion of experiences. The basic model is presented in Ref. 28; all other models are variants and/or extensions of this model. According to this basic model, each event that can influence the degree of trust is interpreted by the agent to be either a *trust-negative experience* or a *trust-positive experience*. If the event is interpreted to be a trust-negative experience the agent will lose his trust to some degree, if it is interpreted to be trust-positive, the agent will gain trust to some degree.

The first model is a simple qualitative model that assumes four discrete trust states (unconditional trust, conditional trust, conditional distrust, unconditional distrust) and transitions between these states based on experiences. In Ref. 28 it is also explained how this model can be converted to a quantitative model, where the four trust states are replaced by a simple numerical trust value (in the domain [0,1]), and the transitions are replaced by mathematical formulae. The four other models extend this basic model in various ways. In particular, the second model[25] addresses relative trust (i.e., the idea that trust in one entity has an impact on the trust in other entities) and the notion of exploration of trustees during decision making (i.e., exploring their trustworthiness by having interactions with them). The third model[32] addresses affective factors (e.g., the interaction between feelings triggered by certain entities and the trust in those entities). The fourth model[27] addresses population-based trust (i.e., the notion of a collective trust state of a whole group of agents in one particular entity), and the fifth model[24] addresses biased trust (where biases refer, for instance, to the phenomenon of having more trust in agents within the own social group).

H. Formal Organisation

This model construct[33] can be used to model formal organisations from three interrelated perspectives (views): the process-oriented view, the performance-oriented view, and the organisation-oriented view. A formal organisation is imposed on organisational agents, described in the agent-oriented view. The internal structures and behaviour of agents are not defined by the formal organisation. Agents may or may not follow the prescriptions of the formal organisation.

The process-oriented view contains information about the organisational functions, how they are related, ordered and synchronised and the resources they use and produce. The main concepts are: task, process, and resource type, which, together with the relations between them, are specified in a formal language. A *task* represents a function performed in the organisation and is characterised by *name*, *maximal* and *minimal duration*. Tasks can range from very general to very specific. General tasks can be decomposed into more specific ones using AND- and OR-relations thus forming hierarchies. A *workflow* is defined by a set of (partially) temporally ordered *processes*. Each process is defined using a task as a template and inherits all characteristics of the task. Decisions are also treated as processes associated with decision variables taking as values the possible decision outcomes. The (partial) order of execution of processes in the workflow is defined by sequencing, branching, cycle and synchronisation relations specified by the designer.

Tasks use/consume/produce resources of different types. Resource types describe tools, supplies, components, data or other material or digital artifacts and are characterised by *name*, *category* (discrete, continuous), *measurement_unit*, *expiration_duration* (the length of the time interval when a resource type can be used). Resources are instances of resource types and inherit their characteristics, having, in addition, *name* and *amount*. Some resources can be shared, or used simultaneously, by a set of processes (e.g., storage facilities, transportation vehicles). Alternative sets of processes sharing a resource can be defined.

Central notions in the performance-oriented view are goal and performance indicator (PI). A PI is a quantitative or qualitative indicator that reflects the state/progress of the company, unit or individual. The characteristics of a PI include, among others: *type* – continuous, discrete; *unit* of measurement; *time_frame* – the length of the time interval for which it will be evaluated; *scale* of measurement; *source* – the internal or external source used to extract the PI: company policies, mission statements, business plan, job descriptions, laws, domain knowledge, etc.; *owner* – the performance of which role or agent does it measure/describe; *hardness* – soft or hard, where soft means not directly measurable, qualitative, e.g. customer's satisfaction, company's reputation, employees' motivation, and hard means measurable, quantitative, e.g., number of customers, time to produce a plan.

PIs can be related through various relationships. The following are considered in the framework: (strongly) positive/negative causal influence of one PI on another, positive/negative correlation between two PIs, aggregation – two PIs express the same measure at different aggregation levels. Such relationships can be identified using e.g. company documents, domain knowledge, inference from known relations, statistical or data mining techniques, knowledge from other structures of the framework. Using these relations, a graph structure of PIs can be built.

Based on PIs, PI expressions can be defined as mathematical statements over PIs that can be evaluated to a numerical, qualitative or Boolean value. They are used to define goal patterns. The *type* of a goal pattern indicates the way its property is checked: *achieved (ceased)* – true (false) for a specific time point; *maintained* (*avoided*) – true (false) for a given time interval; *optimised* – if the value of the PI expression has increased, decreased or approached a target value for a given interval.

Goals are objectives that describe a desired state or development and are defined by adding to goal patterns information such as desirability and priority. The characteristics of a goal include, among others: *priority*; *evaluation type* – achievement goal (based on achieved/ceased pattern – evaluated for a time point) or development goal (based on maintained/avoided/optimised pattern – evaluated for a time interval); *horizon* – for which time point/interval should the goal be satisfied; *hardness* – hard (satisfaction can be established) or soft (satisfaction cannot be clearly established, instead degrees of *satisficing* are defined); *negotiability*.

A goal can be refined into sub-goals forming a hierarchy. Information about the satisfaction of lower-level goals can be propagated to determine the satisfaction of high-level goals. A goal can be refined into one or more alternative goal lists of AND-type or balanced-type (more fine-tuned ways of decomposition - inspired by the weighted average function). For each type, propagation rules are defined.

In the organisation-oriented view organisations are modelled as composite roles that can be refined iteratively into a number of (interacting) composite or simple roles, representing as many aggregation levels as needed. The refined role structures correspond to different types of organisation constructs (e.g., groups, units, departments). Yet many of the existing modelling frameworks are able to represent only two or three levels of abstraction: the level of a role, the level of a group composed of roles, and the overall organisation level. The organisation-oriented view provides means to structure and organise roles by defining interaction and power relations on them.

One of the aims of an organisational structure is to facilitate the interaction between the roles that are involved into the execution of the same or related task(s). Therefore, patterns of role interactions are usually reflected in an organisation structure. Each role has an input and an output interface, which facilitate in the interaction (in particular, communication) with other roles and the environment.

Besides interaction relations, also power relations on roles constitute a part of the formal organisational structure. Formal organisational power (authority) establishes and regulates normative superior-subordinate relationships between roles. Authority relations are defined w.r.t. tasks. Roles have rights and responsibilities related to different aspects of tasks (e.g., execution, monitoring, consulting, and making technological and/or managerial decisions). Roles with managerial rights may under certain conditions authorise and/or make other roles responsible for certain aspects of task execution. In many modern organisations rewards and sanctions form a part of authority relation, thus, they are explicitly defined by appropriate language constructs.

I. Learning

This model construct[38] addresses learning in the context of decision making. In decision making tasks different options are compared in order to make a reasonable choice out of them. Options usually have emotional responses associated to them, relating to a prediction of a rewarding or aversive consequence. In decisions such an emotional valuing often plays an important role. In recent neurological literature this has been related to a notion of value as represented in the amygdala. In order to learn the emotional responses, experiences with the environment (from the past) are used. Hence, by learning processes the decision making mechanism is adapted to these experiences, so that the decision choices made are reasonable or in some way rational, given the enviroment reflected in these past experiences.

The computational model is based on such neurological notions as valuing in relation to feeling, body loop and as-if body loop[11]. The adaptivity in the model is based on Hebbian learning[15].

J. Goal-oriented attention

This model construct[7] describes how an 'ambient' agent (either human of artificial) can analyse another agent's state of attention, and to act according to the outcomes of such an analysis and its own goals. This process requires some specific facilities:

A *representation of a dynamical model* is needed describing the relationships between different mental states of the other agent. Such a model may be based on qualitative causal relations, but it may also concern a numerical dynamical system model that includes quantitative relationships between the other agent's mental states. In general such a model does not cover all possible mental states of the other agent, but focuses on certain aspects, for example on beliefs and desires, on emotional states, on the other agent's awareness states, or on attentional states. In this case, indeed a model of (bottom-up) attention is used for this (as described in Section 2A).

Furthermore, *reasoning methods to generate beliefs on the other agent's mental state* are needed to draw conclusions based on the attention model and partial information about the other agent's mental states. This may concern deductive-style reasoning methods performing forms of simulation based on known inputs to predict certain output, but also abductive-style methods reasoning from output of the model to (possible) inputs that would explain such output.

Moreover, when in one way or the other an estimation of the other agent's mental state has been found out, it has to be *assessed whether there are discrepancies* between this state and the agent's own goals. Here also the agent's self-interest comes in the play. It is analysed in how far the other agent's mental state is in line with the agent's own goals, or whether a serious threat exists that the other agent will act against the agent's own goals.

Finally a *decision reasoning model* is needed to decide how to act on the basis of all of this information. Two types of approaches are possible. A first approach is to take the other agent's state for granted and prepare for the consequences to compensate for them as far as these are in conflict with the agent's own goals, and to cash them as far as they can contribute to the agent's own goals (*anticipation*). For the case of air traffic control, an example of anticipation is when it is found out that the other agent has no attention for a particular object, and it is decided that another colleague or computer system will handle it (dynamic task reallocation). A second approach is not to take the other agent's mental state for granted but to decide to try to get it adjusted by affecting the other agent, in order to obtain a mental state of the other agent that is more in line with the agent's own goals (*manipulation*). Both approaches can be used for training as well as for real world support.

K. Extended Mind

This model construct[6] represents the philosophical notion of an *extended mind*, which can be roughly defined as an 'external state of the environment that has been created by an agent and helps this agent in its mental processing'[10]. The model can be used to explain the similarities and differences between reasoning based on internal mental states (e.g., beliefs) and reasoning based on external mental states (e.g., notes on a piece of paper, or flight process strips in an aviation context).

To illustrate the model, think of a scenario where a person reads a user manual in order to build a closet. In this case, according to a normal situation, the human would first read this manual, would then generate a belief about how the closet should be built, after which (s)he would actually build the closet, resulting in the actual presence of the closet. In terms of the extended mind model, instead of an internal belief about the closet, an external mental state is used. This state could represent, for instance, a picture that the person drew on paper. Thus, instead of remembering how the closet should be built, these instructions are written down, after which they are read and executed.

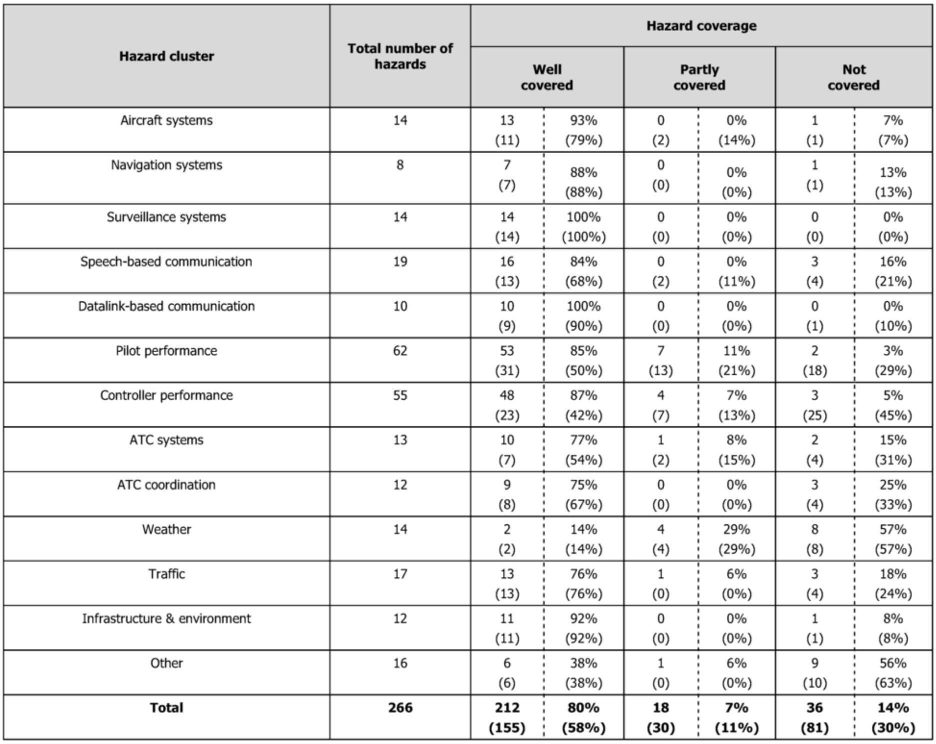
This model illustrates that for a concrete task, the consequences of using an 'extended mind' state are on the one hand that less internal states (thus: less cognitive capabilities) have to be exploited in the reasoning process. On the other hand, a more intensive interaction with the external world (in the sense of continuously creating and observing the external mental state) is needed. In terms of situation awareness, this could be represented by making some beliefs (which in a way are replaced by the external mental states) less easily accessible.

III. Coverage of Hazards by Model Constructs

In the previous section, a total of 11 agent-based model constructs (co-)developed by VU are described. In the current section it is analysed to what extent these model constructs extend the hazard modelling capability of the existing TOPAZ agent-based model constructs assessed in Ref. 37.

The assessment whether hazards are 'covered' by a certain model construct is here done in an informal way. That is, for each hazard-model construct combination, the nature of the hazard in question was studied and by performing 'mental simulation' (i.e., imagining that the model construct in question was actually executed) the analyst would assess whether this 'simulation' could reproduce the hazard as described in Ref. 37. Thus, in some cases full modelling of a particular hazard could be done by a combination of multiple model constructs.

Table 1. Coverage of Hazards per Cluster. *Between brackets are the results obtained in Ref. 37.*



Hazard cluster	Total number of hazards	Hazard coverage					
		Well covered		Partly covered		Not covered	
Aircraft systems	14	13 (11)	93% (79%)	0 (2)	0% (14%)	1 (1)	7% (7%)
Navigation systems	8	7 (7)	88% (88%)	0 (0)	0% (0%)	1 (1)	13% (13%)
Surveillance systems	14	14 (14)	100% (100%)	0 (0)	0% (0%)	0 (0)	0% (0%)
Speech-based communication	19	16 (13)	84% (68%)	0 (2)	0% (11%)	3 (4)	16% (21%)
Datalink-based communication	10	10 (9)	100% (90%)	0 (0)	0% (0%)	0 (1)	0% (10%)
Pilot performance	62	53 (31)	85% (50%)	7 (13)	11% (21%)	2 (18)	3% (29%)
Controller performance	55	48 (23)	87% (42%)	4 (7)	7% (13%)	3 (25)	5% (45%)
ATC systems	13	10 (7)	77% (54%)	1 (2)	8% (15%)	2 (4)	15% (31%)
ATC coordination	12	9 (8)	75% (67%)	0 (0)	0% (0%)	3 (4)	25% (33%)
Weather	14	2 (2)	14% (14%)	4 (4)	29% (29%)	8 (8)	57% (57%)
Traffic	17	13 (13)	76% (76%)	1 (0)	6% (0%)	3 (4)	18% (24%)
Infrastructure & environment	12	11 (11)	92% (92%)	0 (0)	0% (0%)	1 (1)	8% (8%)
Other	16	6 (6)	38% (38%)	1 (0)	6% (0%)	9 (10)	56% (63%)
Total	**266**	**212** **(155)**	**80%** **(58%)**	**18** **(30)**	**7%** **(11%)**	**36** **(81)**	**14%** **(30%)**

A detailed overview of the results of this analysis is presented in Ref. 9. This document shows for each hazard if it can be (partly) modelled and by which combination of TOPAZ and VU model constructs. Based on this analysis, Table 1 provides an overview of the numbers of hazards that are (partly) covered by (one or more TOPAZ and/or VU) model constructs per hazard cluster (as defined in Ref. 37). The numbers between brackets indicate the model coverage based on the TOPAZ model constructs that were already identified in Ref. 37.

Due to space limitations, the detailed analysis explaining which model constructs can be used to cover which hazard is not included in this paper (see Ref. 9 for this purpose). However, a sketch of such an analysis for one individual hazard is as follows. Hazard #325 is defined as "improper use of flight progress strips". For coverage of this hazard, two model constructs were considered relevant, namely the model constructs for situation awareness (Section 2F) and extended mind (Section 2K). The underlying explanation is that flight progress strips can be represented within the extended mind model construct as an 'extended mental state'. Since this mental state has to be created and observed by the controller, an additional point for potential error is introduced in the creation of this state. Next, within the situation awareness model construct, these flight progress strips play the role of the mental model upon which situation awareness is built. Hence, in case this mental model is impaired, the creation of correct situation awareness will also be influenced negatively.

As can be seen in Table 1, complementing the existing TOPAZ model constructs with the library of model constructs (co-)developed by VU has led to a significantly increased percentage in agent-based model coverage of hazards. In particular, 80% of the generalised hazards is now well captured by the considered combination of model constructs (which was 58% based on the existing TOPAZ model constructs), 7% is partly captured (which was 11%), and 14% is not captured (which was 30%).

When analysing the table in detail, it is evident that the largest gain was made in the human performance-related hazard clusters (Pilot performance, Controller performance). This also shows that the clusters that still have significant percentages of unmodelled hazards are related to 'Weather' and 'Other'.

IV. Conclusion

In this paper, 11 model constructs (co-)developed by VU have been identified, and by an informal comparison these model constructs have been found capable of modelling many of the remaining hazards identified in Ref. 37. In particular, the percentage of hazards that has thus been found to be well modelled has increased from 58% to 80%. The largest gain in percentage comes from human related hazards. In particular, the percentage in modelling hazards related to pilot performance increases from 50% to 85% and for controller performance related hazards from 42% to 87%.

The identification of these 11 complementary model constructs forms an important step in improving the modelling of hazards in ATM. In subsequent stages of the MAREA project, additional agent-based model constructs will be identified through exploring other literature sources, and the integration of all model constructs will be addressed. In particular order to fully assess the applicability of the model constructs, they will be tailored to the ATM domain, formalised and potentially be integrated with other model constructs. Since the model constructs have been set up in a generic manner, no large changes in their structure are expected. For example, the Extended Mind model can be applied to the ATM domain in a rather straightforward manner, by defining flight progress strips as a particular instance of an 'external mental state', and defining the interaction that an operator has with such strips in terms of the observation and action states that are part of the model. Moreover, to fully explore the emergent behaviour of a complex system like ATM from a Resilience Engineering perspective, the integration of multiple model constructs will be an important next step. This integration may be achieved in various ways. For instance, the Operator Functional State model (OFS) may be connected to the Bottom-up Attention model by establishing an explicit relation between the experience pressure state in the OFS model and the available attention state in the Attention model (e.g., by stating that more experienced pressure leads to less available attention). Other potential combinations include the integration of the Decision Making (DM) model with the Situation Awareness (SA) model, the integration of the DM model with the Trust model, the integration of the SA model with the OFS model, and the integration of the SA model with the Trust model.

In follow-up research, validation of the formalised model constructs will be pursued by performing 'proof-of-concept simulations'. These simulations will qualitatively describe ways that hazards can evolve in ATM scenarios (similar to use case modelling within Software Engineering). The behaviour of the models will be evaluated by comparing it against a second set of hazards (as defined in Ref. 37) and by having experts judge the plausibility of the resulting proof-of-concept simulations.

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From uncertainty to robustness and system's resilience in ATM: a case-study

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This paper presents results of interviews with experts from DLR, DFS and Frankfurt and Hannover Airport. Based on the experience of survey respondents, uncertainties and disturbances are categorized by their sources as well as by their effects over different time horizons. Moreover, robustness and resilience are defined in the contexts of ATM planning. Finally, the concept of plan robustness and the gap from uncertainty to robustness and system's resilience are discussed.

I. Introduction

In the context of air traffic management efficient use of limited ATM resources is required, e.g. aircraft, fuel, gates, runway capacity, arrival and departure routes. Although performance-based ATM [SE] is heavily promoted by SESAR, it is impossible to create schedules for future use which never need to be adapted. Reasons are uncertainties which lead to intended and unintended deviations from schedule. State-of-the-art is to update and thereby change the plans by occurrence of uncertainties. But every intervention affects the whole ATM-system. Such problems arise in different ATM applications, for instance, in the tactical arrival and departure management which efficient design is studied in [CH, ER, HE, NEU, VO] and in the pre-tactical runway flow control considered in [GI1, GI2, GL]. Examples for other ATM problems occur at Airline Scheduling at Airports and Aircraft Turnaround Operations [WU], congested airport and sectors [GI3] as well as speed adjustments [WA]. To handle uncertainty in a more efficient way, the aim is to "robustify" airline, air traffic and airport schedules/processes beforehand taking into account requirements on plans over different time horizons.

Because of the different meaning of uncertainty, robustness and resilience in the various research domains, we need to have a clear and consistent definition from the viewpoint of ATM-system. The working group of ComplexWorld quotes in the ComplexWorld ATM White Paper [CW] several useful definitions of uncertainty and disturbance. The White Paper contributes to the overview of resilience meaning and its understanding in other research domains. The concept of resilience is examined, for instance, in sociology [RO, LU], ecology [BE, FO, GU1, GU2] and engineering [CO, HO1, HO2, JA]. However, the comprehensive definitions of resilience and robustness in the ATM context are still missing and should be formulated in order to investigate these concepts in the ATM-system.

Within the ComplexWorld PhD project "Uncertainty Models for Robust and Optimal ATM Schedules" interviews with experts from DLR (German Aerospace Center), DFS and with stakeholders at airports were performed. For this case-study wide range of specialists in the Institute of Flight Guidance at DLR from the departments Controller Assistance, Pilot Assistance, Operations Control, Air

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Transportation and Human Factors were interviewed about plans which are carried out in ATM-system, about role and source of occurring uncertainties/disturbances and reduction of their negative effects. Furthermore, we contacted experts, especially air traffic controllers, at Frankfurt and Hanover Airport to get their opinion on this matter. Based on the performed interviews we suggest the definitions of robustness and resilience from the ATM point of view.

The rest of the paper is organized as follows. In section II we describe the sources of uncertainty. In section III the effects of uncertainty are explained and in the last section we bridge the gap from uncertainty to robustness and system's resilience.

II. Sources of uncertainty

Uncertainty in ATM-system is defined by the ComplexWorld's White Paper [CW] as the condition being partially unknown or in doubt, whereas disturbance is any influence that causes the ATM-system to deviate from the planned workflow. As a concequence from the performed experts' interviews we divide the sources of uncertainties/disturbances into four major groups: human, transparency of data, meteorology and equipment. These groups are described shortly in the table below.

Human	*Transparency of data*	*Meteorology*	*Equipment*
Human's (pilot, controller, ground handler, passenger, …) actions, reactions, decisions, punctuality and cooperativeness in ATM-system;	Availability and accessibility of data; not optimal data flows;	Weather conditions, especially wind, fog, thunderstorm, snowfall;	Aircraft/vehicle breakdown; system failure;

Individualities of a person such as psychological, mental, national etc. and the aims the person follows play the main role in the occurrence of the human caused disturbances. This group is the most extensive and difficult to prognosticate and to model. Pilot's actions on controller's advisories/instructions, controller's decisions on sequence of actions, aircraft ground handling, duration and extensiveness of security check, passenger's punctuality and cooperativeness, strike, collective bargaining illustrate only a small part of human's actions in ATM-system. Human caused disturbances can be direct or indirect and often result from situations where individuals are unaware of the impact of their operations. Situation awareness can help to minimize the negative effects of human's actions.

Non-transparency of some data which are necessary for planning of workflow represents another source of uncertainties often closely connected to the first one. Uncooperative policy of stakeholders, inaccessibility of existing data, not optimal data flows contribute to uncertainty by the planning in ATM-system.

Meteorological conditions are the next wide group which causes uncertainties. Wind velocity, fog, snowfall and thunderstorm regions and time intervals, temperatures which require deicing are good predictable for the short time horisonts only. Therefore, often plans have to be done using estimated data which are far away from reality.

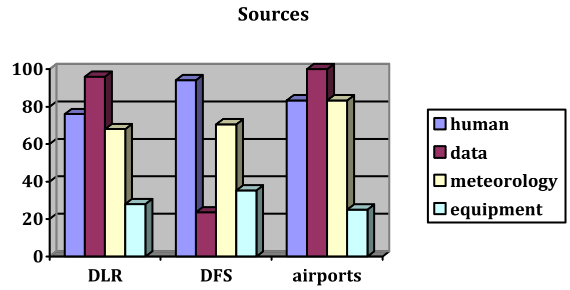

Figure 1. Reference of each source group in experts' answers as a percentage of the respondents' number

Problems with

equipment such as aircraft/vehicle breakdown or system failure complete the base class of uncertainties' origins. As a rule, other sources are mixes of the considered above. Figure 1 illustrates the described partition into groups and shows how often sources of uncertainties from them were mentioned by the respondents from DLR, DFS and airports. It should be noticed, that only about 25% of experts asked at DFS believe that transparency of data is uncertain. In contrast, nearly all respondents from DLR and the airports refer to it as a source of uncertainty. The human factor is the most uncertain group for the DFS. The percentage of the references to meteorological conditions and to problems with equipment differs in all three institutions insignificantly.

How are these uncertainties influenceable?

Increase of capacity by expansion of an airport can reduce certain uncertainties, but there are natural borders reached rapidly. Economic efficiency has to be considered, too. Of course, training of human as well as machine improves the liability to uncertainty, but failures can never be completely excluded. And it is well-known, that transparency of data is a difficult, often discussed topic.

Thus, to handle uncertainty and disturbances, we have to accept and incorporate them in the ATM plans. For that reason it is important to know the effects they cause.

III. Effects of uncertainty

First of all, we have to mention that every airport is unique in its infrastructure, in the number and size of the aircraft arriving and departing at the airport as well as in the time intervals when the resource utilization is affected. Therefore, problems caused by the same uncertainties/disturbances can vary significantly from one airport to another.

Taking into account requirements on plans over different time horizons, tactical, pre-tactical and strategic planning should be investigated separately. Uncertainty which plays a crucial role for one mentioned planning horizon can be irrelevant for other ones. If uncertainty has to be taken into account, its impact can be considered as insignificant or substantial. We can disregard the negligible factors and measure the important ones in terms of delay minutes and costs.

Importance of an uncertainty	*Tactical (from minutes to hours)*	*Pre-tactical (from hours to days)*	*Strategic (from days to years)*
considerable	meteorological conditions such as velocity and direction of wind, fog/ thunderstorm/snowfall, temperature/deicing	capacity bottlenecks	collective bargaining
	estimates	predicted meteorological conditions	strikes
	human factors		long perspective changes
negligible	gusts of wind	trajectories	human factors
	altitude dependence of wind	descent profiles	wind

There is no clear-cut between these impact levels. The borderline should be negotiated for every planning problem depending on the operational situation at the airport and on the stakeholders' strategies. It is reasonable not to tackle uncertainties with negligible impact on stability aspects of a plan.

Uncertainties with considerable impact on a plan can appear and/or disappear randomly at any time, e.g. vehicle breakdown. On the other hand, they can be characterized by the possible time of commencement, some duration time and intensity with a temporal and spatial propagation, e.g.

thunderstorms. The ATM-system is complicated and involves a lot of plans and decisions. Hence, heuristics become obsolete and mathematical models are required. To handle uncertainties at an airport, investigation of their probability distributions is needed.

IV. From Uncertainty to Robustness and System's Resilience

The current counteraction of uncertainty is rescheduling, but this cannot be an optimal strategy. On the one hand, each rescheduling is based on the more exact data. However, the new plan can differ significantly from the previous one thereby bringing chaos in the process of its implementation.

The concept of robustness and resilience indicates such planning of processes in a system that either a plan incorporates uncertainty in beforehand or the system returns promptly to the normal condition status when disturbances cannot be neutralized by the plan. Due to the performed interviews we define *plan robustness in ATM* by the capability of a plan to absorb uncertainty by acting flexible towards the appearance of disturbances. Furthermore, we describe *system's resilience* as the ability of a system to return back quickly to the normal working conditions after the occurrence of expected and unexpected uncertainties or disturbances. Resilience of a system is measurable by the required recovering time or the costs caused by the recovery.

The interaction between plan robustness and system's resilience has many benefits and advantages. If a plan is robust enough against an uncertainty then it is absorbed by the plan. In other words, the plan is stable relative to the uncertainty and resilience of the system is not utilized. Considering substantial uncertainties for which the robust plan cannot be realized any more, system's resilience accompanies the return to normal working conditions. Consequently, robust plans are indirectly measurable. Also the time which the system needs to run ordinarily after an uncertainty occurs can be efficiently evaluated.

Robust schedules in ATM-system should incorporate uncertainties by alternatives or buffers in bottle-neck points to avoid significant capacity losses. They should absorb random arising uncertainties to conserve maximally the efficient use of the available capacity. Therefore, the trade-off between strategic contingencies and tactical effects has to be explored because of impacts consequences. For example, buffers have a large cost impact but lessen the costs of disruptions on the day of operations. Robustness achieved only with buffers is an opponent to efficiency. In fact, if a plan is maximally efficient there are in general no more buffers left to react even on small changes. In contrast, a plan which is robust enough to handle every uncertainty could be very poor in terms of capacity utilization. Thus, buffer has to be applied accordingly to the impact which can be produced by the recognized uncertainty. Moreover, robust plans should have such management of resources which allows their smooth utilization. If one stakeholder cannot use the resource in the planned time because of the appearance of an uncertainty, the resource has to be deblocked for another stakeholder.

Plan robustness in a system can be also realized by the performance-variability of the system and by hierarchy of plans. If the system does not absorb uncertainties by the robustness of the plan, another higher-ranked plan can be used to turn back to normal condition status. This ranking, gives another instrument for realization of robustness. Furthermore, two different types of robustness can be considered. The first one is absolute robustness. It prevents worst-case scenarios. The second one is relative robustness which characterizes robustness in the mean.

V.Conclusion

Results of interviews with experts from DLR, DFS and from Frankfurt and Hannover Airport have been discussed in this paper. Hire the sources of uncertainties indicated by responders were divided in four major groups: human, transparency of data, meteorology and equipment. These uncertainties are hardly influenceable, so we have to accept and incorporate them into ATM schedules. If an uncertainty has to be taken ito account its impact was considered as insignificant or substantial. However, the borderline between those two types of impact should be negotiated for each planning problem depending on the operational situation at the airport and on the stakeholders' strategies. Impact of an uncertainty is measureable in terms of delay minutes and costs.

Moreover, it was found out that effects uncertainties cause should be investigated separately for tactical, pre-tactical and strategic planning horizons.

Finally, robustness and resilience were defined in the context of ATM-system. Furthermore, the concept of plan robustness and its interaction with system's resilience as well as a way to measure them have been described.

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Airport Performance Modeling using an agent-based Approach

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Because of the many interacting elements at the airport, the uncertainty in system behavior, and the degree of human agency involved, the airport has become a highly complex system. Its overall behavior is influenced by dynamic interactions between distributed elements in a rapidly changing and unpredicted environment. Motivated by the need to understand such a complex system, this research explores an agent-based approach to model the airport airside behavior emerging from the interactions between various system elements both at the airport and TMA. Agent-Based Modeling is increasingly recognized as a powerful approach to simulate complex systems, because it can represent important phenomena resulting from the characteristics and behaviors of individual agents. These phenomena are usually referred to as emergence which is a key property of complex systems. Unlike existing models which tend to capture the impact on one Key Performance Area (KPA) without considering other KPAs, the objective of this research is to model and optimize the airport airside behavior in terms of multiple KPAs being safety, capacity, economy, and sustainability. This paper presents the results of the first step of this research which is about identifying the human agents relevant for airport modeling and mapping their goals in terms of the various KPAs.

I. Introduction

As in any industry, the ATM community is continuously seeking to improve the ATM system performance and identify best practices [1]. Within SESAR, a performance framework for the future European ATM system has been proposed [2]. This framework is not only helpful in monitoring performance, which is critical to ensure the effectiveness of current operations, but also in terms of continuously improving these operations, which is important to accommodate the future traffic growth. This paper focuses on performance-based airports, which are seen as a pre-requisite for a performance-based approach, as airports make up the fixed nodes on which the ATM system is built [3].

Because of the many interconnected heterogeneous airport components, the various airport processes, and the difficulty to predict emergent behavior, the airport has become a highly complex system. A system is considered to be complex when it is composed of a group of interrelated components and subsystems, for which the degree and nature of the relationships between them is

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imperfectly known, with varying directionality, magnitude and time scales of interactions [4]. In addition to this, airport operations are embedded in an institutional system characterized by various stakeholders each bringing his own organizational interests. As a result, two ways of interconnections exist increasing the level of complexity, since many differences arise between the stakeholders in terms of goal settings.

This paper explores an agent-based approach for airport airside modeling, covering both airport and TMA operations. Agent-based modeling has been extensively used in the literature to model complex socio-technical systems. Its applications include a wide range of areas such as Cooperation and Coordination [5, 6], Resource Allocation [7, 8], Web-based applications [9, 10], electronic commerce [11, 12], just to name a few. This has led to an increasing recognition of agent-based modeling as a powerful approach to simulate complex systems [13, 14]. Firstly, because it enables reducing the system complexity by making abstraction levels that lend themselves a natural way of modeling the problem domain; and enhance the robustness and adaptivity of systems by virtue of increasing the autonomy of subsystems and their self-organization [15]. Secondly, it enables representing phenomena resulting from the attributes and behavior of lower level agents. In addition, agent-based modeling is suited to problem domains that are geographically distributed, where the subsystems exist in a dynamic environment, and the subsystems need to interact with each other more flexibly [16-19]. This makes the airport by its very own nature a multi-agent system.

The multi-agent paradigm does not only apply to systems where complexity is the main criterion, and the whole is more than the sum of the parts. But it is also worth exploring especially for cases that are characterized by conflicts, with the aim to solve the problem in a distributed fashion. Besides, it is especially designed for systems where data modeling must be done according to the four basic components: agents, environment, interaction, and organization [20, 21]. This decomposition provides means to simulate and validate initial hypotheses [20, 22-24], through representing the various actors and modeling the impact of their goals on system behavior.

Various definitions of agents are used in the multi-agent systems literature [14, 20, 25, 26]. For the purpose of this work, in particular where different actors, hardware, and software are interacting elements of a socio-technical system being air transport, our definition for an agent will be an autonomous entity that is able to perceive its environment and act upon this environment. The agent environment is understood as the agent surrounding that includes both active entities such as systems and passive entities such as databases.

The main aim of this paper is to identify the human agents relevant for airport modelling, and map their goals relative to the airport KPAs being safety, capacity, economy, and environment. For this purpose, the paper is organized as follows. Section 2 provides a short background on airports explaining their main characteristics and describing the two main components of an airport, namely the landside and airside. An overview of existing airport models from the literature is also provided. Section 3 discusses key challenges airports are facing in terms of the different KPAs. Section 4 identifies the relevant actors for airport modelling. Here the actors are represented across three aggregation levels, and their goals in terms of different KPAs are mapped across these levels. Section 5 analyses the differences in actors goals and proposes solutions to overcome these differences. Section 6 gives concluding remarks.

II. Airports

An airport is a very complex enterprise comprised of a variety of facilities, users, sub-systems, human resources, rules, and procedures. Different parties are involved in its operation with varying boundaries of responsibility per airport or country. In Europe, different airport categories can be distinguished. These include major international airports, regional airports, hub airports, and non-hub airports. Furthermore, each airport is characterized by a number of runways, stands, terminals, technology, and so forth. Additional differences are also related to the conditions under which each airport operate. These could be of environmental, political, or commercial nature.

In general, the mission of an airport can be seen as serving aircraft, travelers, cargo, and ground vehicles. Each of these elements is served by two key airport components, namely the airside and landside with the apron being in between. The first component is for accommodating movements of departing, taxiing, and landing aircraft. This is normally enabled by common facilities such as taxiways, runwas, navigational aids, stop-bars, markings and so on. The second component is for accommodating movements of ground vehicles, passengers, and cargo. Although landside operations might have an impact on airside operations (e.g. check-in, security checks, delayed boarding due late passenger, etc.) and vice versa, this research only focuses on airside operations and their relation to the KPAs safety, capacity, economy, and environment. Section 3 discusses more in detail some of the key challenges corresponding to each of these KPAs.

Airport and TMA models

In their work on airport systems [27], De Neufville and Odoni classify airport models with respect to three aspects. (1) level of detail (2) methodology, and (3) coverage. For the first aspect, models can be either macroscopic or microscopic. Examples of macroscopic models in the literature are MACAD [28], Blumstein model [29], and the FAA Airfield Capacity Model [30]. These models provide a high level of modelling detail, and are typically used in policy analysis and strategy development. In contrast to macroscopic models, microscopic models such as TAAM [31], SIMMOD [32], or TOPAZ [33] provide high faithful representation of operations at and nearby the airport. These models are used in detailed traffic flow analysis or safety risk analysis. Regarding the second aspect of classification, the methodology used could be either of analytical or simulation type. In the former case, mathematical representations of airport operations are used, and quantities of interests like capacity or delays are derived. Blumstein [29] was the first to propose analytical models for determining the capacity of a single runway, which he defined as the number of possible movements (landings and take-offs) per period of time in the presence of separation constraints. For the simulation case, objects moving through parts of the airports are described depending on the model scope. Measures of performance such as accident risk, or runway capacity are computed. In both methodologies, models can be further classified whether they are (a) static or dynamic and (b) stochastic or deterministic. De Neufville and Odoni [27] acknowledge that there is a strong correlation between model methodology and the level of detail. Analytical models tend to be mostly macroscopic. Whereas, microscopic models are in most of the cases simulations. Finally, airport models can be either limited i.e. when covering a specific part of airport operations, or comprehensive, when dealing with the entire range of airfield and TMA operations. Table 1 summarises airside models from the literature and maps them according to these three aspects.

Table 1: Classifying models of airport and TMA operations (Source [27])

Level of detail (type of study)	Model coverage/scope		
	Aprons and taxiways	Runways and final approach	Terminal area airspace
Macroscopic	- MACAD [28]‡	- Blumstein model [29]† - FAA Airfield Capacity Model [30]† - DELAYS [34]† - LMI Capacity and Delays Model [35]† - MACAD [28]‡	
Microscopic	- SIMMOD [32] - TAAM [31] - The Airport Machine - HERMES - TOPAZ-TAXIR [18]	- SIMMOD - TAAM - The Airport Machine - HERMES - TOPAZ-TAXIR [18]	- SIMMOD - TAAM - RAMS - TOPAZ-2MA [33] - TOPAZ-ASAS-IM [36] - TOPAZ-WAVIR [37]

†Indicates an analytical model

‡MACAD is an analytical model, except for its apron model, which is a simulation

III. Airport Performance Challenges

This paper focuses on four key challenges airports are facing in terms of safety, capacity, economy, and environment

Safety Challenge

Safety has always been the prime objective of ATC and subsequently of ATM. Statistics of aviation accidents show a significant decrease during the last 50 years [38]. As a result, the air transport became one of the safest modes of transport. However, in spite of this improvement, there is still a serious safety concern regarding airport safety performance. Roelen and Blom [39] show that for take-off, landing, and ground operations, the accident rate is not improving over the period 1990-2008. This is in contrast to the accident rate of airborne operations, which shows a systematic decrease over the same period of time. To better understand the different accident types and their characteristics, table 2 summarizes the main aviation occurrence categories used by CAST/ICAO [40]. These categories include airborne, aircraft, ground operations, miscellaneous, non-aircraft related, take-off and landing, and weather.

Table 2: Summary of aviation occurrence categories (Source [40])

Airborne		
Abrupt Maneuvre	The intentional abrupt maneuvering of the aircraft by the flight crew	AMAN
Airprox/TCAS Alert/ Loss of Separation/ Near Mid-Air Collision/Mid-Air Collisions	Airprox, TCAS alerts, loss of separation as well as near collisions or collisions between aircraft in flight. Both ATC and pilot separation-related occurrences are included	MAC
Controlled Flight Into/Toward Terrain	Inflight collision or near collision with terrain, water, or obstacle without indication of loss of control	CFIT
Fuel Related	One or more powerplants experienced reduced or no power output due to fuel exhaustion, fuel starvation/mismanagement, fuel contamination/wrong fuel, or carburettor and/or induction icing	FUEL
Glider Towing Related Events	Premature release, inadvertent release or non-release during towing, entangling with towing, cable, loss of control, or impact into towing aircraft/winch	GTOW
Loss of Control – Inflight	Loss of aircraft control while, or deviation from intended flight path, in flight	LOC-I
Loss of Lifting Conditions En-Route	Landing en-route due to loss of lifting conditions	LOLI
Low Altitude Operations	Collision or near collision with obstacles/objects/terrain while intentionally operating near the surface (excludes takeoff or landing phases)	LALT
Unintended Flight in IMC	Unintended flight in Instrument Meteorological Conditions (IMC)	UIMC
Aircraft		
Fire/Smoke (Non-Impact)	Fire or smoke in or on the aircraft, in flight, or on the ground, which is not the result of impact	F-NI
System/Component Failure or Malfunction (Non-Powerplant)	Failure or malfunction of an aircraft system or component other than the powerplant	SCF-NP
System/Component Failure or Malfunction (Powerplant)	Failure or malfunction of an aircraft system or component related to the powerplant	SCF-PP
Ground Operations		
Evacuation	Occurrence where either; (a) person(s) are injured during an evacuation; (b) an unnecessary evacuation was performed; (c) evacuation equipment failed to perform as required; or (d) the evacuation contributed to the severity of the occurrence	EVAC
Fire/Smoke (post impact)	Fire/Smoke resulting from impact	F-POST
Ground Collision	Collision while taxiing to or from a runway in use. E.g. collisions with a ground vehicle or obstacle, etc. while on a surface other than the runway used for take-off and landing	GCOL
Ground Handling	Occurrence during (or as a result of) ground handling operations e.g. during servicing, loading, or towing the aircraft	RAMP
Loss of Control - Ground	Loss of aircraft control while the aircraft is on the ground e.g. due to a system failure or a contaminated runway/taxiway as a result of snow	LOC-G
Runway Incursion – Animal	Collision with, risk of collision, or evasive action taken by an aircraft to avoid an animal or a runway in use	RI-A
Runway Incursion-Vehicle, Aircraft or Person	Any occurrence at an aerodrome involving the incorrect presence of an aircraft, vehicle, or person on the protected area of a surface designated for the landing and take-off of aircraft	RI-VAP

Miscellaneous		
Bird	Occurrences involving collisions/near collisions with bird(s)/ wildlife	BIRD
Cabin Safety Events	Miscellaneous occurrence in the passenger cabin of transport category aircraft	CABIN
External Load Related Occurrences	Occurrences during or as a result of external load or external cargo operations	EXTL
Other	Any occurrence not covered under another category	OTHR
Security Related	Criminal/Security acts which result in accidents or incidents (ICAO Annex 13)	SEC
Unknown or Undetermined	Insufficient information exists to categorize the occurrence	UNK
Non-aircraft-related		
Aerodrome	Occurrences involving aerodrome design, service, or functionality issues	ADRM
ATM/CNS	Occurrences involving ATM or CNS service issues	ATM
Takeoff and Landing		
Abnormal Runway Contact	Any landing or take-off involving abnormal runway or landing surface contact (e.g. hard landings, long landings, etc.)	ARC
Collision with Obstacle(s) during take-off and landing	Collision with obstacle(s) during take-off or landing while airborne (example of obstacles are trees, power cables, antennae, etc.)	CTOL
Undershoot/Overshoot	A touchdown off the runway surface	USOS
Runway Excursion†	A veer off or overrun off the runway surface	RE
Weather		
Icing	Accumulation of snow, ice, freezing rain, or frost on aircraft surfaces that adversely affects aircraft control or performance	ICE
Turbulence Encounter	In-flight turbulence encounter	TURB
Thunderstorm	Occurrences related to lightning strikes, wind-shear and heavy rain	WSTRW

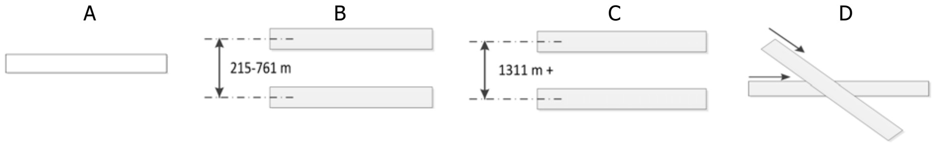
† in [40] runway excursions are categorized as occurrences in ground operations

Capacity Challenge

The runway is the most critical airport element, in that the number of aircraft movements it can accommodate is a crucial factor for determining the airport capacity [27, 41]. It is believed among airline executives and aviation officials, that one of the principal threats to future air transport operations is the inability of runway capacity to keep up with the growing demand [27]. Airports are therefore seen as constraints to growth in the future air transport system. Many capacity measures are designed to estimate the number of hourly movements at which operations can be performed. Examples of such measures include the ultimate capacity, sustainable capacity, and declared capacity. In general, the more runways an airport have, the higher traffic demand it can handle. Table 3 shows the number of aircraft movements per unit of time for various runway configurations. The values vary within each range depending on the aircraft mix, percentage of arrivals, etc. for each runway configuration.

Table 3: Runway configuration and capacity (Source [42])

Runway Configuration	Hourly Capacity ops/h		Annual Service Volume (Operation per year)
	VFR	IFR	
A	51-98	50-59	195.000 – 240.000
B	94-197	56-60	260.000 – 355.000
C	103-197	99-119	305.000 – 370.000
D	72-98	56-60	200.000 – 265.000



Single Runway Close-Parallel Runways Independent Parallel Runways Crossing Runways

Next to the airport layout, other factors can greatly influence the runway capacity. E.g. weather in case of low visibility conditions, snow, strong winds, etc. Safety requirements are an additional constraint to capacity. These are translated into separation distances which vary per aircraft mix. E.g. the larger the size of the leading aircraft in the arrival sequence, the higher the separation distance required for the trailing aircraft. In addition, the state and performance of the ATM system can also negatively affect capacity in case of non-nominal conditions. Finally, other limiting factors might include airspace constraints, ATC workload, and environmental constraints.

Economical Challenge

The cost of flight operations is the largest single element of operating costs. It has risen more dramatically than any other single cost element. Between 1970 and 1982 the unit cost of flight operations rose by almost 400 per cent [43]. This very rapid escalation of flying costs was mainly due to the rise in fuel prices. The fuel consumption varies per route and depends on many factors including sector lengths, aircraft size, wind conditions, cruise altitude, etc. Other major costs are associated with the flight crew, airport, and en-route charges. For airport charges, various elements are associated and may vary per airport. These include landing fees, passenger service charge, airport noise charge, aircraft parking charge, ground handling charge, etc. Table 4 shows a complete structure for the flight operating costs from an airline perspective.

Table 4: Structure of operating costs (Source [43])

- Direct Operating Costs (DOC)
  - 1 Flight Operations
    - Flight crew salaries and expenses
    - Fuel and oil
    - Airport and en-route charges†
    - Insurance
    - Rental of flight equipment and/or crews‡
  - 2 Maintenance and overhaul
  - 3 Depreciation and amortization
    - Flight equipment
    - Group equipment and property (could be IOC)
    - Extra depreciation (in excess of costs)
    - Amortization of development costs and crew training
- Indirect Operating Costs (IOC)
  - 4 Station and ground expenses
  - 5 Passenger services
    - Cabin crew salaries and expenses (could be DOC)
    - Other passenger service costs
  - 6 Ticketing, sales and promotion
  - 7 General and administrative
  - 8 Other operating costs

†ICAO classifies airport and en-route charges as an indirect operating cost under 'Station and Ground Expenses'
‡The Civil Aeronautics Board (CAB) classified rentals under depreciation

In this paper, we consider an ATM concept to be economically efficient than another if it can accommodate more traffic using the same resources without compromise on other KPAs. Reducing taxiing time in a safer way for instance, can have multiple effects on different actors. From an airport perspective, it will enable handling more traffic demand and improve the overall airport capacity as well as generate more aeronautical and non-aeronautical revenues. From an airline perspective, less fuel will be burned which goes hand in hand with reducing the impact on the environment. Another important aspect is reducing delays which could save important costs for the airlines [44]. Passengers might also benefit from these cost savings in terms of cheap tickets. Not to mention ground controllers who would greatly appreciate less queuing aircraft in the taxiway because of reduced workload. All in all, it will contribute to reducing delays which have received a great amount of attention, not only by aviation professionals, but also by the civil society at large since it quickly make it to the world press and news headlines.

