Agent-Based Modelling and Simulation of Safety and Resilience in Air Transportation

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To my parents

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Summary

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Purpose: In order to improve the safety, capacity, economy, and sustainability of air transportation, revolutionary changes are required. These changes might range from the introduction of new technology and operational procedures to unprecedented roles of human operators and the way they interact. Implementing such changes can introduce both negative and positive emergent behaviour. i.e. behaviour that arises from the interactions between system entities as proposed in innovative concepts. Currently, the inability to understand and control such behaviour prevents us from avoiding undesired negative emergent behaviours and promoting positive ones. In order to address this problem, this thesis aims to understand emergent behaviour in the complex socio-technical air transportation system.

Methods: The thesis proposes Agent-Based Modelling and Simulation (ABMS) as a method for capturing emergent behaviour of the socio-technical air transportation system, and evaluating novel system designs. The popularity of ABMS is driven by its capability of handling the increasing complexity of real world socio-technical systems that exhibit emergent behaviour. This thesis focuses on two main applications namely: 1) the identification of emergent safety risk of an active runway crossing operation; and 2) the evaluation of the role of coordination in Airline Operations Control (AOC) resilience. In both applications, ABMS has emerged as a key method because it is widely used in complexity science to understand how interactions give rise to emergent behavior. The agent-based models include all relevant human and technical agents, such as pilots and controllers and the decision support systems involved. Simulation of these agents interacting together is conducted to predict the impact of both existing and future concepts of operation.

Results: The applications in this thesis highlight that ABMS has the capability to reveal unexpected emergent behaviour and provide novel insights in air transportation. For the airport safety application, various types of emergent behaviour have been revealed due to the development and simulation of the agent-based model that covers the totality of interactions of components and their variability in performance over time. The Monte Carlo simulations make it possible to understand the potential of agents in restricting the risk in off-nominal scenarios, through capturing their stochastic nature and accounting for uncertainty. For the airline resilience application, novel insights were gained about the role of coordination in airline resilience. Capitalizing on established airline practice and research about human coordination from the psychology domain, the agent-based simulations evaluated the operational effects of AOC coordination policies on a challenging disruption scenario.

Conclusions & possible applications and implications: This thesis demonstrates that ABMS of air transport operations is a viable approach in gaining knowledge about emergent behaviour which was unknown before. This knowledge includes both bottlenecks of system designs and identified opportunities, and hence can be used to control and further optimize the socio-technical air transportation system. This also implies that ABMS can be a cost-effective method for evaluating new concepts during the early design phase of air transport operations.

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1

Introduction

This chapter provides an introduction to the safety and resilience topics addressed in this thesis. It describes the thesis goal and objectives, the problem, the agent-based approach, and the applications. Furthermore, the thesis overview will be clarified by means of short chapter descriptions which explain how each individual chapter is linked to the overall research.

1.1 Thesis goal and Objectives

In 2012, the European Commission has set high-level goals to be achieved by 2020 and beyond. These goals include a 3-fold increase in capacity, an improvement in safety by a factor of 10, and a reduction in ATM service costs by 50% (SESARJU 2015). In order to realize these challenging goals, significant changes in the air transportation infrastructure are foreseen. Past experience has shown that implementing such changes might sometimes lead to counterintuitive behaviours. For instance, Bar-Yam (Bar-Yam 2005) discusses the failure of design and implementation of the Advanced Automation System (AAS) in the previous century. A centrepiece of AAS was the replacement of the air traffic control system near airports. This process faced so many problems in terms of cost overruns, program delays, and safety issues, that it could only be partially completed after an FAA emergence decree. Bar-Yam argues that due to the level of complexity, different parts of the AAS design are so interdependent that changes in one part may have unforeseen effects on other parts, i.e. the causes and effects are not obviously related. This has become more and more apparent in our efforts to solve problems not only in air transportation, but also in other complex domains such as ecology and society.

Civil air transportation is an example of a large complex socio-technical system. It comprises interactions between different types of entities, including technical systems, operational stakeholders, regulators, and consumers (DeLaurentis and Ayyalasomayajula, 2009). Technology plays a central role as does the social context within which the various parties operate. The main characteristics of such systems is the appearance of emergent behaviours, i.e. collective properties that arise from the properties of the constituent parts. Due to the interactions between various heterogeneous components, the socio-technical air transportation system shows a plethora of different emergent behaviour impacting multiple spatial regions on multiple time scales. Such behaviours can be classified as either positive or negative emergent behaviours. Typical examples of the negative type include catastrophic accidents involving one or more aircraft, and network-wide consequences that may dramatically affect the performance the air transportation system, or in a future context, risk that was not anticipated before and might emerge from a new concept of operation, or new tools, or procedures. Examples of the positive type are the various control loops that are working in current aviation, within each aircraft itself and also those formed by the interplay between the aircraft crew and other ATC and airport operators. This type also concerns existing vulnerabilities that might disappear as a result of new changes (Woods et al. 2010). The key challenge is to learn understanding emergent behaviour and use this knowledge in design strategies allowing the mitigation of negative emergent behaviours and promoting positive ones.