Environmental Challenge

Next to its economic and social benefits, an airport has two localized environmental impacts that are of major concern at European airports. The first primary impact is related to noise which affects individuals in the vicinity of airports in different ways, and the second is related to air pollution, especially due to Nitrogen oxides and particulates. This section addresses both of these environmental impacts.

Noise

The growth in air traffic has significantly increased the number and frequency of airport noise events. These events can be related to aircraft operations, ground handling activities, or infrastructure related operations. During take-off and climb, the engine is the primary source of noise. For the approach and landing, the airframe becomes also a significance noise source. In general, airport noise can negatively affect nearby communities in many different ways. Exposure of residential areas to noise can affect sleep with consequences on health and quality of life of residents. Workplaces and schools might also be exposed resulting in negative effects on communication, concentration, and productivity. Although significant efforts have been done to reduce aircraft noise in terms of re-designing the engine and airframe, the cumulative effects due to traffic increase as well as to the growing number of nearby communities, seem to outweigh these efforts.

In the literature there are various measures of airport noise which can be divided into two main categories, namely single event measures and cumulative measures, also known as time-average measures [27, 45]. The first category considers a single aircraft movement, whereas the second category tend to capture the cumulative effects of many aircraft movements over a certain period of time. The last category is mostly used when analyzing the impact of airport noise. popular measures in this category include the day-night average sound level L_{dn} used by the FAA, the day-night-evening measure L_{den} used by the European Environmental Noise Directive, and the equivalent noise level L_{eq} used by the UK. While these noise measures relate to specific locations around the airport, the main product of such assessments is a set of noise contours which illustrates noise levels at different areas such as arrival or departure routes. It should be noted that although current metrics may not fully reflect the health and social impacts of noise, they at least give a better indication on which areas are greatly affected. Table 5 gives a qualitative description of typical effects of L_{dn} on nearby communities.

Table 5: Effects of noise levels on communities (Source [46])

Ldn† value in decibels	Hearing Loss	Annoyance	Average Community Reaction	General Community Attitude Towards Area
	Qualitative description	% of population highly annoyed		
75 and above	May begin to occur	37%	Very severe	Noise is likely to be the most important of all adverse aspects of the community environment
70	Will not likely	22%	Severe	Noise is one of the most important adverse aspects of the community environment
65	Will not occur	12%	Significant	Noise is one of the important adverse aspects of the community environment
60	Will not occur	7%	Moderate to slight	Noise may be considered an adverse aspects of the community environment
55 and below	Will not occur	3%		Noise considered no more important than various other environmental factors

† Ldn is the average sound energy recorded over a 24-hour period. It includes a weighting to reflect increased human sensitivity to noise at night: a weighting of 10 dB is added to the night-time (2200-0700 hours) sound levels

Air quality

Aircraft are considered to be the fastest growing contributor to emissions [47]. According to the latest ICAO's environmental report [48], the total volume of aviation CO_2 emissions in 2006 (both domestic and international) is estimated to be in the range of 600 million tonnes. At airports, air pollution is not only caused by aircraft, but also by supporting ground vehicles, airport shuttles, and other traffic that runs throughout the day. The engines of most of these vehicles emit products that have different impacts. These emissions are roughly composed of about 70 percent CO_2, a little less than 30 percent of water vapor H_2O, and less than 1 percent of emissions that have negative health impacts [49]. The last category includes nitrogen oxides NO_x, carbon monoxide CO, oxides of sulfur SO_x, unburned or partially combusted hydrocarbons (known as Volative Organic Compounds VOCs), particulates, and other trace compounds. As a result higher concentrations of pollutants were reported nearby airports [50]. Emissions of these products varies per engine type, fuel used, and operation type. For aircraft, carbon monoxide and hydrocarbons are highest when the engine is idling, whereas nitrogen oxides emissions are highest in the take-off phase. Table 6 shows that the main health effects of these emissions are related to respiratory complaints. As a consequence, the friction between airport authorities and nearby communities is rising more than ever. Airports are not only becoming a source of noise, but also a source of pollution due to landing, taxiing, idling, and taking-off aircraft, as well as supporting and surrounding ground traffic.

Table 6: Significance of main effects of emissions (Source [51])

Pollutant	Health effects
Nitrogen Oxides NO_x	Lung irritation and lower resistance to respiratory infections
Particulate Matter	Premature mortality, aggravation of respiratory and cardiovascular disease, changes in lung function and increased respiratory symptoms, changes to lung tissues and structure, and altered respiratory defense mechanisms
Sulphur Oxides SO_x	Sulphur oxides include sulphur dioxide SO_2, which causes constriction of the respiratory airways, especially in individuals with asthma and chronic lung diseases
Carbon Monoxide CO	Carbon monoxide reduces the oxygen-carrying capacity of the blood, presenting a particular risk to individuals with pre-existing respiratory or cardiovascular diseases
Volatile Organic Compounds VOCs	Eye and respiratory tract irritation, headaches, dizziness, visual disorders, and memory impairment

IV. Identifying the actors and their goals

In complex and distributed air transport organizations, the level of performance is the result of interactions between many entities at different levels. The roles of these various entities may be elucidated by using the sharp-end blunt-end concept [52, 53]. The sharp-end refers to the people who actually interact with the safety critical process in their roles as pilots, controllers, or ground handlers. At the blunt end, regulators, management units, or policy makers control the resources, constraints, and multiple incentives that the people at the sharp-end must integrate and balance. Based on previous work where actors in the air transport sector were analyzed to develop validation strategies [54-56], figure 1 identifies key actors including their hierarchical relationships across three levels. In this paper, we consider air transport operations as the set of all air transport movements in the airspace that has the intention to transport passengers and/or goods, with support from all infrastructure and services that are necessary to establish these movements in an efficient and safe way [56]. The first aggregation level in the figure refers to the stakeholder level and represents high level actors ranging from ANSPs, airlines, to regulators. The second level, or division level, represents principal units, teams, departments, divisions, etc. that belong to a certain stakeholder. Finally, the third level represents the individual roles at the sharp-end directly involved in the safety critical process. In our context, we consider an actor as any individual or composite actor that is assumed to be capable of making purposeful choices among alternative courses of action [57]. It should be noted that, although figure 1 can vary per region, organization, and so forth, it gives a good picture of the diversity of actors. Such diversity means that one change in ATM operations can have an impact on various stakeholders in different ways. Therefore, it is quite important to know what the main goals are of these stakeholders, to better understand the added value of new concepts for each stakeholder.

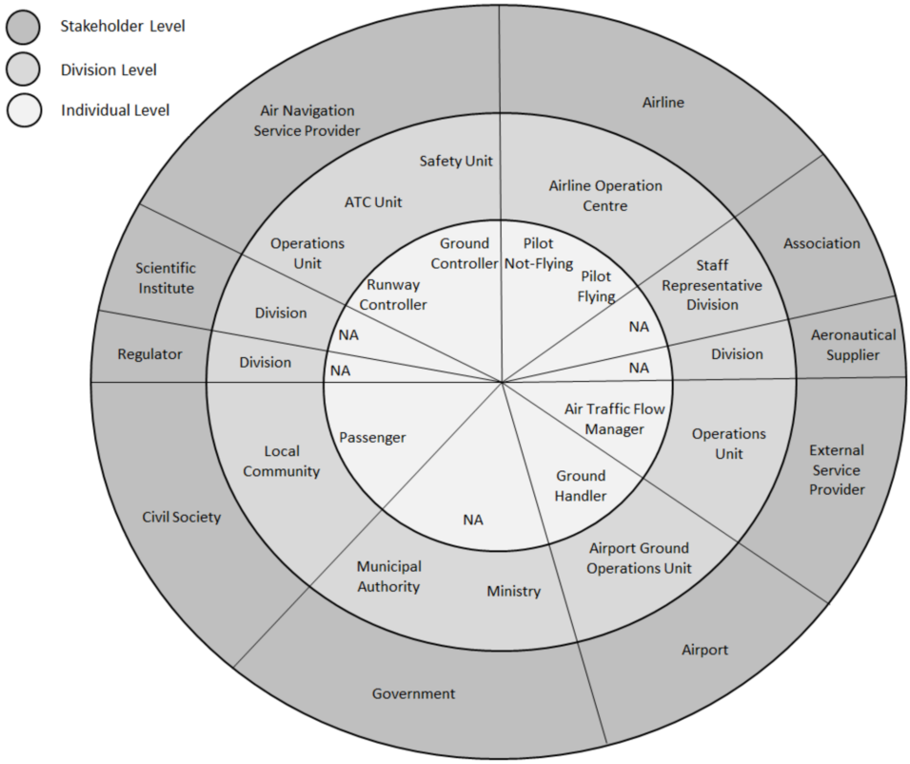


Figure 1: Key Actors in the air transport sector

The various goals of the identified actors are addressed below in line with the KPAs safety, capacity, economy, and environment

Airport

The main goal of an airport is to provide, operate, and maintain air transportation facilities to meet the air transportation and economic development needs of its customers. Although capacity is a primary matter of interest for an airport, since it enhances its competitive position, safety can never be compromised for the sake of accommodating more traffic. In terms of economy, an airport wants to minimize infrastructure investments as well as human resources. Therefore, ATM systems and services should be developed and operated in a way that allows airports to interact with them in a cost-effective manner [55]. These systems should also support the reduction of pollution and noise e.g. through reducing taxi distances or avoiding unnecessary queues of departing aircraft before take-off.

Regulator

For regulators, the most important goal is the safety of passengers and people over-flown by aircraft. This goal is strict, in a way that aviation authorities will not allow the use of the ATM concept if safety levels are below the target level of safety [55]. Usually, countries transfer this responsibility to an organization of which the rule is to monitor activities, perform licensing, and ensure compliance with safety regulations. In terms of capacity, regulators aim for equity in the sense that airlines should not be discriminated and that big aircraft have priority in landing. In addition, regulators also coordinate to establish common rules (e.g. Chicago convention 1944), since it would be economically not feasible if each country would require aircraft to use different systems. Finally, environmental protection is also one of the regulators goals. E.g. when a new runway is built, the authorities will check if the requirements regarding noise levels are met, however they will not take immediately the wishes of nearby communities.

ANSP

The main goal of an ANSP is to manage the flow of traffic safely and efficiently in the air in a dedicated airspace or in the ground. Dangerous situations should be identified in time for recovery, and safety levels have to be maintained under abnormal circumstances (abnormal weather conditions, system failure, etc.). From a capacity perspective, the goal of an ANSP is to prevent delays in busy hours through providing more resources. In addition, charges for the services should be affordable to the customers and the services should be provided such that the environmental effects are minimized.

Airline

The main goal of an airline is to satisfy the customer need by providing the highest standards of quality and safety. Kemp and Dwyer [58] analysed 50 mission statements of airlines and found that the most focus is on customers, products/services, and market. In terms of economy, airlines would like to be cost-efficient through minimizing airport parking charges or towing costs for instance, and offering good prices to their customers. In addition, because of the high fuel prices, fuel efficient engines are preferred by most of the airlines which also reduce the impact on the environment.

Civil Society

Civil Society or the aggregate of NGOs and institutions promote the interests and will of citizens. The main goal of civil society (which includes both passengers and local communities) towards air transport is safety [55]. The risk of being hit by an aircraft falling down is an important factor for people that are in areas close to the final approach paths or departure routes. In terms of capacity and economy, passengers want to reach their destination without delays or being charged an unaffordable price. Last but not least, civil society expects that an airport is operated in such a way that environmental impacts such as noise and pollution are minimized.

Scientific Institute

A scientific institute conducts R&D activities that support the evolution of the air transport system at different levels. In terms of safety, new methods and models are being developed to prevent the occurrence of air traffic accidents and maintain good safety records. For capacity, continuous efforts are made to find new solutions to the traffic flow problem that would help accommodate more traffic. In the economic and environment performance areas, new methods are constantly developed to optimize flight operations and trajectories as well as fuel usage, therefore reducing both operating costs and the impact on the environment.

External Service Provider

In ATM different functions and services are required to ensure the safe and efficient movement of aircraft during all phases of flight. One of the key functions is Air Traffic Flow Management (ATFM) which regulates air traffic respecting existing airspace, ATC, and airport capacity constraints. In Europe, this function is performed by the Central Flow Management Unit (CFMU) of Eurocontrol. Another important function is Airspace Management, which increases airspace availability for civil flights by making for instance use of military airspace. This function is performed on a country-by-country basis by Airspace Management Cells (AMC's) containing representatives from both civil and military aviation authorities. Next to these two functions, there are other air traffic services that ensure the safety, capacity, and efficiency of flight operations (table 7). In some countries, the role of these services is also extended to reduce the noise and emissions within the constraints of safety and operational possibilities.

Table 7: Summary of air traffic services other than ATC (Source [59])

Air Traffic Services	Goal
Aeronautical Information Service (AIS)	Provision of information on the operational status of airports and potential hazards
Aeronautical Meteorological Service (MET)	Provision of relevant actual and forecasted weather information which contributes to the quality of ATM in terms of safety
Alerting Service (ALS)	Notification of appropriate organizations regarding aircraft in need of Search and Rescue (SAR) aid and the provision of necessary assistance to those organisations during SAR actions
Flight Information Service (FIS)	Provision of information necessary for safe and efficient conduct of flights
Aeronautical Telecommunication Services	Provision of all communications necessary to conduct flights safely (both ground-ground, and ground-air)

Aeronautical Supplier

Aeronautical suppliers play an important role in the air transport industry since they develop concepts and technologies for various actors such as pilots, controllers, or airports with the purpose to deliver safer and efficient air transport services. Key suppliers are aircraft manufacturers, avionics suppliers, and ATM infrastructure providers.

Association

An association represents key stakeholders such as airlines, pilots, ANSPs, controllers, or airports at different levels, and promote their interests in terms of different areas such as economy and capacity. Examples of these associations include CANSO, IFATCA, AEA, ERA, IATA, IACA, IFALPA, IOPA, ECA, and ACI.

Government

A government weighs up different interests and invests in the future in line with the public good, and expert knowledge.

Table 8 summarizes the various goals that have been discussed in terms of the KPAs safety, capacity, economy, and environment. The table also reflects on the goals corresponding to the individual level which might not necessarily be similar to stakeholder or division level corresponding to the same type of stakeholder.

Table 8: Mapping actors' goals in relation to key performance areas at different levels. The (+) sign means that the KPA is of high importance for the stakeholder. A (–) sign reflects a lower priority

Key Actor	KPA			
	Safety	Capacity	Economy	Environment
Stakeholder Level				
Airline	+	-	+	-
Air Navigation Service Provider	+	+	+	+
External Service Provider	+	+	+	+
Airport	+	+	+	-
Government	+	+	+	+
Civil Society	+	+	+	+
Regulator	+	-	-	+
Aeronautical Supplier	+	-	+	+
Association	+	+	+	-
Scientific Institute	+	+	+	+
Division Level				
Airline Operations Centre	+	-	+	-
ATC Unit	+	+	-	-
Safety Unit	+	-	-	-
ANSP Operations Unit	+	+	+	+
ATFM Operations Unit	+	+	+	+
Ministry	+	+	+	+
Municipal Authority	+	+	+	+
Individual Level				
Pilot Flying	+	+	-	-
Pilot Not-flying	+	+	-	-
Runway Controller	+	+	-	-
Ground Controller	+	+	-	-
Air Traffic Flow Manager	+	+	-	-
Passenger	+	+	+	-
Nearby Resident	+	-	-	+

V. Conflicting Goals

As illustrated in the previous section, different types of conflicts might arise due to differences in goal settings. These conflicts not only exist between different stakeholders, but even within different entities of the same stakeholder. A conflict was defined by Tessier et al. [20] as follows: Let P be the set of propositional attitudes representing the agents' context at a given time. Let C be a subset of P. C is a conflict if and only if C must be reduced. Tessier et al. [20] distinguish between two classes of conflict, namely physical conflicts and knowledge conflicts. In the first type, conflicts are mainly resource conflicts. Here, even agents's goals might be the same in terms of a certain KPA, they are not compatible because of the resources required to achieve them. An example could be aircraft waiting to be serviced at the airport (e.g. for de-icing, fueling, etc.) or holding in the air to get landing clearance on a busy runway. The second type of conflict is mainly due to the fact that the agent's information is not the same, for instance as a result of different skills or sensors. Such conflicts, often called epistemic conflicts, includes agents' beliefs, knowledge, and opinions. Two classical strategies to cope with conflicts are avoiding them or solving them [20]. In the former case, agents apply common rules [60] i.e. conventions, or rely on mutual representations of others' goals, intentions, and capabilities [61]. More complex approaches try to represent tasks and resources dependencies [62]. In the second case, conflict solving cannot be avoided because agents have limited knowledge of their environment and other agents. To deal with this, various synchronization algorithms [63] and negotiation protocols [64] have been introduced in the literature.

In many situations, the realization of a strategy or solution of a problem requires the support of several actors [65]. This means, that actors often depend on each other to achieve their objectives. These dependencies are determined by the distribution of resources over the actors and the goals of the actors. Because of this dependency, an interaction process is required between key actors in order to realize their strategies. when effective, such interaction process clarifies both actors goals and provide a plan to achieve them. When it is not, in case the actors involved for instance seem to be trapped in discussions that circle around the same arguments, a deadlock might occur. An interaction process is considered to be a deadlock when two requirements are met, (1) a problematic situation exists which attracts the attention of actors, and (2) the interaction process related to the situation stagnates [66]. These deadlocks have usually significant societal costs, since problems are not solved and therefore people continue to be dissatisfied (e.g. airport noise), and the deadlocked interaction process itself is costly, and might lead to frustration and disturbed relations. Many factors that lead to the stagnation of interaction processes around a large airport have been identified in [66]. These include non-cooperation due to different jargon, exclusion of some actors in the interaction process, or conflicting interests and values (e.g. environmentalist vs. entrepreneur).

Daams [66] discusses various potential solutions that can be combined to overcome deadlocks. In his work, a distinction was made between solutions that involve an external actor and solutions that do not necessarily involve an external actor. In addition, a distinction was made between solutions that focus on the substantial aspects of the deadlock and solutions that focus on the process. Table 9 summarizes these potential solutions. Based on deadlocks that occurred in the Netherlands aviation sector, Daams [66] shows that that in all cases external actors are involved in the resolution of a deadlock. Their involvement was reported to be essential for the implementation of the solution. This however does not mean that the external actors are always involved in the conception of the solution as well. A pattern that was observed by Daams [66], is that the actors who are involved in the deadlock arrive at a proposed solution themselves and next the co-operation of the external actors is necessary for the implementation of the solution.

Table 9: Potential solutions to deadlocks (Source [66])

	Internal	External
Social (process)	Committees and Working Groups	Procedural Approach
		Committees and Working Groups
Cognitive (Substance)	Scientific Investigation	Political Decision
		Scientific Investigation

VI. Concluding Remarks

This paper has identified human agents relevant for airport modeling and has mapped their goals in terms of the KPAs safety, capacity, economy, and environment. In this paper, an airport is considered to be a complex system that has many interconnected components and is characterized by the diversity of actors. It was shown that with such diversity, it could be challenging to solve key issues airports are facing since actors do not necessarily share the same goals, values, and beliefs which might lead to deadlocks. Potential solutions to these deadlocks include setting up committees and working groups to address the problem, designing decision making procedures in a way that the core values of actors are respected, or initiating a scientific investigation to help increase the knowledge about the problem at hand. Regarding the last approach, this paper proposes the multi-agent paradigm as a powerful approach to model and analyse complex socio-technical systems such as operations at and around an airport, which are characterized by conflicts, since it enables representing phenomena resulting from the attributes and behaviour of lower level agents. It is expected that the results of this approach might give more insights on what actors should do in order to achieve their different goals.

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List of Abbreviations

ACI	Airports Council International
AEA	Association of European Airlines
AIS	Aeronautical Information Service
ALS	Alerting Service
AMC	Airspace Management Cell
ASM	Airspace Management
ATC	Air Traffic Control
ATFM	Air Traffic Flow Management
ATM	Air Traffic Management
CANSO	Civil Air Navigation Services Organisation
CAST	Commercial Aviation Safety Team
CFMU	Central Flow Management Unit
CNS	Communication, Navigation, and Surveillance
EASA	European Aviation Safety Agency
ECA	European Cockpit Association
ERA	European Regions Airlines Association
FAA	Federal Aviation Administration
FIS	Flight Information Service
HERMES	HEuristic Runway Movement Event Simulation
IACA	International Air Carrier Association
IAOPA	International Council of Aircraft Owner and Pilot Associations
IATA	International Air Transport Association
ICAO	International Civil Aviation Organisation
IFALPA	International Federation of Airlines Pilots Associations
IFATCA	International Federation of Air Traffic Controllers Associations
IFR	Instrument Flight Rules
MACAD	Mantea Airfield Capacity and Delays Model
MET	Aeronautical Meteorological Service
NA	Not Applicable
NGO	Non-Governmental Organization
RAMS	Reorganized ATC Mathematical Simulator
SAR	Search and Rescue
SIMMOD	Airport and Airspace Simulation Model
TAAM	Total Airspace and Airport Modeler
TOPAZ	Traffic Organization and Perturbation AnalyZer
VFR	Visual Flight Rules

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Agent-Based Safety Risk Analysis of Time Based Operation in Future TMA

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The SESAR and NEXTGEN drivers to invest in the development of Time Based Operations (TBO) are the expected capacity, economy and safety benefits in accommodating future traffic demands. This paper addresses safety analysis of a SESAR developed TBO approach in the Terminal Manoeuvring Area (TMA) from a complexity science perspective, and presents estimated safety risks and sensitivities emerging from the behaviour of a multi-agent model.

I. Introduction

In [1], it has been identified that in a future busy Terminal Manoeuvring Area (TMA) the minimum distance between centrelines of fixed routes/dynamic routes/reference trajectories should be reduced to 5 NM; currently this distance is 8 NM or more. At the same time, the minimum radar separation between aircraft should be maintained at current values of 3 NM. The reduced spacing between centrelines to 5 NM should accommodate many more flights in a future TMA. The question addressed in this paper is whether such reduction of lateral distance between centrelines can safely be done in a future TMA under an advanced Air Traffic Management (ATM) operational concept of Time Based Operations (TBO), where aircraft aim to fly according to agreed four-dimensional (4D) trajectory intents.

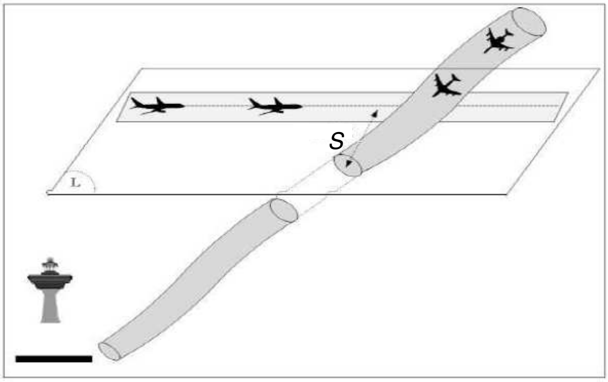

Figure 1: Encounter type considered with aircraft on a STAR and aircraft en-route, with spacing *S* between the centrelines of the STAR and the en-route lane going down to 5NM; currently this is 8 NM or more. The radar separation minimum remains at 3NM.

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Figure 1 shows a typical TMA encounter scenario, in which there are two flows of traffic. The first flow is on a Standard Arrival (STAR) route where the aircraft are on their initial descent to their destination airport. The second flow consists of a sequence of aircraft cruising along a lower-level en route lane. The minimum lateral spacing between the centrelines of the STAR and en-route lane is denoted by a parameter S. In [1] a target of S = 5 NM is proposed, in combination with a radar separation minimum of S_{radar} = 3NM. Typically, the 4D trajectory intent of an aircraft in this scenario includes the STAR or the en route lane. The specific TBO concept of operation considered has been described in [2], and is named TMA T1. The main difference between the TMA T1 concept and today's way of working is due to the *4D trajectory planning*. Such 4D trajectory planning is accomplished between pilots and planning controller with support from Air Ground Data Link (AGDL) and Controller to Pilot Data Link Communication (CPDLC). The support of the executive controller is improved through Automatic Dependent Surveillance – Broadcast (ADS-B) and a *trajectory deviation monitoring support tool*. The key question is whether these novel future functionalities of the TMA T1 concept of operation allow to safely reduce the parameter S to a value of 5 NM? The aim of this paper is to make a valuable start in addressing this question using complexity science techniques.

The paper is organized as follows. Section II places the above question into the perspective of complexity science techniques. Section III describes the specific concept of operation considered. Section IV outlines the modelling of specific non-nominal encounter scenarios. Section V presents Monte Carlo simulation results obtained for these non-nominal encounter scenarios. Section VI conducts a sensitivity analysis. Section VII derives Safety Objectives. Section VIII draws conclusions.

II. Complexity Science Perspective

The aim of this section is to place the safety analysis question posed in section I into the perspective of complexity science [3]. In ATM safety, three types of safety metrics are of consideration, namely, safety perception, dependability, and accident risk [4]. Safety perception is how humans involved perceive the risk. Dependability addresses the performance of technical systems in terms of reliability, availability, maintainability and safety (RAMS). Accident risk is a metric commonly used in safety analysis of safety-critical operations, including aviation [5]. In line with this, in [6] a future target level of safety has been derived in terms of maximum probability of collision between aircraft under the TMA T1 concept of operation. Although this means that accident risk is the ultimate metric to analyse the safety of the TMA T1 operational concept, this does not mean that the other two safety metrics can simply be ignored. The key issue is that ATM operations define a complex socio-technical system in which the interaction between pilots, controllers, technical systems and environment determine accident risk as a weakly emergent property [7],[8]. This means that the analysis of accident risk can only be accomplished by analysing the behaviour of and interactions between the agents involved along the slopes of the safety pyramid depicted in Figure 2.

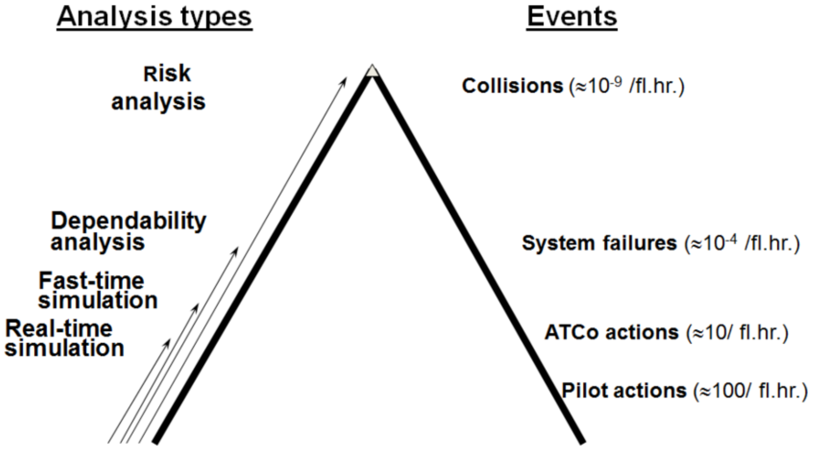

Figure 2: ATM Safety Pyramid: ATM safety analysis extends over many time scales [9]

Motivated by the need to model the dynamic interactions of safety-critical multi-agent systems, NLR has developed the Traffic Organization and Perturbation Analyzer (TOPAZ) safety risk assessment methodology [4],[10], which analyses accident risk to be influenced by positive and negative dynamics of distributed and open socio-technical systems, i.e. accident risk emerges from the interactions between humans, procedures, and equipment. The quantitative modelling and analysis in use within TOPAZ integrates five complementary technologies:

- Agent Based Modelling and Simulation (ABMS);
- Human performance modelling
- Rare event Monte Carlo (MC) simulation;
- Stochastically and Dynamically Coloured Petri Nets (SDCPN);
- Sensitivity and Bias and uncertainty analysis.

From a complexity science perspective, ABMS forms a logical choice for the evaluation of advanced ATM designs. ABMS has the capability to integrate cognitive and technology models in their operating environment [11],[12]. Simulation of these individual models acting together can predict the results of transformations in procedures and technology. This emergent behaviour typically cannot be foreseen and evaluated by examining the behaviour of each individual model on its own. In the development of the quantitative safety analysis part of the TOPAZ methodology, ABMS has explicitly been embraced in order to extend the human directed situation awareness (SA) model of Endsley [15] to a multi-agent SA propagation model [13],[14]. Human agents as well as technical agents are covered by using the wide sense agent type definition of [16]: An agent is anything that can be viewed as perceiving its environment through sensors and acting upon that environment through effectors. The motivation for developing this extension was threefold: 1) [17] showed that more than 60% of the causal factors underlying aircraft accidents involving major air carriers in USA involved problems with proper SA; 2) TOPAZ experience showed that many hazards identified through brainstorming with pilots and controllers could only be captured through such a multi-agent SA propagation model; 3) The need to integrate the multi-agent SA model with other human performance submodels [18],[19]. The multi-agent SA approach of [13],[14] makes explicit that in a multi-agent system, SA propagates from one agent to another agent. This is comparable to the game of 'Chinese whisper', where the first person whispers a sentence in the ear of the next person, who whispers what he understood to the next person, etc. Just as in Chinese whisper, where mishearing may sneak in without noticing by the participants, errors may sneak in the SA's of agents in a multi agent system without noticing by the agents.

As is shown in Figure 2, in ATM safety analysis, ten magnitude orders in time scale have to be covered. This can only be accomplished through making use of dedicated rare event MC simulation. ATM applicable rare event MC simulation techniques have been developed in [20],[21], the proper working of which is guaranteed for processes that satisfy specific mathematical properties. The largest class of stochastic processes satisfying these mathematical properties is the set of General Stochastic Hybrid Systems (GSHS) [22],[23]. A GSHS provides an integrated framework to capture uncertainty and dynamics in computer science models, in control theory models and in any combination of these two.

In order to bring ABMS and rare event MC simulation for GSHS together, [24],[25] has developed the Stochastically and Dynamically Coloured Petri Net (SDCPN) formalism. SDCPN extends the coloured Petri nets of Jensen [36] and the stochastic Petri nets of Haas [37] in the sense that the colours are allowed to vary according to the solution of stochastic differential equations, and that the transitions and the firings are allowed to be dependent on current stochastic and dynamic colour values. The SDCPN formalism also provides a way to develop a complex multi agent based system in a compositional way [26]. Moreover, it has been proven that an SDCPN instantiation uniquely defines a GSHS [25],[27],[28]. This power of SDCPN allows to conduct rare event MC simulations for a complex agent based model of an ATM operation that is specified in SDCPN language.

Finally there is the sensitivity and bias and uncertainty analysis which allows assessing the impact of potential differences between the true operation and the agent-based model on the risk level assessed for the agent-based model [29]. The types of differences that can be taken into account are: errors in parameter values, hazards not modelled, model structure differences from reality and potential differences in ConOps interpretation by the modellers and how it was meant to be by the ConOps design team.

III. TMA T1 Concept of operation

This section provides background and context information to the operational concept referred to as TMA T1. This TMA T1 concept is presented in [2], and is further detailed in non-public documents [30] and [31]; most of this material has been included in public documents [6] and [32].

Before departure of an aircraft, the airline will downlink a Systemized Business Trajectory (SBT). Before take-off, this SBT is agreed between Airline and ATM, becomes registered as a Reference Business Trajectory (RBT), and is distributed through System Wide Information Management (SWIM). After take-off, this RBT is updated and down linked by the pilot to ATC using Air Ground Data Link (AGDL), and when it is accepted by both pilot and ATC it will be registered as an Update in SWIM. From then on, it is referred to as a Registered RBT. Every stakeholder will have access to the RBTs in SWIM. The RBT may be updated a few times during flight, e.g. if during the flight there is any change or delay (delay in landing, or due to wind or a flight conflict). In the end, the updates should converge.

Prior to the moment that an aircraft passes top of descent, the Planning Controller uses Controller to Pilot Data Link Communication (CPDLC) to uplink to that aircraft a request to downlink its current RBT. The pilot-not-flying then downlinks (using AGDL) the RBT that is in the Flight Management System (FMS). Next, the RBT that has been received by the ATC system is compared with the already known RBTs of other aircraft: the RBTs are sent by the Planning Controller to the arrival management controller, who determines a sequencing that leads to an arrival time over waypoint. This time is then sent back by the arrival management controller to the Planning Controller. If the outcome of the comparison is negative because there is a conflict or another problem, then the Planning Controller sends through CPDLC a constraint to the aircraft; this constraint will be a Target Time of Arrival (TTA), which is a planned time over an exit waypoint. The Planning Controller en-route has to make sure that each aircraft gets a plan that is compliant with TTA. If needed, the Executive Controller comes to help through R/T communication with pilots.

The pilot-not-flying will work together with his FMS to judge the constraint on feasibility. If the constraint is considered feasible, the pilot-not-flying uses CPDLC to accept the constraint, and make the trajectory planning "current". If the constraint is judged not to be feasible for the aircraft, then the pilot will use R/T to report back to the Executive Controller. Subsequently, the Executive Controller reports to the Planning Controller, who is asked to provide a new constraint. If the aircraft has successfully modified its RBT in line with the ATC requested constraints, then this RBT is registered via AGDL into SWIM. Prior to the start of the CDA (Continuous Descent Approach), the Planning Controller requests an aircraft to submit a calculated 4D trajectory to the ground. This request is by data link to the FMS, whereupon the FMS calculates 4D trajectory information from its RBT information.

The Executive Controller maintains situation awareness via their traffic situation display, via communications with other controllers, and via communications with the pilots. The Pilots maintain situation awareness mainly via their navigation displays, communications with ATC, communications with each other (i.e. between pilot-flying and pilot-not-flying), and the windows.

There are three conflict directed decision support tools for the controllers: Medium Term Conflict Detection (MTCD), Monitoring Aids (MONA) and Short Term Conflict Alert (STCA). MTCD regularly verifies whether 4D trajectory plans of the various aircraft are anywhere in conflict with each other. In principle, MTCD is a Planning Controller tool. In support of conflict-free planning, the controller will always want to do 'what-if modelling' in order to see the effect of alternative planned trajectories. The 'what-if modelling' is part of the MTCD system.

MONA uses as input estimated aircraft state information (position and velocity) received through ADS-B and radar data. MONA regularly verifies whether the aircraft indeed realizes the 4D trajectory or not. If MONA identifies some mismatch, in principle, the Executive Controller is informed. However, the Planning Controller responsible for a flight phase further down the route might have interest in the problem as well, for example if the flight is delayed but is not affected by any tactical separation problem.

Normally, if MTCD or MONA identifies a conflict or a deviation, then one of the involved aircraft is requested to modify its RBT. A planning conflict may ultimately become a tactical conflict, especially when the aircraft arrives in a sector. Note that MTCD detected conflicts get priority over MONA detected deviations. If the conflict has become tactical, the Executive Controller can take any action deemed necessary to maintain separation, even open-loop instructions. A planning action by a

Planning Controller should take care of recovery, i.e. create a valid RBT and if possible readmit the aircraft in the landing sequence.

The role of Short Term Conflict Alert (STCA) in this advanced concept will be as today: a last resort conflict detection tool for the Executive Controller, who may give an instruction to an aircraft that deviates from its RBT.

Note that, on the ground, most of the RBT-related activities will be done by the Planning Controller. In the air, the RBT-related activities will be done by the pilot-not-flying. The pilot-flying is not involved in activities related to RBT. If this all works well, then the Executive Controller will only need to give clearances and make sure the aircraft is handed over to the next controller.

The Executive Controller will be the one directly communicating with the pilot. Most communication will be done through R/T, unless there is no hurry, in which case CPDLC is used. Information directly communicated from ATC system to FMS without human involvement will be restricted to e.g. meteo information. Information directly communicated from FMS to ATC system without human involvement may include more, e.g. flight status information, updated estimates over waypoints, local meteo, etc.

In dense TMA airspace, an RBT for a departing or approaching aircraft will include a SID (Standard Instrument Departure route) or a STAR (Standard Arrival Route) respectively. Aircraft on a SID and aircraft on a STAR spaced at 5 NM are generally under control of two different controllers (particularly if the SID and the STAR considered are to/from two different airports), i.e., the Arrival controller and the Departure controller will be two different persons. However, it is judged that for an operation of opposite direction traffic at a spacing of 5 NM to be close to feasible, these two controllers should work next to each other, or the work should be done by one controller. In case of a conflict, the departing aircraft could be kept on the ground a bit longer or shorter. If the departing aircraft is already airborne, it is suggested that the departing aircraft should get an instruction. In case of one aircraft on a STAR and one aircraft at level, the most logical choice would be to give the aircraft at level a lateral deviation instruction. An alternative is to let both aircraft level off and separate them vertically.

IV. Agent Based Modelling

The quantitative safety risk analysis of the TMA T1 operation makes use of agent based modelling and simulation (ABMS). The development of the agent based model is done in a hierarchical way. At the highest hierarchical level the relevant "agents" involved with the operation to be evaluated are distinguished. For safety risk analysis of ATM scenarios, an "agent" typically is any entity that defines the true situation or maintains situation awareness (SA) components about any of the other agents [13],[14]. For the TMA T1 concept, Figure 3 depicts the agents and their interactions modelled:

- Weather, particularly wind and heavy weather affecting the flight path of the aircraft.
- ATC system, including all technical equipment of the air traffic controller, such as traffic situation display, MONA, systems providing surveillance data, STCA, and ground communication means such as CPDLC and R/T communication. Other elements considered in this agent are the Airspace structure and the current RBTs known to ATC.
- Tactical Controller, including his/her actions, performance and situation awareness.
- Aircraft i, including aircraft type and the actually flown flight path (referred to as aircraft evolution). In addition, this agent includes an entrance list of aircraft to the routes (i.e., each aircraft has a particular time and location of entry into the sector).
- Guidance Navigation and Control system of the i-th aircraft. This includes the auto flight system, the navigation system (FMS), control panel, aircraft performance data and a deviation alerting system. It also includes communication systems such as CPDLC and R/T communication, and the RBT as available in the FMS.
- Flight crew of i-th aircraft, including their actions, performance and situation awareness.

For each of the first three agents there is only one agent in the model. For the other three agents there is one agent per aircraft.

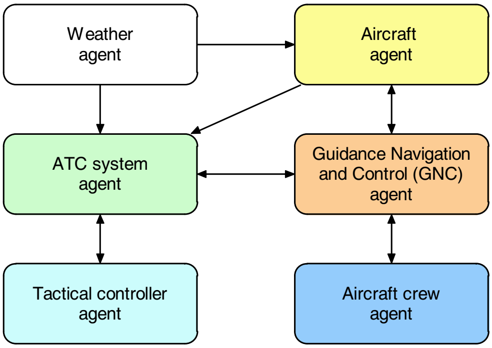

Figure 3: Agents distinguished, and their interactions

Having defined the agents to be distinguished in the safety analysis, the next step is to perform an analysis of relevant non-nominal scenarios that may potentially happen within the TMA T1 operation. More specifically, a qualitative analysis has been performed on various combinations of differences in intent situation awareness of agents in the TMA T1 operation. By combining the various differences in situation awareness of the four main agents in the operation (i.e. GNC of aircraft i, Flight Crew of aircraft i, the ATC system and the Tactical Controller), about the aircraft trajectory intent (e.g. the RBT), sixteen combinations were identified. These combinations are further analysed in [32], and this shows that the riskiest situations are the ones in which an aircraft is making a turn away from its current course, in the direction of another route. For example, in Figure 1 this could mean that a level flying aircraft makes a sudden turn into the direction of the STAR. These risky situations are clustered into the following four main non-nominal encounter conditions:

- In the first encounter condition (referred to as "No ATC"), the Controller does not, or is not able to give an instruction to an aircraft in order to solve a potential problem.
- In the second encounter condition (referred to as "Controller own detection"), the Controller becomes him/herself aware of a conflict, and provides an avoidance instruction to resolve the conflict.
- In the third encounter condition (referred to as "STCA only"), the Controller becomes aware of a conflict through STCA (Short Term Conflict Alert) and then gives an avoidance instruction.
- In the fourth encounter condition (referred to as "MONA first"), the Controller becomes first aware of a conflict because MONA detects a deviation of an aircraft position/velocity from the 4D intent (RBT) in the ATC system.

In addition to these four non-nominal encounter conditions there also is the fifth encounter condition under which encountering aircraft stay at their STAR or en route lane according to RNP1 required navigation performance, i.e. they are required to stay within 1 NM from their route centreline during 95% of the time. This nominal encounter condition is not evaluated in this paper.

Due to the low level of detail currently available on the TMA T1 way in which controllers and pilots should react on conflicts which they detect themselves, in this paper we also do not evaluate the second non-nominal encounter condition. Hence we focus on the first, third and fourth non-nominal encounter conditions, i.e. "No ATC", "STCA only" and "MONA first". For these three non-nominal encounter conditions the behaviour of and interactions between the agents in Figure 3 are modelled using the compositional specification approach of the SDCPN formalism [26]. Rather than giving the details of the SDCPN specified model, we briefly describe how this model works for each of the three selected non-nominal encounter conditions.

Non-nominal encounter condition "No ATC" considers a situation in which the Controller does not, or is not able to give a conflict recovery instruction to an aircraft in conflict. In this situation, we assume that the aircraft on the en route lane makes a turn away from its lane; the aircraft on the STAR maintains a straight line. However, no instruction is given to resolve any conflict. This situation may occur, e.g., due to failing communication or failing ground surveillance equipment. Studying this situation helps to understand the effect of Controller actions on reducing collision risk, and to set Safety Objectives on failure of communication and surveillance equipment.

Non-nominal encounter condition "STCA only" considers a situation in which the aircraft makes a turn, while the Controller and the ATC system have the intent situation awareness that the turn can be safely made. Here, we make the assumption that the aircraft en route makes this turn, i.e., the aircraft on the STAR maintains a straight line. This means, according to the ATC system, the aircraft on approach has an RBT according to the STAR, and the aircraft en route has an RBT that is making a turn away from the en route lane. The Controller is monitoring the positions and velocities of all aircraft that are available to him through surveillance equipment and the traffic situation display. In this scenario, about two minutes before a conflict is due to occur (i.e. two minutes before separation is less than S_{radar}), the short term conflict alert (STCA) system warns the Controller of a conflict. Upon this, after a (random) reaction time, the controller takes action: he uses R/T to give the flight crew of one of the aircraft an avoidance instruction. R/T is assumed to be working properly. One option is to give the aircraft on the STAR an instruction to level off, thus ensuring vertical separation. Another option is to send the aircraft en route back to the en route lane. In the simulation model, STCA gets as input only position information, from which it derives velocity information. After a (random) reaction time, the pilot-flying of the aircraft that has been given the instruction, reacts and follows the instruction.

Non-nominal encounter condition "MONA first" considers a situation in which the aircraft makes a turn, and the Controller has the situation awareness that the turn can be safely made. However, the ATC system has the intent situation awareness that the aircraft should continue to fly in a straight line. This means, according to the ATC system, the aircraft on approach has an RBT according to the STAR, and the aircraft en route has an RBT according to the en route lane. Again, we make the assumption that the aircraft en route makes this turn, i.e., the aircraft on the STAR maintains a straight line. The Controller is monitoring the positions and velocities of all aircraft that are available to him through surveillance equipment and the traffic situation display. In this scenario, MONA is the first to detect that the aircraft is making a turn away from its intent RBT. The Controller is alerted to this deviation, and after a (random) reaction time, the controller takes action: he uses R/T to give the flight crew of one of the aircraft a recovering instruction; R/T is assumed to be working properly. One option is to give the aircraft on the STAR an instruction to level off, thus ensuring vertical separation. Another option is to send the aircraft en route back to the en route lane. It is assumed that MONA gets as input precise state information (position, velocity) of aircraft, e.g. through ADS-B or Mode S. In addition, about two minutes before a conflict is due to occur STCA warns the Executive Controller of a conflict. Upon this, after a (random) reaction time, the controller takes action, by using R/T to give the flight crew of the aircraft on the STAR an instruction to level off, or to send the aircraft en route back to the en route lane. After a (random) reaction time, the pilot-flying of the aircraft that has been given the instruction, reacts and follows the instruction.

The non-nominal occurrences of the technical systems are covered by non-nominal encounter condition "No ATC". In line with this, for both non-nominal encounter conditions "STCA only" and "MONA first", it is assumed that all technical systems (communication, navigation, surveillance) are working normally. Obviously, any delays in communication, surveillance updates, etc, are taken into account, as well as the variable reaction times of controller and pilot. Note that these reaction times are taken from a particular probability distribution, which covers variability in reaction time due to stress, fatigue, distractions, etc.

V. Monte Carlo simulation of encounter conditions

This section presents the results of conditional Monte Carlo simulations of the three non-nominal encounter conditions "No ATC", "STCA only" and "MONA first" using baseline settings of all model parameter values. Table 1 lists the baseline parameter values adopted. In Figure 4, the MC simulation obtained conditional risk results are shown for the baseline parameter values, and plotted against the distance S between the centrelines of the routes on which the aircraft fly in the TMA, including the baseline value $S = 5$ NM.

The horizontal axis in Figure 4 shows various values for the spacing between the en route lane and the STAR, in nautical miles (NM). The vertical axis provides the conditional collision risk for the three conditions described. Between one hundred thousand and 60 million Monte Carlo simulations were run for each point estimate on the graph, depending on the number of collisions counted per run (i.e., a lower collision risk requires more runs to obtain more accurate results). The small green blocks in the figure indicate the upper bound and lower bound of a 95% confidence interval for conditional risk.

Table 1: Main model parameters and baseline values adopted

Model Parameter	Baseline value
RNP value	1 NM
Minimum spacing *S*	5 NM
Radar separation minimum	3 NM
Vertical spacing minimum	1000 ft
Aircraft length/width	50 m
Aircraft height	20 m
Aircraft speed	325 knots
Angle of sudden turn	60 degrees
Aircraft bank angle	25 degrees
Vertical acceleration/deceleration	2 m/s^2
Time distance between aircraft on STAR/level lane	2 minutes
Mean controller response time to MONA or STCA	7.6 s (Rayleigh density)
Mean pilot delay in executing controller instruction	5.7 s (Rayleigh density)
Mean duration of resolution monitoring by controller	14.7 s (Rayleigh density)

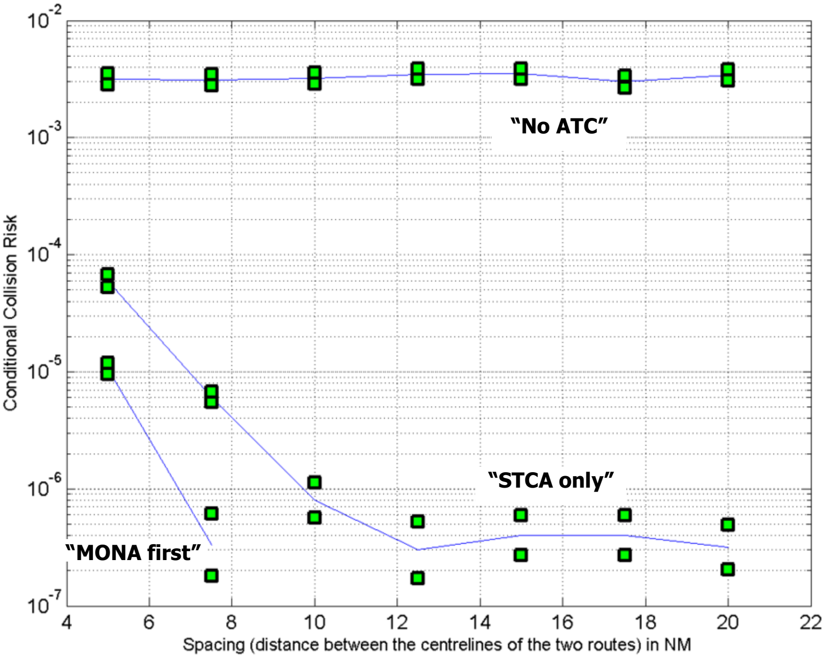

Figure 4: Monte Carlo simulation results for non-nominal encounter conditions "No ATC" (top figure), "STCA only" (middle figure) and "MONA first" (bottom figure).

The results in Figure 4 show the following:

For "No ATC" (top curve), the conditional collision risk results are at a constant level of about 3.3E-3, for all values of the spacing. This means that according to the model, if the Controller does not give instructions, each en route aircraft entering the sector has a probability of 3.3E-3 to collide with an aircraft on the STAR.

For "STCA only" (middle curve), the conditional collision risk is 6.0E-5 at a spacing of 5 NM, and it quickly decreases to a level of about 2.5E-7 at larger spacings. The result that the conditional risk becomes constant as the spacing further increases can be explained by the fact that STCA works with a fixed look ahead time. Since in this situation considered, the Controller only gives instructions after an alert from STCA, it is found that further increasing the spacing does not help to decrease risk, since in such case, STCA would simply alert later.

For "MONA first" (bottom curve), the conditional collision risk is 1.1E-5 for a spacing of 5 NM, and is 3.3E-7 for a spacing of 7.5 NM. It appears that for larger spacings, no collisions have been counted in the 30 million Monte Carlo simulation runs done, and hence that the conditional risk for spacings larger than 7.5 NM are less than 1 in 30 million (i.e. less than 3.33E-8).

At a spacing of 5NM, the conditional collision risk results of "STCA only" are a factor 53 better than those of "No ATC". At a spacing of 7.5 NM, the difference is even a factor 700, and the factor increases to over 1E4 for larger spacings. This shows that according to the model, the Controller has a major contribution to solving conflicts, even if the controller only reacts upon an STCA alert. At a spacing of 5 NM, the conditional collision risk results of "MONA first" are a factor 5.6 better than those of "STCA only". For a spacing of 7.5 NM, the difference is even a factor 13.5, and the factor increases to at least 15 for larger spacings. This shows that according to the model, MONA has a significant contribution to detecting (and solving) potential conflicts, in addition to STCA.

Comparison of the "MONA first" curve and the "STCA only" curve shows that the addition of the MONA tool alone supports a reduction of the *S* value by 2 NM. Although this is a significant reduction, it is less than what is needed for a reduction from 8 NM to 5 NM. This forms a sound reason to perform sensitivity analysis and to derive safety objectives in the next two sections.

VI. Sensitivity Analysis

This section presents results from a sensitivity analysis which aims at providing insight into the effects of variations in parameter values on conditional risk. We refer to [32] for the complete results. The first value varied is that of required navigation performance (RNP). Under baseline parameter value settings, all aircraft are assumed to fly at RNP1, meaning that they are required to stay within 1 NM of the centreline of their lane, during 95% of the time.

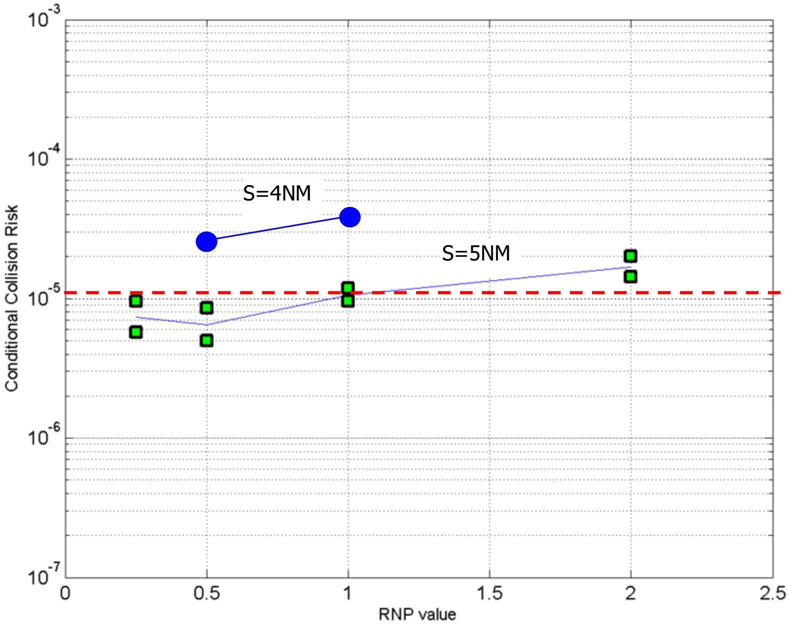

Figure 5: Sensitivity of conditional risk to variations in RNP value at spacing of S = 5 NM and S = 4 NM for the non-nominal encounter condition "MONA first". The red line denotes the estimated level of risk for the baseline situation.

Figure 5 shows the sensitivity results for non-nominal encounter condition "MONA first", for various RNP values. The bottom curve shows the result for a spacing of 5 NM and RNP values of 0.25, 0.5, 1 and 2. The top curve shows the result for a spacing of 4 NM and RNP values of 0.5 and 1. The red dashed line denotes the estimated level of risk at 5 NM spacing for the baseline situation.

The results in Figure 5 show that if the spacing is 5 NM (bottom curve), there is a decrease of conditional collision risk with decreasing RNP value; however, the decrease is minor only. If the spacing is 4 NM (top curve), there is also a decrease of conditional collision risk with decreasing RNP value; again, the decrease is minor only.

The results represented by the top curve were derived to test a statement in [2, page 90] which suggested that the reduced spacing of 5 NM could be further reduced to 4 NM, if the required navigation performance is improved from RNP1 to RNP0.5. As one may expect, the conditional collision risk increases as the spacing is further reduced from S = 5 NM to S=4 NM (the increase is about a factor 4). However, Figure 5 shows that under the conditions modelled, this increase is not compensated by improving the required navigation precision from RNP1 to RNP0.5 (the decrease is less than a factor 2).

We present some other sensitivity results. In the baseline situation all aircraft are assumed to fly at 325 knots, which is quite a high value for the TMA. And the reaction time of the controller is from a Rayleigh probability distribution, with an average reaction time of 7.6 seconds.

The left-hand-side of Figure 6 shows how conditional collision risk changes with varying aircraft speed. The right-hand-side of Figure 6 shows how conditional collision risk changes with varying average controller reaction time upon detection of a problem. Both figures are for the case of non-nominal encounter condition "MONA first" and a spacing of 5 NM.

One may see that the conditional collision risk decreases with decreasing speed and decreases with decreasing controller reaction time. The reasons are that in case of lower aircraft speed and in case of lower controller average reaction time, the controller has more time available to resolve a conflict.

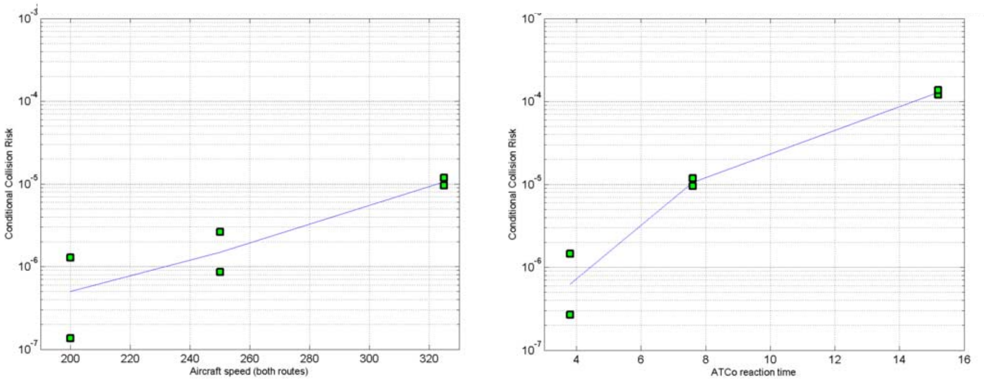

Figure 6: Monte Carlo simulation sensitivity results: Non-nominal encounter condition "MONA first" for S = 5 NM. Left-hand-side figure: Conditional collision risk for various values of aircraft speed. Right-hand-side figure: Conditional collision risk for various values of average controller reaction time.

A summary of all sensitivity results, including the ones illustrated above, is given in Table 2. This Table refers to log-sensitivity (= elasticity) which is approximated by (*ln Risk(A)* – *ln Risk(B)*) / (*ln A* – *ln B*), where *ln* denotes natural logarithm, and *Risk(X)* denotes the conditional collision risk if we use *X* as value for the parameter considered (and with all other parameters at their baseline value).

The main conclusion that can be drawn from the sensitivity results is that according to the model, the conditional collision risk is highly sensitive to changes in any parameter that influences the time available to resolve a conflict between two aircraft. If there is more time available, the risk decreases by a high factor; if there is less time available, the conditional risk increases by a high factor. This available time is smaller if aircraft fly faster, if they turn away from their route at a sharper turn angle, if the average reaction time of the controller and pilots is higher, or if STCA uses a larger separation minimum. It appears that reducing RNP value has only negligible to minor impact under the conditions considered. And it appears that the risk increase that would result from further reducing the spacing from 5 NM to 4 NM cannot be compensated by improving required navigation performance from RNP1 to RNP0.5.

Table 2: Summary of sensitivity results; + denotes a positive log-sensitivity (= elasticity), i.e. risk <u>in</u>creases as the parameter value is <u>in</u>creased; – denotes a negative elasticity, i.e. risk <u>de</u>creases as the parameter value is <u>in</u>creased. If the absolute value of elasticity is about 0.125/0.25/0.5/1/2/4, we say the sensitivity is negligible/small/ minor/significant/considerable/major, respectively.

Parameter	No ATC	STCA only	MONA first
Required Navigation Performance value	+ and Negligible	+ and Negligible	+ and Minor
Aircraft speed	– and Significant	+ and Major	+ and Major
Angle of sharp turn	– and Significant	+ and Major	+ and Major
Controller reaction time	Zero	+ and Considerable	+ and Major
Flight Crew reaction time	Zero	+ and Considerable	+ and Considerable
STCA used separation minimum	Zero	– and Considerable	– and Minor
Vertical acceleration to avoid conflict	Zero	– and Significant	– and Minor

It should be noted that a parameter being sensitive has two potential implications:

1. From a design perspective, the first implication of a parameter value being sensitive, is that this parameter provides a potential direction for redesign of the operation to reducing its risk. However, this only applies when the parameter value is or can be made controllable within the operation design. If this is feasible, then a safety requirement can be posed upon the specific parameter value. In such case a larger sensitivity means that it is in principle easier to realize a controlled reduction of risk during design. For the specific encounter scenario considered this could mean that safety risk might be reduced by training pilots and controllers to avoid very slow responses (which are in the tail of the probability density function) to MONA triggered alerts/instructions.
2. The second implication is that if the uncertainty value of a sensitive model parameter cannot be reduced, then a high sensitivity leads to high uncertainty in the estimated risk value. This effect can in principle be mitigated by determining the parameter value more accurately, e.g. by gathering more statistical data about the parameter value, thus decreasing its uncertainty. Often however, and especially during the early lifecycle stages of an operation design, statistical data is sparse, and there will remain some level of uncertainty or variability about the "true" value of a parameter.

VII. Safety objectives

In this section, we derive Safety Objectives for the three non-nominal encounter conditions evaluated. For this, we start from the [6, p. 111] derived future Target Level of Safety (TLS) of 4.35E-9 accidents per flight hour. This TLS we break equally down according to:

- 5 particular encounter conditions: one nominal RNP1 and four non-nominal encounter conditions (No ATC, Controller self-detection, STCA only, MONA first);
- 3 directions of flight, i.e. lateral, longitudinal, vertical; and for the specific encounter scenario considered the lateral direction only is considered.
- Half of the lateral TLS budget should be allocated to encounters with aircraft flying on the opposite level lane. The other half of the lateral TLS budget is allocated to the lateral risk of encounters between level flying aircraft and aircraft on a STAR or a SID.
- 4 SIDs or STARs are passed at 5 NM per flight hour during a level flight through a TMA, i.e. 1 SID or STAR is passed at 5 NM every 15 minutes during flying level in the TMA.

The result is that the TLS of 4.35E-9 accidents per flight hour, is equally divided over 3 × 5 × 2 x 4 sub-targets. Hence each of these sub-targets is then equal to 4.35E-9 divided by 3 × 5 × 2 x 4, which is 3.6E-11.

Next, we write risk as a weighted sum of Conditional risks. The weights are equal to the probabilities of the conditions κ.

$$\text{Risk} = \sum \text{Conditional risk } (\kappa) \times \text{Probability } (\kappa) \text{ / TCAS factor}$$

where κ runs through the five encounter conditions identified above, and the TCAS factor stands for the extra factor in collision risk reduction that is due to TCAS.

Hence, for each κ, we have a target level of lateral risk of 3.6E-11 per Level Lane-STAR encounter, which means: Conditional risk (κ) × Probability (κ) / TCAS factor ≤ 3.6E-11.

The latter yields the following Safety Objective for each κ:

$$\text{Probability } (\kappa) \leq \text{3.6E-11 x TCAS factor / Conditional risk } (\kappa).$$

Current TCAS II Version 7.0 provides on average about a factor 4.5 reduction in collision risk in European airspace [33]. With the forthcoming implementation of TCAS II Version 7.1 this is expected to improve to some 10% extra reduction [34]. Because aircraft speeds in TMA are significantly below the average speeds in European airspace, in TMA the factor risk reduction by TCAS II is significantly better [35]. This forms the rationale for assuming a factor 10 collision risk reduction by TCAS in the future TMA considered. Substituting this in the last equation, together with the conditional risk values in Figure 4 at a spacing of 5NM, yields the following Safety Objectives:

- For κ equal to non-nominal encounter condition "No ATC", we derive as Safety Objective: Probability(κ="No ATC") = 3.6E-11 x 10 / 3.3E-3 = 1.1E-7, which means that this non-nominal encounter condition "No ATC" is allowed to occur at most 1.1E-7 times per flight hour.
- For κ equal to non-nominal encounter condition "STCA only", we derive as Safety Objective: Probability(κ="STCA only") = 3.6E-11 x 10 / 6.0E-5 = 6.0E-6, which means that this non-nominal encounter condition "STCA only" is allowed to occur at most 6.0E-6 times per flight hour.
- For κ equal to non-nominal encounter condition "MONA first", we derive as Safety Objective: Probability(κ="MONA first") = 3.6E-11 x 10 / 1.1E-5 = 3.4E-5, which means that this non-nominal encounter condition "MONA first" is allowed to occur at most 3.4E-5 times per flight hour.

VIII. Conclusions

In [1] it has been identified that in a future busy Terminal Manoeuvring Area (TMA) the lateral distance (spacing) between the centrelines of fixed routes/dynamic routes/reference trajectories should be reduced to 5 NM; currently this is 8 NM or more. At the same time the minimum horizontal separation between aircraft should be maintained at current values of 3 NM. The reduction between centrelines to 5 NM in particular should accommodate many more flights in a future TMA. The question addressed in this paper is whether such lateral spacing reduction between centrelines can safely be done in a future TMA under an advanced ATM operational concept of Time Based Operations (TBO), where aircraft aim to fly according to agreed 4D trajectory intents. The specific TBO concept of operation considered has been described in [2], and is named TMA T1. The main difference between the TMA T1 concept and today's way of working is due to the *4D trajectory planning* between pilots and planning controller and the *trajectory deviation monitoring support tool* MONA for the executive controller. For this TMA T1 concept of operations [6] has identified the allowable level of mid-air collision risk probability per aircraft flight hour.

This paper has performed an initial agent-based safety risk analysis in case of two streams of aircraft that are flying on a STAR (Standard Arrival Route) and on an en-route lane, the centrelines of which pass each other at a 5 NM distance only. This safety analysis focuses on the safety consequences of potential situation awareness (SA) confusion about 4D trajectory intent. If for one or more agents the SA about the 4D trajectory intent of an aircraft is confused in some way, then this typically leads to a delay in proper conflict detection and resolution, due to necessary additional situation assessment and additional communication. Quantitative safety risk results are obtained through conducting rare event Monte Carlo simulations of a multi-agent dynamic risk model of this operation. The results show that thanks to the MONA tool alone, the TMA T1 concept of operations supports a reduction of the *S* value by 2 NM, which is a significant reduction, though still less than what is needed for a reduction from 8 NM to 5 NM.

In order to gain further insight into potential directions in making the TMA T1 sufficiently safe, also a sensitivity analysis has been performed regarding the effects of variations in parameter values on conditional risk. For the situations and conditions considered, the conditional risk appears to be sensitive to parameter values that influence the time available for the Controller to resolve a sudden sharp turn, such as spacing value, aircraft speed, the angle of the turn, and controller and flight crew average reaction time. It was also found that for the situations and conditions considered, the conditional risk is not very sensitive to further improvement of the required navigation performance, and as a consequence further improvement of navigation precision does not allow a further reduction of the spacing value below 5 NM. However some other valuable directions have been identified that have significant potential in a further reduction of safety risk. Complementary to this sensitivity analysis, the paper has also derived Safety Objectives (SOs), under the adopted agent-based model and the baseline values for its parameter values, regarding the allowable rate of occurrence of the three most serious conflict and resolution scenarios.

In conclusion, the quantitative safety risk results obtained show that under a series of assumptions (see Appendix), a reduction of the spacing between the centrelines of a STAR and an en-route lane to 5 NM, can be done sufficient safe if the TBO concept of operations considered is going to satisfy some SOs regarding conflicts that are induced by 4D trajectory intent Situation Awareness problems.

Because the focus of this quantitative safety risk analysis has been on the most risky encounter conditions, and under a series of assumptions (see Appendix), follow up safety analysis remains to be conducted, such as:

- Conflicts in longitudinal direction, and conflicts in vertical direction. It is noted though, that T1 focused on reducing spacing in lateral direction only, hence the risks in longitudinal and vertical direction could be expected to be as today.
- Situations in which aircraft do not make a turn but maintain a straight line, generally maintaining their SID, STAR or en route lane. These situations are expected to be of relatively low risk, but given the circumstance of closely spaced SIDs and STARs, this expectation should be verified.
- Situations in which the Controller detects the deviation or conflict him/herself, instead of being triggered only after an STCA or a MONA alert. These situations were intentionally left for follow-up study since the operational concept considered is in a very early lifecycle stage, and it is not determined yet how the Controller would or should react exactly if they detect a difference in intent situation awareness themselves.
- Conflicts in which the aircraft on the STAR is making the turn rather than the aircraft en route, conflicts between aircraft on closely spaced SIDs, conflicts between aircraft on closely spaced STARs, conflicts between closely spaced SIDs and STARs, conflicts between crossing SIDs/STARs/en route lanes, etc.
- Completing the initial sensitivity analysis, and extending this to a full bias and uncertainty analysis of the influence on the assessed risk level of parameter value errors and other differences between the model and a true operation.

The flexibility of the Monte Carlo simulation-based modelling formalism implies that evaluating these remaining issues is certainly feasible. The experience gained during the study will allow focusing these remaining evaluations on the most interesting situations from a capacity / safety perspective.

Appendix. Assumptions adopted in this study.

A1. If an aircraft flies on its FMS and autopilot, then, unless someone intervenes:

- If the FMS has the intent situation awareness to make a turn, the aircraft will make the turn.
- If the FMS has the intent situation awareness to fly in a straight line, the aircraft will fly in a straight line.

A2. If the aircraft flies on pilot control panel (i.e. decoupled from FMS), then:

- If the pilot has the intent situation awareness to make a turn, the aircraft will make the turn.
- If the pilot has the intent situation awareness to fly in a straight line, the aircraft will fly in a straight line.

A3. The TLS per flight hour can be equally divided between 3 directions of a flight: longitudinal, lateral and vertical.

A4. For the lateral direction, the TLS can be equally divided between the following five scenarios:

a. The scenario in which all aircraft either follow their separated SID/STAR or en route lane, or make a turn away from their lane in a direction away from other lanes.
b. The scenario in which an aircraft deviates from its lane towards another lane, but the

controller does not give recovering instructions, e.g. due to ground surveillance or communication being down.

c. The scenario in which an aircraft deviates from its lane towards another lane, the controller detects a potential conflict himself before MONA or STCA gives an alert, and gives an instruction to recover the conflict.
d. The scenario in which an aircraft deviates from its lane towards another lane, and STCA is the first to detect a conflict. The controller next gives an instruction to recover the conflict.
e. The scenario in which an aircraft deviates from its lane towards another lane, and MONA is the first to detect a problem or conflict. The controller next gives an instruction to recover the conflict.

A5. It is assumed that each level flying aircraft (i.e. each aircraft on the en route lane) passes 4 SIDs or STARs per flight hour in the TMA.

A6. TCAS (Traffic Collision Alert System) delivers a factor 10 extra reduction in accident risk.

A7. Controller workload is assumed to be appropriate for the controllers involved.

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Analysis of Accident Risk Related Events and the Roles of Agents in Conflict Recognition and Resolution during a Runway Incursion Scenario

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This paper extends a safety analysis based on a multi-agent dynamic risk model (DRM) of a future mix mode taxiing into position and hold (TIPH) operation. The TIPH operation aims at placing an aircraft on the mixed mode runway, ready for immediate takeoff as soon as takeoff clearance has been issued by the air traffic controller. In the previous safety analysis, accident risk results were obtained by Monte Carlo simulations of a multi-agent DRM for a particular scenario describing the conflict between an aircraft landing and an aircraft lining up while it should not. These risk assessment simulations and results obtained earlier do not provide insight into the underlying conflict detection and conflict recognition events that occur during the simulations. Therefore relevant events were defined and recorded in additional Monte Carlo simulations of the multi-agent DRM in different visibility conditions. An additional aim of the present research is an examination of the capabilities of agents to reduce the accident risk in the operation. This is studied in the DRM by placing agents out of monitoring or control loops in different visibility conditions. The results of the study make clear the extent to which each agent is able to reduce the accident risk and the complementarities between the agents' roles in controlling the accident risk.

Nomenclature

DRM = dynamic risk model
TIPH = taxiing into position and hold

I. Introduction

The next generation Air Traffic Management in Europe has the ambitions to enable a 3-fold increase in air traffic services and capacity, with a reduction of delays on the ground and in the air, along with an improvement of the safety performance by a factor ten[7]. In support of improvement of aerodrome operations, a future taxi into position and hold (TIPH) operation was proposed in the RESET project of the European Commission 6th Framework Program. The phraseology standard of the International Civil Aviation Organization (ICAO) for this operation is "line up and wait". The TIPH operation aims at placing an aircraft on the mixed mode runway, ready for immediate departure as soon as no restrictions apply and the takeoff clearance can be issued by the air traffic controller[11]. As part of a safety assessment of the TIPH operation, a multi-agent Dynamic Risk Model (DRM) was

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developed for a runway incursion scenario involving an aircraft landing and an aircraft lining up while it should not.[10,11] This multi-agent DRM model was developed in the context of the TOPAZ (Traffic Organization and Perturbation AnalyZer) safety assessment methodology, which was first introduced by National Aerospace Laboratory NLR in 2001[1] and extended later with several aspects.[2,5,6,9] The methodology is aimed at the analysis of the safety risk of air traffic operations with the help of Monte Carlo simulations and risk uncertainty evaluations.

The risk results obtained by the multi-agent DRM based safety assessment[10,11] include point estimates of collision probabilities given particular visibility conditions, risk decomposition results for various conditions, collision risk variation results for changes in a number of key parameters of the geometry and agents' performance, and risk sensitivity and risk uncertainty results obtained by a bias and uncertainty assessment of the accident risk. These results provide a considerable insight in the safety risk of the runway incursion scenario and the main risk contributors. Nevertheless, due to the complexity of the causal factors and the interactions between agents in the runway incursion scenario, it is not clear in detail from the earlier obtained results what the effect of the roles of the different agents on the accident risk is and how conflict detection and resolution events by the agents relate to the accident risk. Methods to obtain more insight in the behavior and the roles of agents in conflict detection and conflict resolution aspects for multi-agent DRM were provided in Ref. 8 and applied to a runway incursion scenario for an aircraft taking off and an aircraft crossing the runway while it should not.

The objective of the present study is to obtain more insight into the multi-agent DRM of the TIPH operation by using the methods of Ref. 8. Thus, the safety analysis presented in this paper aims at better understanding the relations between conflict recognition and conflict resolution events that may occur in the TIPH scenario and their relation to accident risk. Examples of such events are detection of the conflict by the pilots of landing or taxiing aircraft, activation of the runway incursion alert and resolution actions of the pilots. Therefore relevant events will be defined and recorded in additional Monte Carlo simulations in different visibility conditions. Based on the data obtained, the probability of each event and the probability of the event given a collision will be evaluated. An additional aim of the present research is an examination of the capabilities of agents to reduce the accident risk in the operation.This is studied in the DRM by placing agents out of monitoring or control loops in different visibility conditions. Accident risk results for a variety of combinations of agents being in or out of the monitoring role or control loop will be described and discussed. These results make clear the extent to which each agent is able to reduce the accident risk and the complementarity between the agents' roles in controlling the accident risk.

The paper is structured as follows. Section II describes the TIPH operation, the runway incursion scenario and the multi-agent DRM. Section III describes the measurement and analysis of conflict detection and resolution events by agents in Monte Carlo simulations of the multi-agent DRM. Section IV describes the analysis of placing agents out of the monitoring role or control loop. Section V presents the conclusions of this paper.

II. TIPH Scenario and Dynamic Risk Model

In the TIPH scenario under consideration an aircraft that has been cleared to taxi into position and hold can enter the runway after the aircraft currently using runway (either landing or taking off) has passed the waiting aircraft's position. The operation is supported by a level 3 advanced surface movement guidance and control system, which includes the uplink of air traffic control (ATC) surveillance data such as aircraft position data and runway incursion alert data. The TIPH procedure is applied during all 4 visibility conditions:[11]

1. Condition1: Visibility sufficient for the pilot to taxi and to avoid collision with other traffic on taxiways and at intersections by visual reference, and for personnel of control units to exercise control over all traffic on the basis of visual surveillance;

2. Condition 2: Visibility sufficient for the pilot to taxi and to avoid collision with other traffic on taxiways and at intersections by visual reference, but insufficient for personnel of control units to exercise control over all traffic on the basis of visual surveillance;

3. Condition 3: Visibility sufficient for the pilot to taxi but insufficient for the pilot to avoid collision with other traffic on taxiways and at intersections by visual reference with other traffic, and insufficient for personnel of control units to exercise control over all traffic on the basis of visual surveillance.

4. Condition 4: Visibility insufficient for the pilot to taxi by visual guidance only.

Three visibility conditions are considered in the model: visibility condition 1 (VC1), visibility condition 2 (VC2) and a combination of visibility condition 3 and visibility condition 4 (VC3/4).

The developed model for this scenario consists of eight agents that represent human operators and technical systems involved in the scenario[10,11] (Fig. 1): landing aircraft (AC_L), taxiing aircraft (AC_T), pilots of the landing aircraft (Pilots_L), pilots of the taxiing aircraft (Pilots_T), avionics of the landing aircraft (Avionics_L), avionics of the taxiing aircraft (Avionics_T), ATC system, and Airport and Environment (A&E).

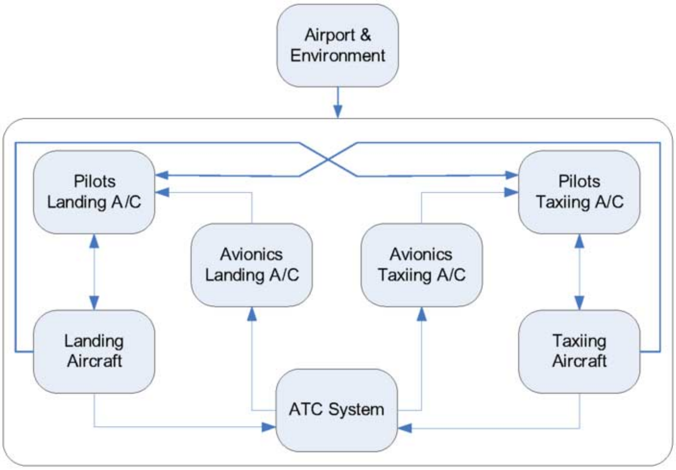

Figure 1. Relations between agents in the multi-agent DRM of the TIPH runway incursion scenario.

Mathematical models developed for each agent are based on a compositional specification approach using a stochastic dynamic extension of the Petri net formalism.[6,12] Within this Petri net formalism a hierarchically structured representation of the agents in the air traffic scenario is developed. Within each agent one or more key aspects are defined that are represented by Local Petri Nets (LPNs). The key aspects may include, for instance, situation awareness, task performance, of a human operator, flight phases, performance modes of aircraft, status of an alert system. Within the key aspects particular modes can be defined, e.g. within task performance of a controller such modes as monitoring, clearance specification and alert reaction are differentiated. This representation includes the dynamics within the modes as well, e.g. the dynamics of the time needed for the task performance, acceleration profile during take-off or the duration of an alert. The detailed specification of the TIPH model per agent can be found in Ref. 10 and Ref.11.

III. Events in the MC Simulations

In this section the safety assessment of the TIPH scenario by means of events related to the performance of the agents will be presented. The following subsections describe the defined events and present the Monte Carlo simulation results of the DRM.

A. Definition of Events

To gain more insight in the performance of the agents in the DRM, the following events were defined:

- E1: the landing aircraft starts the final approach;
- E2: the pilots of the landing aircraft detect the conflict and decide to initiate a missed approach;
- E2′: the pilots of the landing aircraft detect the conflict by own observation (rather than via the up-linked ATC alert) and decide for a missed approach;

- E3: the landing aircraft starts a missed approach maneuver;
- E4: the taxiing aircraft starts taxiing to line up on the runway;
- E5: the pilots of the taxiing aircraft detect the conflict and decide to taxi off the runway (such a decision is made if the aircraft is already on the runway);
- E5′: the pilots of the taxiing aircraft detect the conflict by own observation (rather than via the up-linked ATC alert) and decide to taxi off the runway;
- E6: the pilots of the taxiing aircraft detect the conflict and decide to stop taxiing (such a decision is made if the aircraft can stop in front of the runway);
- E6′: the pilots of the taxiing aircraft detect the conflict by own observation (rather than via the up-linked ATC alert) and decide to stop taxiing;
- E7: the taxiing aircraft comes to stance;
- E7′: the taxiing aircraft comes to stance following conflict detection by the pilots (the other reason of coming to stance is the end of the normal line-up operation);
- E8: the runway incursion alert of the ATC system becomes active;
- E9: the taxiing aircraft has taxied off the runway successfully;
- E10: the taxiing aircraft and the landing aircraft collide.

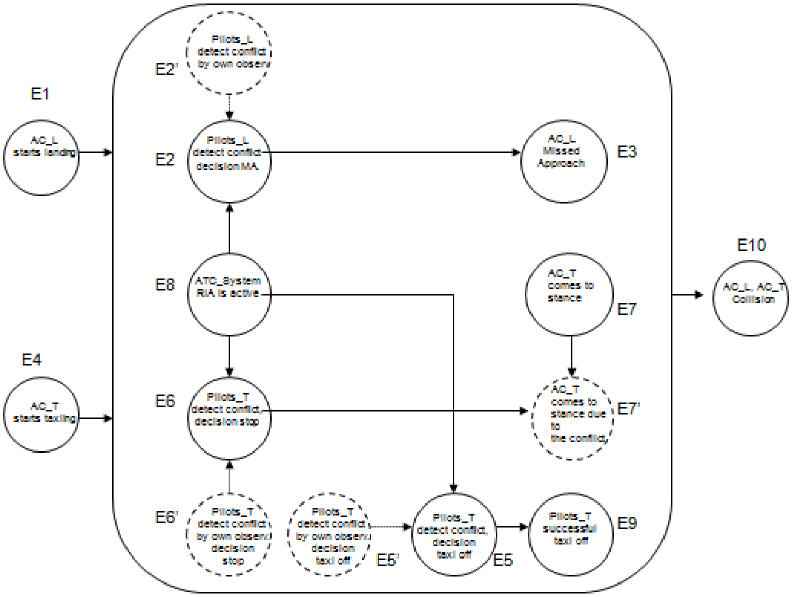

Figure 2. Relations between events in the MC simulations of the multi-agent DRM. Events in the solid circles are recorded in the MC simulations, events in the dashed circles are inferred from the relative timing of recorded events.

Figure 2 provides an overview of the relations between these events based on the DRM. For instance, Fig. 2 indicates that the runway incursion alert of the ATC (event E8) may result in conflict detection by the pilots of the landing aircraft (E2) or by the pilots of the taxiing aircraft Pilots_T, resulting in a decision either to stop (event E6) or to taxi off the runway (event E5). These events, in their turn, may result in the execution of these decisions by the pilots (event E3, E7′ and E9). The times of the first occurrence of the events were recorded in the MC simulations of the TIPH DRM and the occurrence of events E2′, E5′, E6′ and E7′ was inferred from the occurrence of related events.

B. Monte Carlo Simulation Results for Events in the DRM

A total of 10 million Monte Carlo simulation runs were performed for the condition that the pilots of the taxiing aircraft have the intent to line-up on the runway used by the landing aircraft in three visibility conditions. Table 1 shows the probabilities of the defined events and the conditional probabilities of these events given a collision event per three visibility conditions. Key observations from the results in Table 1 are explained next for each of the agents.

Table 1. MC simulation results for the defined events: event probability P(Eq) and conditional event probability given a collision P(Eq|E10) in three visibility conditions.

Agent	*Event*		*VC1*		*VC2*		*VC34*	
	ID	*Description*	*P(Eq)*	*P(Eq|E10)*	*P(Eq)*	*P(Eq|E10)*	*P(Eq)*	*P(Eq|E10)*
AC_L	E1	Final Approach	100%	100%	100%	100%	100%	100%
Pilots_L	E2	Detect conflict and make a decision of missed approach	76%	99%	90%	100%	93%	85%
Pilots_L	E2'	Detect conflict by own observation	0.9%	95%	1%	82%	0.4%	37%
AC_L	E3	Initiates missed approach	70%	46%	84%	45%	85%	10%
AC_T	E4	Starts taxiing	100%	100%	100%	100%	100%	100%
Pilots_T	E5	Detect conflict and make a decision to taxi off the runway	19%	34%	20%	54%	20%	52%
Pilots_T	E5'	Detect conflict by own observation and make a decision to taxi off the runway	3%	12%	0.2%	17%	0.03%	6%
Pilots_T	E6	Detect conflict and make a decision to stop taxiing	77%	23%	75%	13%	74%	7%
Pilots_T	E6'	Detect conflict by own observation and make a decision to stop taxiing	32%	78%	8%	4%	2%	0.4%
AC_T	E7	Comes to stance	85%	16%	85%	38%	83%	46%
AC_T	E7'	Comes to stance as a result of a conflict detection of the Pilots of Taxiing Aircraft	77%	23%	75%	13%	74%	7%
ATC System	E8	Runway incursion alert is active	76%	42%	90%	54%	93%	56%
AC_T	E9	Performs taxi off runway successfully	18%	0%	19%	0%	20%	0%
AC-T, AC_L	E10	Collision	0.06%	100%	0.2%	100%	0.5%	100%

1. Pilots of Landing Aircraft (Pilots_L)

In VC1, Agent Pilots_L detects the conflict and makes a decision to undertake a missed approach (event E2) in 76% of all simulated conflict scenarios. Only in 0.9% of all cases, Pilots_L detects the conflict by own observation (event E2′) and in the remaining 75% Pilots _L detects the conflict via the ATC system. Contributing to this difference is the model assumption that Pilots _L recognize the taxiing aircraft as conflicting if it is within a critical distance of 62 m from the runway center-line, whereas the alert threshold of the ATC system is 124 m. In the simulation runs ending in a collision in VC1, Pilots_L detects the conflict (event E2) in 99% cases. Pilots_L detects the conflict by own observation in 95% of these cases (event E2′) and via the runway incursion alert (RIA) of the ATC system in 42%. Thus for the conditional case given a collision it is found that the probability of conflict detection by Pilots_L is higher than for the unconditional case and the contribution of the ATC system to conflict detection is significantly lower than in the unconditional case.

In VC2, agent Pilots_L detects the conflict and makes a decision to undertake a missed approach in 90% of all simulated conflict scenarios. In 1% of all cases Pilots_L detects the conflict by own observation (event E2′) and in 89% Pilots_L detects the conflict via the ATC system. In the simulation runs ending in a collision in VC2, Pilots_L detects the conflict (event E2) in 100% cases. Pilots_L detects the conflict by own observation in 82% of these cases (event E2′) and via the runway incursion alert (RIA) of the ATC system in 18%. Thus for the conditional case given a collision it is found that the probability of conflict detection by Pilots_L is also higher than for the unconditional case and the contribution of the ATC system to conflict detection is significantly lower in the conditional case than in the unconditional case. It is similar to the findings in VC1.

In VC3/4, agent Pilots_L detects the conflict and makes a decision to undertake a missed approach (event E2) in 93% of all simulated conflict scenarios. Only in 0.4% of all cases Pilots_L detects the conflict by own observation (event E2′). In the simulation runs ending in a collision in VC3/4, Pilots_L detects the conflict (event E2) in 85% cases. Pilots_L detects the conflict by own observation in 36.5% of these cases (event E2′) and via the runway incursion alert (RIA) of the ATC system in 48.5%. Thus for the conditional case given a collision it is found that, contrary to the findings in VC1 and VC2, the probability of conflict detection by Pilots_L is lower than for the unconditional case. This suggests that the low visibility has diminished the detection probability, which leads to an increase in the accident probability. The contribution of the ATC system to conflict detection in VC3/4 is significantly lower in the conditional case than in the unconditional case, similar to the results in VC1 and VC2.

2. Pilots of Taxiing Aircraft (Pilots_T)

In VC1, Pilots_T agent detects the conflict and makes a decision to taxi off the runway (event E5) in 18.5% of all simulated conflict scenarios. Here Pilots_T detects the conflict by own observation in 2.5 % of cases (event E5′). Pilots_T agent detects the conflict and makes a decision to stop taxiing (event E6) in 77% of all simulated conflict scenarios. Here Pilots_T detects the conflict by own observation (event E6′) in 32% of cases. The distance in front of the runway threshold within which the landing aircraft is recognized as conflicting by Pilots_T is 3 NM. In order to resolve the conflict, Pilots_T can initiate stopping if their taxiing aircraft AC_T is beyond the distance of 35 m from the runway center-line; if the taxiing aircraft is at the distance smaller than 35 m from the runway center-line, Pilots_T agent initiates taxiing off the runway. Totally for all simulation runs, Pilots_T detects the conflict in 95.5% cases (events E5 and E6), of which 34.5% cases by own observation (events E5′ and E6′). It is much higher in comparison to the results obtained for Pilots_L agent, which detects the conflict by own observation only in 0.9% of all cases. In most of the conflict situation Pilots_T makes a decision to stop taxiing rather than to taxi off the runway, it means that in most cases the conflict is detected if the taxiing aircraft AC_T is further than 35 m from the runway center-line.

Of the simulation runs ending in a collision in VC1, Pilots_T agent detects the conflict and makes a decision to taxi off the runway in 34% of cases (event E5), Pilots_T detects the conflict himself in 12% of these cases (event E5′), and in 22% Pilots_T detects the conflict via an up-linked ATC alert. Pilots_T agent detects the conflict and makes a decision to stop taxiing in 23% of cases (event E6), Pilots_T detects the conflict himself in 8% of these cases (event E6′), and in 15% the agent detects the conflict via an up-linked ATC alert. Here in most cases Pilots_T makes a decision to taxi off the runway, which indicates that AC_T is within a distance of 35 m from the runway center-line at the moment of the conflict detection for most cases ending in the collision. Totally for the condition when the collision occurs, Pilots_T detects the conflict in 57% cases (events E5 and E6), of which 20% are the cases when the conflict was detected by own observation. Thus for the conditional cases given a collision it is found that the probability of conflict detection by Pilots_T is lower in the conditional case in comparison to the unconditional case and the contribution of the ATC system to conflict detection is significantly lower in the conditional case than in the unconditional case.

In VC2, Pilots_T agent detects the conflict and makes a decision to taxi off the runway (event E5) in 20% of all simulated conflict scenarios. Here Pilots_T detects the conflict by own observation in 0.2% of cases (event E5′). Pilots_T agent detects the conflict and makes a decision to stop taxiing (event E6) in 75% of all simulated conflict scenarios. Here Pilots_T detects the conflict by own observation (event E6′) in 8% of cases. Totally for all simulation runs, Pilots_T detects the conflict in 95% cases (events E5 and E6), of which approximately 8% by own observation (events E5′ and E6′). It is higher in comparison to the results obtained for Pilots_L agent, which detects the conflict by own observation only in 1% of all cases. In most of the conflict situations, Pilots_T makes a decision to stop taxiing rather than to taxi off the runway, which means that in most cases the conflict is detected if the taxiing aircraft AC_T is beyond the distance of 35 m from the runway center-line.

Of the simulation runs ending in a collision in VC2, Pilots_T agent detects the conflict and makes a decision to taxi off the runway in 54% of cases (event E5), Pilots_T detects the conflict himself in 17% of these cases (event E5′), and in 37% Pilots_T detects the conflict via an up-linked ATC alert. Pilots_T agent detects the conflict and makes a decision to stop taxiing in 13% of cases (event E6), Pilots_T detects the conflict himself in 4% of these cases (event E6′), and in 9% the agent detects the conflict via an up-linked ATC alert. Here in most cases Pilots_T makes a decision to taxi off the runway, which suggests that AC_T is within the distance of 35 m from the runway center-line at the moment of the conflict detection in most cases that ended with a collision. Totally for the condition when the collision occurs, Pilots_T detects the conflict in 67% cases (events E5 and E6), of which 21% are the cases when the conflict was detected by own observation. Thus for the conditional cases given a collision it is found that the probability of conflict detection by Pilots_T is lower in the conditional case in comparison to the unconditional case and the contribution of the ATC system to conflict detection is significantly lower in the conditional case than in the unconditional case.

In VC3/4, Pilots_T agent detects the conflict and makes a decision to taxi off the runway (event E5) in 20% of all simulated conflict scenarios. Here Pilots_T detects the conflict by own observation in 0.03 % of cases (event E5′). Pilots_T agent detects the conflict and makes a decision to stop taxiing (event E6) in 74% of all simulated conflict scenarios. Here Pilots_T detects the conflict by own observation (event E6′) in 2% of cases. It is 4 times lower than the results in VC2 and 16 times lower than the results in VC1. Totally for all simulation runs, Pilots_T detects the conflict in 94% cases (events E5 and E6), of which approximately 2% cases by own observation (events E5′ and E6′). It is higher in comparison to the results obtained for Pilots_L agent, which detects the conflict by own observation only in 0.4% of all cases. In most of the conflict situation Pilots_T makes a decision to stop taxiing rather than to taxi off the runway, which means that in most cases the conflict is detected if the taxiing aircraft AC_T is beyond the distance of 35 m from the runway center-line.

Of the simulation runs ending in a collision in VC3/4, Pilots_T agent detects the conflict and makes a decision to taxi off the runway in 52% of cases (event E5), Pilots_T detects the conflict himself in 6% of these cases (event E5′), and in 46% Pilots_T detects the conflict via an up-linked ATC alert. Pilots_T agent detects the conflict and makes a decision to stop taxiing in 7% of cases (event E6), Pilots_T detects the conflict himself in 0.4% of these cases (event E6′). Thus, Pilots_T detects the conflict almost totally via the alerts generated by the ATC and decides to stop taxiing. These results are not surprising taking into account the bad visibility condition. In most cases Pilots_T makes a decision to taxi off the runway, which suggests that AC_T is within the distance of 35 m from the runway center-line at the moment of the conflict detection in most cases ended with the collision. Totally for the condition when the collision occurs, Pilots_T detects the conflict in 59% cases (events E5 and E6), of which 6% are the cases when the conflict was detected by own observation. Thus for the conditional cases given a collision, it is found that the probability of conflict detection by Pilots_T is lower in the conditional case in comparison to the unconditional case and the contribution of the ATC system to conflict detection does not differ much from the unconditional case as the conflict detection occurs primarily via the alert system in both conditions due to the bad visibility.

3. *Landing Aircraft (AC_L)*

The behavior of agent AC_L reflects the conflict resolution actions initiated by Pilots_L. In VC1, Pilots_L makes a decision of Missed Approach in 76% of all cases (event E2) and in 70% of the simulation runs agent AC_L initiates Missed Approach (event E3). In the remaining 6%, the execution of Missed Approach might be not possible since the landing already commenced. For the cases ending in a collision, the Missed Approach is executed in 46% of cases (event E3). The probability of the execution of the missed approach (event E3) is significantly lower for the conditional cases ending in a collision in comparison to the unconditional cases.

In VC2, Pilots_L makes a decision of Missed Approach in 90% of all cases (event E2) and in 84% of the simulation scenarios Pilots_L agent initiates Missed Approach (event E3). For the cases ending in a collision, the Missed Approach is executed in 45% of cases (event E3).The probability of the execution of the missed approach (event E3) is significantly lower for the conditional cases ending in a collision in comparison to the unconditional cases.

In VC3/4, Pilots_L makes a decision of Missed Approach in 92% of all cases (event E2) and in 85% of the simulation scenarios Pilots_L agent initiates Missed Approach (event E3). For the cases ending in a collision, the Missed Approach is executed in 10% of cases (event E3). The probability of the execution of the missed approach (event E3) is significantly lower for the conditional cases ending in a collision in comparison to the unconditional cases. This finding can be observed across all visibility conditions; it indicates that the execution of Missed Approach in most cases was not followed by a collision.

4. Taxiing Aircraft (AC_T)

The behavior of agent AC_T reflects the conflict resolution actions initiated by Pilots_T. In VC1, AC_T comes to stance in 85% of cases (event A7), and comes to stance as a result of conflict detection in 77% of cases (event E7′). In 18% of the simulation runs AC_T agent performs taxiing off the runway successfully (event E9). Pilots_T makes a decision to taxi off in 19% of cases, so only in 1% the pilots do not succeed in their conflict resolution action. For the cases ending in a collision, AC_T comes to stance as a result of conflict detection in 23% of cases (event E7′). This probability is significantly lower for the conditional cases ending in a collision (event E7′) in comparison to the unconditional cases.

In VC2, AC_T comes to stance in 85% of cases (event A7), and comes to stance as a result of conflict detection in 75% of cases (event E7′). In 19% of the simulation scenarios AC_T agent performs taxiing off the runway successfully (event E9). Pilots_T makes a decision to taxi off in 20% of cases, so only in 1% the pilots do not succeed in their conflict resolution action. For the cases ending in a collision, AC_T comes to stance as a result of conflict detection in 13% of cases (event E7′). This probability is significantly lower for the conditional cases ending in a collision (event E7′) in comparison to the unconditional cases.