The field of complexity science (also known as complex systems) has become popular in the literature for studying complex systems and identifying their emergent behaviour (NECSI 2015). In air transportation, a research network named ComplexWorld (ComplexWorld wiki 2015) was recently established by SESAR-JU to explore the potential of complexity science for the ATM domain. This was motivated by the need to understand interdependencies and interactions between system components and identify key lever points (Holland 2006) through which the performance of the socio-technical ATM system can be controlled. In line with this, the ambition of this thesis is to contribute to the understanding, modelling, and eventually optimization of the performance of the air transportation system that emerges from the interactions between system entities. In particular, the objectives of this thesis are identifying emergent behaviour in air transportation to improve ATM safety and AOC resilience. In realizing this, agent-based approaches have emerged as the key methods because they are widely used in complexity science for understanding how interactions give rise to emergent behavior. The next section provides more background about the agent-based approach.

1.2 Agent-Based Approach

1.2.1 What is an agent?

In the AI domain, although there is no widely agreed definition for an agent, there is general consensus that autonomy is central to the notion of agency. (Wooldridge 2009) explains that part of the difficulty is that beyond this autonomy point various attributes associated with agency are of different importance for different domains.

Among the various definitions in the literature for an agent are:

- An agent is anything that can be viewed as perceiving its environment through sensors and acting upon that environment through effectors (Russel & Norvig 2006).
- An autonomous agent is a system situated within a part of an environment, which senses that environment and acts upon on it, over time, in pursuit of its own agenda and so as to effect what it senses in the future (Franklin & Graesser 1997).

- An agent is a computer system that is situated in some environment, and that is capable of autonomous action in this environment in order to meet its delegated objectives (Wooldridge 2009).
- An agent is a system with the following properties (Tessier et al. 2002):
    - It lives in an artificial world W
    - It has facilities to sense W and to manipulate W
    - It has a (at least partial representation of W
    - It is goal-directed, and as a consequence it has the ability to plan its activities
    - It can communicate with other agents

In the context of air transportation, in particular where different actors, hardware, and software are interacting elements of a complex socio-technical system, we consider agents as autonomous entities that are able to perceive and act upon their environment. These agents may be humans, systems, organizations, and any other entity that pursues a certain goal. For instance, an air traffic controller can be viewed as an agent observing his/her environment (displays, alerting systems, runway availability, etc.) and acting upon this environment (e.g. through communicating with other agents like pilots/ other controllers, or turning off runway stop-bars remotely). The agent environment is understood as all surrounding human and non-human agents. However, this does not necessarily mean that an agent need to maintain information about all agents in his environment. Some agents can be relevant for him and some not. Another important point is that agents do not possess a unique memory all the time. For instance in the context of the previous example, the air traffic controller might forget to communicate or perform a certain task.

1.2.2 Two Main Approaches

Although there is significant knowledge and background overlap between technical Multi-Agent Systems (MAS) and ABMS of socio-technical systems (e.g. both use distributed autonomous agents) the two are used in complementary ways. The primary goal in ABMS of socio-technical systems is to search for explanatory insight into the collective behaviour of agents obeying simple rules, rather than solving specific practical or engineering problems as in MAS (Wikipedia 2015a). Researchers in ABMS of socio-technical systems develop simulations that can reveal system behaviour emerging from the agent's collective actions and interactions. In these simulations, the agent entities are used to represent actors in the real world (E.g. individuals or teams) and need not be intelligent technical system agents only. They are programmed to react to the computational environment in which they are located, where this environment is a model of the real environment in which the actors operate (Gilbert 2008). So with this comes the need for instance to represent human behaviour and social interactions. On the other hand, a technical MAS is a computerized system composed of multiple interacting intelligent agents. Here intelligence can include some methodical, procedural or algorithmic search. When running simulations of a technical MAS then this also is referred to as ABMS. In Nikolic & Kasmire (2013), a distinction was made between ABMS and MAS, however the explicit mentioning of technical MAS and ABMS of socio-technical systems was not done. According to their distinction, the main difference between ABMS and MAS is that ABMS sets up agents believed to have crucial characteristics of real world analogs to see what happens when they do whatever they do; while in a MAS agents are set up with exactly the characteristics, connections and choices that they need to achieve certain desired emergent states.

In air transportation, agent-based models of socio-technical systems and of technical MAS have been developed and used by the aviation community. These models have been applied to fulfil several purposes, e.g. to evaluate current and future operational concepts, to assess safety risk, or optimize ATC or airline processes. Table 1.1 gives an overview of these models and classifies them in the two distinct categories of technical MAS and ABMS of a socio-technical system. This overview has revealed interesting findings: 1) Technical MAS have been used before ABMS of socio-technical systems; 2) ATM systems apparently are among the oldest application areas of technical MAS and have been a standard application of research in the field since the work of Cammarata et al. (1983). It is also relevant to recognize that ABMS is known by many names, e.g. ABM (agent-based modelling), IBM (individual-based modelling), ABS (agent-based systems or simulation) are all widely-used acronyms, but ABMS will be used throughout this thesis.