In VC3/4, AC_T comes to stance in 83% of cases (event A7), and comes to stance as a result of conflict detection in 74% of cases (event E7′). In 20% of the simulation scenarios AC_T agent performs taxiing off the runway successfully (event E9). Pilots_T makes a decision to taxi off in 20% of cases, thus the pilots almost always succeed in their conflict resolution action. It is similar to the results found in VC1 and in VC2. For the cases ending in a collision, AC_T comes to stance as a result of conflict detection in 7% of cases (event E7′). This probability is significantly lower for the conditional cases ending in a collision (event E7′) in comparison to the unconditional cases across all visibility conditions; it suggests that in most cases stopping taxiing was not followed by a collision in all visibility conditions.

5. ATC System

In the model a runway incursion alert is provided by the ATC system when the landing aircraft is within 5556 m (3NM) of the runway threshold and the taxiing aircraft is within 124 m from the runway center-line. In VC1, the runway incursion alert (RIA) is active in 76% of all cases (event E8) and in 42% cases ending in a collision. In VC2, RIA is active in 90% of all cases and in 54% cases ending in a collision. This percentage is much higher in comparison to the results obtained in VC1. It can be explained by the fact that in a good visibility condition the conflict had been detected and resolved before the alert became active. In VC3/4, RIA is active in 93% of all cases and in 56% cases ending in a collision. This percentage is approximately similar to the results obtained in VC2.

IV. Simulations with changed roles of agents in the control loop

In the following subsections the conditions of placing agents out of the monitoring role or control loop are described and the simulation results of these changes in the operation are discussed.

A. Definition of changing the role of agents in the control loop

To better understand the potential of agents to restrict the risk increase in cases where the performance of other agents is affected, additional Monte Carlo simulations were performed, where the agents are placed out of the monitoring role or out of the control loop. This was done for the following agents: Pilots Landing Aircraft (Pilots_L), Pilots Taxiing Aircraft (Pilots_T) and ATC System. The conditions for changing the role of these agents are:

- Pilots_L does not perform active monitoring of the traffic situation, neither visually nor via the Cockpit Display of Traffic Information (CDTI); however, it may detect a conflict via up-linked alerts generated by the ATC system.
- Pilots_T does not perform active monitoring of the traffic situation, neither visually nor via the Cockpit Display of Traffic Information (CDTI); however, it may detect a conflict via up-linked alerts generated by the ATC system.
- ATC system does not specify alerts, since the Runway Incursion Alert (RIA) component of the ATC system does not work.

B. Simulation Results

For all combinations of these conditions, the conditional collision risk of the runway incursion scenario given the visibility condition has been determined by Monte Carlo simulations, using 1 million simulations per scenario. Table 2 shows the accident risk and the risk increase factor with respect to the risk for the nominal case A1 (with all agents monitoring / alerting).

Table 2. Conditional collision risk results and risk increase factors for various conditions with agents in ('yes') and out ('no') of the monitoring/alerting role in three visibility conditions.

Case	Pilots_L	Pilots_T	ATC: RIA	VC1		VC2		VC34	
				Accident Risk	Risk increase factor	Accident Risk	Risk increase factor	Accident Risk	Risk increase factor
A1	yes	yes	yes	1.48e-08	1.00	4.80e-08	1.00	1.41e-07	1.00
A2	yes	yes	no	2.56e-07	17.3	5.07e-06	106	2.21e-05	157
A3	yes	no	yes	4.69e-08	3.17	6.83e-08	1.42	1.49e-07	1.06
A4	yes	no	no	8.89e-07	60.1	5.77e-06	120	2.18e-05	155
A5	no	yes	yes	3.89e-08	2.63	9.46e-08	1.97	1.44e-07	1.02
A6	no	yes	no	1.72e-06	116	1.38e-05	286	2.13e-05	151
A7	no	no	yes	1.45e-07	9.79	1.44e-07	3.01	1.40e-07	0.99
A8	no	no	no	2.11e-05	1425	2.18e-05	455	2.14e-05	152

Table 2 shows that the collision risk of the runway incursion scenario increases by a factor 1426 in Visibility Condition 1 (VC1), by factor 455 in Visibility Condition 2 (VC2) and by factor 152 in Visibility Condition 3/4 (VC 3/4) if none of the agents would be actively monitoring the traffic situation (case A8). In this case an accident is thus only prevented by chance. The accident risk of case A8 thus forms an upper bound for this particular runway incursion scenario.

The collision risk of the runway incursion scenario increases only by factor 9.8 in VC1 if none of the human agents would be actively monitoring the traffic situation while the ATC alert system is working nominally (case A7). The collision risk increases only by factor of 3 in VC2 for the same case A7. It is three times lower in comparison to the findings in VC1. These results are quite predictable as they are related to the case where none of the human agents is actively monitoring the traffic situation and thus the worse visibility condition does not play a crucial role here. The collision risk of the runway incursion scenario is about constant in VC 3/4 if none of the human agents would be actively monitoring the traffic situation while the ATC system is working nominally. It does not differ from case A1, which forms the lower bound for this particular model. In other words, it demonstrates that the RIA of the ATC system plays a dominant role in conflict detection and resolution.

If only the alert system of ATC is out-of-the-loop (case A2), the collision risk is increased by factor 17 in VC1, which is almost two times higher than the risk increase of case A7, where both pilots are out of the monitoring role. For case A2 in VC2, the collision risk increases by factor 106. It is 6 times higher than the risk increase factor found for this case in VC1. This finding indicates the increasing role of the ATC system in the condition where the visibility is diminished. In VC2, the risk increase factor of case A2 is 35 times higher in comparison to case A7. Compared to VC1, where the difference between cases A2 and A7 was much lower, it indicates the significant contribution of the ATC system to conflict detection and resolution in this visibility condition. In VC3/4, if only the alert system of ATC is out-of-the-loop (case A2), the collision risk is increased by factor 157. It is 9 times higher than the risk increase factor found for this scenario in VC1 and 1.5 times higher than the risk increase factor for this scenario in VC2. The risk increase factor for this scenario (A2) in VC3/4 is 157 times higher than for case A7. In fact, human agents do not play any role in this visibility condition and all collision risk is determined by the alerts of the ATC system.

Almost equal risk increase factor can be observed in all cases in VC3/4 where the RIA of the ATC system does not work. These are cases A2, A4, A6 and A8. In all other cases, where the ATC system is working properly and one or more human agents are not actively monitoring the traffic situation, the risk increase factor approximates the value of 1.

In general, the highest risk increase in all visibility conditions is observed for cases when the ATC system is out of the loop. These are scenarios A2, A4, A6 and A8.

Based on the Monte Carlo simulation results of the modified TIPH model, three main conclusions can be drawn about the performance of the agents of the given DRM across three visibility conditions:

1. The up-linked ATC alerts support reducing the collision risk far more than active monitoring by the pilots of both aircraft.
2. Active monitoring by the pilots of the landing aircraft supports collision risk reduction more than active monitoring by pilots of the taxiing aircraft in VC1 and VC2.
3. Pilots of both aircraft play barely any role in a collision risk reduction in VC3/4.

V. Conclusion

In the present study the additional risk analysis based on the TIPH DRM was performed. First, several events were defined and recorded in the MC simulations of the DRM. Second, additional simulations of changes in the operations were performed by means of excluding of agents capable of conflict detection and/or resolution out of monitoring or control loop. It was done for three agents of the DRM: pilots of the landing aircraft, pilots of the taxiing aircraft and the Runway Incursion Alert (RIA) component of the ATC.

In previous work[8] it was found that for a runway incursion scenario in VC1 between an aircraft taking off and an aircraft crossing while it should not, the accident risk reducing capability of ATC runway incursion alerts is very small and the roles of the pilots quite important. This can be explained by the operation assessed in Ref. 8, where the alerts are communicated to the pilots of both aircraft via the air traffic controller, which leads to an additional delay with respect to the direct up-linked ATC alert in the TIPH operation.

The main finding of the present study is that, in contrast to the findings in Ref. 8, for this particular TIPH scenario the RIA component of the ATC system plays a crucial role in conflict detection, and the pilots of the landing aircraft play a somewhat larger role in conflict detection and resolution in comparison to the pilots of the taxiing aircraft. The additional value of the present research is improving transparency of the given multi-agent DRM. In general, the results of this study provide more insight in the role of agents and their behavior in the TIPH DRM. As such, the obtained results provide useful feedback to operational designers.

In future research, the results of the present study will be taken into consideration for establishing interlevel relations between the multi-agent DRM of the TIPH operation and other agent-based models in ATM at different abstraction levels according to the framework presented in Ref. 3 in the context of the ComplexWorld project[4].

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The impact of airlines' collaboration in Air Traffic Flow Management

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Aircraft operators need some flexibility when executing flight operations such as taking off, landing or entering into a sector, because the exact time of these operations is often affected by uncertainty. We express this flexibility in terms of time windows which are periods of time assigned to flights under the agreement that when a flight performs all its operations within the corresponding time windows no downstream delay is caused to any other actor of the air traffic system. If some last minute inconveniences make a flight unable to meet its time windows, some delay may also be caused to other flights. Relying on simulated and real air traffic data of the European airspace, this paper shows that this additional delay can be significantly reduced if there is the opportunity to reallocate unused airport or sector capacity, especially when airlines collaborate by updating and disclosing their expected times of departure, arrival and entry into sectors.

I. Introduction

All currently available forecasts agree on predicting a worldwide increase of passenger and cargo air traffic in the years to come. While this positive trend makes the air traffic industry a still attractive business, it also sets new challenges to any air traffic stakeholder. In fact, each actor of this industry needs to manage and operate its activities as efficiently as possible, in order to provide high quality services to its customers in an economic and sustainable way, and thus face the existing fierce competition. In the specific context of the Air Traffic Management (ATM), the efficiency of the system is constrained by the fact that airport and airspace sector capacities are limited. Hence it may become economically unattractive, or even unfeasible, to operate too many flights in some congested areas and/or times of the day. On the ground, capacity is generally limited by the available number of runways at airports and the utilization of the terminal airspace around them[1]. In en-route airspace sectors, capacity is usually limited by the maximum workload acceptable by air traffic controllers[2]. This mismatch between high demand of air traffic and limited resources is likely to cause congestion, i.e., local delays which may propagate throughout the air traffic system, which results in high expenses for airspace users. In 2010, the estimate of these costs amounted to 1,350 M€ for the European air traffic only[3].

Currently, ATM capacity is allocated after a negotiation process between a Network Manager (e.g., FAA in the United States and EUROCONTROL in Europe) and aircraft operators, resulting in approved flight plans. Assuming that no major disruptions occur at the very last minute (e.g., due to weather conditions), the execution of a flight is supposed to adhere to its approved flight plan. Unfortunately, it also often happens that aircraft operators are unable to meet flight plans for reasons that are within the airline's control, such as crew disruptions, aircraft cleaning, baggage loading, or refueling. However, the failure to comply with approved flight plans can have different effects on different flights. On one side, if a flight has to be performed in a highly congested environment where

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interdependencies among different flights are strict, a 'small delay' may cause a large downstream effect. We refer to these flights as *critical.* On the other side, a flight is *non-critical* when operated in a non-congested area where the same amount of delay may not have any impact other than the delay on the flight itself. In other words, should a non-critical flight depart 'slightly after' the originally scheduled time, it will not cause any disruption into the system.

To better clarify whether a flight is critical or not (i.e., to quantify what a 'small' delay' or 'slightly after' mean), we can therefore associate to each operation (departure, arrival or entry into a sector) of a flight the concept of *time window* that is defined as the interval of time where the given flight operation can be executed without causing any additional delay to any other flight in the system, at any time. It follows that the width (or size) of a time window is a measure of the flexibility that can be granted to the airline to perform the associated flight operation: the wider the time window, the larger the flexibility, of course. Since in the network critical and non-critical flights may coexist at the same time, the width of time windows may vary among different flights and/or among different operations of the same flight. Hence non-critical flights may be vaguely defined as those flights to which it is possible to provide some flexibility that is expressed in terms of 'large' time windows. On the contrary, critical flights do not have any flexibility to perform their operations, i.e., they are characterized by a sequence of 'narrow' time windows. The identification of critical flights is important information to the Network Manager and to the aircraft operators as it spots where to allocate resources to improve the ATM system performance. Hence the time window concept is consistent with the Single European Sky ATM Research Program (SESAR), as it enhances the responsibility of airlines in the context of the ATM system and fosters collaboration with the Network Manager[4].

A time window is characterized by its position (starting instant) and width (closing instant). We define the position of a time window as the instant at which the associated operation should be executed in order to minimize the system delay, given the air traffic demand and the available capacities. This position can be computed as the solution of the Air Traffic Flow Management (ATFM) problem[5]. In Ref. 6, we introduce a formulation which guarantees both minimum ATFM delays and maximum widths for time windows, but the model turned out to be intractable. Hence we propose a new approach[7,8], where, in accordance with Ref. 9, the solution of the ATFM problem is used to fix the position of time windows, granting minimum ATFM delays and a near optimal width for time windows.

The scope of this paper is to investigate the resiliency of time windows, i.e., to evaluate the effects of operations executed outside their time windows on the air traffic system. In fact, for a specific flight it may happen that some of its operations take place after the closing instant of the associated time windows as the consequence of some last-minute inconveniences. This fact may cause additional delays to the specific flight and also to other flights in the network. We show that these additional delays may significantly be reduced if some unused capacity is appropriately allocated. We also show that the amount of the delay reduction varies in accordance with the airlines' attitudes to disclose their expected times of executing their flight operations. Relying on simulated and real air traffic data of the European airspace, we first simulate a collaborative airlines' attitude where all airlines are supposed to provide timely information on the status of their flights, consistently with the collaborative decision making (CDM) philosophy. Then we consider non-collaborating airlines that provide information on the status of their flights when it is the most convenient for them to do so. Our results show that the amount of additional delay generated at the departure is limited under both airlines' attitudes, thus demonstrating the robustness and the practical viability of the proposed approach.

This paper unfolds as follows: Section II specifies the concept of time windows. Section III introduces an algorithm that allows to reduce delays by reallocating unused capacity. Section IV describes the difference between the collaborative and non-collaborative airlines' attitudes. Section V describes the results of the computational experimentations performed, either using simulated and real air traffic data, and analyzes them. Finally, Section VI summarizes the conclusions and indicates the future research steps.

II. Time Windows

When the available airport and airspace capacities are not large enough to accommodate all the traffic demand, some flights may be requested to delay their departure time and/or increase their flight duration. Clearly, these deviations from the desired flight plans come at a cost for airlines. The primary objective of the Network Manager – being safety guaranteed, of course – is the minimization of the system delay, computed as the sum of all individual flight delays. These delays are possibly assigned in a fair way, i.e., without systematically penalizing or favoring a specific flight or airline operator. This is usually referred to as the ATFM problem[10]. Ref. 5 and 9 propose an integer programming formulation to solve the ATFM problem and determine the minimum flights' delays, also known as ATFM delays (not to be confused with the European definition of ATFM delay which is due to an ATFM regulation imposed by the EUROCONTROL Central Flow Management Unit), by calculating the time instants (or ATFM times) at which each flight departs, enters all air sectors along its route and arrives at the destination airport.

In our time window framework, ATFM times can be considered as time windows of unitary size. In fact, given the available airport and airspace capacities, they represent the earliest times to execute flight operations, while minimizing the overall ATFM system delay. However, the solution of the ATFM problem does not indicate which are the effects on the network in the case a flight is not able to meet its ATFM times to execute the associated flight operations. Depending on the level of congestion of the airspace and/or the time of the day where the flight operation should take place, an additional delay with respect to the already existing ATFM delay may or may not have severe consequences. In particular, when operating in a non-congested environment such an additional delay may not lead to a conflict in the allocation of the capacity, meaning that there is no need to 'steal' resources previously allocated to other flights. Hence, it is reasonable to allow a flight operation to be executed also after the ATFM time as long as it does not harm any other flight. The size of a time window quantifies this admissible time span after the ATFM time. In other words, the instant at which a time window closes corresponds to the last time instant in which the flight is able to perform the associated flight operation without the need to allocate new capacity in the network. The width of a time window can therefore be considered as the degree of flexibility for a flight to execute the corresponding flight operation.

Figure 1 shows a time window associated to the departure of a flight. The time window size is assumed to be equal to three time instants. The time window position (or starting instant) is the ATFM departure time t=1. However, the flight could also depart at t=2 or t=3 without the need to request new capacity, granting therefore the flight some flexibility to deal with possible delays that it may incur in between the time of the assignment of its departure time and the execution of the departure itself. An integer programming formulation for identifying all time windows for a given set of flights and airport and airspace capacities is available[8].

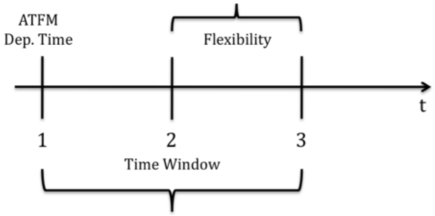

Figure 1. Flexibility by using time windows

When a flight approaches its scheduled departure time, uncertainty on the events that can affect the departure time usually decreases. The flight's airline operator is therefore able to make a good estimate of the time in which the departure actually takes place. If the airline expects the flight to depart within its departure time window, it needs not to take any further action, and operations can be carried on as scheduled. In other circumstances, some last minute and unexpected events may force the flight departure to take place after the end of its departure time window, say at t=4 (see Fig. 2). We refer to this time instant as the flight's *earliest departure time*. In this case the flexibility granted to the flight departure is not large enough and additional capacity is needed at the earliest departure time. However, the allocation of this new capacity is not guaranteed, as capacity is limited and may not be available at this new departure time. Hence we need to solve the ATFM problem again to obtain new ATFM times. We refer to them

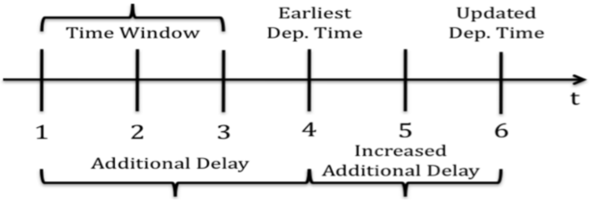

Figure 2. Increased Additional delay

as the *updated departure times* (t=6 in Fig. 2). The difference between the updated and earliest departure times is referred to as the *increased additional delay*.

III. Delay Reduction Algorithm

If it becomes clear that some time windows cannot be met, the current ATFM solution is, a fortiori, no longer valid and a new set of time windows is required to accommodate the new (delayed) demand. This paper presents an algorithm to modify the current time windows by appropriately exploiting the available capacity. In fact, once a flight has departed all the time windows along its route can be restricted to one time instant, starting from the time when the departure takes place and executing the flight at the speed specified by the flight plan. Hence the capacity previously reserved for this flight's time windows can be released and used by other flights.

Figure 3 describes how the capacity can be released along the route of a flight that departs on time. Above each node, we show the time windows assigned to the flight. On the arcs, we indicate the traveling time between two nodes, which we assume to be equal to 2 time instants for every pair of nodes. Below each node, we show the time when a flight operation takes place in practice, and the time instants at which capacity can be released when this flight departs. Similarly, when a flight cannot meet one of its time windows, all the capacity that had been allocated to this time window can be released, as the flight's delay will prevent it from using this capacity.

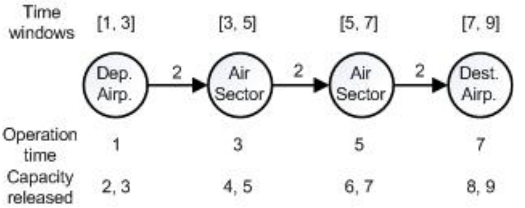

Figure 3. Capacity released by a flight departing on time

All the capacity that becomes available can be reallocated to other flights that are expecting a delay so that they can get an improved updated time of departure. Two different kinds of delays can be reduced:

- initial ATFM delays, for those flights that do not have additional delay;
- increased additional delays, for those flights that do have additional delay.

Since at each time instant of the day some capacity can be released into the network to the benefit of all flights, at each time instant we assume to run the algorithm that allows to reduce flight delays (similar in principle to the compression algorithm in ground delay programs[11]). The first step of the algorithm is to select and sort the flights that may get their delays reduced. These flights are those that had been assigned an ATFM delay, or those that have been assigned an updated departure time, i.e., they were assigned an increased additional delay. The selected flights should have enough time to react to the delay reduction, i.e., flights that are scheduled to depart at the following time instant are excluded as a reduction of their delay would require them to depart immediately. After the selection, flights are ordered in accordance with the following priority rules, in order of importance:

1. flights with a larger arrival delay get the precedence;
2. flights with an earlier scheduled arrival time get the precedence.

The algorithm tries to anticipate the departure of delayed flights starting from the largest possible anticipation (complete recovery of the delay) up to the minimum one (1 instant of delay recovered), with respect to the earliest feasible departure time.

Since the anticipation of the departure of a flight causes the release of capacity that is not needed by this flight anymore, capacity released by a flight f_1 processed by the algorithm after a flight f_2 might be useful for the latter to reduce its delay. Therefore, the algorithm is executed repeatedly until no delay reduction is obtained.

We now provide an example of the functioning of this algorithm. We consider 3 flights, called f_1, f_2 and f_3, that are scheduled to depart from the same airport. Also, we only consider what happens at the departure airport, and suppose that capacity is only missing here, while there is enough capacity outside the airport to reschedule any flight. At time t=1 the following information is available:

- f_1 is assigned a departure time window [1, 3] and can depart at t=1;

- f_2 is assigned a departure time window [1, 2], but its operating airline is not able to make it depart before t=3 and requests the allocation of capacity for this departure time. However, the flight is assigned an updated departure time at t=4;
- f_3 is assigned a departure time window [1, 3], but its operating airline is not able to make it depart before t=4 and requests the allocation of capacity for this departure time. However, the flight is assigned an updated departure time at t=6.

The departure of f_1 at t=1 causes the release of the capacity that it is not going to use. Specifically, there will be 1 more unit of capacity respectively available at t=2 and t=3 for flights to depart. The algorithm for the reallocation of capacity can be at this point executed, resulting in the following operations:

- ordering of the flights: we assume that the result of the ordering is such that f_3 will be analyzed before f_2;
- analysis of f_3: capacity to reschedule the departure at an earlier time is not found;
- analysis of f_2: the flight can depart at t=3, and capacity to depart at t=4 is released;
- the algorithm managed to reduce some delay during the last execution, so it is executed again;
- ordering of the flights: f_3 is the only flight left;
- analysis of f_3: the flight can depart at t=4, and capacity to depart at t=6 is released;
- the algorithm managed to reduce some delay during the last execution, so it is executed again;
- ordering of the flights: no flight is left, and the algorithm is terminated.

This example results in the complete removal of the increased additional delay assigned to flights: both f_2 and f_3 will be able to depart at their earliest departure times.

IV. Collaborative and non-collaborative airlines' attitudes

The amount of delay reduction obtained through the algorithm can vary depending on the behavior that airline operators may have with respect to the disclosure of their operating practices. In fact, it is reasonable to assume that an airline operator knows the exact departure time of any of its flights some time before the opening of the corresponding departure time window. The announcement of the exact time of departure of a flight can follow two different attitudes:

- Collaborative attitude: the exact time of departure of a flight is always announced by its operating airline a specified amount of time before the ATFM departure time of the flight;
- Non-collaborative attitude: the exact time of departure of a flight is announced by its operating airline before its ATFM departure time only if the flight is willing to recover some ATFM delay or some increased additional delay, i.e., if it is going to depart outside the departure time window; otherwise no early announcement takes place.

The difference between the two attitudes lays on the announcement of an exact time of departure for flights departing within their time windows. The natural attitude is the non-collaborative one, as airline operators wish to maintain their flexibility unaltered. This flexibility, however, comes at a cost: using the collaborative attitude it is possible to reduce the size of the departure time windows ahead of time, thus releasing in advance more capacity at departure airports compared to what happens under the non-collaborative attitude. The early reduction of time windows is a fact which would not be desired by airline operators, as it would grant them flexibility only up to some time before the execution of the flight. However, by implementing this attitude, we are able to calculate the cost of not announcing the exact time of departure for these flights.

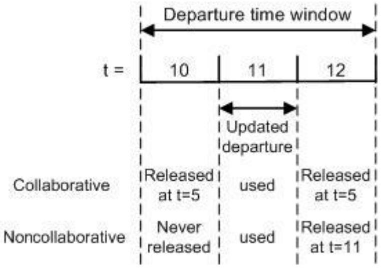

Figure 4. Comparison of collaborative and non-collaborative airlines' attitudes

For both attitudes, if the exact time of departure is outside the original time window, the flight has no allocated capacity to operate with, and will need to request a new allocation of capacity. The algorithm therefore looks for the earliest reallocation for the flight to operate, verifying the feasibility of all the possible departure times, starting from the earliest departure time, until it finds a feasible one. At this point, the updated departure times are assigned to the flight and we compute a new set time windows, each of minimum width, i.e., 1 time instant large, which means that no additional flexibility is given to this flight.

To give an example of the difference between the two attitudes, see Fig. 4. Here we describe what happens when a flight whose departure time window is 3 time instants wide departs with 1 time instant of additional delay. Specifically, the flight is scheduled to depart at t=10, but only departs at t=11. We suppose that the exact departure time is known 5 instants before the ATFM departure of the flight, i.e., at t=5, and that there are no delays on resources needed for the execution of the flight. Under the non-collaborative attitude, the flight reserves and never releases capacity to depart at t=10, while under the collaborative attitude this capacity becomes available at t=5. Also, with the non-collaborative attitude, capacity to depart at t=12 becomes available only at the previous instant, while using the collaborative attitude it can be released at t=5.

V. COMPUTATIONAL EXPERIENCE

We here present the results of some computational experiments performed to assess the practical viability of the proposed approach. Each experiment consists in identifying the time windows, inserting an additional delay and executing the delay reduction algorithm on a set of simulated and real European air traffic data. We consider both the non-collaborative and collaborative airlines' attitudes.

A. Simulated data

Our computational experiments follow the framework introduced in Ref. 9 and are conducted on a series of four randomly generated instances whose dimensions represent a near continental scope in Europe. In fact, each instance considers 30 airports, 10 of which are hubs (direct flights between non-hub airports are not allowed), 145 air sectors, 50 time periods that represent a 4 hour 10 minute time horizon (each time instant is 5 minute-wide), and 6,475 flights. For each instance, we evaluate different levels of congestion due to bad weather fronts that cause the reduction of capacity for some time instants on sets of adjacent sectors. Capacity levels start from an available capacity equal to 10% of the nominal one on some sectors up to full available capacity, with 10% steps. We set the width of a time window from a minimum of 1 time instant to a maximum of 3 time instants, i.e., from 5 to 15 minutes. The computation of the time windows is performed in accordance with the mathematical formulation introduced in Ref. 8.

Figure 5 shows the width distribution of departure time windows. The percentage of 1 time instant wide time windows decreases from 31.4% in the most congested cases to 27.0% when all capacity is available. In contrast, the percentage of time windows that are 2 time instants wide increases from 42.9% in the most congested cases to 46.3% when at full capacity. 3 instants wide time windows vary from a percentage of 25.5% when capacity is reduced to 20% of the nominal one (the percentage when capacity is reduced to 10% is equal to 25.8%) to a percentage of 26.7% when there is no congestion. It is possible to note that the most sensible tradeoff takes place between 1 and 2 time instants wide time windows, with the smallest time windows enlarging when capacity increases.

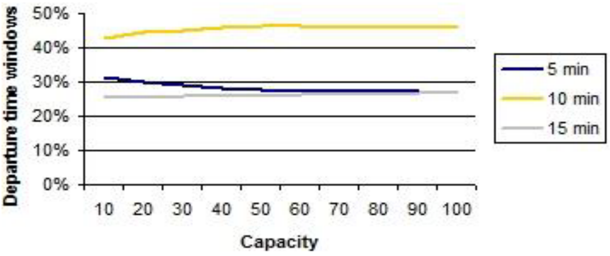

Figure 5. Distribution of the size of departure time windows

We define the additional delays in accordance to a realistic probability distribution of delays based on data derived from the EUROCONTROL's Demand Data Repository (DDR)^{12}. In particular, based on data from 19 December 2011, we computed the additional delay as the difference between the radar off block time and last filled flight plan off block time. These figures are available in the DDR m3 and m1 .s06 files, respectively. Relying on a set of 200 simulations per instance and per capacity level, we then determine the percentage of departures that are executed within the assigned time windows. Figure 6 shows that this percentage varies from 73.3% to 74.1% with capacity varying from 10% to 100% of the nominal one, respectively.

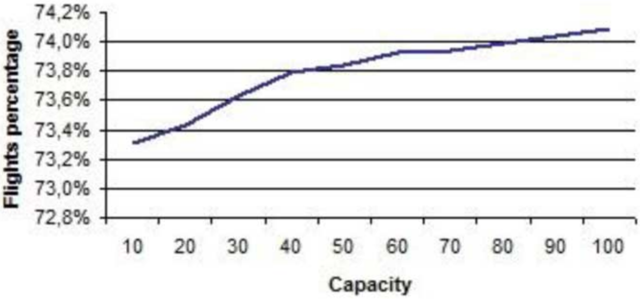

Figure 6. Percentage of respected departure time windows

For all flights not respecting the departure time windows an increased additional delay may occur as it may not be possible to allocate their departures at the earliest times of departure, thus leading to later updated times of departure. However, the total amount of increased additional delay in the network is strongly influenced by the airlines' attitude to share their information. In fact, assuming that 5 time instants (25 minutes) before the ATFM times a flight operator is in the position to know whether it can respect or not its departure time window, Figure 7 shows that the increased additional delay is much higher under the non-collaborative than the collaborative attitude. For example, in the most congested case (capacity reduced to 10% of the nominal one), the increased additional delay is equal to 28,910 min and 36,497 min under the collaborative and non-collaborative attitude, respectively. Among all the different capacity levels, the increased additional is from 24.3% to 26.6% higher under the non-collaborative attitude.

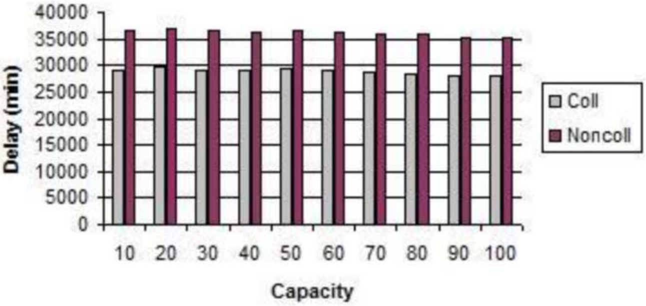

Figure 7. Increased additional delay

Once the increased additional delay is assigned to all flights, it is possible to start reducing it through the delay recovery algorithm. Figure 8 shows that most of the increased additional delay can be eliminated. The increased additional delay is reduced up to 99.8% in the least congested scenarios for both collaborative and non-collaborative attitudes. The smallest gain is obtained in the most congested scenarios, where 97.6% and 97.8% of the delay is reduced under the collaborative and non-collaborative attitude, respectively. We also notice that the quantity or remaining delay is very much dependent on the available capacity: under the collaborative attitude, delay ranges from 696 to 46 minutes, while under the non-collaborative attitude it ranges from 785 to 85 minutes. The difference between the two attitudes is small, as it ranges between 89 and 39 minutes on the whole system. Then we can justify the use of the non-collaborative attitude, as the price to pay, in terms of added delay, is very low. Furthermore, a non-collaborative attitude

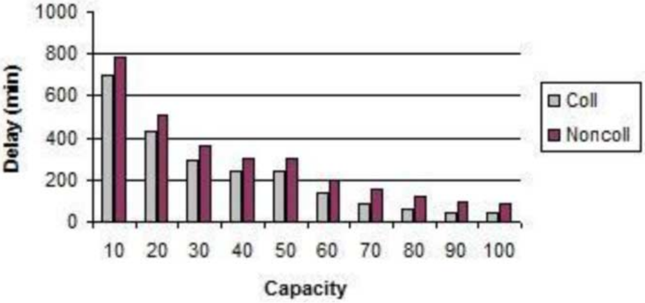

Figure 8. Increased additional delay after executing the delay recovery algorithm

allows airline operators to deal with possible delays that may be added to a flight between the time when the exact time of departure is formulated and the departure itself, as flights maintain their time windows until they actually depart.

The percentage of respected time windows and the limited increased additional delay obtained with a non-collaborative attitude show that it is possible to efficiently operate flights using time windows even in uncertain situations where flights may not respect them. This fact is very relevant for their possible application to real flights, where the ability of dealing with uncertainty is fundamental.

All tests were executed on a standard laptop, and the execution of the delay reduction algorithm lasted on average 49 ms and 61 ms under the collaborative and non-collaborative attitudes, respectively. These estimates refer to executions of the algorithm that considered for delay reduction at least 100 flights. Therefore, the practical impact of performing such an algorithm to reduce delays is negligible.

B. Real data

We also consider a set of experimental computations based on real European air traffic data. Here, we rely on EUROCONTROL DDR data from 23 to 29 May 2011. It is a whole week, from Monday to Sunday, with significant differences in the number of flights flown: Friday is the busiest day, and then comes Thursday, the other weekdays and finally the two weekend days. We only consider scheduled flights departing from European airports in the time interval between 12:00 to 18:00 every day. In Table 1, Column 2 shows the number of flights considered for each day. As the analysis of these data is at its preliminary stages, we only take airports as capacitated resources of the air network, i.e., we assume that all airspace sectors have unlimited capacity. The figures of airport capacities are also taken from DDR data. Clearly, the computation becomes much faster in the case of uncapacitated sectors because there is no need to calculate the entry times at each airspace sector and the corresponding time windows. Therefore only departure and arrival time windows have been determined. As in the simulated experimentations, additional delays have been derived as the difference between the radar off block time and the last filled flight plan off block time. Column 3 shows the average additional delay per flight. Column 4 shows the percentage of departure time windows that can be respected after the introduction of the additional delay. Note that they are inversely proportional to the average additional delay (correlation coefficient = -0.99). It is also important to highlight that in high traffic days (26 and 27 May) this percentage is significantly lower than in the case of simulated data, also at the highest congestion level.

Day	**Flights**	**Additional Delay**	**Respected TW (%)**	**Increased Additional Delay**				**Saved delay**	
				Collaborative		**Non-collaborative**			
				Initial	**Final**	**Initial**	**Final**	**Sec**	**%**
29	7991	1′ 23″	76.7%	13′ 44″	46″	14′ 20″	57″	11″	19.8%
24	7649	1′ 29″	76.4%	11′ 23″	42″	11′ 40″	50″	8″	16.9%
25	7952	1′ 40″	75.5%	9′ 10″	44″	9′ 36″	51″	7″	14.1%
23	8029	1′ 59″	74.4%	14′ 59″	38″	15′ 12″	45″	7″	15.1%
28	6344	4′ 11″	70.6%	11′ 40″	36″	16′ 56″	1′ 02″	26″	42.2%
26	8028	5′ 28″	67.3%	15′ 30″	50″	15′ 28″	59″	9″	15.0%
27	8372	5′ 46″	65.0%	28′ 35″	1′ 17″	28′ 46″	1′ 31″	13″	14.5%

Table 1. Results of experimental computation on real data (23 – 29 May 2011)

Columns 5 to 8 of Table 1 present the average amount of increased additional delay before and after the execution of the delay recovery algorithm for both collaborative and non-collaborative attitudes. Again, we notice that in the cases of high traffic the system performances are significantly lower. Initial increased additional delays are very similar under the two attitudes. Instead, the delay recovery algorithm allows to reduce the increased additional delay to a larger extent under the collaborative attitude. The last two columns of Table 1 show that when airlines collaborate it is possible to save at least 14% of the increased additional delay.

VI. CONCLUSIONS

Imbalances between airport and airspace capacities and air traffic demand may force the ATM Network Manager to delay some flights with respect to their scheduled departure times. However, disruptions and inconveniences occurring at the very last minute can cause airlines not to meet even these delayed departure times. If this happens, additional delay is introduced into the network, especially in highly congested areas and/or times of the day. Nevertheless, such an additional delay can be much less problematic if associated to flights operating in an uncongested environment. Hence different levels of flexibility can be assigned to flights for coping with unexpected events. A measure of the flight flexibility can be expressed in terms of its maximum additional delay that does not cause any downstream effect to any other flight in the network.

By defining as time window the interval of time between the maximum additional delay and the delay imposed by the Network Manager, this paper evaluates the practical applicability of the time window concept in realistic scenarios. In particular, when a flight has a departure time window of, say, three time instants, this means that this flight occupies one unit of the airport capacity at each of these time instants. However, if the actual time of departure within this time windows is known in advance, only one unit of the airport capacity has to be reserved to the flight, thus allowing the remaining units to be used by other flights. Then in accordance with the airlines' capabilities to predict their operations and their willingness to disclose them, two different attitudes can be identified: a collaborative attitude where airline operators always announce the exact departure time of a flight some time before its execution, or a non-collaborative attitude where airline operators do not announce delays within a flight's departure time window. Using the latter attitude, unused capacity is released by airline operators late, or may not be released at all, resulting in increased delays for other flights. This attitude however allows airline operators to deal with other unexpected delays that may occur between the time of the formulation of the updated time of departure and the departure itself.

Relying on simulated air traffic data, we show that the reallocation of unused capacity is just slightly more effective (i.e., the overall network delay is lower) when airlines collaborate and disclose their exact departure time in advance. Hence we might conclude that the non-collaborative attitude is justifiable because it produces only a tiny deterioration of the network performances while granting higher flexibility to all flights. However, our preliminary results based on real air traffic data of the European airspace suggest that the network average delay per flight is indeed significantly lower when airlines collaborate.

The next steps of this study will be devoted to refining and updating the analysis of the real instances. In addition, we also envisage to evaluate different priority rules to be used in the delay recovery algorithm, and to study the trade-off between the fairness, in the allocation of delay, among airspace users and the overall network delay.

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Part IV

ASDA

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Optimal Scheduling of Fuel-Minimal Approach Trajectories

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In the paper at hand, the simultaneous computation of fuel-minimal approach trajectories for multiple aircraft present in the vicinity of an airport at a certain point of time is treated. At this, the trajectory optimization task includes the determination of the optimal aircraft queuing sequence on the ILS glide path, minimizing the total fuel consumption of all aircraft involved. The trajectory optimization is based on aircraft point-mass simulation models with parameters taken from the BADA database of EUROCONTROL. Specifically tailored path constraints are introduced that define the permitted airspace and that enforce the aircraft to follow the ILS glide path once they have passed the final approach fix. Furthermore, path constraints are implemented that guarantee certain separation distances between the involved aircraft throughout the approach flights. An algorithmic procedure is set up which is supposed to produce a good initial guess for the multi-aircraft trajectory optimization task. The proposed framework is applied to a generic scenario where the fuel-efficient approach scheduling for four civil passenger aircraft has to be determined.

Nomenclature

A = Aerodynamic Frame / Aerodynamic Motion / Aerodynamic Force
K = Kinematic Flight Path Frame / Kinematic Motion
$\bar{K}$ = Kinematic Flight Path Frame K rotated around the x-axis by μ_K
N = Navigation Frame
O = North-East-Down Frame (NED)
G = Center of Gravity / Gravitational Force
P = Propulsive Force
$\vec{\mathbf{V}}$ = Velocity vector
$\vec{\mathbf{F}}$ = Force vector
x = Northward position
y = Eastward position
z = Downward position
h = Altitude
χ = Flight-path course angle
γ = Flight-path climb angle
μ = Flight-path bank angle
α = Angle of attack

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β = Angle of sideslip
n = Load factor
$\mathbf{M}$ = Transformation matrix
T = Thrust
$\mathbf{x}$ = State vector
$\mathbf{u}$ = Control vector
m = Aircraft mass
C_L = Lift coefficient
C_D = Drag coefficient
C_Q = Side force coefficient
$\bar{q}$ = Dynamic pressure
g = Gravitational constant
δ_T = Thrust lever position
L = Aerodynamic lift
D = Aerodynamic drag
Q = Aerodynamic side force
ρ = Air density
S = Reference area
b = Wing span
t = Time
τ = Normalized time
n_ρ = Density exponent

Declaration: $\left(\vec{\mathbf{V}}^{\text{Reference Point}}_{\text{Type of Motion/Source of Force}}\right)^{\text{Reference Frame}}_{\text{Notation Frame}}$

I. Introduction

IN the last few years, fuel costs as well as the amount of air traffic have increased and they are supposed to increase further within the next few decades. Thus, fuel-efficient operating procedures are sought by the airlines in order to reduce their operating costs. Not only in due time, new airport projects are facing a lot of resistance in the public but also in the past there has been a lot of protest by the residents around airports if a new airport is to be built or if an existing airport shall be enlarged. Therefore, airport operators are seeking noise-minimal approach trajectories in order to reduce the noise nuisance around airports as far as possible.

For this reason, the computation of fuel-minimal respectively noise-minimal approach trajectories has received significant attention and has been the subject of many research publications over the last time[1-7]. At this, often stand-alone approach trajectories have been considered and the optimal approach procedures for an individual aircraft have been sought, not taking into account the limitations due to other aircraft in the air space around the respective airport. Although the approach procedures found thereby are optimal for the respective aircraft, they often cannot be put into practice due to the limitations arising from the remaining air traffic and the daily airport business. Thus, in the paper at hand not only the approach trajectory of a single aircraft shall be optimized with respect to a certain cost function. Moreover, the optimal approach trajectories for multiple aircraft present at a certain point of time in the vicinity of an airport shall be determined simultaneously, minimizing the total amount of fuel burned or noise emitted by all aircraft taken into account. The aircraft sequence is not pre-determined and it has to be determined by the optimization in which order the different aircraft have to land so that their overall fuel consumption becomes minimal. In Refs. 8 and 9, the task of determining the optimal landing sequence is tackled by introducing discrete controls. There, the discrete controls indicate whether a particular aircraft is in free flight, is located on the ILS glide path or has already landed. In this paper, the multi-aircraft optimization task is formulated such that the introduction of discrete controls can be avoided since this enlarges the optimization problem and makes it harder to solve.

In contrast to the standard trajectory optimization task for an individual aircraft, the simultaneous optimization of multiple aircraft requires special adaptation. The trajectory optimization problem is formulated such that the individual aircraft are initially located at a certain distance from the runway. Finally, the aircraft shall be queued on the ILS glide path, keeping a certain separation distance between each other depending on the specific aircraft types. At this, the permitted airspace respectively the ILS glide path is constructed by *tangens hyperbolicus* functions. With the help of these functions, the positions of the aircraft are restricted such that they have to be positioned on the ILS glide path once the final approach fix has been passed. Furthermore, the heading angle, the flight path inclination angle and the aircraft velocity are restricted by similar functions using the *tangens hyperbolicus* function such that the ILS conditions are met after the aircraft have flown over the final approach fix.

The multi-aircraft trajectory optimization task also has to be augmented by path constraints with respect to the minimum separation distances between the various aircraft. At this, the flight times of all aircraft are normalized and a single parameter for the flight time is introduced that represents the flight times of all aircraft. Then, the constraints with respect to the minimum separation distance between the aircraft can be checked directly because of the direct correlation of the time elapsed of all aircraft. This causes the aircraft to be located at different positions on the ILS glide path at the final point of time. For that reason, the cost function portion of a particular aircraft that is caused by the flight along the ILS glide path is not taken into account in the overall cost function, utilizing again the *tangens hyperbolicus* function. By doing so, the cost function contributions of the different aircraft are weighted equally, regardless of their final position on the ILS glide path. In practice, the flight along the ILS glide path has to be absolved by each aircraft anyway and is therefore not subject to optimization.

The subsequent paper is organized as follows: first, the aircraft simulation model based on the BADA database is given in paragraph II. In paragraph III, the multi-aircraft trajectory optimization problem is formulated and the specific adaptations together with the algorithmic procedure for determining the optimal landing sequence are given. Results for the aircraft scheduling problem are depicted in paragraph IV, before finally a conclusion is drawn in paragraph V.

II. Aircraft Simulation Model

For the trajectory optimization task, an aircraft point-mass simulation model is implemented based on the BADA database published by EUROCONTROL[10]. Besides the subsystems describing the point-mass motion in space, subsystems for the computation of the fuel flow respectively the noise emissions are incorporated in the simulation model. The various subsystems are described in the following paragraphs.

A. Position Equations of Motion

The position equations of motion are formulated using the position vector in the Local Fixed Frame N that is derived from the NED-Reference Frame with its origin fixed to the Earth's surface. The x-axis of the Local Fixed Frame N is pointing northward, the y-axis eastward and the z-axis downward. This means the downward position z of the aircraft describes just the negative value of the flight altitude h.

$$\begin{pmatrix} \dot{x} \\ \dot{y} \\ \dot{z} \end{pmatrix}_N^E = \begin{pmatrix} V_K^G \cdot \cos\chi_K^G \cdot \cos\gamma_K^G \\ V_K^G \cdot \sin\chi_K^G \cdot \cos\gamma_K^G \\ -V_K^G \cdot \sin\gamma_K^G \end{pmatrix} \tag{1}$$

B. Translation Equations of Motion

The translation equations of motion, written with reference to the Kinematic Reference Frame K, are computed as a function of the total sum of forces given in the Kinematic Reference Frame K. The according states are represented by the kinematic velocity V_K, the kinematic course angle χ_K and the kinematic flight path inclination angle γ_K. The first order time derivatives of those states are a function of the sum of all forces acting on the aircraft's center of gravity G:

$$\begin{pmatrix} \dot{V}_K^G \\ \dot{\chi}_K^G \\ \dot{\gamma}_K^G \end{pmatrix}_K^{EO} = \begin{pmatrix} 1 \\ \\ \dfrac{1}{V_K^G \cdot \cos \gamma_K^G} \\ -\dfrac{1}{V_K^G} \end{pmatrix}_K \left(\frac{1}{m} \left(\sum \vec{\mathbf{F}}^G \right)_K \right) \tag{2}$$

The total sum of forces comprises aerodynamic and propulsion forces as well as the gravitational force acting on the aircraft's center of gravity G:

$$\left(\sum \vec{\mathbf{F}}^G \right)_K = \left(\vec{\mathbf{F}}_A^G \right)_K + \left(\vec{\mathbf{F}}_P^G \right)_K + \mathbf{M}_{KO} \cdot \left(\vec{\mathbf{F}}_G^G \right)_O \tag{3}$$

The gravitational attraction force is assumed to be constant over the regarded altitude interval and is given in the NED-Reference Frame O. It is transformed into the Kinematic Reference Frame K by the transformation matrix $\boldsymbol{M}_{KO}$ between the Kinematic Reference Frame K and the NED-Reference Frame O.

C. Forces

The aerodynamic forces acting on the aircraft are the lift force L, the side force Q and the drag force D. They result from the relative motion of the aircraft to the surrounding airflow given by the aerodynamic velocity V_A. While the lift force vector is perpendicular to the aerodynamic velocity, the drag acts in parallel to the aerodynamic velocity. Therefore, the forces are calculated in the Aerodynamic Reference Frame A whose x-axis coincidences with the aerodynamic velocity vector. The calculation of the drag force D is based on the BADA model[10]:

$$D = \bar{q} \cdot S \cdot C_D = \bar{q} \cdot S \cdot \left(C_{D0} + C_{D2} \cdot C_L^2 \right) \tag{4}$$

It is assumed that for the approaches considered the aircraft are flying without any sideslip angle β_A, therefore the side force Q is set equal to zero:

$$Q = \bar{q} \cdot S \cdot C_Q = \bar{q} \cdot S \cdot C_{Q\beta} \cdot \beta_A = 0 \tag{5}$$

For the lift force L, the following equation is implemented in the simulation model:

$$L = \bar{q} \cdot S \cdot C_L = \bar{q} \cdot S \cdot \left(C_{L0} + C_{L\alpha} \cdot \alpha_A \right) \tag{6}$$

The dynamic pressure used in the equations above is given by:

$$\bar{q} = 0.5 \cdot \rho \cdot V_A^2 \tag{7}$$

The thrust force T is computed by

$$T = \delta_T \cdot T_{\max} \tag{8}$$

In accordance to the BADA database[10], the maximum climb thrust T_{max} is calculated at ISA standard atmosphere conditions as a function of the aircraft's actual altitude value and can then be corrected for possible deviations from the standard atmosphere conditions. The following equations hold for jet-powered aircraft (with the altitude given in feet):

$$T_{\max} = T_{\max,ISA} \cdot \left(1 - C_{Tc5} \cdot \Delta T_{ISA,eff} \right) \tag{9}$$

$$T_{\max,ISA} = C_{Tc1} \cdot \left(1 - \frac{h}{C_{Tc2}} + C_{Tc3} \cdot (h)^2 \right) \tag{10}$$

$$\Delta T_{ISA,eff} = \Delta T_{ISA} - C_{Tc4} \tag{11}$$

$$0 \le C_{Tc5} \cdot \Delta T_{ISA,eff} \le 0.4 \tag{12}$$

The resulting force vector with its components given in the Aerodynamic Reference Frame A is given by the equation below, where the forces are mainly functions of the aerodynamic angle of attack α_A and the thrust lever position δ_T:

$$\left(\vec{\mathbf{F}}^G\right)_A = \left(\vec{\mathbf{F}}_A^G\right)_A + \left(\vec{\mathbf{F}}_P^G\right)_A = \begin{pmatrix} -D \\ 0 \\ -L \end{pmatrix}_A + \begin{pmatrix} T \\ 0 \\ 0 \end{pmatrix}_A = \begin{pmatrix} T-D \\ 0 \\ -L \end{pmatrix}_A \tag{13}$$

The force vector given in the Aerodynamic Reference Frame A can then be transformed into the Kinematic Reference Frame K by the appropriate transformation matrix $\boldsymbol{M}_{KA}$ that could take into account the influence of wind:

$$\left(\vec{\mathbf{F}}^G\right)_K = \mathbf{M}_{KA}\left(\vec{\mathbf{F}}^G\right)_A \tag{14}$$

D. Fuel Consumption

The calculation of the fuel consumption is derived from the BADA model[10]. Herein, the fuel consumption (in kilogram per minute) is computed depending on the actual aerodynamic velocity V_A (given in knots), the altitude of the aircraft h (given in feet), the maximum available thrust T_{max} (in kiloNewton) and the thrust lever position δ_T . For jet-aircraft, the maximum and idle fuel consumption are computed by:

$$\dot{m}_{fuel,\max} = C_{f1} \cdot \left(1 + \frac{V_A}{C_{f2}}\right) \cdot T_{\max} \tag{15}$$

$$\dot{m}_{fuel,idle} = C_{f3} \cdot \left(1 - \frac{h}{C_{f4}}\right) \tag{16}$$

Between the idle fuel consumption and the fuel consumption for maximum thrust, a linear interpolation with respect to the thrust lever position is implemented to calculate the fuel consumption for a specific thrust lever position:

$$\dot{m}_{fuel} = \dot{m}_{fuel,idle} + \delta_T \cdot \left(\dot{m}_{fuel,\max} - \dot{m}_{fuel,idle}\right) \tag{17}$$

The differential equation for the aircraft mass is then given by the following formula:

$$\dot{m} = -\dot{m}_{fuel} \tag{18}$$

E. Noise model

A noise model[11] is incorporated in the simulation model that allows for the computation of the numbers of awakening for a given population distribution around an airport. At this, the sound pressure level L_A is computed by

$$L_A(T,r) = a \cdot T + b \cdot \lg(r) + c \cdot \lg(r)^2 + d \tag{19}$$

where T is the actual aircraft thrust and r the distance between the source and the receiver. a, b, c and d are aircraft specific parameter that characterize the noise emission of a specific aircraft type. From the sound pressure level, the sound exposure level L_{AE} results:

$$L_{AE} = 10\lg\left(\frac{1}{t_0}\int_{t_1}^{t_2} 10^{L_A(t)/10} dt\right) \tag{20}$$

Finally, the number of awakenings n_{AW} can be calculated:

$$n_{AW} = \sum_i 0.0087 \cdot \left(L_{AE,i} - 30\right)^{1.79} p_i \tag{21}$$

Here, p_i is the number of residents at a certain receiver point on the ground and $L_{AE,i}$ is the sound exposure level at those point caused by the aircraft flyby.

F. Static Atmosphere

The static pressure, the static temperature and the density for a specific altitude are computed based on the International Standard Atmosphere DIN ISO 2533[12], where also possible deviations from this standard atmosphere model can be taken into account. First, the geopotential height is computed from the earth radius r_E and the geodetic height h:

$$H_G = \frac{r_E \cdot h}{r_E + h} \tag{22}$$

If the geopotential height is smaller than or equal to the maximum geopotential height for the troposphere layer, that is 11000m, the density ρ and the static pressure p are computed as follows:

$$\rho = \rho_S \left[1 + \frac{\gamma_{Tr}}{T_S} \cdot H_G\right]^{\left(-\frac{g_S}{R \cdot \gamma_{Tr}} - 1\right)} \tag{23}$$

$$p = p_S \left[1 + \frac{\gamma_{Tr}}{T_S} \cdot H_G\right]^{\left(-\frac{g_S}{R \cdot \gamma_{Tr}}\right)} \tag{24}$$

Here, γ_{Tr} is the temperature gradient of the polytropic troposphere layer and R the specific gas constant. g_s, T_s, ρ_s and p_s indicate the gravitational acceleration, the temperature, the density respectively the pressure at mean sea level (MSL).

III. Multi-Aircraft Trajectory Optimization

In the following paragraphs, the multi-aircraft trajectory optimization problem is first stated generally. Then, the various elements of the multi-aircraft trajectory optimization problem are specified in more detail. Finally, the strategy for the solution of the given trajectory optimization task is outlined.

A. General Statement of Multi-Aircraft Trajectory Optimization Problem

In general, the trajectory optimization problem involving N aircraft can be stated as follows: Determine the optimal control histories

$$\mathbf{u}_{i,opt}(t_i) \in \mathbb{R}^m, \qquad i = 1,\ldots,N \tag{25}$$

and the corresponding optimal state trajectories

$$\mathbf{x}_{i,opt}(t_i) \in \mathbb{R}^n, \qquad i = 1,\ldots,N \tag{26}$$

that minimize the Bolza cost functional

$$J = \sum_{i=1}^{N} \left[e_i\left(\mathbf{x}_i\left(t_{f,i}\right), t_{f,i}\right) + \int_{t_{0,i}}^{t_{f,i}} L_i\left(\mathbf{x}_i(t_i), \mathbf{u}_i(t_i), t_i\right) dt_i \right] \tag{27}$$

subject to the state dynamics

$$\dot{\mathbf{x}}_i(t_i) = \mathbf{f}_i\left(\mathbf{x}_i(t_i), \mathbf{u}_i(t_i), t_i\right), \qquad i = 1,\ldots,N \tag{28}$$

the initial and final boundary conditions

$$\boldsymbol{\psi}_{0,i}\left(\mathbf{x}_i\left(t_{0,i}\right), t_{0,i}\right) = \mathbf{0} \qquad \boldsymbol{\psi}_{0,i} \in \mathbb{R}^{q_i} \qquad q_\mathrm{i} \le m_\mathrm{i} + n_\mathrm{i}, \qquad i = 1,\ldots,N \tag{29}$$

$$\boldsymbol{\psi}_{f,i}\left(\mathbf{x}_i\left(t_{f,i}\right),t_{f,i}\right)=\mathbf{0} \qquad \boldsymbol{\psi}_{f,i}\in\mathbb{R}^{p_i} \qquad p_i\le m_{\mathrm{i}}+n_{\mathrm{i}}, \qquad i=1,\ldots,N \tag{30}$$

the interior point conditions

$$\mathbf{r}_i\left(\mathbf{x}\left(t_i\right),t_i\right)=\mathbf{0} \qquad \mathbf{r}_i\in\mathbb{R}^{k_i}, \qquad i=1,\ldots,N \tag{31}$$

and the equality and inequality conditions

$$\mathbf{C}_{eq,i}\left(\mathbf{x}_i\left(t_i\right),\mathbf{u}_i\left(t_i\right),t_i\right)=\mathbf{0} \qquad \mathbf{C}_{eq,i}\in\mathbb{R}^{r_i}, \qquad i=1,\ldots,N \tag{32}$$

$$\mathbf{C}_{ineq,i}\left(\mathbf{x}_i\left(t_i\right),\mathbf{u}_i\left(t_i\right),t_i\right)\le\mathbf{0} \qquad \mathbf{C}_{ineq,i}\in\mathbb{R}^{s_i}, \qquad i=1,\ldots,N \tag{33}$$

B. Detailing of Multi-Aircraft Trajectory Optimization Problem

Utilizing the simulation model described in paragraph II, the state vector and the control vector of the i-th aircraft within the optimal control problem are:

$$\mathbf{x}_i=\left[x_i,y_i,z_i,V_{K,i},\chi_{K,i},\gamma_{K,i},m_i\right]^T \tag{34}$$

$$\mathbf{u}_i=\left[\alpha_{A,CMD,i},\mu_{A,CMD,i},\delta_{T,CMD,i}\right]^T \tag{35}$$

For computing fuel-minimal approaches, the objective is to maximize the aircraft masses at the end of the approach flights:

$$J=-\sum_{i=1}^{N}m_i\left(t_{f,i}\right) \tag{36}$$

If noise-minimal approach trajectories shall be found by the optimization, either the maximum sound pressure level $L_{A,max}$ or the total number of awakenings n_{AW} can be minimized.

The initial boundary conditions are defined by the entry position into the considered air space. The final boundary conditions are defined such that the aircraft is finally located on the ILS glide path. Here it is assumed that the final approach fix is located at the origin of the Local Fixed Frame N with an altitude of h_{FAF}. Then, the ILS glide path is directed parallel to the x-axis of the Local Fixed Frame N, pointing into the direction of the positive x-axis. The following final boundary conditions must hold for the i-th aircraft:

$$x\left(t_f\right)\ge x_{FAF}+\Delta x \tag{37}$$

$$y\left(t_f\right)=y_{FAF} \tag{38}$$

$$h\left(t_f\right)=h_{FAF}+\tan\left(-\gamma_{K,ILS}\right)\cdot x\left(t_f\right) \tag{39}$$

$$\gamma_K\left(t_f\right)=\gamma_{K,ILS} \tag{40}$$

$$\chi_K\left(t_f\right)=\chi_{K,ILS} \tag{41}$$

$$V_K\left(t_f\right)=V_{K,ILS} \tag{42}$$

By Eq. (37) it is ensured that the aircraft has entered the ILS glide path and has travelled a certain distance Δx along the glide path. While no equality path constraints are present in the approach trajectory optimization tasks, numerous inequality path constraints arise. Inequality path constraints are due to the eastward position y, the aircraft altitude h, the kinematic velocity V_K and the load factor n_Z in the direction of the z-axis of the Aerodynamic Frame A:

$$y_{LB}(t) \leq y(t) \leq y_{UB}(t) \tag{43}$$

$$h_{LB}(t) \leq h(t) \leq h_{UB}(t) \tag{44}$$

$$V_{K,LB}(t) \leq V_K(t) \leq V_{K,UB}(t) \tag{45}$$

$$n_{Z,A,LB} \leq n_{Z,A}(t) \leq n_{Z,A,UB} \tag{46}$$

where the subscripts LB and UB denote the lower bounds and the upper bounds respectively. The lower bounds and the upper bounds are formulated such that the aircraft has to follow the ILS glide path once it has passed the final approach fix. The bounds with regard to the eastward position y restrict the aircraft to be $100\ m$ west or east the x-axis (this means the ILS glide path):

$$y_{LB}(t) = 0.5 \cdot [1 - \tanh(a \cdot x(t))] \cdot y_{LB} - 100.0 \tag{47}$$

$$y_{UB}(t) = 0.5 \cdot [1 - \tanh(a \cdot x(t))] \cdot y_{UB} + 100.0 \tag{48}$$

where the parameter a can be utilized to adjust the steepness of the *tangens hyperbolicus* functions. y_{LB} and y_{UB} are the boundaries of the eastward position y if the aircraft is not on the glide path. The limits with respect to the altitude h restrict the aircraft to fly $100\ m$ below or above the ILS glide path:

$$h_{LB}(t) = 0.5 \cdot [1 - \tanh(a \cdot x(t))] \cdot h_{LB} + (h_{FAF} - 100.0) + \tan(-\gamma_{ILS}) \cdot x(t) \tag{49}$$

$$h_{UB}(t) = 0.5 \cdot [1 - \tanh(a \cdot x(t))] \cdot h_{UB} + (h_{FAF} + 100.0) + \tan(-\gamma_{ILS}) \cdot x(t) \tag{50}$$

Here again h_{LB} and h_{UB} give the boundary values of the altitude if the aircraft has not entered the ILS glide path yet. By introducing an imaginary prolongation of the ILS glide path beyond the touchdown point (this means allowing $h(t) < 0\ m$), the number of aircraft can be increased to any number of aircraft, only limited by the number of optimization variables and constraints the NLP-solver can handle. Finally, the bounds with regard to the kinematic velocity V_K restrict the aircraft to hold a velocity of $10\ km/h$ below or above the desired ILS velocity $V_{K,ILS}$:

$$V_{K,LB}(t) = 0.5 \cdot [1 - \tanh(a \cdot x(t))] \cdot (V_{K,LB} - V_{K,ILS} + 10.0) + (V_{K,ILS} - 10.0) \tag{51}$$

$$V_{K,UB}(t) = 0.5 \cdot [1 - \tanh(a \cdot x(t))] \cdot (V_{K,UB} - V_{K,ILS} - 10.0) + (V_{K,ILS} + 10.0) \tag{52}$$

where $V_{K,LB}$ and $V_{K,UB}$ are the boundaries for the velocity if the aircraft is not on the glide path. The path constraints with respect to the eastward position and the altitude are depicted in Fig. 1, the path constraints with regard to the kinematic velocity are illustrated in Fig. 2. Alternatively, similar path constraints for the heading angle χ_K respectively the flight-path inclination angle γ_K that enforce the aircraft to follow the ILS glide path could be added to the trajectory optimization problem.

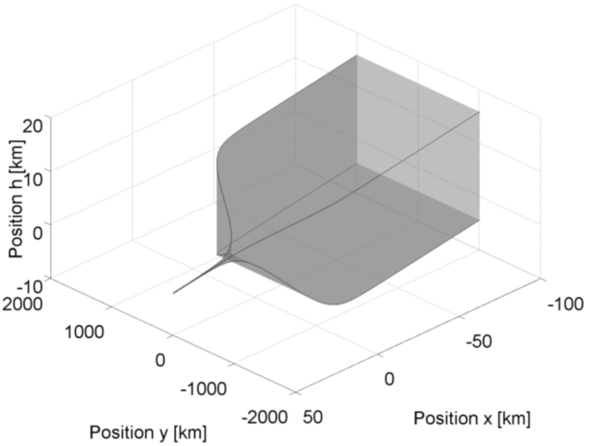

Figure 1. Permitted airspace

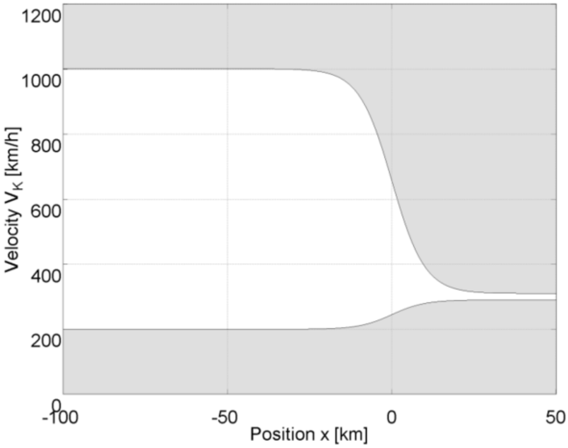

Figure 2. Path constraints w.r.t. kinematic velocity V_K

Furthermore, inequality constraints on the commanded controls have to be imposed:

$$\alpha_{A,CMD,LB} \le \alpha_{A,CMD}(t) \le \alpha_{A,CMD,UB} \tag{53}$$

$$\mu_{A,CMD,LB} \le \mu_{A,CMD}(t) \le \mu_{A,CMD,UB} \tag{54}$$

$$\delta_{T,CMD,LB} \le \delta_{T,CMD} \le \delta_{T,CMD,UB} \tag{55}$$

Besides the path constraints given above that apply separately to each single aircraft, the multi-aircraft trajectory optimization problem has to be augmented by path constraints with respect to the separation distances between the involved aircraft. The distance between two aircraft is obtained by:

$$d_{ij}(t) = \sqrt{\left[x_i(t) - x_j(t)\right]^2 + \left[y_i(t) - y_j(t)\right]^2 + \left[z_i(t) - z_j(t)\right]^2}, \quad i = 1,\ldots,N,\ j = i+1,\ldots,N \tag{56}$$

Here it has to be mentioned that the flight times of all aircraft are normalized with respect to their final flight times:

$$\tau_i = \frac{t_i}{t_{f,i}}, i = 1,..., N \tag{57}$$

Then, one single parameter for the final flight times of all aircraft is introduced:

$$t_f = t_{f,1} = t_{f,2} = ... = t_{f,N} \tag{58}$$

At this, the time elapsed is the same for all aircraft. Thus, the constraints with respect to the minimum distances between the aircraft can be checked directly and their implementation is straightforward as given by Eq. (56) because of the direct correlation of the time elapsed of all aircraft. The corresponding path constraints with respect to the separation distance are:

$$d_{ij}(t) - d_{\min} \geq 0 \tag{59}$$

Due to enforcing the same total flight time t_f for all aircraft, the aircraft will be located on different positions on the ILS glide path at the final time t_f. This means that there are aircraft that have flown the whole way along the ILS glide path while there are also aircraft that just have entered the ILS glide path at the final time of the trajectory optimization problem. Thus, if an integral cost function is considered, the portion of the cost function originating from the flight along the ILS glide path must not be taken into account in order to achieve an equal weighting of all aircraft. For the fuel cost function, this can be done by adjusting the fuel flow as follows:

$$\dot{m}_{fuel,eff}(t) = \dot{m}_{fuel}(t) \cdot 0.5 \cdot \left[1 - \tanh\left(a \cdot \left[x(t) - \Delta x_{fuel}\right]\right)\right] \tag{60}$$

This reduces the fuel flow to zero once the aircraft has entered the ILS glide path by Δx_{fuel}. The distance Δx_{fuel} can for example be set to the distance between the final approach fix and the runway threshold. Since the *tangens hyperbolicus* function does not become zero instantly at Δx_{fuel}, a final position Δx (see Eq. (34)) is required that is larger than Δx_{fuel} in order to weight all aircraft equally.

C. Solution Strategy

It is unlikely that the optimizer will alternate the aircraft landing sequence at any time during the optimization once a specific sequence of the aircraft on the ILS glide path has been established. For this reason, an algorithmic procedure is set up that is expected to deliver the optimal solution for the aircraft sequencing on the ILS glide path. Therefore, the approach flight paths are first optimized without the distance path constraints taken into account. This means that the aircraft are completely independent of each other and that each approach trajectory is first optimized regardless of the other aircraft residing in the vicinity of the airport. Then, the optimal approach trajectories of the individual aircraft are taken as initial guess for the simultaneous optimization of all aircraft, taking into account the path constraints with respect to the minimum required aircraft separation distances. In the seldom cases where the path constraints are already fulfilled by the initial guess (this means the distances between the aircraft are already larger than required), the optimal solution for the unconstrained problem is also the optimal solution for the original constrained problem. Otherwise, the aircraft will be separated by the optimizer until all path constraints are met and the cost function of the constrained problem becomes minimal. At this it is assumed that the optimal solution of the unconstrained trajectory optimization problem provides an excellent initial guess for the constrained trajectory optimization problem since the cost function of a specific optimization problem is always less than or equal to the cost function of the same trajectory optimization problem with additional constraints.

The optimal control problem is solved using a simultaneous method[13,14]. The method transforms the continuous time optimal control problem into a discrete nonlinear program by discretizing both the states and the controls. Furthermore, the discretized form of the differential equations (Eq. (25)) of the respective flight system are transformed into additional equality constraints. Those equality constraints have to be added to the nonlinear program that is then solved by the commercial software SNOPT[15].

IV. Results

The multi-aircraft trajectory optimization approach has been applied to a generic scenario following the example in Ref. 9. There, the optimal approach trajectories and landing sequence for four aircraft is sought. The initial boundary conditions for the involved aircraft are given in Table 1.

AC No.	1	2	3	4
$x_{i,0}$	$-100000\,m$	$-80000\,m$	$-40000\,m$	$-100000\,m$
$y_{i,0}$	$100000\,m$	$50000\,m$	$-120000\,m$	$-70000\,m$
$h_{i,0}$	$4000\,m$	$4000\,m$	$5000\,m$	$6000\,m$
$\chi_{K,i,0}$	$-60.0°$	$-45.0°$	$95.0°$	$45.0°$
$\gamma_{K,i,0}$	$0.0°$	$0.0°$	$0.0°$	$0.0°$
$V_{K,i,0}$	$450.0\,km/h$	$360.0\,km/h$	$540.0\,km/h$	$600.0\,km/h$

Table 1. Initial Conditions

The final boundary conditions are such that the aircraft are finally located on the ILS glide path which is given by Eqs. (37) to (42). The specific values for the final approach fix are $x_{FAF} = 0.0\,m$, $y_{FAF} = 0.0\,m$, $h_{FAF} = 450.0\,m$, $\Delta x = 8.0\,km$ and $\Delta x_{fuel} = 16.0\,km$. The parameters for the ILS glide path are $\chi_{K,ILS} = 0°$, $\gamma_{K,ILS} = -3°$ and $V_{K,ILS} = 300.0\,km/h$. The lower bounds and the upper bounds for the path constraints involved in the trajectory optimization problem are listed in Table 2.

	Lower Bounds	Upper Bounds
$n_{Z,A}$	0.85	1.15
y	$-1000\,km$	$1000\,km$
h	$-10\,km$	$10\,km$
V_K	$200\,km/h$	$1000\,km/h$
$\alpha_{A,CMD}$	$-5.73°$	$20.05°$
$\mu_{A,CMD}$	$-45°$	$45°$
$\delta_{T,CMD}$	0.0	1.0

Table 2. Lower and upper bounds of path constraints

In Fig. 3, the optimal approach trajectories for the four aircraft are depicted. The optimal landing sequence can be seen by the queuing of the aircraft on the ILS glide path. The green aircraft is first, followed by the turquoise aircraft, the red aircraft and finally the blue aircraft.

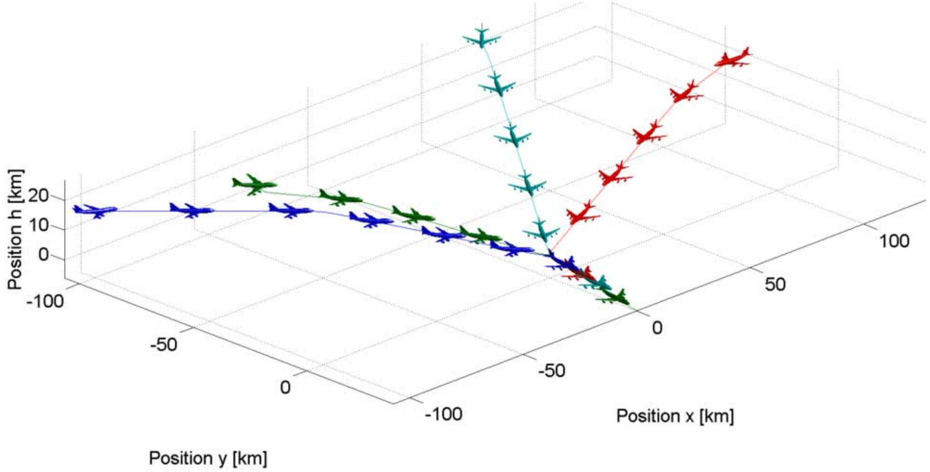

Figure 3. Optimal approach trajectories

In Fig. 4, the aircraft velocities together with the lower and upper bounds are given. Fig. 5 depicts the corresponding controls. Finally, in Fig. 6 the distances between the aircraft are presented. Here it can be seen that the minimum distance of $7\ km$ is maintained all the time.

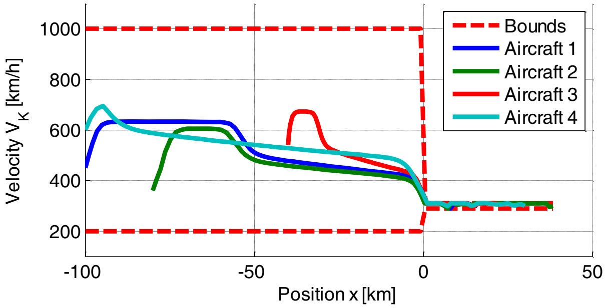

Figure 4. Aircraft velocities V_K

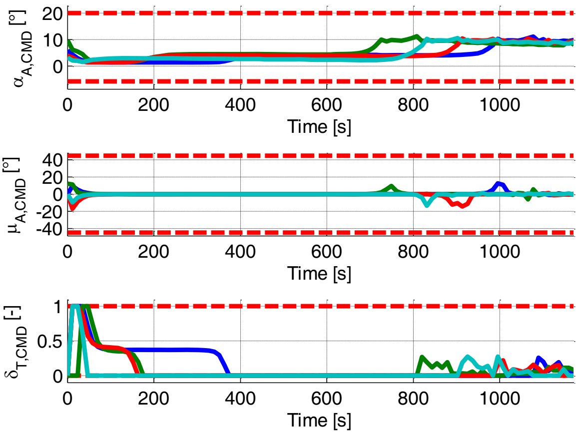

Figure 5. Time histories of aircraft controls

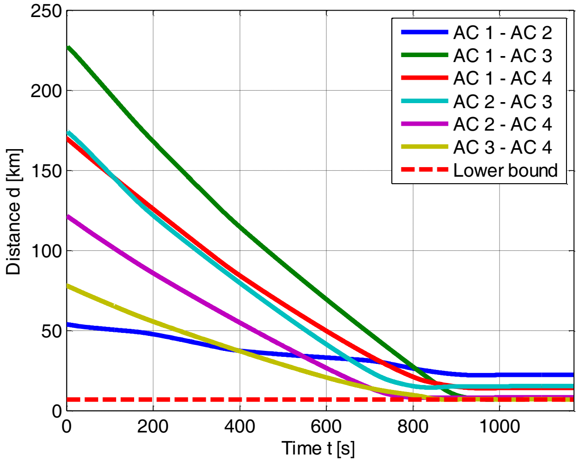

Figure 6. Distances d between aircraft

V. Conclusion

By the proposed optimization procedure, the overall fuel consumption of multiple aircraft present in the vicinity of an airport is minimized, while a certain separation distance between the respective aircraft is maintained and the aircraft are finally queued on the ILS glide path in the optimal sequence.

For a more sophisticated description of the permitted airspace, splines could be utilized to describe the centerline of the allowed flight path corridors for each single aircraft. Then, path constraints with respect to the maximum horizontal and vertical deviations from the centerline can be enforced. For the ILS glide paths, the flight path corridor centerlines would then be identical to the ILS glide paths. Furthermore, the distance path constraints between the aircraft can be developed further. Instead of constructing spheres around the aircraft for checking the separation distances, ellipsoids could be implemented with larger minimum separation distances behind and in front of the aircraft and smaller minimum lateral separation distances. Also the aircraft types could be taken into account for computing the minimum separation distance. For example, the minimum separation distance between a medium and a heavy weight aircraft is different from the minimum separation distance between two heavy weight aircraft.

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Coupling of ATM Planning Systems with Different Time Horizons

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Within Total Airport Management a pre-tactical planning for the next 24h is performed, to enable a pro-active and common decision making for the stakeholders. Especially the air traffic flow and pre-tactical decisions influence later on the tactical phase, supported by controller assistance tools like Arrival and Departure Manager with a planning horizon of about 90min. This paper gives an overview of the participating components, describes the information flows and suggests coordination profiles for coupling those ATM Planning Systems with different time horizons.

I. Introduction

The idea of Total Airport Management (TAM) is to 1. Spot at the airport holistically, 2. Enable situation awareness and pro-active, collaborative handling of disturbances like capacity shortfalls. The stakeholder at the airport like ground handler, air navigation service providers, airport operators, and (major local) airlines optimize their operations for a given situation by their current needs. With TAM they consider negotiated constraints of other stakeholders to reach a better outcome for the whole airport. To support the support human decision makers in the pre-tactical phase (time horizon up to 24 hours) of operations planning, a decision support tool, called TOP (Total Operations Planner), was developed during the last years. TOP performs a re-planning of the day schedule taking the changing constraints into account, e.g. weather, and updated flight data like takeoff from outstation or an update of the estimated time of arrival. The result illustrates the impacts to the operations under the newly given or assumed circumstances. This enhances the situational awareness and opens room for decisions to be taken pro-actively. The operational concept of TAM [1] and adaptations to projects [2][3] suggests also negotiations between the stakeholders. Those are necessary especially for new tasks introduced by TAM like e.g. setting commonly agreed and supported performance goals. To realize an efficient negotiation process, each stakeholder is represented by an agent and has a special role depending on the task to solve. Defined roles are supporter, initiator, decision maker and - if necessary - moderator. The negotiation process itself could be steered by a negotiation support tool. To find the best fitting decision, the agent should have a strong connection to his operation centre, and he should be aware of the operational information (tactical and pre-tactical) of his company. The most important information should generate constraints for TOP.

To provide support also to negotiations, the TOP includes capabilities for what-if probing. So the actors are supported in producing alternative plans taking into account different constraints (like weather), and different preferences (e.g. prefer throughput instead of punctuality) and compare them with each other.

The results of the negotiation and planning process are collected in the Airport Operation Plan (AOP). This information is shared amongst all stakeholders, and each stakeholder is responsible for implementation of its part of the plan. Furthermore, this plan could be added to the Network Operations Plan (NOP) and shared with other airports.

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When having TAM and support by TOP, we have to think about the interaction between the pre-tactical planning and the tactical one performed by controller assistance tools like AMAN or DMAN. If, for instance, the pre-tactical decision was to prefer more departures because the parking positions are full, this should be taken into account when time comes into the planning scope of the tactical planning systems. Also tactical or ad-hoc disturbances like a runway closure will influence the pre-tactical planning. Here, the pre-tactical planning can help to ease the recovery.

One aim of using a pre-tactical planning system before tactical optimization is to regulate the traffic before it reaches the TMA or planning horizon of AMAN and DMAN. This may have influence to other sectors, other traffic, and even other airports. At this point of discussion such effects are not in focus of this paper. It concentrates on the arrival and departure air traffic control part of one particular airport, introduces the mentioned planning systems, and describes how the systems could be coupled.

II. Pre-tactical Planning system (TOP)

The first work at DLR in designing and implementing a pre-tactical planning system was started in 2003 together with Deutsche Flugsicherung GmbH (DFS, the German air navigation service provider). 2007 in co-operation with Eurocontrol Experimental Centre, the planning algorithm was reworked to reach better performance and be able to represent the planning results for a large time horizon within seconds. This What-if enabled system is introduced as Total Operations Planner (TOP).

The main goal of TOP is to support human decision makers in the pre-tactical phase of operations planning with a time horizon of up to 24 hours. This is done by performing a planning taking into account the changed constraints. The results illustrate the impacts to the operations under the given circumstances. Because of being a support tool for live interactive human communication at negotiation process, alternative solutions depending on individual preferences are expected within seconds. Fulfilling these contradictory goals, namely producing of possible exact prediction of events with optimized control suggestion within a very short time had to be solved aiming the main target a human centred decision system. Since the resolutions are not safety relevant and there is always still enough time to correct infelicitous suggestions (especially because of humans involved in the decision loop) one can slightly sacrifice exactness to meet the most important requirements.

In TOP the optimization problem is separated in two levels of abstraction. First, using a simplified model of an airport operating system, defined as a set of interacting traffic flows of abstract entities, resources and control parameters, a prediction of future state will be calculated and optimized towards individual objectives under constraints predefined in contract of quality of service. Based on predicted abstract results the detailed plan of target event times for all traffic objects will be generated taking into account all individual constraints for events and resources being skipped on traffic flow abstraction level.

Assuming that the exact time definition for events for which even the source data are burdened with uncertainties of more than 5 minutes and the realization of suggested solution alike, we decide to transform the final stage of the original problem. At the Events and Resources Level we assume a given table of possible event independent times for each resource (fulfilling capacity and temporal causality restrictions of original). Within this projection from continuous time space into discrete domain a solution has to be found as a simple scheduling of events. This search of a solution takes place in a subset of key resources followed by simple chained resource assignment for intermediate ones.

The necessary set of possible times for resources can be generated with a feasible accuracy using a system simulation. This leads to the Traffic Flow Level. Basing on given operational procedures at an airport a deterministic traffic flow model of resource usage has been constructed, where individual input events are transformed into abstract flow streams traversing the process model according to predefined restrictions. Within the system simulation changes of model states take place at evenly distributed time stamps which leads to selected tapped flows corresponding to usage of certain resource and therefore founds a source for counterpart time series. The behaviour of the system is controlled by parameter settings, which are used to optimize the total system performance towards a set of derived cost functions (defined on another subset of tapped flows, additionally expanded in the discrete space of model time intervals).[4]

III. Tactical Controller Assistance Systems

One of the first tactical controller assistance systems was COMPAS [5],an arrival management system. Today different kinds of AMAN Systems are on the market, each with slightly different features. More sophisticated systems taking into account complex air space structures and complete 4d-trajectories are part of international research programs. Future "advanced" AMAN systems will support controllers not only in standard traffic situations, but also in benefit from new on-board features and ease new environmentally friendly complex procedures.

With having a good prediction for landing times through an arrival management, another system shall make best use of the tight resource runway and reduce the engine running times on the ground: the departure management system [6][7]. As arrival and departure management systems compete for the same resource, a coordinated coupling of both was developed [8].

The following section will describe the DLR prototypes for the mentioned systems. They all have one in common: They are adaptive planning systems. This means, if aircraft or controllers deviates from the recommended plan, they re-calculate and come back with an adjusted solution for the changed traffic situation.

A. The Arrival Manager 4D-CARMA

During the last fifteen years, the DLR-Institute of Flight Guidance in Braunschweig has researched and developed arrival management systems for different kinds of applications on various international airports. The latest development is the 4-dimensional Cooperative Arrival Manager (4D-CARMA) to assist controllers at civil airports in scheduling and guiding inbound traffic. It is the latest implementation of DLR's previous arrival managers (AMAN) "COMPAS"[5] and "4D-Planner" [9], both research projects in close cooperation with the DFS. Taking different constraints into account like weight classes, runway separation criteria, and runway allocation, 4D-CARMA uses radar data and additional information of all arriving aircraft and calculates sequences with 4d-trajectories from the current position to the assigned runway threshold. Furthermore, the AMAN provides advisories for controllers to guide the aircraft through the Terminal Manoeuvring Area (TMA).

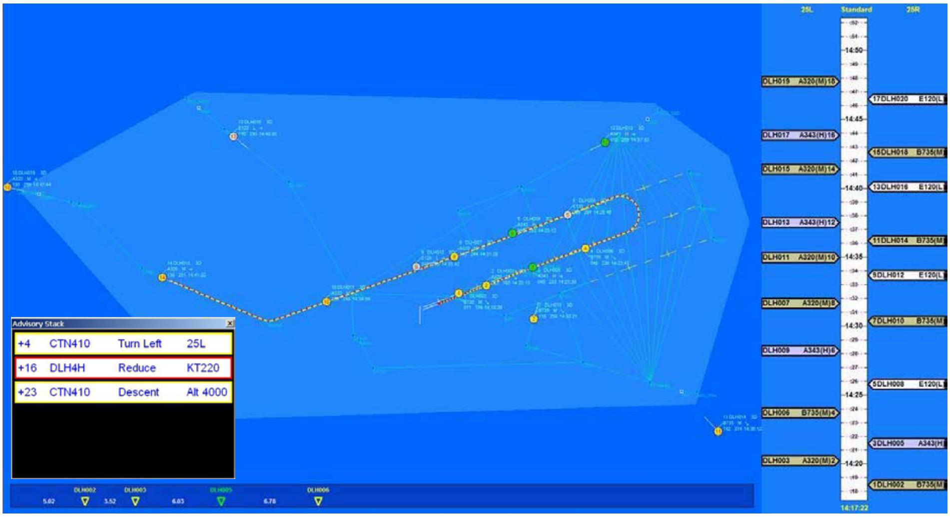
In a first step 4D-CARMA calculates the shortest and the longest possible flight route through the TMA from the current aircraft position to the runway. On the basis of these two boundary conditions a time-based window between the earliest and the latest arrival time (without holdings) is estimated and a sequence for all arriving aircraft is created. Taking wake vortex safety distances into account, 4D-CARMA calculates the target times of arrival and finally generates the individual trajectories. If connected to a departure manager like CADEO (Controller Assistance for Departure Optimization) the AMAN-human-machine-interfaces (HMI) provides for a common overview of the planned arrival and departure sequence real-time time-lines for each runway showing aircraft labels ordered by its scheduled arrival respectively departure target landing and take-off times.

Furthermore, 4D-CARMA supports various kinds of HMIs for controllers to handle the growing air traffic in the vicinity of larger airports. Conventional radar displays can be upgraded to show the sequence position of each arriving aircraft next to the common aircraft label to assist controller at the planning and guiding exercise without treating him to distract his attention from the radar display (Fig. 1).

If required 4D-CARMA generates three different controller advisories on the basis of calculated 4d-trajectories. The controller gets an advisory stack with a time countdown in the first column assisting him in giving clearances at the right time so that the inbounds may precisely follow the planned trajectory (Fig. 1, box on the left). Currently 4D-CARMA supports descent, speed reducing, and turn to base advisories for the controller working positions pick-up and feeder.

If there are deviations between the flight track and the ground based calculation of the 4d-trajectory, the 4D-CARMA conformance monitoring detects this and adapts the next trajectory and thereby the advisories to the modified situation. If the aircraft turns too early the next reduce command will be given earlier or a smaller target speed value will be chosen. In an analogous manner 4D-CARMA handles the case when an aircraft turns too late.

In cooperation with DLR's Departure Manager (CADEO) and the DLR AMAN-DMAN Coordinator (ADCO) 4D-CARMA support mixed mode operations on one or more runways by taking departures into account within the arrival sequence optimization process.



Advisory Stack

+4	CTN410	Turn Left	25L
+16	DLH4H	Reduce	KT220
+23	CTN410	Descent	Alt 4000

Figure 1. The Radardisplay "RadarVision" used as HMI for approach controllers on the working positions pick-up and feeder. The green (heavy) and yellow (medium) circles represent arriving aircraft, the number indicates the current position in the landing sequence for both runways. In the left box examples for controller advisories are inserted, generated on the basis of individual aircraft 4d-trajectories. On the right is the dynamic time line with aircraft labels marking the target landing times (TLDT). At the bottom of the picture the actual separations between the aircraft on the final are displayed.

B. The Departure Manager CADEO

Without tool supported departure management it was quite common at the airports to let the departures start-up their engines when they ask for (First come first served, FCFS). This may – and will in peak traffic situations - lead to a departure queue at the runway holding points. It may also be the case, that the FCFS sequence is not optimal for runway throughput due to separation criteria (wake vortex and/or SID separation).

DMAN as a tool to support departure management can be understood in two ways: 1. As "pre-departure sequencer", which focuses on the off-block sequence and at least prevent long queues. It supports mainly the Clearance Delivery controller. 2. As "departure sequence optimizer" which focuses on the runway-sequence and derives the off-block sequence. The latter one deviates more likely from the FCFS sequence and prevent queues more strictly. It supports all Tower Controllers: Clearance Delivery, Ground/Apron and Local Control.

The DLR DMAN prototype CADEO is of second kind: It optimizes the runway sequences, calculates Target Takeoff Times (TTOT), derives Target Startup Approval Times (TSAT) and supports the controllers in establishing the sequence [10]. The main objectives are to build an optimized departure sequence, taking into account arrivals, if mixed mode is used, and reduce the engine running times in keeping the departures at gate with not-started engines as long as feasible and therewith reduce runway holding point queues [11]. One important constraint for calculating the departure sequence is the off-block time. Adding times it takes to push, taxi and lineup, the result is the earliest takeoff time. This is the left border constraint within CADEOs optimization to find a sequence and calculate the TTOTs. The off-block time is one key element of Airport Collaborative Decision Making (A-CDM) [12]: The Target Off-block Times (TOBT) have to be set accurately by the responsible entity. This does not only have positive impact to the departure planning, but – together with the A-CDM information sharing - to other stakeholders, which get a better situation awareness and may change their plans accordingly.

Each change of relevant planning input data will trigger CADEO to re-plan, which may lead to changed TTOTs or even to a changed sequence [10]. If a runway is used in mixed mode, this is also valid for Target Landing Times as input data to CADEO. Vice versa, with calculating reliable TTOT through runway sequence optimization, an AMAN-DMAN coordination can be done.

C. The AMAN-DMAN-Coordinator ADCO

For larger airports mixed mode operations are commonly considered as one important mean to increase the capacity of their runway systems [13][14]. From this point of view a coupling component (ADCO) [15] has been developed for the coordination of arrival and departure management (CADM) when applying mixed mode operations at an airport. It is based on an appropriate tailoring of arrival gaps by automatic introduction of so-called arrival free intervals (AFI) and a corresponding path stretching for the respective arrivals. Thereby the coordination system takes into account both the departure traffic situation on ground and the arrival situation in the TMA, which is contained implicitly in state and planning information coming from controller decision support tools for the arrival and departure management (AMAN and DMAN). The CADM concept is designed to be applicable for any AMAN and DMAN as long as they meet a set of well-defined requirements. The concept has been worked out by DLR within the German project "Kooperatives Air Traffic Management" (K-ATM) [16], but under consideration of the results of both the relevant European projects, like Gate-to-Gate [17] and the PHARE [18]. The Total Airport Management Concept [1], which was elaborated jointly by EUROCONTROL and DLR was also taken into account.

The implementation of AFI is the core functionality of the ADCO. The first step is to determine repetitively (e.g. once a minute) promising points in time. A fuzzy inference system is used for evaluation and selection of a suitable time for placing an AFI. Provided with data from approach control (AMAN) and tower control (DMAN) which characterize the actual traffic situation, ADCO can derive values for particular attributes as input for a fuzzy inference system. The attributes describe the impact on the arrival sequence, the remaining flexibility of arrivals, the exigency for an AFI in view of DMAN and the probability of using the AFI efficiently for take-offs. A set of rules is defined which describe whether it is advisable to have an AFI at a selected time or not. The consequences of all rules are aggregated by a fuzzy inference system which yields a total value indicating the suitability of the AFI. Finally a comparison of the value delivered by the fuzzy inference system and a threshold leads to a decision whether the AFI actually is to be introduced or not [8]. Fig. 2 shows AFIs inserted into the arrival sequence.

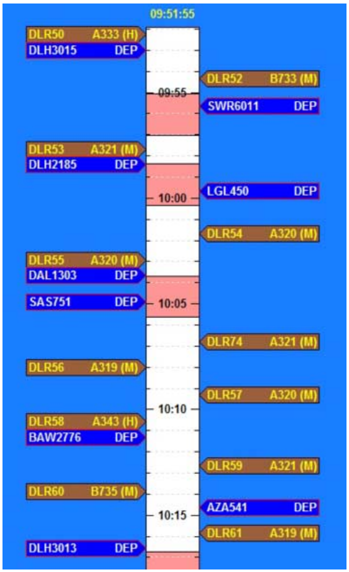


Figure 2. AFIs (magenta), arrivals (brown) and departures (blue) displayed in a dynamic time line.

A dedicated input value for ADCO is the arrival-departure ratio provided by TOP when using an appropriate coordination profile. In combination with respective additional rules and adjustments in the inference system the resulting AFIs are the controlling method to achieve the aimed traffic flows. Due to the principle of operation ADCO is limited to assist the departing traffic, so arrivals are only supported by refraining from introducing AFIs. This is not disadvantageous in the sense of ratio performance respecting the interaction of AMAN and DMAN without AFIs where departures utilise the remaining gaps between arrivals. An AMAN is able to adjust the ratio towards more arrivals whereas a DMAN needs to be backed by ADCO.

IV. Coupling

A simple, indirect and uni-directional kind of coupling happens, if the traffic is controlled in an early stage in accordance with the pre-tactical plan and then enters the tactical time horizon. This coupling could be advanced, if the controllers know the intention of the pre-tactical control and if even the tactical planning systems support the pre-tactical plan. This is especially valid, if the constraints remain similar when entering the tactical time scope. If the constraints change a lot in the tactical time frame, we recommend the bi-directional coupling: The tactical plan shall be taken into account by the pre-tactical planning, because this plan changes the traffic situation.

Coupling of the pre-tactical and tactical systems takes place in that way, that the pre-tactical system creates constraints based on early known information for the tactical planning horizon, and the tactical systems give back (tactical) plans regarding the more detailed data to be taken as constraints for the pre-tactical planning. Data for the pre-tactical planning system with a time horizon of e.g. about 24 hours are sometimes quite raw like scheduled times (SIBT, SOBT) and incomplete like the exact type of aircraft or amount of passengers. To give a first impression of the time-based traffic demand over the next hours and to check how it fits to the updated operational constraints, or better, how the demand would be planed to fit the constraints, those raw and incomplete data are sufficient. Based on a pre-tactical plan, the real traffic can be controlled accordingly to these circumstances in an early stage. Results of this planning could be additional information for tactical planning systems. Data like planned flows, feasible arrival-departure ratio or (pre-tactical) target times are given. Taking into account this information, the tactical planning systems create their target times and traffic flows for the time horizon they are used to optimize. Because of a shorter time horizon for the near future the input data are more accurate than for the pre-tactical phase. So, the planning result is more precise than the pre-tactical plan and generates a better knowledge of the traffic in tactical time horizon. Therefore, the pre-tactical planner should take the tactical plan into account for his next re-planning as changed constraints.

Our expectations from the combination of the pre-tactical and tactical planning are early indications of impacts, possibility of early reaction on this and less over demand when it comes to the point of the disturbance. For an AMAN e.g. this means: without pre-tactical planning and control, arriving traffic has to be hold in holding pattern or deviated at a late stage, whereas with pre-tactical planning and control the demand can be handled using the optimization functions of AMAN in the tactical phase. For DMAN it is analogue: We take as an example a scenario where the runway capacity will drop. Without pre-tactical planning and control, the DMAN would produce TSATs with high delay when it comes to the shortfall. With the pre-tactical planning and control the airlines will see the probable impacts to their flights and adjust the TOBT, so the boarding process could start later, the passengers can enjoy longer the leisure facilities or could be rebooked to other flights. For short-haul flights it may also be possible to redirect the passengers into a train, so the flight could be cancelled. All those possible decisions will help to mitigate the problem, and DMAN will issue TSATs that are more close to the TOBT as without pre-tactical planning and control.

Operationally the judgment, where data come from and how accurate they are, is enabled with giving each planning data a clearly defined name, e.g. TTOT for the tactical Target Takeoff Time and PTOT or topTTOT for the pre-tactical planned takeoff time, which is less accurate than the TTOT. Currently we prefer to name the new times with more than 4 letters to mark, that they are not defined within the A-CDM implementation manual [19] from EUROCONTROL and may be not yet understood commonly.

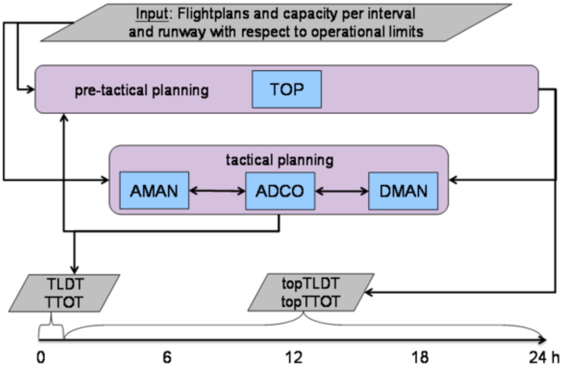


Figure 3. Coupling of pretactical and tactical planning tools. The figure shows the involved systems and the information flows.

There are a lot of coupling conceptions, which we name "coordination profiles", how pre-tactical planning performed by TOP and tactical planning performed by 4D-CARMA, CADEO and ACDO should work together. However, some preconditions must be set:

- TOP and the tactical tools have to take into account the same operational restrictions and capabilities e.g. available capacity because of bad weather (Fig. 3) as well as available flight plan data.
- TOP and the tactical tools should have no contrary optimization functions.

- A data connection between TOP and the tactical systems exists.

A. The Information Flow

Capacity limits of an airport runway are defined as the maximum number of arrivals and departures that can be managed during a fixed time interval under given operational conditions and an accepted medium delay [20]. Arrival and departure capacity limit values in the mixed mode of capacity utilization are interdependent and given by a convex piecewise linear Pareto-curve. This curve is derived by statistical methods combined with air traffic managers' and controllers' experience from historical airport performance data observed over a long period of time [21]. Considering possible operational conditions at an airport one can always construct a finite set of Pareto-curves which describe capacity limits of the airport runway(s) or restrict the capacity of runway(s) in the case of other bottlenecks [22][23].

Coupling two scheduling and guidance systems with the different time horizons and level of details requires study guides for their cooperative work and for the interpretation of the received planning information. The downstream tactical systems like AMAN and DMAN have to transpose the TOP calculated flow values for the in- and outbound traffic on the runway system. Since pre-tactical planning operates with capacity limits per time interval, the tactical systems should consider this time dependent information. Moreover, AMAN and DMAN have to know which set of rules should be used to utilise the given capacity. For instance, wet track conditions may extend the braking distances and thereby increase the runway occupancy time of each landing aircraft, i.e. decrease the runway capacity per time interval. Therefore, TOP reduces the number of approaches for the affected runways. The AMAN has to know these constraints, since it would push all landing aircraft together only taking ICAO’s wake vortex separations into account.

To get the best of TOP’s pre-tactical planning, the tactical tools have to know, how to deal with it. Hence, TOP or another source like a responsible operator should deliver additional information to the tactical tools how much to stick to the plan or which parameters of the plan shall be kept: the coordination profile. This information together with common coupling information data must be communicated to each tactical tool for each time interval.

Common coupling information per time interval from the pre-tactical system to the tactical ones:

- Start and end time of the considered time interval
  The pre-tactical TOP looks up to a 24h into the future, split them up into time intervals and calculates flows and arrival-departure ratios for each interval. The tactical tools have to know from which time and how long the corresponding flow and ratio targets and the coordination profiles are valid.
- Identifier of the runway
  Name of the runway for which the parameter are valid.
- Operational capacity
  This is the TOP-calculated capacity for each runway taking all known and available constraints into account. Additionally, possible inputs by operators were utilized and integrated in the capacity estimation.
- Planned arrival flow
  The TOP-planned arrival flow for each runway.
- Planned departure flow
  The TOP-planned departure flow for each runway.
- Ratio
  The recommended ratio between arrivals and departures for each runway in the operation mode of the belonging time interval. The ratio is the outcome of the TOP-planned arrival and departure flow.
- Pre-tactical Target times
  The TOP-target times (topTLDT for arrivals and topTTOT for departures) for each planned aircraft.

Common coupling information from the tactical systems to the pre-tactical one:

- Target Times: TTOTs for departure from DMAN and TLDTs for arrivals from AMAN.

Coordination profiles, which are considered per time interval, too, are summed up into two groups “Maintain TOP’s sequences” and “Optimize TOP’s sequences”:

1. **Maintain TOP's sequences:**
   - Keep the pre-tactical target times
     The tactical systems have to keep topTLDTs and topTTOTs as the target time for scheduling of aircraft. Due to safety reasons the only limitation is the consideration of the minimum wake vortex separations in dependence of the applied runway operation modes and for departures additionally the SID-separation.
   - Only reduce separations
     The tactical systems are only authorised to reduce the TOP-planned separations within the pre-tactical planned in- and outbound traffic sequence. Due to safety reasons the only limitation is the consideration of the minimum wake vortex separations in dependence of the applied runway operation modes and for departures additionally the SID-separation.
   - Only increase separations
     The tactical systems are only authorised to increase the TOP-planned separations within pre-tactical planned in- and outbound traffic sequence.
   - Equal distance distribution with fixed sequence
     The tactical tools have to keep the TOP's sequences and as far as possible reduce the gaps between the aircraft to the wake vortex separations (for departures: maximum of wake vortex and SID separation). If the tactical planning shows that the aircraft can be planned more dense together than they were planned pre-tactically , the remaining time is divided by the number of aircraft and added consistent to the wake vortex separations (for departures: maximum of wake vortex and SID separation.
   - Just keep the sequences
     The tactical tools are free to shift the target times in both directions, but have to keep the TOP's sequences.

2. **Optimize TOP's sequences:**
   - Complete optimization
     The tactical systems are allowed to optimize the complete arrival and departure sequence including target times calculation.
   - Optimization keeping the flow
     The tactical systems are allowed to optimize the complete arrival and departure sequence including target times calculation. The only constraint is to hold the pre-tactical planned flow values.
   - Optimization keeping the ratio
     The tactical systems are allowed to optimize the complete arrival and departure sequence including target times calculation. The only constraint is the pre-tactically given arrival-departure ratio.
   - Modify ratio supporting more arrivals
     The tactical systems may change the arrival-departure ratio on the runways by favouring arrivals. If the separation regulation does allow reducing the gaps between the aircraft, the free space should be used for arrivals.
   - Modify ratio supporting more departures
     The tactical systems may change the arrival-departure ratio on the runways by favouring departures. If the separation regulation does allow reducing the gaps between the aircraft, the free space should be used for departures.
   - Fixed flow with equal distance distribution
     The tactical tools have to keep the TOP's flow value. If the tactical planning shows that the aircraft can be planned more dense together than they were pre-tactically planned, the remaining time is divided by the number of aircraft and added consistent to the wake vortex separations.

All coordination profiles include, that traffic, which is already planned by a tactical system (means: having TTOT or TLDT), is taken into account by the pre-tactical planning as fixed and may not be shifted to another time or runway by the pre-tactical system.

B. Using coordination profiles for coupling

The idea of the cooperative coupling is to take the best out of both planning systems on different time levels. This coupling may allow optimization by the tactical planning, but take some parameters resulting from the pre-tactical planning as constraints. It is conceivable that the coupling of the described systems operates in different ways depending on expected traffic volume, runway operation modes, and weather conditions. We consider the more or less extreme coordination positions of a strict and a much more coordinated interaction of the systems.

The first group of the presented coordination profiles introduced in the last section offers a strict approach which skips the tactical planning to a greater or lesser extent, because the plan is already optimized with certain criteria. This would mean to waive the optimization benefits of the tactical systems, which take into account newer and much more detailed input data. However, the pre-tactical planning is performed so that the resource usage in the tactical period is in accordance with the usage in the remaining planning time.

The second group presents the cooperative coupling which takes the best out of both kinds of planning. This coupling allows to a greater or lesser extent optimization by the tactical planning based on the information about flexibility or inviolability of pre-tactical planned flow and of pre-tactical capacity partitioning between arrivals and departures. The human operators act and solve the problems, which became visible through the pre-tactical TOP planning. If disturbances on the upcoming traffic volume are taken into account, which is a part of the TAM concept, those pre-tactical plans may help the operators to see the influences onto the schedule. So, pro-active decisions can be taken to avoid ad-hoc 'chaos'-situations. If those decisions are made and traffic is influenced in that manner, traffic flows are smoother during the disturbance.

Optimization of the tactical planning based on the TMA and on the departure processes at the airport should back the traffic flow smoothed by the pre-tactical planning up and not cause new operational problems. This means the tactical tools are allowed to make the best out of the traffic-situation, which is smoothed in advance through actors actions based on TOP's flow planning [24][25].

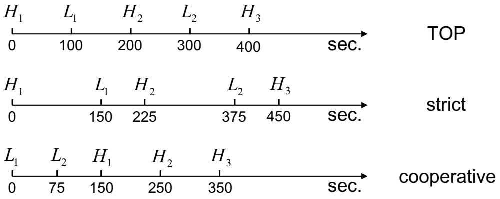


Figure 4. Example of pre-tactical planning with strict and cooperative coupling where H_1, H_2, H_3 stand for heavy and L_1, L_2 for light aircraft.

We think from the operational perspective the cooperative planning is in many traffic situation the more valuable approach (Fig. 4). But, sometimes there may be predominant operational constraints calling for a strict implementation of the pre-tactical scheduling into operations. The above introduced coordination profiles give such possibility allowing a gradual differentiation of the tactical realisation. The profile "Keep the target times" is the strictest coupling, because the tactical systems have to keep the sequences (both inbound and outbound) and schedule all aircraft at the long-ago planned target times based upon an average traffic mix. A little less strict coupling is provided by the profiles "Only reduce separations" and "Only increase separations". Here the tactical systems get the possibility to optimize at least the separations between the air traffic, even though only in one direction. The profile "Equal distance distribution with fixed sequence" on the other hand includes the order to distribute potential existing free time spaces between the aircraft equally over the sequence in the respective time interval.

The most beneficial coupling between the systems with different time horizon is enabled by the coordination profiles "Complete optimization" and "Optimization keeping the flow" chosen dependent on the situation. Using these profiles the tactical systems are allowed to take all arriving and departing aircraft and optimize the sequences as well as the individual target times, but keep the flow restriction if needed to ensure the sustainability for the pre-tactical horizon. Ignoring the pre-tactical sequence and target times, the tactical systems benefit from the air traffic flow regulated by TOP and implemented by the agents accordingly to the estimated capacities of runways.

The profile "Optimization keeping the ratio" is also a quite cooperative coupling. The tactical tools are free to optimize sequences and times keeping the pre-tactical planned ratio.

The profiles "Modify ratio supporting more arrivals" and "Modify ratio supporting more arrivals" allow the tactical systems to optimize the target times, sequences, and the ratio between arrivals and departures in the respective time interval. When more aircraft as pre-tactically estimated can use the available capacity, the AMAN-DMAN-Coordinator (ADCO) should prefer inbounds or outbounds, respectively.

A profile ranging between strict and cooperative is the "Fixed flow with equal distance distribution". The downstream systems have to implement the calculated number of aircraft and distribute potential existing open time space after the last scheduled aircraft in the corresponding time interval and the end of the interval as additional space between each aircraft in the interval. However, the tactical systems have the possibility to change the arrival and departure orders to achieve an optimized sequence.

The presented coordination profiles which describe the rules of tactical subsequent processing are not complete. More or less complex pre-tactical and tactical systems may require clearly advanced or partly simplified calculation rules for a coordinated coupling of planning systems with different time horizons. Also combinations of planning profiles differentiated for inbound and outbound traffic are imaginable.

V. Summary and Outlook

We introduced briefly the concept of Total Airport Management and concentrated on in- and outbound air traffic flows regarding the airport's runways. The pre-tactical planning system TOP, as well as the tactical air traffic controller assistance systems AMAN and DMAN, in particular the DLR prototypes 4D-CARMA and CADEO, were described. ADCO is an example for a component coordinating AMAN and DMAN.

We raised the need for interaction between pre-tactical and tactical planning, described the data flow between TOP and the tactical planning systems and presented coordination profiles as rule sets for the coupling.

We think that a situation dependent combination of the coordination profiles "Complete optimization" and "Optimization keeping the flow" will be the best for coupling, especially, if actors control the traffic pro-actively. The traffic flow will be smoothed already when entering the tactical horizon, the tactical systems optimize based on up-to-date and detailed information and adhere to the pre-tactical intention through keeping flow restrictions, if needed. So the current tactical planning and the resultant ad-hoc action will be as well optimized as sustainable.

As next step, we will examine the coordination profiles through trials with our prototypes and various complex scenarios for different airport configurations.

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Future strategies for airports

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In air transport, the evolution of traffic depends upon many economic factors, and on the way in which the markets participants respond to those factors. Although airlines are the main actors, the airports are by no means passive, and their strategies will also have an impact on airline behaviour and route development. Our methodology analyzes the potential evolution of airport strategies in the next decade, using a typology of airports that has been designed for this purpose. It shows in particular that diversification strategies, which are usually reserved for large firms, can also be successfully applied to smaller airports.

I. Introduction

During the last decade, the European air transport market saw the emergence and development of the low cost carriers which now represent a significant share of intra-European flights. Another noticeable trend was the change in the way many airports are managed: many went from public to private ownership and/or management. In this context, airports have tried to play a more active role in the air transport industry, by improving their attractiveness and their competitiveness. Instead of waiting for airlines and traffic, they have developed more active strategies towards airlines and particularly towards low cost carriers.

In this context, it is worth focusing on airport strategies and their future evolution. Although airlines' strategies will be the main drivers of traffic evolution, the airports are by no means passive, and their own strategies will have an impact on airline behaviour and route development. Will new trends in airport strategies appear? Which strategies will be adopted by which airports?

The present paper provides some answers to these questions by analyzing the potential evolution of airport strategies. After examining the characteristics and requirements of airport clients (passengers and airlines), we identify the generic strategies that could be developed by an airport towards those clients. Not all strategies, however, are feasible for any airport: it depends on the airport characteristics. This fact led us to build an original typology of airports, taking into account three elements: airport size and potential for growth in capacity and in demand.

Even though they are less optimistic than a few years ago, traffic forecasts are indeed still very good for the air transport sector. The relevant question at the airport level is the ability to receive more passengers in the future, i.e. its capacity to grow. This element will characterize the possible evolution/adaptation of supply to a general increase of demand. Of course, certain destinations will receive even more passengers, and taking into account the specific demand of an airport is very important. The role of the third element,

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airport actual size, is to take into account the current situation of an airport. This allows us to take a picture of the past strategies of a given airport.

With the help of this typology and the generic strategies defined, we are able to describe the future strategies available to a given airport.

The next section sets up a framework in which we describe all the possible airport strategies and develop an airport typology. Section 3 uses the former elements to identify the strategic options by airport type.

This method was developed in the scope of the FAST project funded by EUROCONTROL in 2008-2009, and was illustrated by an application to Bordeaux airport in France. Three years after the end of this project, it is then interesting to observe and compare the strategy developed by the airport, with the analysis made in the FAST project.

II. Methodology

A. Airport strategies

1. Airport customers and revenues

As a service platform, airports have several types of clients or customers. From the aeronautical perspective, the main airport clients are airlines of all types: traditional airlines, low cost airlines, but also freight airlines and integrators. Airports provide them with infrastructure (e.g. runways, taxiways and aprons) and services (e.g. refuelling and handling). Services can be provided directly by the airport, or externalised to private firms. Passengers are also direct clients of airports in the sense that they are provided with terminals which they use to gain access to the planes.

From the non-aeronautical perspective, shops, restaurants and bars provide services to the passengers and bring revenues to the airport. Firms providing support services to airlines are also airport clients. Airports will have to cater to the different needs of the above identified customers. Their needs or preferences can be conflicting: for example, passengers wish to have short connections between flights, while shop owners would prefer to have passengers stay longer in the terminals to increase the potential for sales.

The revenues of an airport are usually separated into aeronautical revenues and non-aeronautical revenues. The aeronautical revenues are directly related to the aeronautical activities of passengers and aircraft, and the non-aeronautical revenues are all other revenues: These can in turn be separated into two groups: revenues from service providers located at an airport, providing services either to the airlines or to the passengers; and revenues from activities the airport has diversified into in order to use its expertise, such as consultancy or management services. The strategies of specialization will aim at developing the aeronautical revenues, whereas the strategies of diversification will have the objective of increasing the non-aeronautical revenues.

2. Strategies of specialization

Strategies of specialization are used to develop the aeronautical activity of the airport. Some will be related to aeronautical infrastructure, while others will aim to increase service levels, or improve the communication or marketing towards clients.

Concerning the infrastructure, examples are:

- Increase of the runway capacity by extending the existing runway and/or building a new runway and/or investing in all other aeronautical infrastructure (for instance taxiways, car parks)
- Investment in passenger terminal capacity by building a new terminal or extending existing ones
- Investment in freight terminal capacity by building a new terminal or extending existing ones
- Investment in a low-cost terminal to enable differentiation of the airport service quality

Strategies of specialization centred on quality improvement can include:

- Improvement of airport accessibility via bus shuttles, car parking, road and/or rail infrastructure (which often requires financial support from the region, town, etc.)
- Investment in terminal infrastructure to improve the efficiency of aeronautical services (e.g. luggage transfer and passengers flows)
- Development of intermodality with a high-speed rail interconnection (which requires financial support from the country, region, town, etc.)

Finally, policies towards clients could include:

- Development of commercial policies to airlines (e.g. lower passenger taxes to airlines reaching a certain level of traffic at the airport, lower taxes on subsidized routes and lower taxes for passengers in transit)
- Investment in communication and marketing towards airlines (market studies, advertisement) or towards passengers (advertising the region's attractiveness, …)

3. *Strategies of diversification*

A diversification strategy of a firm consists in developing activities which are not related to its core business. This strategy can correspond to a reduction of a firm's exposure to a risk. Indeed, if its core business is affected by a crisis, the firm can still generate profits through another strategy. For airports, strategies of diversification aim to develop the non-aeronautical activities. They are considered increasingly important strategic axes by airports to stabilize and balance the airport economy.

These diversification strategies mainly aim at:

- Improving the financial results by increasing non-aeronautical revenues with the development of commercial activities
- Diversifying the financial risks by investing in other airports or other economic sectors
- Finding a way to allocate the airport's capital elsewhere than in the airport capacity when the potential of capacity growth of the airport is low

The most common strategy of diversification is the development of commercial activities by increasing the areas for shops, restaurants, car rentals, etc., at the airport. An emerging strategy of diversification concerns the development of services to the airport passenger independently of the airlines (lounges, wireless internet (free or not), trip planner websites…). The objective is to increase revenues and to secure the loyalty of passengers toward airports. This type of strategy improves revenues, but does not reduce the exposure to risk, because the revenues are still mostly dependent on the number of passengers attracted by the airlines. In case of a traffic decrease, these revenues will also be impacted. These strategies are applicable to any airport, even small ones, and particularly the strategy consisting of developing the commercial activities.

Other strategies of diversification of midsize or large airports consist in selling the airport know-how to other airports by developing consultancy or management services. Airports can also invest in other airports or other economic sectors. These last strategies of diversification however require financial resources and are therefore generally developed only by large airports.

B. **Typology of airports**

The strategies available to a particular airport depend on its characteristics not only in terms of current traffic, but also considering the potential of this airport with regards to capacity and demand. The current situation of an airport in terms of passenger numbers, or traffic flows, is not necessarily a good indicator of what the airport could become in 10 or 20 years. Some airports have grown tremendously in the past 10 years, while others have not. Analyzing the future evolutions of airport strategies therefore requires us to confront the information on the airport traffic with other elements.

We are interested in identifying the characteristics of an airport in terms of potential: what can explain why a given airport will develop, while another will not? We are looking at airports from the point of view of traffic evolution. To be able to grow, an airport need to have "good characteristics" in terms of supply (mainly capacity) and demand.

1. *Airport capacity*

There must be capacity for passengers or freight and capacity for aircraft. Indicators of the airport potential for growth in capacity relate to the current runways and terminal capacity and to their possibility of extension.

2. *Airport demand*

In order to grow, an airport should have spare capacity, to accommodate more flights and/or more passengers, but it would be to no avail if there is no demand. Indicators of the potential for growth of the airport in terms of demand are based on passenger numbers on incoming/outgoing segments of the market. Some airports have mostly incoming passengers, leisure or business, because of some attractiveness of the area. Others have mostly outgoing passengers, and this has to do with different factors, linked to population wealth in the region (depending on an adequate supply of flights at the airport). Some airports are hubs, and have an important proportion of connecting passengers, for whom the region around the airport will be unimportant. Last, cargo demand will have different requirements. Overall, indicators of the potential for growth in demand relate mainly to intrinsic characteristics of the airport region.

3. Typology

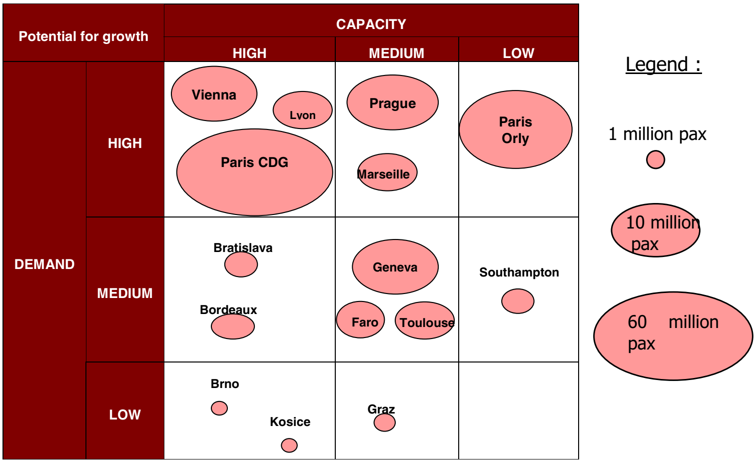
All indicators of the airport potential for growth in capacity and demand can then be used to develop a typology of airports that will be used as a basis for the FAST project. In addition to the potential for growth in capacity and demand the analysis of the possible strategies takes into consideration the airport size according to the ACI airport size typology:

- Small size for airports with no more than 5 million passengers a year
- Medium size for airports with more than 5 million passengers a year and fewer than 10 million passengers a year
- Large size for airports with more than 10 million passengers a year.

Our typology of airports is therefore based on three measuring scales: the airport size as number of passengers, the level of potential for growth in capacity, the level of potential for growth in demand. Both levels of potential for growth are decomposed into low, medium and high potential levels. Table 1 illustrates this three dimensional typology with examples of airports.

Application to Bordeaux airport:

Bordeaux is a small regional airport with available capacity. The airport is in a monopoly situation (in a single-till context) but may be in strong competition with the high-speed train in the future with a reduction of one hour in the journey time between Bordeaux and Paris (two hour journey time in 2016 instead of three). Bordeaux has a high potential for growth in capacity (with possibilities of building a new runway and a new terminal) and a medium potential for growth in demand (by taking into consideration the population around the airport which is 1.5 million within a one hour drive, and the region's attractiveness for tourism and business).



Potential for growth		CAPACITY		
		HIGH	MEDIUM	LOW
DEMAND	HIGH	Vienna Lyon Paris CDG	Prague Marseille	Paris Orly
	MEDIUM	Bratislava Bordeaux	Geneva Faro Toulouse	Southampton
	LOW	Brno Kosice	Graz	

Table 1: Illustration of the three dimensional typology

III. Strategic options and future network

A. Method of identification of strategic options

The approach we used to identify the strategic options for a particular airport and to make predictions of its future route network evolution can be broken down as follows:

- Description of the past strategies of the considered airport
- Identification of the future strategic options of the analyzed airport according to its position in our typology of airports

- Identification of a reference airport which has developed past strategies similar to the future strategies of the considered airport
- Analysis of the past route network evolution of the reference airport following the strategy it developed
- Use of this past route network evolution of the reference airport to make predictions on the future route network evolution of the analyzed airport

1. Past strategies

The future strategic options of an airport are strongly related to the strategies it developed in the past. These past strategies were influenced by the airport characteristics and environment.

It is therefore essential to analyze the past strategies of an airport before being able to identify its future strategic options.

Application to Bordeaux airport:

In order to find a way to revitalize the traffic that decreased by 8% between 2001 and 2003 (following the 9/11 crisis) the airport decided to develop an active strategy from 2004. The strategy guaranteeing graduated discounts on passenger fees during a three year period proved successful since the airport traffic grew by 18% between 2004 and 2007. This large growth was mainly due to the low cost traffic increase that was multiplied by a factor of three in three years, to represent 11% of the total traffic in 2007 (source: www.usinenouvelle.com).

2. Future strategies by airport type

The strategies that can be developed by an airport will first be strongly dependent on its type. For example, a medium sized airport with spare capacity will not behave in the same way as a large airport with capacity constraints. The situation in terms of demand will also condition the type of passengers the airport wishes to attract (local or foreign? business or tourists?). Besides the type of the airport, the degree of development of these strategies will be strongly linked to the level of competition with other airports, the level of congestion of the airport but also to the airport ownership and management and the perimeter of regulation of the airport.

Our method of identification of the possible strategies of an airport therefore comprises three steps: We first identify all the possible strategies of specialization for this type of airport, then all the possible strategies of diversification. Finally, we refine these strategic options (specialization and diversification strategies) with other factors: congestion level, competition level, regulation type, airport status. As a result, we identify the airport objectives and strategic options at a five to eight year time horizon.

Application to Bordeaux airport:

Table 2 highlights with a red circle all the possible strategies of specialization for Bordeaux. It highlights the most relevant strategies of specialization for a medium-sized airport (between 5 and 10 million pax a year). Figure 2 highlights the most likely strategies of diversification for a medium-sized airport (Note that the strategies of diversification exist whatever the potential for growth in capacity and demand, but will be more or less developed according to the situation of the airport).

This analysis leads us to conclude that the airport, in its effort to anticipate the future drop in demand due to the strong incoming competition with the high-speed train, has two main objectives: Securing the loyalty of passengers and airlines and attracting additional low cost airlines on the platform

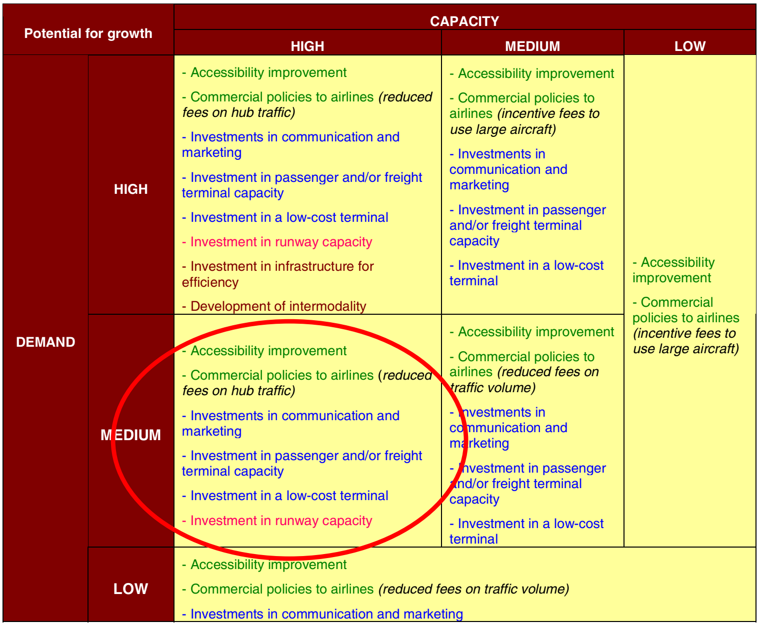
To reach such objectives, we have identified the following future strategic options for Bordeaux in a 5-8 year time horizon:

- Future strategies of specialization at Bordeaux airport:
  - Airport accessibility improvement
  - Development of commercial policies to airlines
  - Investments in communication and marketing
  - Investment in a low cost terminal
- Future strategies of diversification of Bordeaux airport:
  - Development of commercial activities
  - Development of services to passengers

Observed strategy developed at Bordeaux airport since the end of the FAST project (March 2009):

In June 2009, Bordeaux Merignac airport decided to build a low-cost terminal, named Billi, which opened in May 2010.

The declared objectives of this new strategy are fully in line with the results we obtained with the FAST method: attracting additional low-cost and securing the loyalty of passengers in expectation of strong future competition with the high-speed train in 2017.



Potential for growth		CAPACITY		
		HIGH	MEDIUM	LOW
DEMAND	HIGH	- Accessibility improvement - Commercial policies to airlines *(reduced fees on hub traffic)* - Investments in communication and marketing - Investment in passenger and/or freight terminal capacity - Investment in a low-cost terminal - Investment in runway capacity - Investment in infrastructure for efficiency - Development of intermodality	- Accessibility improvement - Commercial policies to airlines *(incentive fees to use large aircraft)* - Investments in communication and marketing - Investment in passenger and/or freight terminal capacity - Investment in a low-cost terminal	- Accessibility improvement - Commercial policies to airlines *(incentive fees to use large aircraft)*
	MEDIUM	- Accessibility improvement - Commercial policies to airlines (*reduced fees on hub traffic)* - Investments in communication and marketing - Investment in passenger and/or freight terminal capacity - Investment in a low-cost terminal - Investment in runway capacity	- Accessibility improvement - Commercial policies to airlines *(reduced fees on traffic volume)* - Investments in communication and marketing - Investment in passenger and/or freight terminal capacity - Investment in a low-cost terminal	
	LOW	- Accessibility improvement - Commercial policies to airlines *(reduced fees on traffic volume)* - Investments in communication and marketing		

Table 2: Strategies of specialization by airport type

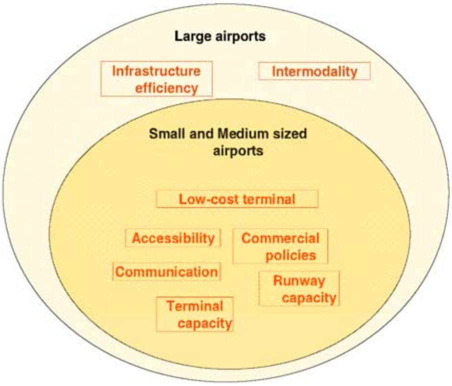


Figure 1: Strategies of specialization by airport size

Figure 2: Strategies of diversification by airport size

IV. Conclusion

Airports are becoming essential actors in the air transport market, with a growing role and independence in strategic decision-making. Analyzing the impact of these strategies on the evolution of the airport route network is significant and could give important clues as to the direction of future development of the industry.

This paper describes some aspects of the FAST project, which developed a methodology for identification of the future airport strategies that can be applied to any European airport. In particular we showed that while strategies of diversification are often considered the preserve of large firms, they have been successfully applied by (and should be considered by) rather small airports.

The future airport strategies should also put more stress on avoiding so called "curb-to-curb" approach. Airports should be considered as an integral part of regional, national or international transport infrastructure rather than being perceived as an isolated transportation system. Quality of airport ground access/egress and level of airport integration into ground transport network significantly influences its competitiveness, operations and capacity.

While only applied to a few airports in the study, the conceptual framework we developed could be applied and extended to all airport types, including airports in the new European member states, but also to airports with overlapping catchment areas as well as to the competing hubs, or to complementary airports in case of multi-airport management as well as in case of complementarity between hub and secondary airports.

The relevance of the results of our methodology was confirmed by the Bordeaux airport strategy. In June 2009, three months after the end of the FAST project, Bordeaux Merignac airport decided to build a low-cost terminal of 4,000m² which opened in May 2010. This strategy is fully in line with the results we obtained for Bordeaux airport: attracting additional low-cost and securing the loyalty of passengers in expectation of strong future competition with the high-speed train in 2016.

Three years after the opening of Billi, the low-cost terminal, this strategy proves successful since the airport traffic already increased by 1 million passengers since 2010, while the impact of the high-speed train competition in 2016 is expected to reduce the airport traffic by 800,000 passengers. To reach the final objective of getting one additional million passengers by 2017, the airport plan to enlarge by 2,000m² the Billi terminal from 2013.

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Quantitative Assessment of Technology Impact on Aviation Fuel Efficiency

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In the effort to achieve carbon neutral growth on the path to a zero emission future in aviation IATA outlined its "Technology Roadmap for Environmentally Sustainable Aviation" (TERESA) initiative bringing together manufacturers, scientists, government agencies, infrastructure service providers and airlines. Under this initiative the German Aerospace Center (DLR) and the Aerospace System Design Laboratory (ASDL) of Georgia Tech conducted the screening, description, selection, modelling and assessment of appropriate technologies. Furthermore the application of the technologies into reference aircraft was on their particular mission was modelled. Following the aircraft manufacturers announcements to postpone all new developments until after 2020 the model's technology database is revised. Furthermore the scope of TERESA is expanded with a world fleet forecast model. Therefore the model accounts for the effects of CO_2 reduction potential via technology introduction on world fleet level.

Nomenclature

ACARE	Advisory Council for Aeronautic Research in Europe
ACM	Aviation Carbon Model
ATS	Air Transportation System
ASDL	Aircraft System Design Laboratory
DLR	German Aerospace Center
DoE	Design of Experiments
DPMA	German Patent and Trademark Office
FSRL	Feed Stock Readiness Level
IATA	International Air Transport Association
NASA	National Aeronautics and Space Administration
NTRS	NASA Technical Report Server
PrADO	Preliminary Aircraft Design Optimisation Program
RSE	Response Surface Equation
TERESA	Technology Roadmap for Environmentally Sustainable Aviation
TIES	Technology, Identification, Evaluation and Screening
TRL	Technology Readiness Level
UTE	Unified Trade-Off Environment

I. Introduction

In the summer of 2009 IATA announced the airline industries commitment of carbon neutral growth by the year 2020. This announcement succeeds IATA's 2008 Zero Emission Future obligation which is also in line with the world-wide demand for a more environmentally friendly aviation industry. [a] The carbon neutral growth goal is the cornerstone of IATA's vision of a carbon-emission-free aviation and the availability of zero carbon-emission aircraft. The achievement of these ambitious goals is strongly correlated with the development and implementation of new technologies by aircraft and systems manufacturers. The ultimate propagation of these technology impacts to the environment (e.g. a better fuel efficiency and thus lower carbon emissions) will come from the airlines and their fleet operations. There is an underlying challenge to select the appropriate technologies as they are driven by uncertain factors such as their current development status, risk, benefits and R&D costs. To assist the airlines in this endeavor, IATA has created the Technology Roadmap for Environmentally Sustainable Aviation (TERESA) initiative that provides an overview of green technologies and their impacts on aircraft level. This paper looks back on the objectives of the TERESA initiative. Furthermore it gives a survey of the different steps conducted, the current status of the initiative and a recommendation for the way ahead.

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[a] The aeronautical community is researching fuel burn reduction capabilities under a wide range of programs. Other entities working on the topic are ICAO/CAEAP, Greener by Design, and FAA's Partner Consortium, just to name a few.

II. Previous Work - TERESA Phase I and II

Currently the TERESA program includes 3 phases, as illustrated in Figure 1. The first phase, conducted in 2008, consisted of two main activities: [1.] surveying a large set of aerospace technologies that could reduce the aeronautical impact on the environment, and [2.] creating a high level trade-off environment. The trade-off environment enables a comparative view about the technologies. It is based on qualitative assessments from A representative group of subject matter experts who related the surveyed technologies to IATA's goals. The results of the work from this phase were used to create a strategic roadmap which was published as the IATA Technology roadmap report.[1] The second phase of the program, carried out in 2009-2010, focused on a robust subset of the technologies defined in Phase 1. The robust technology set was found repeatedly utilizing a representative expert panel which evaluated the technologies' robustness against different future scenarios. The translation of qualitative into quantitative values was achieved describing the technology application within reference aircraft as test beds on their respective missions. Herefrom technology factors could be derived. Adjacent the technologies could be modeled in a physics-based environment (e.g. technology X will reduce the reference aircraft wing weight by 10%). The results of this quantitative modeling were then compared against the qualitative outcome from the previous workshops, see Figure 4 and Figure 5.
Based on the outcome of the TERESA Phases 1 and 2, the global technology impacts are modeled within Phase 3. More precisely the combined results of the previous computations are used to estimate the fuel burn reduction and consequentially the CO_2-reduction potential of a technology introducion on world fleet level. In the following the approaches taken under each phase of the program will be described more thoroughly.

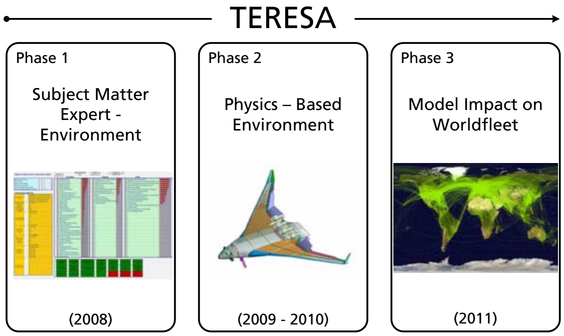

Figure 1. The TERESA-Phases

A. Subject matter experts technology assessment process - Phase I

The subject matter experts qualitative technology assessment is based on ASDL's Strategic Prioritization and Planning (SP2) process.[2] The SP2 process provides a structured, traceable, and transparent approach using a hierarchical decomposition from the top level IATA goals into aircraft attributes (e.g. airframe weight, wing weight). These attributes are then mapped to the different technology alternatives. The process can be tailored to any desired level of detail to enhance the decision-making process for investment strategies, risk mitigation, system integration and so forth. The resulting decision making tool enables the analysis of "what if" scenarios to be played through a dynamic and interactive environment. The hierarchical decomposition enables two types of scenario analysis: [1.] top-down and [2.] bottom-up. The top-down scenarios consists of changing the importance of the IATA goals and analyzing which aircraft attributes are becoming more important. This will result in a prioritized list of technology alternatives. The bottom-up scenarios imply selecting specific technology alternatives which would emphasize the importance of a sub-set of aircraft attributes and consequently highlight how well the technologies could meet the IATA goals. The results of the SP2 process were used to create the technology roadmap published by IATA in June 2009,[1] and it was used as the foundation for the quantitative technology assessment process.

B. Quantitative technology assessment process - Phase II

The identification of robuts technologies was conducted at the IATA workshop in Hamburg, Germany, in October 2009.[4] The workshop objectives were as follows:

1. Down-select the number of technologies from the roadmap document to a manageable set that could be modelled in the physics-based environment,
2. Identify technology factors for the modelling activity (e.g. weight reduction) and
3. Estimate ranges of variability for the technology factors.

A list of technology factors is summarized in Table 1 for the airframe technologies and in Table 2 for the engine technologies. A technology impact factor is a mathematical description used to model the technology within the physics-based environment.

Table 1. Technology Factors Airframe

Airframe	min %	max %
Δ wing weight	-30	+20
Δ fuselage weight	-30	+10
Δ empennage weight	-10	+10
Δ hydraulics weight	-100	0
Δ electrical weight	0	+20
Δ cabin weight	-40	0
Δ APU	-100	0
Δ water weight	-10	0
Δ L/D	0	+25
Δ induced drag	-20	0
Δ friction drag	-25	0

Table 2. Technology Factors Engine

Engine	min %	max %
Δ SFC	-20	+10
Δ engine weight	-20	+10
Δ size	0	+10

The quantitative technology assessment is based on ASDL's Technology Identification, Evaluation and Selection (TIES) process.[5] This process uses the results from the qualitative assessment coupled with the four ACARE scenarios as inputs. The ACARE scenarios[3] represent potential future socio-political reference points to which the technologies are mapped. Typically, a subset of technologies will emerge as being "robust" to multiple scenarios and can thus be identified as attractive to airlines and manufacturers for their cost-benefit attributes. For each robust technology an operational context is identified as well as a quantitative factor, referred to as a technology factor, in order to model the technology within a design environment. Examples of technology factors include weight reduction of specific aircraft components (e.g. wing weight), and performance characteristics such as induced, and friction drag coefficients. For this study the technology impacts were modeled using the Preliminary Aircraft Design and Optimization (PrADO)[6] program, which facilitates the identification of primary and secondary impacts of the technology implementation.

1. Physics-Based Trade-Off Environment

The Physics-Based Trade-Off environment includes six steps, illustrated in Figure 2.

1. The first step defines the baseline vehicles and representative baseline mission; this provides environmental references using mature technologies integrated into state-of-the-art-aircraft as of 2008.
2. The second step identifies specific technologies to be modeled; considering the amount of resources required to model the technologies ("Technology Factors and Ranges").
3. The third step models the reference vehicles and integrated technologies within PrADO ("Design of Experiments, Response Surface Equation").

4. The fourth step explores the technology space to detect the greatest environmental impact ("Interactive Prediction Profiler") (optional: furthermore an individual visualization of the technology).

5. The fifth step synthesizes the modeling and visualization within a unique trade - off environment herein referred as Unified Trade - Off Environment (UTE).

6. Within the sixth step the technology impacts are assessed considering an introduction into the world fleet under different time horizons.

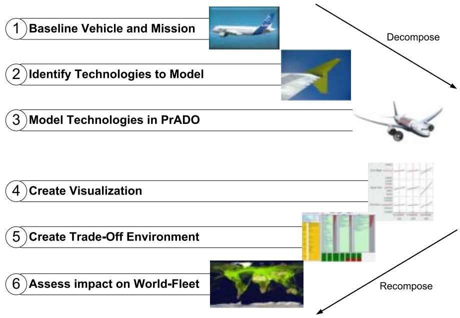

Figure 2. Physics-Based Trade-Off Environment

2. *Technology modelling using PrADO*

The impact of each identified technology is evaluated using PrADO (Preliminary Aircraft Design and Optimization), which was developed by the Institute of Aircraft Design and Lightweight Structures at the Braunschweig University of Technology. It was selected for the technology analysis as it incorporates physical models for most of the design disciplines, namely: aerodynamics, structural sizing and flight performance.

In contrast to fast preliminary aircraft design tools, which are based on historical regressions, PrADO may take several hours for a single design evaluation to converge, due to the use of computationally rather intensive physical models. Thus, to compensate for the long calculation times, PrADO is integrated into DLR's cluster-framework HYdRA, which enables the computation of multiple design trades at once.[7] Novel technologies, which are not yet modeled in the program, can be accounted for by the use of technology factors, which represent their impact on specific aircraft parameters (e.g. component weight). For each selected technology its minimum and maximum impact on the aircrafts mass and aerodynamic properties were estimated by the workshop participants, see Table 1 for the airframe and Table 2 for the engine, from which a space filling design of experiments was created for HYdRA. The quantitative results of the simulation will be compared with the qualitative prediction by the subject matter experts, and will be used to revise the IATA technology roadmap.

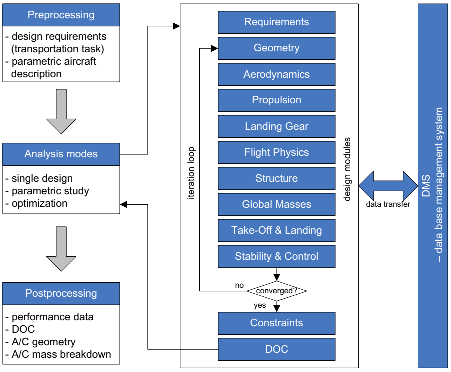

Figure 3. The PrADO Process Chain

A single PrADO analysis is executed as follows[b]: From the input file the basic design requirements are

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[b] The PrADO process chain is depicted in the Appendix in Figure 3

distributed into the disciplinary data bases by the DMS and the iterative aircraft design process commences by estimating the aircraft's mass properties as starting point using handbook methods.

The parametric, geometric input data is read and the aerodynamic surface, the structural design and interior layout of all aircraft components are calculated. The determination of the geometric properties is divided into several modules, one for each aircraft component, e.g. fuselage or wing. The aerodynamics module determines the aerodynamic characteristics of the aircraft for different flight and load cases. For this paper the lifting line code LIFTING_LINE[8] was used. With a thermodynamic cycle simulation for turbo-fan engines the propulsion module determines the engine characteristic and gives a weight and geometry estimation. The landing gear module, the load classification number (LCN), the load factor and the landing gear weight are determined by handbook methods. Subsequently the results of the aerodynamics and propulsion modules are used in the flight physics module for the prediction of the aircraft's flight performance and later in modules that determine the stability and control properties as well as the take-off and landing capabilities. The structural mass of fuselage and wing is computed by an analytical beam model coupled with aerodynamic loads from LIFTING_LINE for several defined load cases. Together with operational items, airframe services and equipment the resulting structural masses compose the operational empty weight (OEW). In addition the global airframe masses, e.g. MTOW, MLW are computed.

In the end of the analysis run the direct operation costs are determined. Furthermore it is checked whether the aircraft violates any design constraint.

C. Comparison of Qualitative and Quantitative Results

In the following Figure 4 and Figure 5 the fuel reduction potential and the thereby inherent CO_2 reduction potential is given in percent compared to the 2005 baseline aircraft.[c] The five different timelines: Baseline 2005, Retrofit, Modifications, Before 2020 and After 2020, were used to cluster the researched technologies due to their availability for the commercial aeronautical market in connection to their fuel reduction potential. The delay in the aircraft manufacturers new aircraft delivery timeline made this assumption obsolete and a new timeline necessary, see chapter IV. The natural uncertainty inherent in the qualitative analysis is visualized applying a fade-in and a fade-out of every bar in Figure 4.

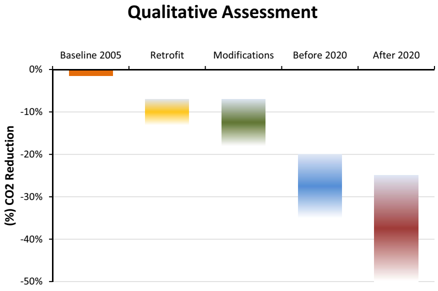

Figure 4. Results of the qualitative assessment

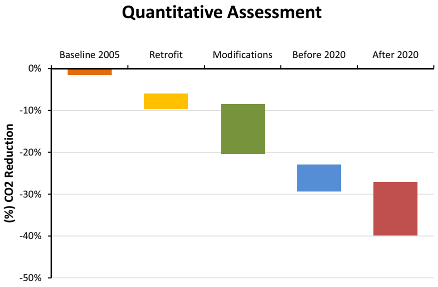

Figure 5. Results of the quantitative assessment

A comparison of the qualitative results from TERESA Phase 1 depicted in Figure 4 with the quantitative results calculated under TERESA Phase 2 visualized in Figure 5 show a great deal of similarity. This is especially true for the first three time phases, which can be explained by the ability of the subject matter experts to forecast technology impact in the near term relatively accurate. However, in general the qualitative analysis overestimates the quantitative results, see Table 3. The main reason for this difference can be linked to the limited number of selected technologies for the quantitative assessment. Only 24 technologies, identified as most promising and robust against the different ACARE scenarios were considered within the quantitative analysis compared to the 74 technologies identified in total under the 2008 qualitative IATA workshop. In addition technology modeling only comprised technologies from the fields aircraft and engine.

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[c] A more thorough description of the qualitative to quantitative assessment can be found in the paper AIAA 2011-6968[10]

Furthermore pioneering designs like the open rotor, the blended wing body, and the like, were not modelled. Therefore a smaller technology basket considered leads to a reduced CO_2-reduction potential.

Table 3. Minimum and maximum gains through technology introduction

	Qualitative		Quantitative	
	Min	Max	Min	Max
Baseline	0%	-1,5%	0%	-1,5%
Retrofit	-7%	-13%	-5,9%	-9,5%
Modification	-7%	-18%	-8,5%	-20,4%
Before 2020	-20%	-35%	-23%	-29,4%
After 2020	-25%	-50%	-27,1%	-39,8%

III. World Fleet modeling - Phase III

For Phase III of the TERESA project, DLR has developed a methodology dubbed F-FWD (read: 'fast-forward') to assess the impact of new aircraft carrying TERESA-identified technology on global CO_2-emissions of airline traffic. We describe the approach and important findings in the following paragraphs. The basic F-FWD metholodogy is depicted in Figure 6. It consists of two seperate working blocks. First, on a bottom-up basis, we project the development of the world fleet of commercial passenger aircraft (fleet forecast: steps 1-4). Second, to each aircraft model in the forecast, we assign fuel consumption and performance information (steps 5-6). Global CO_2 emissions and traffic are then calculated by aggregating the single aircraft estimates. The results can be used to forecast the development of fuel and CO_2 efficiency under the influence of new technology.

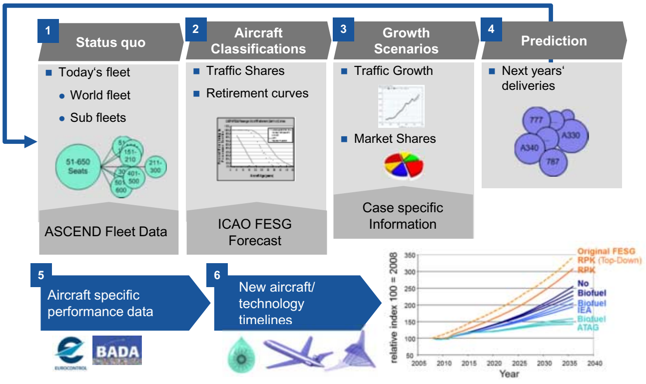

Figure 6. General CO2 Forecast Schematic: Bottom-up Forecast based on Year-to-Year Dynamics

A. Working Block 1 - Fleet Forecast

The TERESA-Phase III fleet forecast is a bottom-up forecast based on year-to-year dynamics. The first step is to identify today's fleet of aircraft from the ASCEND Fleet Database[d]. From the detailed information provided by ASCEND, we then project next year's retirements for each make and model in the world fleet, based on the specific age of each active aircraft. The retirement process is driven by so-called 'retirement curves', which have been estimated through a survival analysis from historical data for the ICAO Committee

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[d] http://www.ascendworldwide.com/

on Aviation Environmental Protection (CAEP).[13] We further estimate the number of additional aircraft needed to satisfy our traffic growth scenario (with the help of information on traffic shares in the latest ICAO FESG forecast[12]). The sum of aircraft needed for replacement and growth constitutes our next year's aircraft demand = new aircraft deliveries. The original aircraft that are forecasted to remain active (i.e. are not retired) plus the new aircraft deliveries (with yet unfixed make and model) make up the new world fleet. This process of simulating yearly fleet changes is repeated until we reach the final year of the forecast period.

There are additional, specific assumptions for the TERESA-Phase III fleet forecast which we summarize in Figure 7. The most important assumption concerns future aircraft deliveries (see schematic). We assume that all aircraft that are currently on fix order (i.e. excluding options and statements of interest) are being delivered according to schedule. We get very detailed information (e.g. size, make, model, and delivery date) on these aircraft from the ASCEND database. Further, we assume that the current IATA traffic forecast holds in the long-run. That is, additional to the aircraft on order, further aircraft are needed to satisfy projected traffic growth up to the year 2030. Traffic growth in our model is modelled separately for eight different aircraft size categories according to the ICAO CAEP/8 Forecast: 51-100 seats, 101-150 seats, 151-210 seats, 211-300 seats, 301-400 seats, 401-500 seats, 501-600 seats, and 601-650 seats. After assigning fixed orders (according to the ASCEND information on seat count) to this demand, we are left with 'unfixed aircraft demand' in each seat category. We do not assign specific aircraft models to this demand, but use a 'generic aircraft' (i.e. a virtual, average aircraft) for each seat category.

- World Fleet = Passenger, Airline Service, 50+ Seats
- Base Year = 2006 (Index = 100)
- Information Set: Year End 2011
- Future Retirements: FESG Retirement Curves
- Future Deliveries: According to following schematic

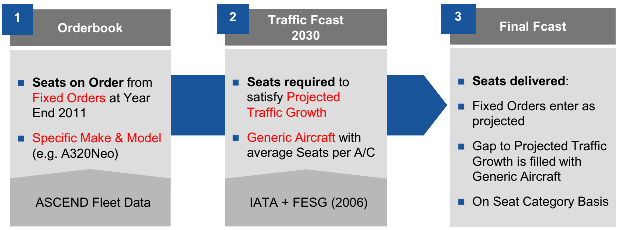

Figure 7. Major Case-Specific Forecast Assumptions for TERESA-Phase III

Figures 8 and 9 show two major results of the TERESA-Phase III fleet forecast that stem from above approach. Figure 8 shows the forecasted size of the global aircraft fleet, while Figure 9 shows projected deliveries per year. In both figures, we have classified aircraft into four different groups: 'Old Technology', 'Current Technology', 'New Technology' and 'Unfixed Demand' (generic technology). The first three groups capture all aircraft with fixed make and model, i.e. aircraft that have been in service or on fix order at the end of year 2011, while the last consists of the eight generic aircraft (one per each seat category). The group 'New Technology' includes all aircraft models that (from our perspective) introduce new, CO_2-relevant technology into the world fleet[e] and thus, from a technological perspective, differ from the 'Current Technology' group, which includes all aircraft that are currently in mass-production (e.g. the 777). Finally, the category 'Old Technology' consists of out-of-production aircraft such as the MD-80.

Two important conclusions are immediate from Figures 8 and 9. First, current technology keeps dominating the active world fleet (Figure 8) over the entire forecast horizon, and second, because today's fixed orders take up most of the projected aircraft demand up to the year 2020 (Figure 9), technological uncertainty is relatively small in the next decade. On the contrary, only a few fixed orders stand at the moment for 2021-2030. It is this 'open' demand, which constitutes the 'free' technological lever for influencing global CO_2 emissions through new aircraft projects. In Figure 9, we also show how this 'open' demand is allocated

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[e] These include, for example, the not yet in service A320neo, A350, 737max, 787, CSeries, and Mitsubishi MRJ.

to the different aircraft size categories. Clearly, technological uncertainty is small for the size categories 151-400 seats, where fixed orders satisfy projected demand until or beyond 2020. There is more room for speculation in the smaller (51-150 seats) and very-large (401-650 seats) categories. For better accessibility of the results, market shares (shares of total yearly deliveries per technology group and size category) are displayed in Figure 10.

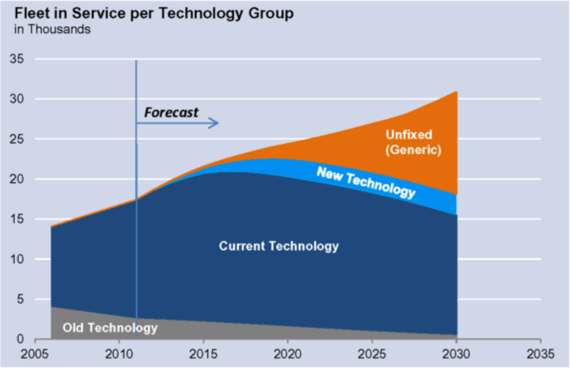

Figure 8. Fleet in Service per Technology Group 2006-2030 (Forecast)

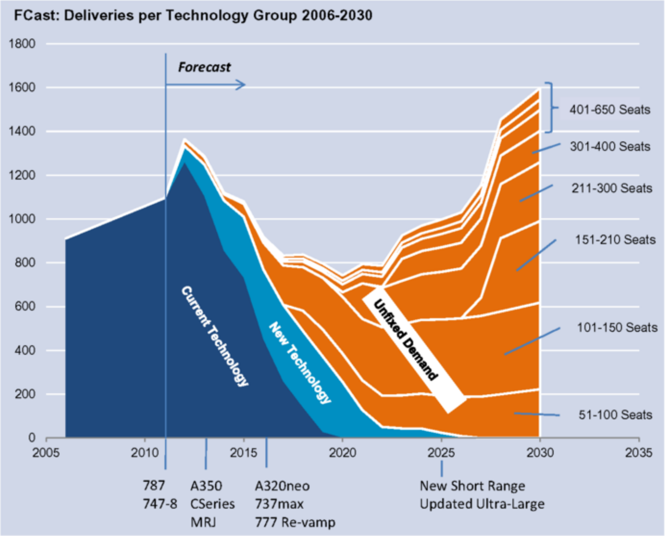

Figure 9. Yearly Deliveries per Technology Group and Seat Category 2006-2030 (Forecast)

B. Working Block 2 - Technology and Global CO_2 Emissions

To assess the influence of new technology (new aircraft) on global CO_2 emissions, in the second working block, we assign yearly fuel consumption and traffic to each active aircraft. For existing aircraft of given make and

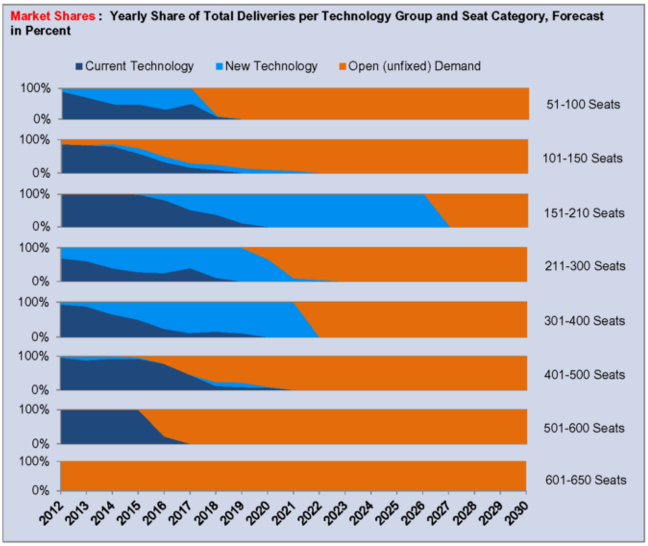

Figure 10. Market Shares (Delivery Shares) per Technology and Seat Category 2012-2030 (Forecast)

model, we use the EUROCONTROL Base of Aircraft Data (BADA) Aircraft Performance Model (APM).[f] In particular, we use a tool developed at DLR, which estimates the block fuel consumption using BADA Datasets[g], a given flight distance and a given payload, to generate a huge dataset over the entire operational range of an aircraft type. On this dataset we estimate, for each aircraft model i, a 'fuel function' of the form $blockfuel_i = \beta_{i0}+\beta_{i1}\cdot distance+\beta_{i2}\cdot payload+\beta_{i3}\cdot distance^2+\beta_{i4}\cdot payload^2+\beta_{i5}\cdot distance\cdot payload$. These fuel functions represent the original calculation very well, with an average $R^2 > 0.99$.[h] Yearly fuel consumption is then estimated as $yearlyfuel_i = flights_i \cdot blockfuel_i$. Payload is calculated as $loadfactor_i \cdot seats_i \cdot 95$ kg. Corresponding traffic (in RPK) is $flights_i \cdot distance_i \cdot seats_i \cdot loadfactor_i$. For distance, load factor, and flights we take the average values of the corresponding size categories (different for each year) from the ICAO CAEP/8 forecast.[i] The number of seats is individual for each aircraft and is taken from the ASCEND database.

New technology (according to the IATA TERESA definition) enters the world fleet through projected deliveries of 'New Technology' and, possibly, 'Unfixed Demand' (generic aircraft). For these aircraft, we construct similar fuel functions as for existing aircraft. In particular, we use BADA-fuel functions of a (weighted) set of adequate reference aircraft and multiply the resulting function with a 'technology factor' that accounts for improved fuel efficiency from new technology.

For new aircraft models of fixed make and model (included in fixed orders, group 'New Technology'), technology levels are mostly fixed and assumptions about fuel/CO_2 efficiency improvements over today's models can be made with high certainty. Reference aircraft (= reference fuel functions) and technology factors (= fuel function multipliers) for these aircraft are presented in Figure 11. The assumptions stem from TERESA studies of earlier phases. They are in broad accordance with publicly available industry and research data.

More uncertainty surrounds unfixed demand. Here, we base our assumptions on TERESA studies regard-

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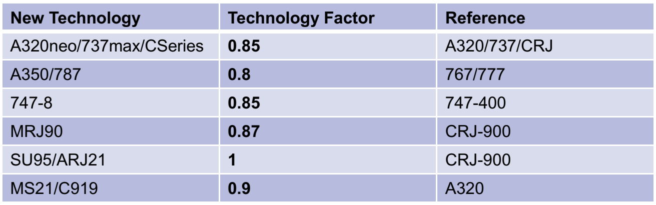
[f] `http://www.eurocontrol.int/products/bada`

[g] BADA datasets contain the specific values of the coefficients present in the model specification that particularize the BADA model for a specific aircraft type.

[h] Unfortunately, due to EUROCONTROL policy, we cannot publish the independent β-results.

[i] Load factors are adjusted downwards for the years 2011-2019 on the basis of IATA-internal estimates to account for post-crisis effects.



New Technology	Technology Factor	Reference
A320neo/737max/CSeries	**0.85**	A320/737/CRJ
A350/787	**0.8**	767/777
747-8	**0.85**	747-400
MRJ90	**0.87**	CRJ-900
SU95/ARJ21	**1**	CRJ-900
MS21/C919	**0.9**	A320

Figure 11. Assumptions Concerning Fuel Efficiency Improvement of New (fixed) Aircraft Models

ing the production lifespan of aircraft projects, historical production overlap times of predecessor/successor aircraft and the fuel reduction potential of new aircraft projects. In Figure 12, we present TERESA findings on the fuel reduction potential of technology if realized on a 'retrofit on current aircraft', a 'design update before 2020' (e.g. a re-engined aircraft), a 'new design after 2020' and a 'new design after 2030'. For this study, the information on new aircraft projects in the forecast horizon is of relevance, i.e. the information on a 'design update before 2020' and on a 'new design after 2020'. We combine this information with knowledge about market entry and fuel reduction potential of new aircraft projects with fixed make and model (the 'New Technology' group) and an analysis of the probability of further new aircraft projects being realized by aircraft manufacturers in the timeframe 2011-2030.

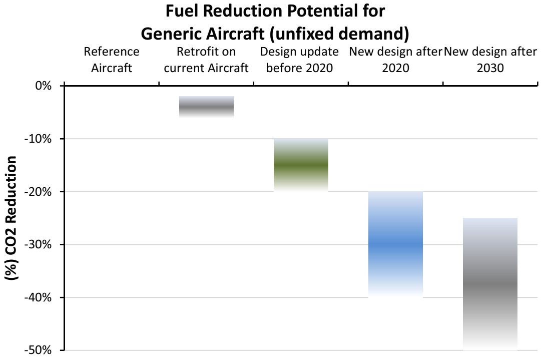


Figure 12. Fuel Reduction Potential for a Generic Aircraft Model (results from TERESA technology studies)

As we have explained in the fleet forecast chapter above, we do not aim to detail the realization of unfixed demand by forecasting market shares for specific makes and models. Instead, we let a 'generic aicraft' (one per each size category) represent this demand. This generic aircraft stands for the average delivered aircraft of a specific forecast year. By changing its performance (year by year), it can thereby account for the combined impact of a fleet of multiple aircraft models. In particular, all our assumptions regarding new aircraft projects, market shares, ramp-up times and technology in a specific size category can be reflected by adjusting a single parameter: the technology factor (fuel function multiplier) of the generic aircraft. We present our final assumptions concerning the development of this parameter graphically (as it enters our calculations) in Figure 13.

The intuition behind the curves in Figure 13 is as follows.

- In the 51-100 seats category (1st sub-figure), our reference are the current state-of-the-art aircraft CRJ-900 and ATR 72-600. There are many new entrants currently pushing into the regional jet market (Sukhoi SSJ, ARJ21, etc.). However, of these, only the Mitsubishi MRJ holds a real fuel burn potential over current aircraft. We believe that all market share will slowly move to similar N+1 aircraft (e.g.

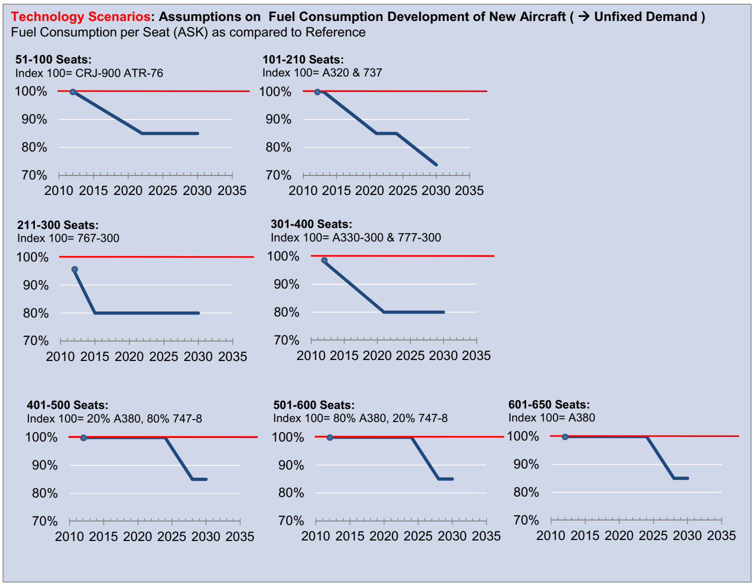


Figure 13. Technology Scenarios: Assumptions on Yearly Fuel Consumption of Generic Aircraft (Representing Assumptions on Market Shares, Fuel Reduction Potential, New Aircraft Projects and Ramp-Up Times)

the MRJ), as the incumbents (Embraer, Bombardier) develop similarly capabable aircraft to retain market share. This point is reached in 2022.

- In the 101-150 and 151-210 seats categories (2nd sub-figure), the dominating aircraft today are the A320 and 737, which constitute our references (with equal weight). We model a two-step entry of new aircraft in these size categories. First, we see a shift to aircraft with roughly 15% fuel reduction potential over current aircraft, beginning in 2014 with the entry of the CSeries and ending in 2021, 4 years after the market entry of the re-engined A320neo and 737max. Second, following current marketing policy of Airbus and Boeing, we model the entry of newly designed narrowbody aircraft in the mid 2020s. These aircraft are assumed to entail technology improvements that lead to roughly 30% fuel reduction over the current aircraft (see Figure 12).

- The technology factors in the 211-300 and 301-400 seats categories (3rd and 4th sub-figure) are mainly influenced by the market entry of the 787 and A350. Both hold an efficiency improvement of about 20% over the reference aircraft 767, A330 and 777. There is further Boeing's promise of a 're-vamped' 777 later this decade, which we assume will bring similar fuel benefits. In the smaller size category (211-300 seats) there is a relatively near shift to 100% market share of the new aircraft: 787-8 deliveries have already begun and market entry of the A350-900 is projected for 2014. The shift takes longer in the 301-400 seats category, because the larger aircraft of the A350 and 787 series, as well as the 777 re-vamp, have a later market entry. Historically, new aircraft have been in production without a successor for about 20 years. Because of the high development cost that Airbus and Boeing incurred when realizing the A350 and 787, we do not believe in additional new aircraft designs (or serious updates) for later years in our forecast: the curves thus remain flat.

- Finally, in the 'very-large' size categories (401-650 seats, subfigures 5-7), our reference aircraft are the A380 and 747-8. These aircraft are relatively new to the market and we expect no changes until the mid 2020s. At that time, the A380 will have seen a production lifetime of about 20 years and we believe a technological change to be inside the bounds of realism. However, according to current market outlooks, Airbus and Boeing aim at bringing new narrowbody aircraft to the market at the same point in time. As, in contrast, there is no indication of new development efforts for the very-large aircraft category, and realizing two entirely new aircraft projects simultaneously seems unrealistic (due to financial and engineering capability constraints), we model 'only' a moderate step: a design update, which is able of pushing fuel consumption to around 85% of the reference aircraft.

Combining the fleet forecast of working block 1 with our estimates of fuel consumption and traffic of the individual aircraft and with the assumptions concerning technology development throughout the forecast horizon, we can now state results on the impact of TERESA technology (for new aircraft projects) on global fuel and CO_2 efficiency. We restrict here to presenting two major results. First, in Figure 14, we show the development of fuel efficiency of aircraft *entering* the global aircraft fleet. We call this measure the 'technology frontier'. It is given by the fuel consumption per seat-km (i.e. fuel/ASK in litres per 100 km). The curves show the combined fuel efficiency of all aircraft being delivered in a specific year of the forecast. These include fixed orders of aircraft with given make and model ('Current Technology' and 'New Technology') and 'Unfixed Demand', which is modeled by the generic aircraft as defined in Figure 13. Recall that the shares of each are given in Figure 10. In early years of the forecast, the development is mainly set by the deliveries of fixed aircraft models. In later years, the assumptions on generic aircraft play the major role. Clearly, the smaller aircraft categories show the highest technological impact, with only the 'two-step approach' of first updating and later replacing the current technology inherent in the 101-210 seats category bringing constant improvement.

As a second result, in Figure 15 we show the yearly development in fuel efficiency of the entire active world fleet. The measure of fuel efficiency is the average fuel consumption per passenger-km (i.e. fuel/RPK in litres per 100 km). Here, the basic fleet build-up for each year, as presented in Figure 8, is the main driver. On a world fleet level, influences other than the 'technology frontier' (i.e. the fuel efficiency of aircraft being delivered) play major roles: most importantly, the retirement of old, less efficient aircraft and the development of load factors. The smallest size category (51-100 seats) shows the biggest improvement in relative terms, while the largest category show the smallest. The reason for the latter effect is that the very-large seat categories are effectively only building up over the forecast: Currently, only a few aircraft exist of this size. Naturally then, fuel efficiency cannot improve largely from the retirement of older aircraft as it is the case in all other size categories. The most efficient aircraft are clearly found in the large narrowbody segment. Average fuel consumption per passenger in the 151-200 seats class drops below three litres before 2020.

C. Conclusions

From the viewpoint of CO_2 reduction, what are the conclusions to be drawn from the world fleet forecast for future technology research? Concerning technology that can only be equipped to entirely new aircraft designs, the first advise for research is to concentrate on aircraft projects that still allow for new technology to be considered in the planning process. With the next generation aircraft projects (787, A350, A320neo and the like) being already technologically frozen and demand for the next decade being nearly fully saturated due to fixed orders, the focus can thus only be on aircraft projects with market entry dates beyond 2020. The second conclusion is that research should take into account the most likely time-frame of new aircraft projects. As we have laid out in the chapter above, we believe that no (entirely) new aircraft model with market entry in the 2020s is likely in the large and very-large size categories, while Airbus and Boeing have both promised successors to the A320 and 737 in that decade. Accordingly, research should center on technologies adequate for regional and narrow-body seat categories that can be market-ready in the mid 2020s (e.g. open rotor technologies). At the same time, research into technologies to improve CO_2 efficiency in the large and very-large classes should prepare for a market entry after 2030. If started now, the long preparation time might finally allow truly revolutionary aircraft concepts to be realized. In a broader sense, the main conclusion to be drawn from the fleet analysis is that it is necessary to also pursue research into technologies than can bring benefits without requiring an entirely new aircraft model. Only then, goals such as carbon neutral growth may be realized. Most importantly, this means retrofits and alternative fuels. However, the examples of the A320neo, 737max and 777re-vamp show that design updates, which can be realized more frequently by aircraft manufacturers than new aircraft models (because of lower development cost), can bring surprisingly high benefits. This possibility should be brought into the focus especially for the large and very-large aircraft categories, where an engine-update may be possible (and environmentally

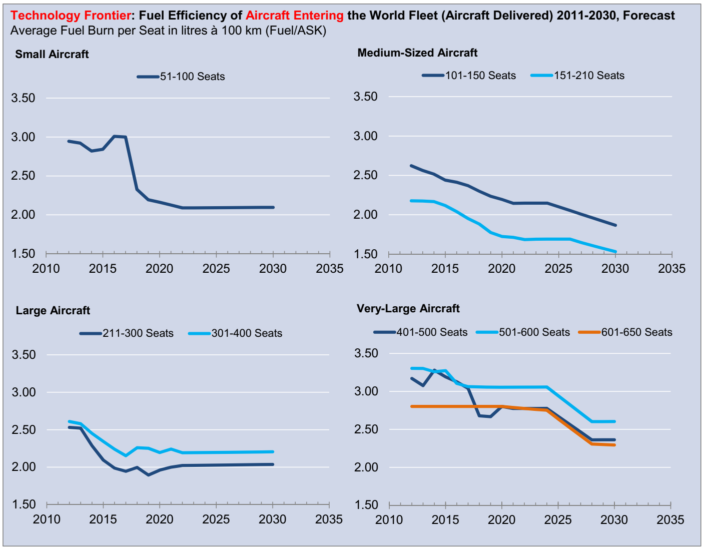


Figure 14. Technology Frontier: Fuel Efficiency of Aircraft Entering (Being Delivered to) the World Fleet (Forecast)

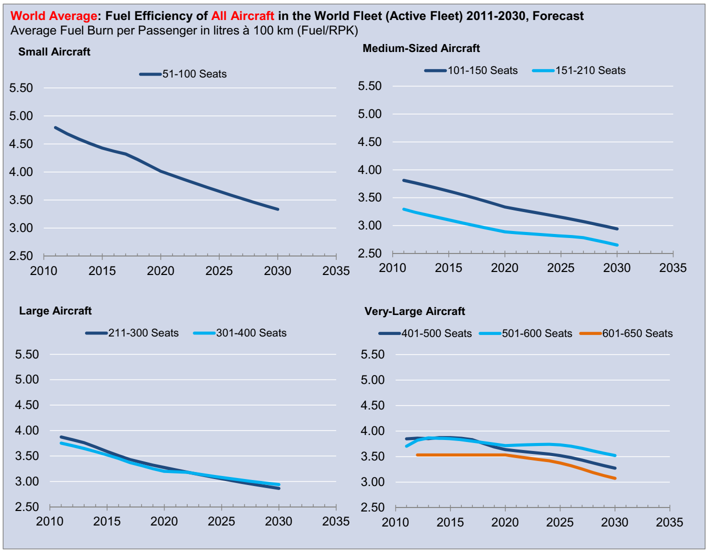


Figure 15. Average Fuel Efficiency of the Entire World Fleet (Forecast)

necessary) in the 2020s.

IV. Update of the Technology Roadmap - Phase III

The third phase of the TERESA project was asking for an update of the technology database which was set up prior to the first subject matter expert workshops and is now operational since 2008. Under the first phase of the TERESA project the availability of technologies was described coupled to the expected introduction of new aircraft programs for that time[j]. The manufacturers shift to delay the introduction of new aircraft designs made this timeframe obsolete and lead to the necessity to decouple the forecasted technology availability from the introduction of new aircraft programs. Instead a metric to describe the estimated time needed to bring the technology from the current development status to being ready for market introduction needed to be found[k]. It is apparent that aeronautical technology development can rarely be seen as a process being independent from aircraft programs and introductory timelines. The urge for a technology to progress and the assigned amount of labour and financial backup to it certainly influence the speed of the technology advancement. Nevertheless, an approach is going to be described which gauges the time needed for technology development solely based on historical data. Furthermore this section has a closer look on former commercial aircraft programs and their accumulated development costs. The collected data will be used as an indicator for future activities of the current aircraft manufacturers, i.e. the introduction of new aircraft programs, on the commercial aircraft market.

A. From Technology Readiness Level to a timeline

In the 2009 IATA Technology Roadmap[1] the information regarding the particular development status for each technology is given in the qualitative metric of Technology Readiness Level (TRL). This metric was first introduced by NASA through J.C. Mankins in 1995.[14] It is used to formally describe the development status for a technology with the help of a given set of qualitative descriptions and enables the clustering of technologies respectively to their development status in 9 different levels[l].

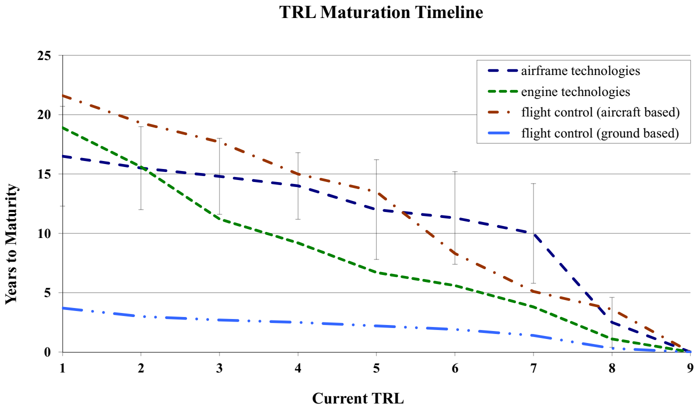


Figure 16. Technology Readiness Level Maturation Timeline

To describe the technology development status by TRL's has been adapted by various research entities

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[j] the four different timeframes for technology applications were identified as: applicable for aircraft modification, applicable for aircraft retrofit, applicable for a new program available before 2020, and applicable for a new program available after 2020

[k] In addition to developping the metric the timeframes used prior were updated as well. The new technology clusters are: applicable to retrofit on current aircraft, applicable to new design before 2020, applicable to new design after 2020, and applicable to new design after 2030

[l] The technology readiness level (TRL) rank from TRL 1-9, some examples follow: TRL 1, Basic principles observed and reported; over TRL 5, Component and/or breadboard validation in relevant environment; to TRL 9, Actual system "flight proven" through successful mission operations; more information can be found in Mankins White Paper[14]

and companies around the world. A novelty within this study is the introduction of a rough translation estimate from the given qualitative TRL to the years it will take to introduce the technology into service. We call the measure the Years to Maturity for a Current TRL as depicted in Figure 16. Currently this estimate is solely based on historical data and does not account for the influences of e.g. financial incentives, administrative restricions or supports, limited or also unlimited resources among others.

Figure 16 depicts the four different timelines developed. One timeline for airframe technologies, one for engine technologies, one for flight control systems employed on board, and one for flight control systems employed on ground. The differentiation between flight control systems on board and on ground was mandatory because the times for system development and approval differ considerably for this technology field. The principle procedure contained the identification of a technology followed by a thorough description of its subsequent stages from the phase of patenting until its common aeronautical application. The underlying database for Figure 16 contains various co-existing development paths for the same technology.[m] Therefore Figure 16 contains the plotted standard deviation per data point in years to Maturity for the airframe technologies as an example. The research needed was enabled utilizing the online available data bases from the "German Patent and Trademark Office" (DPMA)[n], "Free patents online"[o], "NASA Technical Reports Server (NTRS)"[p], among others.

Individually selected results for the fields engine and airframe from Figure 16 are explained as follows. In the field of engine technologies the turbofan technology shall serve as an example. The patent submission for a turbofan engine by Hans von Ohain[15] was choosen as the starting point for TRL 1. The patent was filed on the 12th of September in 1939. Then it took until 1954 that an aircraft, the Avro 706 Ashton, was equipped with a turbofan engine. In this case the Rolls Royce Conway, had its maiden flight and the technology had its introduction into a commercial testbed, at this point the TRL 7 level was reached. It took the turbofan technology 15 years to overcome those seven technology levels. Another four years were needed to bring the technology to TRL 9 and introduce it into commerical aircraft service on the Boeing 707 with the Pratt&Whitney turbofan JT3. In the field of airframe technologies the rather important step from TRL 7 to TRL 9 with its 10 years to maturity in between can be explained using for example the A380 introduction into service (EIS). After the maiden flight was executed in 2005 the EIS of the A380 already happened only two years later in 2007. But from todays point of view one has to state that the first delivered aircraft were more likely in the condition of TRL 8 than TRL 9, as only the location of minor fatigue cracks in the wing will entail maintenance work and production process adaptation which will result in an A380 delivered without any rework needed most likely in the years 2013-15.

For alternative fuels the application of TRL alone as a measure of readiness is no longer considered suitable. The TRL would be sufficient to describe processes and the scaleability of those to enable an industrial production of biofuels. But with biofuels the availability of feedstock presents a more severe challenge than the improvement of processes as literature review shows. Therefore the authors recommend to apply the already introduced Feed Stock Readiness Level (FSRL) in combination with the Technology Readiness Level (TRL) for the assessment of biofuels[q].

B. When will a new aircraft program enter the market? How to give a rational

To give a rational for the likelihood of a new aircraft program being introduced by an airframer we decided to examine the development costs and times of former aircraft programs. The following Table 4 shows the development cost for selected new aircraft programs and Table 5 respectively for selected retrofitted/reengined aircraft programs over the last 70 years of aeronautical history. The found $-values have been escalated to 2012 constant Dollars for the purpose of a more exact comparison.[r] [s] [t] [u] The aircraft programs are ranked due to the accumulated development costs per aircraft seat. Interestingly the development time needed for a new program could hardly be reduced since the 1960s when it took 6-7 years to develop the B707 or the

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[m] The development path can be devided when one technology is researched within different companies, countries or research entities.

[n] http://depatisnet.dpma.de/DepatisNet/depatisnet?action=einsteiger

[o] http://www.freepatentsonline.com/

[p] http://ntrs.nasa.gov/search.jsp

[q] See the work of Steiner[16] for a more comprehensive introduction to the idea of FSRL

[r] The inflation has been calculated utilizing the consumer price index (cpi) or retail price index (rpi)

[s] Some valuable websites for the calculation of constant Dollars or currency conversion are:

[t] http://www.measuringworth.com/index.php or

[u] http://www.dollartimes.com/calculators/inflation.htm

DC-8 to nowadays 7 years of development time needed for the B787 or the A350. It is furthermore visible that the development costs rose in general. While the development of a "cutting edge" supersonic aircraft like the Concorde consumed "only" approximately eleven and a half billion Dollars in the seventies, the development of an "ordinary" aircraft like the Boeing 787 consumed up to thirty two billion dollars. Before one argues about the reasons of this rise in costs, which would also be a great research topic but go way beyond the intention of this paper, we just want to use the development costs as an indicator for the shape of a new or upcoming aircraft program probably under the 2020+ timeframe.

Table 4. Development Costs of Aircraft Programs - New Designs

Aircraft Model	Number Built/Ordered as of 2012	Development Time in Years	Year Entered Service	Development Costs	Development Cost/Seat	Development Cost/Seat Built
				(in millions of constant 2012 US $)		
DC-3	607	2	1936	4.8	0.23	0.000377
DC-6	704	3	1947	161	2.88	0.004084
B707	1010	6	1958	1453	10.38	0.010276
B747	521	4	1970	5500	12.17	0.023355
DC-8	556	7	1959	1011	12.64	0.022729
B777	400	6	1995	7800	19.50	0.014265
A380	253	7	2007	16100	30.67	0.121212
A350	555	7	2013	15200	55.07	0.099229
Concorde	20	9	1976	11495	114.95	5.75
B787	873	7	2011	32000	121.21	0.138845

It was tried to account for the numbers of aircraft built under the same development level / production batch as good as possible. The development costs for following stretched or reengined versions were accumulated. In the case of the B747 for example only the development costs of the first development phase could be found, therefore just the 205 aircraft of the B747-100 and the 316 aircraft of the B747-200 production line, before a major design upgrade was performed, were taken into account. Due to this fact the number of aircraft built, which were taken into account for this study, can vary from the total number of aircraft built in the program by the manufacturer.

The comparison of results between for example the B707, see table 4, and the A320neo, see table 5, give some valuable insight into developments in the aeronautical industry. While Airbus, with its A320 neo, is the manufacturer to achieve a development cost of under 10.000$ per seat built for the first time since the development of the B707, they still just "reengined" an existing design. And while the development cost for the B707 equalled Boeings market value at that time it was backed up by the US government through ordering the model in its KC-135 version. Airbus nowadays converted to a public company has to provide the research funds for design updates while still fulfilling its' shareholders dividend interests.

Table 5. Development Costs of Aircraft Programs - Retrofit / Reengined

Aircraft Model	Number Built/Ordered as of 2012	Development Time in Years	Year Entered Service	Development Costs	Development Cost/Seat	Development Cost/Seat Built
				(in millions of constant 2012 US $)		
A320 neo	1196	6	2016	1300	7.93	0.006628
B747-8	106	6	2012	4000	8.57	0.080805
A340-500	131	5	2002	4100	11.42	0.087180
B737 max	451	6	2017	3000	18.29	0.040560

In the following Figure 17 the development costs per seat for different aircraft programs under the last 70 years of aeronautical history are mapped. The development costs per seat in Million$ are plotted in a logarithmic scale over the years of introduction of the respective aircraft programs. The costs per seat for new aircraft programs are 5 to 10 fold higher compared to the ones for retroffited or reengined programs.

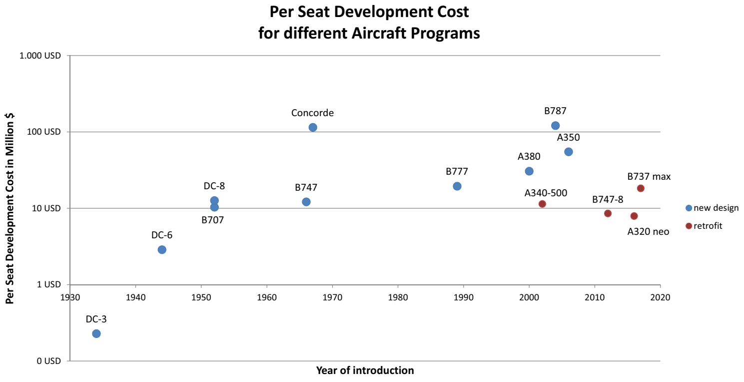

Figure 17. Per Seat Development Cost for different Aircraft Programs

The Figure 18 illustrates the development costs per built aircraft seat of different aircraft programs. While the A380, B787 and A350 all accumulated costs per seat of approximately 100.000$ - 130.000$ per built aircraft seat. The development of the Concorde consumed up to 5.000.000$ per aircraft seat built. If one compares the B787 and the Concorde as an example for the introduction of pioneering aeronautical technology at that time, it becomes visible how much more pressure aircraft manufacturers are facing nowadays to get it right as there are no national governments available to bail them out if the design fails. The need to cover development cost simply through aircraft sales explains why manufacturers prefer to choose the reengined aircraft variant over the general new development. To achieve a quantum leap and foster the introduction of a really innovative design under the 2020+ era it seems mandatory to ask for more governmental funding for aeroanautical research which is not coupled to the shareholder demands of a high dividend.

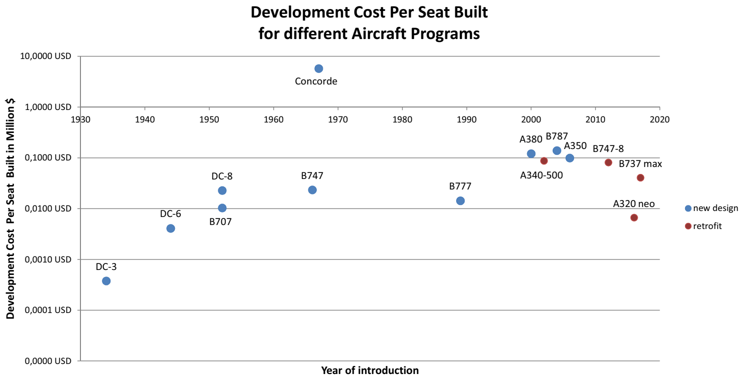

Figure 18. Development Cost per Seat Built for different Aircraft Programs

V. Summary and Conclusion

This paper gives a survey about the status and current work performed under IATAs TERESA project. The project is contributing to IATA's four pillar strategy which called for the mitigation of aeronautical CO_2 production and identified improved technologies as the most contributing factor. TERESA is operative since 2008 and has recently completed it's third phase. After the formulation of a framework for technology screening, selection and assessment within the first project phase, workshops with subject matter experts were held to gather relevant technology and system information. Initially the qualitative technology screening started in the four fields of interest airframe, engine, air traffic management and biofuels. Building on that the most promising technologies of each field were selected and quantitatively described. Successively robust technologies from the fields aircraft and engine were modeled in a physics based environment and assessed considering their CO_2 savings potential on aircraft level. Under the herein presented third phase the technology impact per aircraft size category on world fleet level was simulated. Furtheremore a framework to translate the qualitative Technology Readiness Level approach into quantitative values is introduced. In addition to that a very brief outlook on further activities on the commercial aircraft market is given based on the accumulated cost for elapsed aircraft program development by different aircraft manufacturers.

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Analysis of Removal and Decomposition Pathways of Vaporized Hydrogen Peroxide (VHP) for Aircraft Decontamination Operation

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In response to possible terrorist attacks and epidemic/pandemic diseases, there is a need for efficient infection control and sanitization of airliners. Use of vaporized hydrogen peroxide (VHP) is a promising method to achieve the goal. However, the impact of disposed VHP on atmospheric environment after decontamination operation needs to be fully understood to avoid any detrimental consequence caused by airliner decontamination. This paper analyzed the removal and decomposition pathways of VHP in the atmosphere, including physical and chemical pathways. Absorption by water droplets in atmosphere and photolytic decay mechanisms have been investigated. The results show that the uptake to water droplets in the air appears to be a major pathway for the removal of VHP.

Nomenclature

H_2O_2 = Hydrogen peroxide
HO^* = Hydroxyl
SO_2 = Sulfur Dioxide
VHP = Vaporized Hydrogen Peroxide

I. Introduction

Modern civil aviation provides unprecedented systems for rapid transport, and the industry is growing by 5% each year. However, there are significant ongoing concerns over routine air travel and these concerns are vastly magnified in the event of an epidemic/pandemic/terrorist attack using chemical and biological agents because:

A).air travel transports infected individuals to new locations;
B).aerosol person to person transmission can occur within the cabin;
C). transmission can occur via cabin surfaces;

In all three cases, efficient infection control strategies are needed such as decontamination or sanitization of aircraft. Aircraft Decontamination consists of delivering VHP (Vaporized Hydrogen Peroxide) through a stand-alone system, in an efficient way, without requiring bulky vaporizers or other heavy equipment within the cabin, such that the system is capable of delivering controlled quantities of VHP to achieve sporicidal conditions throughout the cabin. In this process, hydrogen peroxide from a concentrated liquid source (35 % hydrogen peroxide) is flash vaporized and delivered to the space to be decontaminated in the vapour phase. Some hydrogen peroxide decontamination processes can employ hydrogen peroxide aerosols. However, the design objective in the VHP process is to deliver hydrogen peroxide in the vapour phase. Thus for the purpose of the present paper aerosolization during initial delivery to the aircraft in neglected. The concentrations (120-170 ppm) employed for the aircraft are far below the dew point and the VHP process is nominally all vapour phase. At the end of the operation, the concentration of VHP was reduced to 1 ppm and then

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released to atmosphere. Some hydrogen peroxide decontamination processes can employ aerosols. However, the design objective in the VHP process is to deliver hydrogen peroxide in the vapour phase. Thus for the purpose of the present paper, aerosolisation during initial delivery to the aircraft is neglected.

In seeking industry and government input on the deployment of VHP for civil aviation applications, two key concerns were raised frequently in workshops and consultations:

- Compatibility with aircraft materials and systems.
- The extent to which any environmental release of hydrogen peroxide presents a safety threat to adjacent aviation operations.

The first of these issues was addressed in earlier work by one of the authors[1, 2]. However, the second remains a key concern and this is the motivation for this paper.

There are two scenarios for the release of hydrogen peroxide by the VHP aircraft decontamination operations: normal release (1 ppm) and accident release ((120-170 ppm). These gaseous releases are much harder to manage than a liquid spill so in this paper the focus is on the environmental fate of vapour phase escapes.

The fate of vaporized hydrogen peroxide released to atmosphere from aircraft decontamination operation using VHP involves two aspects: removal and decomposition by physical and chemical processes and dispersion of H_2O_2 in the atmosphere. This work has focused on the removal and decomposition aspects and reviewed major pathways of removal and decomposition of VHP in atmosphere and assessed the fate of disposed VHP and discussed possible interactions with air pollutants in normal operation and accidental leakage of aircraft decontamination.

Although there has been research on the atmospheric behavior of hydrogen peroxide[3-12], this work differs in that the source hydrogen peroxide concentration is much high, which has implications for the fate of the hydrogen peroxide.

II. Removal and Decomposition Pathways of Released Hydrogen Peroxide

A. Overview of Pathways

In general, released hydrogen peroxide from aircraft decontamination could be removed from atmosphere in two pathways: physical and chemical pathways. Absorption to water droplets is a typical physical pathway though there are chemical reactions occurring after absorption in the aqueous phase. The chemical pathways include spontaneous decomposition (photolytic decay) and reactions with those sink compounds[5]. These pathways could happen in both gaseous and aqueous phase. The third one, reactions with sink compounds, has particular implications for aviation because the aircraft decontamination would be operated at the airport vicinity, which could be a polluted area especially at major airports. The chemical reactions could happen between hydrogen peroxide and engine and combustion emitted pollutants such as SO_2 and NOx. SO_2 is well known as a major sink for hydrogen peroxide[5]. However, the mechanism of reactions between hydrogen peroxide and these compounds is complicated and the parameters that affect the sinking effect are multiple. Moreover, as the aviation fuels have been reducing their sulfur content and SO_2 concentrations in the airports are therefore getting lower and lower (this is also due to the reduction from power generations), the effect of SO_2 as a sink for hydrogen peroxide is less significant. So in this paper the pathways due to reactions with pollutants are not discussed and will be reported in a separate paper.

The pathway of the removal and decomposition of hydrogen peroxide can be classified and expressed in Fig. 1 below:

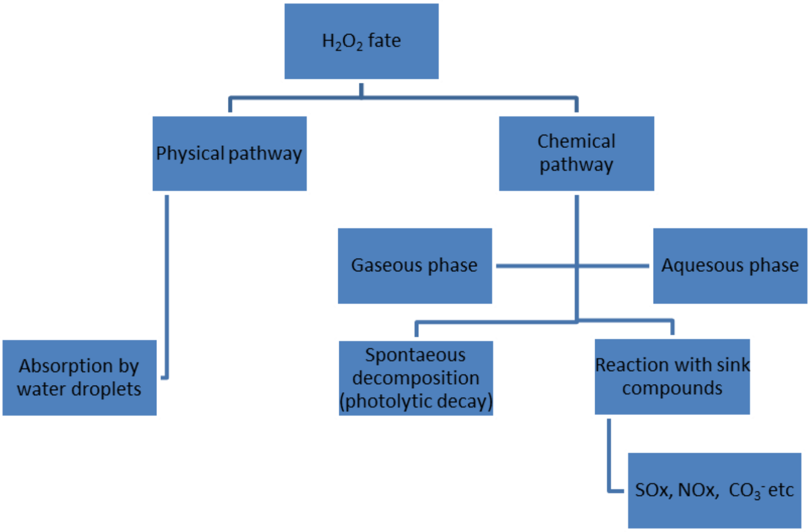

Figure 1. The fate of hydrogen peroxide released from aircraft decontamination.

B. Physical Pathway - Uptake to Water Droplets

1. Partition between gaseous and aqueous phase

Hydrogen peroxide has excellent solubility in water and can be dissolved in water in any ratio. This made uptake to water droplets become a major pathway for the removal of gaseous hydrogen peroxide. Olszyna[3] and Jacob et al[4] measured the ambient H_2O_2 concentrations at different weather conditions. They observed a significant decrease of gas phase H_2O_2 during the formation of clouds and rainfall, which proved that the absorption of gaseous H_2O_2 to water droplets was a major pathway for the removal of gaseous H_2O_2.

The solubility of H_2O_2 in water droplets is determined by the Henry's law, which can be expressed as follows[13]:

$$K_{H,(cp)} = C_{H2O2(}aq_{)} / P_{H2O2(}g_{)} \tag{1}$$

Henry's Law can also be written in other forms, with different definition of the constant K_H and different dimensional units. For example:

$$K_{H,(cc)} = C_{(H2O2aq)}/C_{H2O2(g)} \tag{2}$$

Where:

- $C_{H2O2(}aq_{)}$ is the molar concentration of H_2O_2 in a solution which is in equilibrium with the gas phase, mol/L.
- $C_{H2O2(g)}$ is the molar concentration of H_2O_2 in gaseous phase, mol/L.
- $P_{H2O2(}g_{)}$ is the gas phase partial pressure of H_2O_2 in equilibrium with its aqueous solution.
- $K_{H,(cp)}$ is the proportionality constant (the Henry's Law constant) in mol/L· atm. $K_{H,(cp)}$ is a function of temperature (given by the van't Hoff equation below), pressure and the chemical composition of the system. The pressure dependence of $K_{H,(cp)}$ is normally neglected because the pressure effect on the condensed phase is small.
- $K_{H,(cc)}$ is the proportionality constant (the Henry's Law constant) dimensionless.

The relation between $K_{H,(cp)}$ and $K_{H,(cc)}$ is given in equation (3) below:

$$K_{H,(cp)} = R^* T^* K_{H,(cc)} \tag{3}$$

Where, R is gas constant, 8.314 J/mol. T is the ambient temperature in Kelvin.

Henry's law constant is a function of temperature, which has been investigated by Martin et al[14] and can be expressed in equation (4) below:

$$K_{H,(cp)} = e^{(a/T-b)} \tag{4}$$

Where:

T is the ambient temperature in Kelvin,

a=7024,

b=11.97

The correlation between ambient temperature and Henry's law constant $K_{H,(cc)}$ for hydrogen peroxide is calculated as shown in Fig. 2. Overall, the value of Henry's Law constant of H_2O_2 is high, showing that the ratio of $C_{H2O2(aq)}$ to $P_{H2O2(}g_{)}$ or $C_{H2O2(g)}$ is high and this indicates that the H_2O_2 has a strong tendency to be present in aqueous phase. As a result the large proportion of gaseous phase H_2O_2 released to the atmosphere would be dissolved in the water droplets, clouds or raindrops in humid weather. The results in Fig. 2 showed that solubility of H_2O_2 in aqueous phase decreases as the ambient temperature rises.

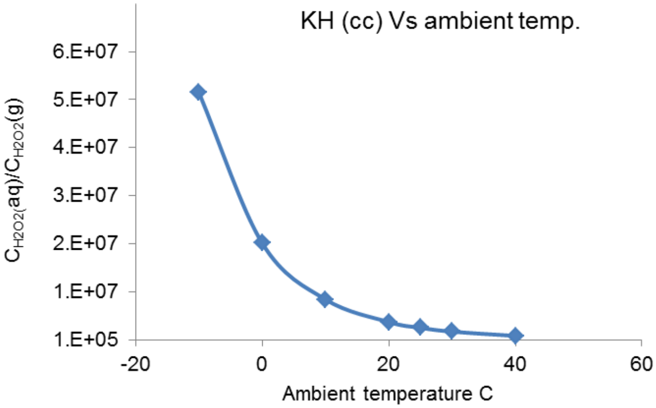

Figure 2. The partition between aqueous and gas phase H_2O_2 as a function of ambient temperature.

2. Uptake capability of hydrogen peroxide by air at different relative humidity and ambient temperatures

The strong tendency of H_2O_2 dissolving in the water droplets means that the amount of water available in the air is one of the key parameters affecting uptake of H_2O_2 from aircraft decontamination operation. Another important parameter is temperature. The relations between the amount of gaseous H_2O_2 (1ppm scenario) absorbable by 1 m^3 air, relative humidity and ambient temperature of air were modelled by calculating the available amount of water vapour in 1 m^3 air at each relative humidity and ambient temperature, assuming a concentration of H_2O_2 in aqueous phase 50% after absorption. Figure 3 shows that the absorption of H_2O_2 in water vapour has a good linear relationship with relative humidity of air and increases as the ambient temperature rises. In a hot humid summer day (e.g. above 22^{O}C), 1 volume of air could absorb at least ten volumes of H_2O_2. However, under cold weather conditions such as 10C or below, the absorption capability of water droplets is much reduced even at high relative humidity. The ambient temperature has significant influences on the absorption capability of water droplets to hydrogen peroxide. The relationship between air humidity and absorption capability of hydrogen peroxide depended on ambient air temperatures. At low ambient temperatures, the humidity of air has much less impacts on absorption of hydrogen peroxide. This indicated that the removal of H_2O_2 by water droplets in cold weather is a slow process whatever the air humidity is.

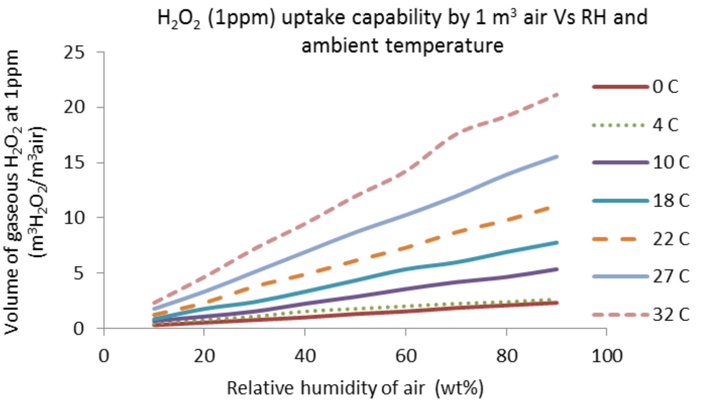

Figure 3. Volume of gaseous H_2O_2 (1ppm) that can be absorbed by 1 m^3 of air as a function of relative humidity and ambient temperature.

C. Chemical pathways

3. Spontaneous decomposition (Photolytic decay)

The decomposition of hydrogen peroxide is a spontaneous process at room temperature. The rate of the reaction is increased by the presence of light. However, the research on the detailed rate of photolytic decay reaction of hydrogen peroxide in atmosphere has been limited, especially for high concentration scenarios. Jacobi et al[15, 16] investigated the photochemical decomposition of H_2O_2. They measured the decay rate of H_2O_2 in the artificial snow made in lab under the influence of highly intensive UV and visible radiation. They found that H_2O_2 in the gas and liquid phase significantly absorb solar radiation and thus photolytic reactions are good sinks for H_2O_2 in the atmosphere. A first order photolytic decomposition reaction of hydrogen peroxide was observed as described below in reaction (R1) and equations (5) and (6):

$$H2O2 + hv \rightarrow 2OH* \tag{R1}$$

$$d[c]/dt = -k[c] \tag{5}$$

$$\ln([c]/[c_0]) = -kt \tag{6}$$

Where,[c] is the concentration of hydrogen peroxide at t time, mol/L.

$[c_0]$ is the initial concentration of hydrogen peroxide, mol/L.

k is the rate constant, here corresponding to the photolysis rate, h^{-1}.

Jacobi et al[16] measured the k values for various initial concentrations of hydrogen peroxide and found a value of 0.48 h^{-1} at a radiation intensity of 1200 W m^{-2}. However this radiation intensity was under lab condition. In reality, the light radiation is affected by weather, location, season and many other parameters. Burgess[17] reported measured clear day solar radiation in South England in June, September and December and found a fourfold difference between June and December. He also reported clear day solar radiations at three latitudes in the UK (50°N: Penzance; 55°N: Newcastle, and 60°N: Shetland) and found that the major difference was in winter and there was little gap in summer between different locations. The maximum radiation intensity observed at 52°N was 800 W m^{-2} in June and 150 W m^{-2} in December for clear days. As the k is a function of radiation intensity and the measured radiation intensity in the UK was weaker than that of the lab conditions, the k values for typical UK conditions accordingly were a fraction of laboratory determined values (0.48 h^{-1}). Two k values, one for summer and the other for winter scenario, were obtained as 0.32 h^{-1} and 0.16 h^{-1} based on 800 W m^{-2} and 150 W m^{-2} radiation intensity. From these two k values, decay rates in terms of percentage relative to the initial hydrogen peroxide concentration (1 and 170 ppm) for June and December scenarios were calculated as a function of time using equation (6) and shown in Figs. 4 and 5. The results show that it will take approximately ~8 hours in June and ~40 hours in December for 90% of hydrogen peroxide to decompose by photolysis, indicating that the photolytic decay mechanism is a slow process for the decomposition of hydrogen peroxide.

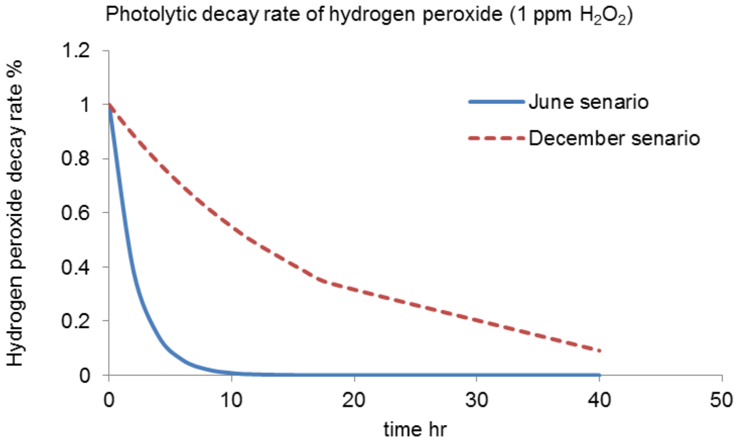

Figure 4. The rate of photolytic decay of 1 ppm H_2O_2 based on a summer and a winter scenario in the UK.

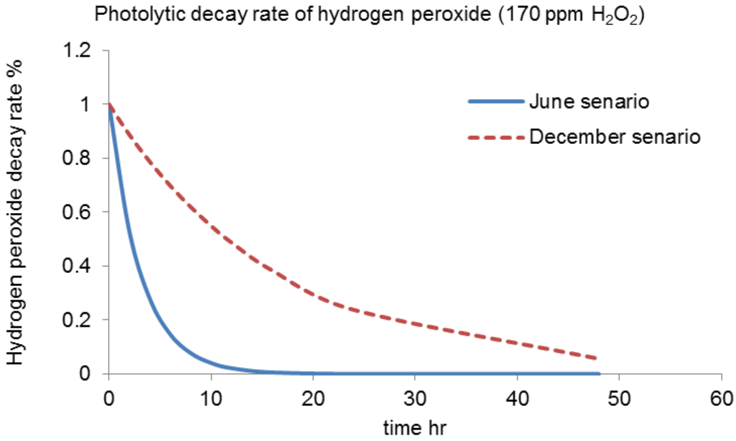

Figure 5. The rate of photolytic decay of 170 ppm H_2O_2 based on a summer and a winter scenario in the UK.

III. Conclusion

Vaporized hydrogen peroxide (VHP) is a promising method for infection control and sanitization of aircraft. However, there is a concern on the environmental impact and safety threat to adjacent aviation operations by released hydrogen peroxide from decontamination operation. So it is essential to fully understand its impact to avoid any detrimental consequence caused by aircraft VHP decontamination. Two scenarios of VHP release have been considered in the paper: normal operation release (1 ppm VHP) and accidental leak during the operation (170 ppm VHP). The removal and decomposition pathways of VHP in the atmosphere has been analyzed and examined.

In general, the pathway can be classified as physical and chemical pathways. The uptake to water droplets in the air, as a physical pathway, appears to be a major pathway for the removal of VHP due to high Henry's law constant of hydrogen peroxide. The removal efficacy of hydrogen peroxide by water droplets is increased as the ambient temperature and humidity increases.

Photolytic decay, as a chemical decomposition pathway, is a slow process. Based on example scenarios (UK, summer and winter) calculation in the paper, it needs approximately 8 hours in summer and 40 hours in winter for 90% of hydrogen peroxide to decay or decompose.

There are other chemical pathways such as reactions with air pollutants SO_2. The mechanism for that is more complicated and will be reported in a separate paper.

Acknowledgments

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The Economic Analysis of Satellite-Based CNS/ATM Application in Iranian Air Transportation

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The International Civil Aviation Organization (ICAO) has developed the operational concepts known as satellite-based CNS/ATM to improve aviation communication, navigation, surveillance, and air traffic management. However, switching from land-based CNS/ATM to the satellite-based imposes a significant budget on the states, airlines, stakeholders etc. which acts as a barrier. To date, in spite of the special attention on replacing the current CNS/ATM systems no concrete action has been taken in many ICAO member countries. Driving forces behind it are economic considerations. In other words, the states do not have a clear outlook for the economic benefits of the new systems. Therefore, it has been questioned whether replacing existing systems has an economic justification or not. In this regard, conducting an economic analysis contributes to ascertain the possible economic impact of the measure and explore the financial efficiency of the new systems. Correspondingly, in this study NPV method and cost/benefit analysis are used to evaluate the implementation of satellite-base CNS/ATM in the case of Iranian air transport.

I. Introduction

The air transport industry is developing a new operational concept for the Air Traffic Management (ATM) system. This operational concept involves substantial changes to airplanes and ground systems with the introduction of new satellite-based technologies. The current mature ATM systems, based on ground navigational aids, radar, and voice communications, will be unable to cope with expected air traffic growth. A number of states lack such infrastructure and find themselves with a confusing selection of technologies and no clear direction to base decisions on. The industry, lacking a global transition strategy, is in danger of strangling on its own success.

The aviation industry has developed an operational concept known as the Future Air Navigation System (FANS), which relies on satellite-based navigation and communication to provide the improvements needed in communication, navigation, and surveillance (CNS) to efficiently cope with future traffic levels. The FANS development required industry to consider ATM as a system with interacting ground, space and airborne components. The International Civil Aviation Organization (ICAO) FANS committee also committed to certain technical solutions for improvements to CNS such as the Aeronautical Telecommunications Network (ATN), Global Positioning System (GPS) navigation, and satellite communications. However, since the adoption of the ICAO FANS committee suggestions, progress towards this envisioned end state has been slow. This lack of movement towards full FANS implementation is not due to any particular technical problem; it is due to the lack of consideration given to the economic aspects of the problems that FANS was designed to solve. The lack of consideration of the economics of transition to the new operational concept has slowed the pace of the implementation process[1].

A. Statement of Problem

Islamic Republic of Iran as a member of ICAO is located in a zone which has a high potential for more domestic transit flights and attraction of international flights to traverse within the country. With regard to the potential, it is necessary to follow the ICAO international plans such as installing the future CNS/ATM in order to enhance air traffic management as well as being in accordance with the other members. When it comes to the future CNS/ATM, to date, in spite of the special attention on replacing the current systems no concrete action has been taken in Iran.

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Driving forces behind it are economic considerations. In other words, the state authority does not have a clear outlook for the benefits of the new systems in terms of economy. Therefore, it has been questioned whether replacing existing systems in Iran has an economic justification or not. In this regard, conducting an economic analysis contributes to ascertain the possible economic impact of the measure and explore the financial efficiency of the new systems.

B. Research Question

This paper aims to introduce the benefits of the new satellite-based CNS/ATM systems in Iranian air aviation. The direct and indirect benefits of the measure for the state, passengers, airlines and even environment are considered in this paper. Considering the qualities of the current and new systems, their costs and benefits, ICAO regional and international planning and Iranian air aviation infrastructure a scheduled plan regarding switching from the existing CNS/ATM to the future one for a Implementation period of twenty years (since 2010 to 2030) is also provided. It is worth mentioning the scheduled plan is provided in the framework of assumptions in this paper. Furthermore, it is intended to present an economic analysis of installing the new satellite-based CNS/ATM systems in Iran through Net Present Value (NPV) and Benefit/Cost (B/C) methods. The economic analysis is about to show whether replacing the new CNS/ATM systems in Iranian air aviation is economically justified or not.

II. Satellite-Based CNS/ATM and Its Benefits

The process of getting an aircraft safely and efficiently from its origin to destination requires effective air traffic management systems supported by three key functions using satellite technology: **C**ommunications, **N**avigation and **S**urveillance. Communications is the exchange of voice and data information between the pilot and air traffic controllers or flight information centers. Navigation pinpoints the location of the aircraft for the air crew. Surveillance pinpoints the location of the aircraft for air traffic controllers. It includes communication of navigation information from aircraft to air traffic control centers which facilitates the continuous mapping of the relative positions of aircraft. ICAO calls the three functions the CNS systems and regards them as forming the basic support services of Air Traffic Management (ATM) systems. The four main elements of CNS/ATM systems are summarized below [2-5]:

A. Communications

In CNS/ATM systems, the transmission of voice will, initially, continue to take place over existing very high frequency (VHF) channels; however, these same VHF channels will increasingly be used to transmit digital data. Satellite data and voice communications, capable of global coverage, are also being introduced along with data transmission over high frequency (HF) channels. The secondary surveillance radar (SSR) Mode S, which is increasingly being used for surveillance in high-density airspace, has the capability of transmitting digital data between air and ground. An aeronautical telecommunication network (ATN) will provide for the interchange of digital data between end-users over dissimilar air-ground and ground-ground communications sub networks. The regular use of data transmission for ATM purposes will introduce many changes in the way that communications between air and ground takes place, and at the same time offer many new possibilities and opportunities. The benefits expected from the future communications systems lie in the fact that they will allow more direct and efficient linkages between ground and airborne automated systems in conjunction with pilot/controller communications. In fact, digital data link can be seen as the key to the development of new ATM concepts leading to the achievement of real benefits.

B. Navigation

The navigation element of CNS/ATM systems is meant to provide accurate, reliable and seamless position determination capability, worldwide, through the introduction of satellite-based aeronautical navigation or global navigation satellite system (GNSS). The GNSS is a worldwide position and time determination system that includes one or more satellite constellations, aircraft receivers, and system integrity monitoring, augmented as necessary to support the Required Navigation Performance (RNP) for the actual phase of operation. The satellite navigation systems in operation are the global positioning system (GPS) of the United States and the global (orbiting) navigation satellite system (GLONASS) of the Russian Federation. Both systems were offered to ICAO as a means to support the evolutionary development of GNSS. GNSS will provide a high-integrity, high-accuracy and all-weather worldwide navigation service. The successful implementation of GNSS would enable aircraft to navigate in all types of airspace, in any part of the world, offering the possibility for many States to dismantle some or all of their existing ground-based navigation infrastructure.

C. Surveillance

The surveillance systems presently in use can be divided into two main types: dependent surveillance and independent surveillance. In dependent surveillance systems, aircraft position is determined on board and then transmitted to ATC. The current voice position reporting is a dependent surveillance systems in which the position of the aircraft is determined from on-board navigation equipment and then conveyed by the pilot to ATC by radiotelephony. Independent surveillance is a system which measures aircraft position from the ground. Current surveillance is either based on voice position reporting or based on radar (primary surveillance radar (PSR) or secondary surveillance radar (SSR)) which measures range and azimuth of aircraft from the ground station. The major breakthrough, however, is with the implementation of automatic dependent surveillance (ADS). ADS allows aircraft to automatically transmit their position, and other data, such as heading, speed and other useful information contained in the flight management system (FMS), via satellite or other communications links, to an air traffic control (ATC) unit where the position of the aircraft is displayed somewhat like that on a radar display. ADS can also be seen as an application that represents the true merging of communications and navigation technologies, and, along with ground system automation enhancements, will allow for the introduction of significant improvements for ATM, especially in oceanic airspace. Software is currently being developed that would allow this data to be used directly by ground computers to detect and resolve conflicts. Eventually, this could lead to clearances being negotiated between airborne and ground-based computers with little or no human intervention.

D. Air Traffic Management

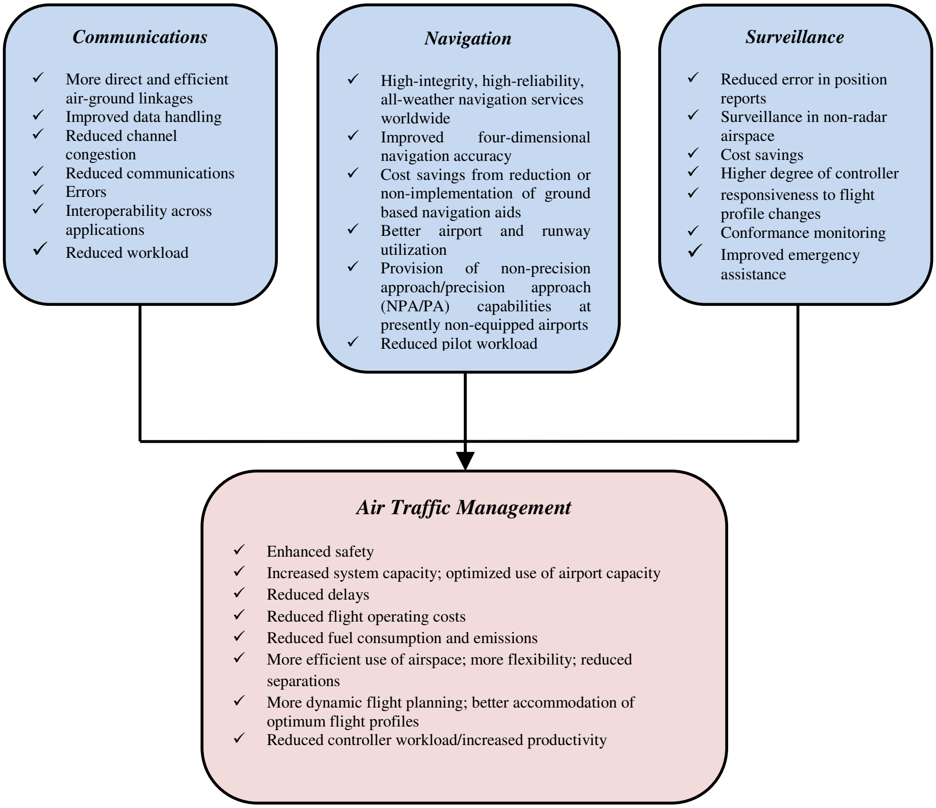
In considering implementation of new communications, navigation and surveillance systems and all of the expected improvements, it can be seen that the overall main beneficiary is likely to be ATM. More appropriately, the advancements in CNS technologies will serve to support ATM. When referring to ATM in the future concept, much more than just air traffic control is meant. In fact, ATM refers to a system's concept of management on a much broader scale, which includes ATS, air traffic flow management (ATFM), airspace management (ASM) and the ATM-related aspects of flight operations. An integrated global ATM system should fully exploit the introduction of new CNS technologies through international harmonization of Standards and procedures. Ultimately, this would enable the aircraft operators to conduct their flights in accordance with their preferred trajectories, dynamically adjusted, in the most optimum and cost-efficient manner. Figure1 illustrates how the utilization of CNS technologies will result in ATM benefits.

E. The Benefits of the New CNS/ATM

The Benefits of the satellite-based CNS/ATM are mentioned below according to Ref. 2, 3, 4 and 6. The satellite-based CNS/ATM systems will improve the handling and transfer of information, extend surveillance using ADS and improve navigational accuracy. This will lead, among other things, to reductions in separation between aircraft, allowing for an increase in airspace capacity. Advanced CNS/ATM systems will also see the implementation of ground-based computerized systems to support increases in traffic. These ground-based systems will exchange data directly with FMS aboard aircraft through a data link. This will benefit the ATM provider and airspace user by enabling improved conflict detection and resolution through intelligent processing, providing for the automatic generation and transmission of conflict-free clearances, as well as offering the means to adapt quickly to changing traffic requirements. As a result, the ATM system will be better able to accommodate an aircraft's preferred flight profile and help aircraft operators to achieve reduced flight operating costs and delays. Table1 describes the objectives and resulting benefits of CNS/ATM systems.

The new CNS/ATM systems bring benefits for the airlines as well. The benefits of CNS/ATM systems will ensue through the formation of a more close-knit relationship, allowing rapid and reliable transmission between ground and airborne system elements. More accurate and reliable navigation systems will also allow aircraft to navigate in all types of airspace and operate closer together. In anticipation of the advantages of CNS/ATM systems, the airlines expect reduced separation standards over oceanic airspace; increased access to remote areas; the gradual introduction of 1000 ft vertical separation above 29000 ft; increased opportunities for more dynamic and direct routings; and an overall enhancement of safety.

For those States that provide and maintain extensive ground infrastructures, a reduction in the overall cost of operation and maintenance of facilities is expected as the traditional ground systems become obsolete and satellite technology is increasingly employed. They will also benefit from enhanced safety. Furthermore, CNS/ATM provides a timely opportunity for developing States to enhance their infrastructures to handle additional traffic with minimal investment. Many of these States have large areas of available but unusable airspace, mainly because of the expense involved in purchasing, operating and maintaining the necessary ground infrastructures. CNS/ATM systems will afford them opportunities to modernize inexpensively, which includes the provision of precision and non-precision approaches.


Communications

- ✓ More direct and efficient air-ground linkages
- ✓ Improved data handling
- ✓ Reduced channel congestion
- ✓ Reduced communications
- ✓ Errors
- ✓ Interoperability across applications
- ✓ Reduced workload

Navigation

- ✓ High-integrity, high-reliability, all-weather navigation services worldwide
- ✓ Improved four-dimensional navigation accuracy
- ✓ Cost savings from reduction or non-implementation of ground based navigation aids
- ✓ Better airport and runway utilization
- ✓ Provision of non-precision approach/precision approach (NPA/PA) capabilities at presently non-equipped airports
- ✓ Reduced pilot workload

Surveillance

- ✓ Reduced error in position reports
- ✓ Surveillance in non-radar airspace
- ✓ Cost savings
- ✓ Higher degree of controller
- ✓ responsiveness to flight profile changes
- ✓ Conformance monitoring
- ✓ Improved emergency assistance

Air Traffic Management

- ✓ Enhanced safety
- ✓ Increased system capacity; optimized use of airport capacity
- ✓ Reduced delays
- ✓ Reduced flight operating costs
- ✓ Reduced fuel consumption and emissions
- ✓ More efficient use of airspace; more flexibility; reduced separations
- ✓ More dynamic flight planning; better accommodation of optimum flight profiles
- ✓ Reduced controller workload/increased productivity

Figure.1 A high-level view of expected benefits of the new systems[3]

As the aviation industry grows more and more rapidly, the impact of air traffic operations on the global atmosphere becomes increasingly important in addition to the local effects of noise and air quality. Efforts to control or reduce the environmental impact of air traffic have identified a range of options that might reduce the impact of aircraft engine emissions. In particular, it is expected that improvements in ATM could help reduce aviation fuel burn, and thereby reduce the levels of aircraft engine emissions.

As a result of implementing CNS/ATM systems General aviation and utility aircraft will find increasing access to avionics equipment that will allow them to operate in flight conditions, into and out of airports, that they would normally have been prohibited from using because of the operating cost and associated requirements. Moreover, many remote areas that are currently inaccessible to most general aviation aircraft because of their inability to communicate or safely navigate over them would become accessible.

In addition to the direct benefits mentioned above, there are also many indirect benefits, such as: lower fares and rates, passenger time savings, transfer of high-technology skills, productivity improvements and industry restructuring, stimulation of related industries, enhanced trade opportunities, and increased employment.

Table 1. The objectives and resulting benefits of CNS/ATM systems[3]

Objective	Air Traffic Management	Flight Operations
General	✓ ensure that all necessary information, including information needed for dynamic flight planning, is available to all ground and airborne systems ✓ enhance functional integration of ground systems with airborne systems and the ATM-related aspects of flight operations ✓ enhance the accuracy of conflict prediction and resolution and the provision of real-time information to controllers and operators	✓ enhance the accuracy of information related to flight progress ✓ enhance functional integration of airborne systems and flight operations with ground systems ✓ ensure the provision of accurate information between airborne system elements and ground system elements necessary for dynamic flight planning
Safety	✓ ensure the provision of well-adapted and harmonized safe procedures on a global basis ✓ ensure that separation between aircraft is maintained ✓ ensure that clearance between aircraft and obstacles is maintained ✓ provide for enhanced contingency planning ✓ ensure that rapid alerting service is available ✓ ensure that safety levels are maintained as the use of automation increases	✓ improve pilot situational awareness ✓ ensure adequate clearance from terrain ✓ enable aircraft to maintain their own separation under specific circumstances ✓ ensure that safety levels are maintained as the use of automation increases ✓ ensure integrity of database information
Regularity & Efficiency	✓ provide for the application of global ATM under ✓ all operational conditions ✓ improve the application of tactical airspace management through dynamic user involvement, leading to more efficient airspace utilization ✓ improve strategic airspace management while increasing tactical airspace flexibility ✓ ensure the provision of information necessary for tactical and strategic ATFM ✓ enhance overall tactical and strategic ATFM so ✓ that demand does not exceed capacity ✓ increase available capacity without increasing ✓ controller workload	✓ ensure that aircraft can operate under all types of weather conditions ✓ provide for the application of user-preferred flight profiles ✓ ensure that the necessary infrastructure is available to support gate-to-gate operations ✓ improve user capability to optimize flight planning dynamically, in order to improve airspace capacity through more flexible operations ✓ minimize aircraft operating cost penalties ✓ minimize differing equipment carriage requirements between regions
Communications, Navigation and Surveillance		
Communications	to enhance coverage, accessibility, capability, integrity, security and performance of aeronautical communication systems in accordance with ATM requirements	
Navigation	to enhance coverage and allow for all weather navigation capability in all airspace, including approach and landing, while maintaining or improving integrity, accuracy and performance in accordance with ATM requirements	
Surveillance	to enhance and extend effective surveillance to oceanic and remote areas while improving air traffic situational awareness in the cockpit in accordance with ATM requirements	

III. The Procedure of Economic Analysis Regarding Satellite-Based CNS/ATM Systems

Economic aspects of air navigation facilities and services can be suitably assessed by analysing their costs and benefits to users and providers in relation to the investment requirements. ICAO developed guidance material to that extent and recommended its Contracting States to conduct a cost-benefit analysis as part of drawing an implementation plan for satellite-based CNS/ATM systems, if and when required. Making cost-benefit studies part of the planning process will enable States to identify cost-effective technical solutions, favourable institutional arrangements and timing of implementation options. The development of a related business case is a complementary planning tool to explore possibilities and limitations of financing schemes, including capital needs, user fee structures and cash flow demands. A cost-benefit model is described in Ref. 6. The model is based on a comparison of costs associated with implementing the new CNS/ATM systems (the project case) with those of maintaining the existing present-technology systems in the long term (the base case). The model uses a widely accepted approach, namely Net Present Value (NPV) of life-cycle. It focuses on discounted annual cash flows, representing the costs and benefits of CNS/ATM systems over a given implementation period. Figure 2 summarizes the Net Present Value (NPV) approach.

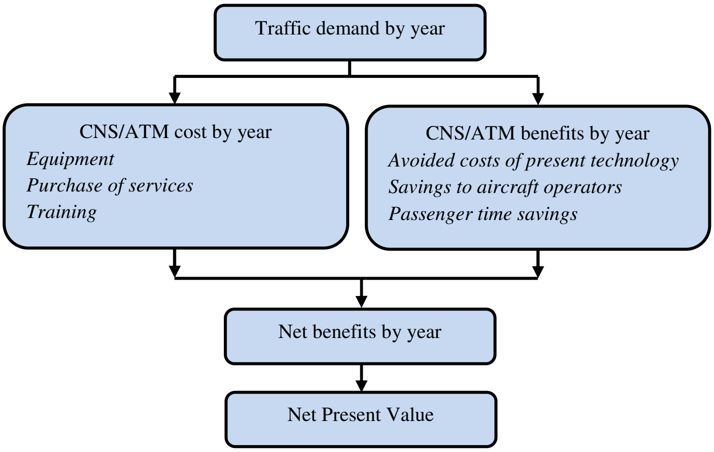


Figure 2. Overview of the Net Present Value (NPV) approach[3]

A. The Net Present Value Method

Net Present Value (NPV) analysis is the process of taking a current investment, and projecting the future net income from this investment. In other words, it is defined as the difference between the present value of the future cash flows from an investment and the amount of investment. Present value of the expected cash flows is computed by discounting them at the required rate of return. NPV is used in capital budgeting to analyze the profitability of an investment or project. NPV analysis is sensitive to the reliability of future cash inflows that an investment or project will yield. NPV is calculated in Eq. (1)[9]:

$$\mathrm{NPV} = \sum_{t=0}^{T} \frac{R_t}{(1+i)^t} \tag{1}$$

Where:
i: Discount rate
t: The time of the cash flow
R_t: The net cash flow (the amount of cash, inflow minus outflow) at time t (for educational purposes, R_t is commonly placed to the left of the sum to emphasize its role as (minus) the investment. The result of this formula will be the net present value.

An NPV greater than zero indicates the project may be accepted economically. An NPV of less than zero indicates that the project should be rejected. Where NPV=0, it shows that the discount rate of the project equals the minimum acceptable rate of return which often abbreviated MARR. Therefore, this attribute could be used in order to calculate MARR. MARR is the minimum rate of return on a project which is considered to accept before starting a project, given its risk and the opportunity cost of forgoing other projects[9].

B. Benefit-Cost Analysis Method

Benefit-cost analysis (BCA) is a systematic process for calculating and comparing benefits and costs of a project. CBA has two purposes[10]:

- To determine if it is a sound investment.
- To provide a basis for comparing projects. It involves comparing the total expected cost of each option against the total expected benefits, to see whether the benefits outweigh the costs, and by how much.

In BCA, benefits and costs are expressed in money terms, and are adjusted for the time value of money, so that all flows of benefits and flows of project costs over time (which tend to occur at different points in time) are expressed on a common basis in terms of their Net Present Value[10].

C. Economic Analysis In The Case of Iranian Air Transportation

Estimating the NPV of future CNS/ATM systems requires many assumptions about prices and quantities of communications, navigation and surveillance equipment on which the configuration of the future system can be based. Other assumptions need to be made about associated air navigation services and potential savings in aircraft operating costs which are attributable to the enhanced operational efficiency of the satellite-based systems. Generally, it is recommended that these assumptions be developed in consultation with experts from equipment manufacturers, service providers and aircraft operators[6]. When it comes to the required assumptions in the case of Iran, in this study a part of them has been made according to Ref. 6, 7 and 8. The assumptions are summarized as follows:

- Implementation period of the project is mentioned as 20 years (since 2010 to 2030).
- Average life of electronic equipments is assumed 15 years.
- In each year's implementation period, the sum of maintenance, repair & operation costs of electronic equipments and user training costs are assumed to be two fifteens of their total cost prices. It is also worth mentioning that this fraction is derived from analysing historical data.
- The annual growth of flights during the Implementation period is forecasted at 10%. Since the economic analysis for the new CNS/ATM is conducted just for the domestic flights in Iran, this percentage is derived from the relevant historical data.
- When it comes to the costs, they include the expenditure on new technologies and the corresponding installation costs as well as the costs of training staff.
- Reduction of airplane operating costs includes travel time, fuel consumption, etc. is mentioned as the benefits of the new system in the economic analysis.
- The quantities of new communications, navigation and surveillance equipments have been determined in consultation with experts from ICAO council in Iran.
- The maintenance costs of the existing navigation systems have been taken into analysis only during the first half of implementation period. With that being said, they will not be in used for the rest of it.
- The maintenance costs of the existing communication and surveillance equipments are considered during the whole implementation period.
- The expenditure on new navigation systems and their installation and maintenance costs are taken into economic analysis through the first half of implementation period.
- The expenditure on new communication & surveillance systems and the corresponding installation & maintenance costs are entered into calculations once the second half of Implementation period begins.
- Discount rate is the rate of return that could be earned on an investment in the financial markets with similar risk[9]. In the case of Iran, it is mentioned as 20% due to that the rate of long term interest regarding bank and government bond market calculates to this percentage.
- It is assumed that after implementation of the new CNS/ATM systems, the average travel time of air flights would be gradually reduced to 6% within the initial ten years of implementation period. However it seems a conservative estimate.
- In this study, the annual rate of inflation has been ignored in the economic analysis.

D. The Method and Results of CNS/ATM Economic Analysis

Considering the above-mentioned features, in order to calculate NPV it is necessary to predict the costs and benefits annually for every part of the CNS/ATM systems i.e. navigation, surveillance and communication. In this context, the annual benefits of the new systems for reducing airplane operating costs have been calculated for each types of airplane served in domestic Iranian air transport. For example, in Table2 the mentioned benefits for Boeing 747 are presented. Note that the annual flights hour, hourly operating costs and travel time reductions have been entered into the calculation. When it comes to the costs, the maintenance of existing systems and the investment in the new technologies have been considered. The corresponding costs have been calculated for the navigation, surveillance and communication systems introduced in both aircrafts and ground stations. In Table3, the annual costs of implementing Global Navigation Satellite System (GNSS) suites being introduced to the aircrafts are shown as an example.

By following the method, all costs and benefits of implementing the future CNS/ATM were obtained. In this regard the summary of results is presented in Table4. In Table4, Net Present Value for the costs and benefits and also the sum of them were calculated. In order to provide a better understanding of the results, a visual presentation is displayed in Fig. 3, 4 and 5.

According to Fig4, it is displayed that although the cost of planning implementation is high at the beginning years of the implementation period; it saw a downward trend as time goes by. Figure 5 clearly indicates that since the seventh year of the implementation period the benefits of the plan have outweighed the costs. In this analysis the NPV of project is higher than zero (NPV>0) which indicates the project is economically acceptable. MARR and the proportion of benefits to costs (B/C) are calculated as approximately 27% and 1.5 proves that installation of satellite-based CNS/ATM systems is economically justified.

V. Conclusion

Due to the growth of aviation in Iran and the advantages of the satellite-based CNS/ATM systems, it is necessary to introduce new technologies in order to attract more transit flights, improve air traffic management and follow the ICAO global planning. However, the implementation of CNS/ATM imposes a significant budget on the states, airlines, stakeholders etc. Accordingly, a clear resistance to switch from the existing systems to the new ones has been observed in the case of many countries such as Iran which are behind the schedule provided by ICAO. It clearly indicates the importance of economic analysis regarding replacing the new systems.

In this study, it has been shown that the introduction of future CNS/ATM systems in Iranian air transportation is economically justified as NPV of project is higher than zero, the proportion of benefits to costs is 1.5% and finally MARR is calculated as 27%. Since the MARR is higher than the assumed rate of return (i.e. 20%) and it is also close to the rate of return of the current high profit projects in Iran, it is likely that the investors would be willing to become involved in the project. Nevertheless, the economic analysis obtained by the NPV method can only provide an overall economic estimation of the project. The NPV method is conducted based upon several assumptions including future traffic, the costs of equipments, pricing strategies, the trend of transition from existing systems to the new ones, etc. Since, the value of NPV is highly dependent on the mentioned assumptions, conducting a sensitivity analysis can be considered as a complementary tool for conducting NPV economic analysis.

Table 2. Reduced operating cost benefits for B747 in domestic flights

	Equipments	**2010**	**2011**	**2012**	**2013**	**2014**	**2015**	**2016**	**2017**	**2018**	**2019**	**2020**	**2021**	**2022**	**2023**	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**
A	**Total flying hours (1000)**	240	264	319	319	351	387	425	468	515	566	622	685	753	829	911	1003	1103	1213	1334	1468
B	**The proportion of total flying hours by the craft B747**	$\frac{10}{109}$	$\frac{10}{109}$	$\frac{10}{109}$	$\frac{10}{109}$	$\frac{10}{109}$	$\frac{10}{109}$	$\frac{10}{109}$	$\frac{10}{109}$	$\frac{10}{109}$	$\frac{10}{109}$	$\frac{10}{109}$	$\frac{10}{109}$	$\frac{10}{109}$	$\frac{10}{109}$	$\frac{10}{109}$	$\frac{10}{109}$	$\frac{10}{109}$	$\frac{10}{109}$	$\frac{10}{109}$	$\frac{10}{109}$
C	**The proportion of the same craft equipped by CNS/ATM**	0.1	0.2	0.4	0.4	0.5	0.6	0.7	0.8	0.9	1	1	1	1	1	1	1	1	1	1	1
D	**The percentage of reduction in flying hours bused on CNS/ATM**	0	0	0.75	1.5	2.25	3	3.75	4.5	5.25	6	6	6	6	6	6	6	6	6	6	6
E	**The reduction in the number of flying hours based on CNS/ATM (1000) E=A*B*C*D/100**	0	0	0.06	0.17	0.36	0.65	1	1.55	2.23	3.11	3.42	3.77	4.15	4.57	5.02	5.52	6.08	6.67	7.34	8.09
F	**The costs of crafts utilization in one hour**	8100	8100	8100	8100	8100	8100	8100	8100	8100	8100	8100	8100	8100	8100	8100	8100	8100	8100	8100	8100
G	**Cost saving (1000$) G=E*F**	0	0	486	1397	2916	5225	8141	12515	18043	25211	27763	30497	33595	36997	40642	44712	49208	54068	59474	65489

Table 3. Costs of GNSS installation in Iranian aircrafts for domestic flights

Equipments		2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029
A	The number of aircrafts	89	98	107	118	130	143	157	173	191	210	230	254	279	307	337	371	408	449	449	544
B	The proportion of GNSS suites to be installed	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1	-	-	-	-	-	-	-	-	-	-
C	The number of GNSS suites to be installed (C=A*B)	9	9	9	9	9	9	9	9	9	8	-	-	-	-	-	-	-	-	-	-
D	The number of GNSS suites to develop the aviation (D=At-A t-1)	0	9	9	11	12	13	14	16	18	19	20	24	25	28	30	34	37	41	45	50
E	The number of GNSS suites replaced due to the out-agedness	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	9	18	18	20	21
F	Total number of GNSS suites (F=C+D+E)	9	18	18	20	21	22	23	25	27	27	20	24	25	28	30	43	55	59	65	71
G	The price of each suite (1000$)	58	58	58	58	58	58	58	58	58	58	58	58	58	58	58	58	58	58	58	58
H	Total investment costs (H=F*G)	522	1044	1044	1160	1218	1276	1334	1450	1566	1566	1160	1392	1450	1624	1740	2494	3190	3422	3770	4118
I	Total maintenance costs (1000$) I=F *G*2/15	70	139	139	155	162	170	178	193	209	209	155	186	193	217	232	332	425	456	503	549
J	Total costs (1000$) J=I+H	592	1183	1183	1315	1380	1446	1512	1643	1775	1775	1315	1578	1643	1814	1972	2826	3615	3878	4273	4667

Table 4. Results of Net Present Value analysis for future CNS/ATM

Equipments		2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029
A	**Benefits: Benefits resulted from the aircraft more efficient operation after CNS/ATM introduction (1000$)**	0	0	2111	4949	12251	19255	35937	54371	78565	109730	118599	132758	146029	160777	176632	194455	213867	235143	258582	284640
B	**Costs: Costs relating to the investment and maintenance of the available systems (1000$)**	3205	2587	2587	1765	1275	617	453	0	0	0	0	0	0	0	0	0	0	0	0	0
C	**Costs: Costs relating to the investment and maintenance of the CNS/ATM (1000$)**	592	1183	1183	1315	1380	1446	1512	1643	1775	1775	2623	3713	3801	4040	4243	5245	6102	6628	6997	7449
D	**Costs of connecting to the satellite of use GNSS (1000$)**	0	0	22000	22000	22000	22000	22000	22000	22000	22000	22000	22000	22000	22000	22000	22000	22000	22000	22000	22000
E	**Total costs (1000$)(E=B+C+D)**	25797	25796	25796	25080	24655	24063	23965	23643	23775	23775	24623	25713	25801	26040	26243	27245	28102	28628	28997	29449
F	**The gap between the costs and benefits per year (1000$)(F=A-E)**	-25797	-25796	-23685	020131	-12404	-4808	11972	30728	54790	85955	93976	107045	120228	134737	150389	167210	185765	206515	229585	255191
G	**NPV the annual gap between the costs and benefits**	-25797	-21497	-16448	-11650	-5982	-1932	4009	8576	12724	16659	15178	14407	13484	12593	11713	10853	10048	9308	8623	7988
H	**NPV the total annual benefits**	0	0	147	2864	5908	7738	12035	15174	18272	21266	19154	17868	16378	15027	13757	12621	11568	10599	9713	8908
I	**NPV the total annual costs (1000$) (I=G+H)**	-25797	-21497	-17914	-14514	-11890	-9670	-8026	-6598	-5529	-4608	-3977	-3461	-2884	-2434	-2044	-1768	-1520	-1290	-1089	-922

$\sum NPV\ benefits$ **=218998000**
$\sum NPV\ costs$ **=-147432000**
NPV of Project =136617000
$^{B}/_{C}$ **=1.5**

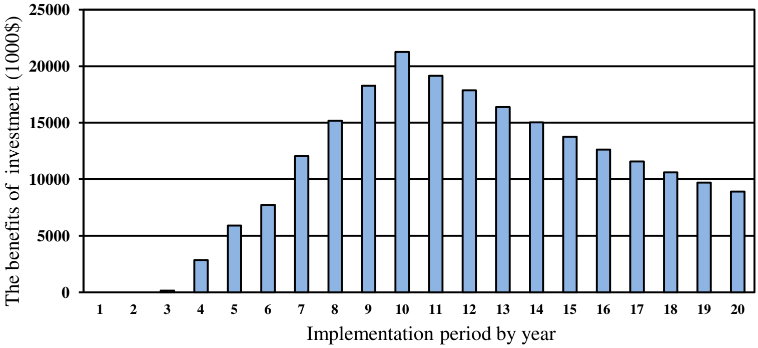


Figure 3. Annual NPV values for the benefits of CNS/ATM during implementation period

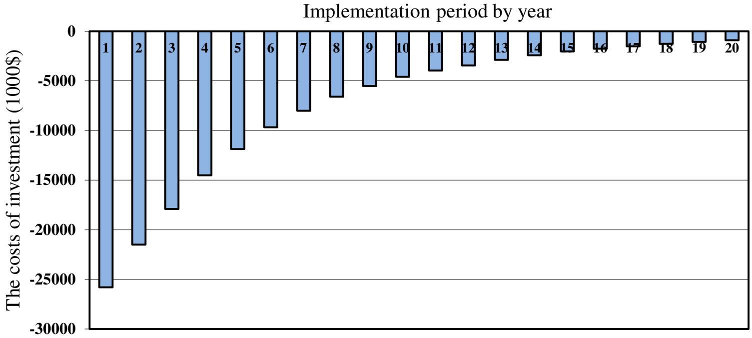


Figure 4. Annual NPV values for costs of CNS/ATM during implementation period

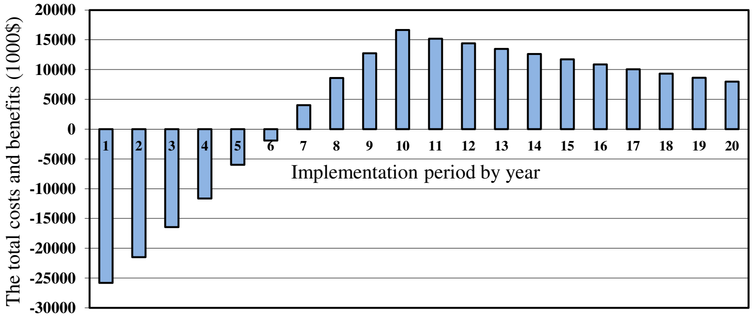


Figure 5. Annual NPV values for total costs and benefits during implementation period

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Air Transport and Operations
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Author Index