Table 1.1: Models in air transportation using the agent-based paradigm

Publications (in chronological order)	Institute	Model purpose
Technical MAS		
Cammarata et al. 1983	Rand	Conflict resolution
Ljungberg & Lucas 1992	Australian Artificial Intelligence Institute	Assisting flow managers to arrange sequence of incoming aircraft
Langerman & Ehlers 1997	Rand Afrikaans University	Airline schedule development
Tomlin et al. 1998	University of California	Conflict resolution
Wangermann & Stengel 1998	Princeton University	Optimization of airline operations through negotiation
Nguyen-Duc et al. 2003	University of Paris 6, EUROCONTROL	Real time traffic synchronization
Wollkind et al	Texas A&M University	Conflict resolution using cooperative

2004		and negotiation techniques
Hwang et al 2007	Purdue University	Verification of collision avoidance algorithms
Sislak et al. 2007	Czech Technical University, US Air Force Research Laboratory	Conflict resolution
Tumer & Agogino 2007	Oregon State University, NASA Ames Research Centre	Traffic flow management
Gorodetsky et al. 2008	St. Petersburg Institute for Informatics and Automation of the Russian Academy of Sciences	Conflict resolution
Mao 2011	Universiteit van Tilburg	Scheduling aircraft ground handling operations
Castro et al. 2014	University of Porto, MASDIMA	Airline disruption management
ABMS of a Socio-Technical System		
Blom et al. 2001	National Aerospace Laboratory NLR	Accident risk assessment of advanced ATM concepts
Corker 1999	San Jose State University	Evaluation of advanced ATC operational concepts
Campbell et al. 2000	The MITRE Corporation	Policy analysis of collaborative traffic flow management
Callantine 2001	San Jose State University, NASA Ames Research Centre	Evaluation of advanced ATC operational concepts
Blom et al 2003a	National Aerospace Laboratory NLR	Accident risk assessment of opposite en-route traffic lanes
Blom et al 2003b	National Aerospace Laboratory NLR	Accident risk assessment of simultaneous converging instrument approaches
Niedringhaus 2004	The MITRE Corporation	Assessing the impact of stakeholder decisions on the NAS
Lee et al. 2005	NASA Ames Research Centre	Evaluation of advanced ATC operational concepts
Mehta et al. 2006	Purdue University, Lockheed Martin and Simulex	Evaluation of advanced ATC operational concepts
Blom et al 2009a	National Aerospace Laboratory NLR	Free flight equipped aircraft
DeLaurentis & Ayyalasomayajula 2009	Purdue University	Assessing the impact of stakeholder actions on the air transport network
Stroeve et al 2009	National Aerospace Laboratory NLR	Accident risk assessment of active runway crossings
Wolfe et al. 2009	NASA Ames Research Centre	Evaluation of air traffic flow management concepts
DeOliveira et al 2010	Atech Tecnologias Críticas , University of São Paulo, National Aerospace Laboratory	Safety risk assessment of an advanced ASAS interval management concept
Kuhn et al. 2010	University of Louisville, Louisiana Tech University, West Virginia University, Argonne National Laboratory	Airline market share prediction
George et al. 2011	Intelligent Automation, University of California Santa Cruz, Raytheon Company, Sensis Corporation, Mosaic-ATM, Aerospace Computing, NASA (Ames, Glenn, and Langley)	Evaluation of current and future operational concepts
Sharpanskykh &	Vrije Universiteit Amsterdam, National	Assessment of safety culture

Stroeve 2011	Aerospace Laboratory NLR	
Darabi et al. 2014	Stevens Institute of Technology	Studying competition and collaboration between airlines
Gurtner et al. 2014	Scuola Normale Superiore di Pisa, Deep Blue, Università degli Studi di Siena, Santa Fe Institute	Studying airspace allocation in various conditions
Molina et al. 2014	Technical University of Madrid	Evaluating the impact of new concepts and regulations on the ATM network

1.2.3 Why ABMS?

We live in an increasingly complex world. Systems that we need to model and analyse are becoming more complex in terms of their interdependencies. Conventional modelling tools may not be applicable as they once were (Macal & North 2014). The popularity of ABMS is driven by its capability of handling the increasing complexity of real world socio-technical systems that exhibit emergent behaviour (Holland 1997, Chan et al. 2010). This is because it can represent important phenomena resulting from the characteristics and behaviours of individual agents and their interactions (Railsback & Grimm 2012). Bonabeau (2002) captures the benefits of ABMS over other modelling techniques in three statement: (1) ABMS captures emergent phenomena; (2) ABMS provides a natural description of a system; and (3) ABMS is flexible. It is clear however that the ability of ABMS to capture emergent behaviour is what drives the other benefits. Jennings (2000) outlines that ABMS and complex system development requirements are highly compatible. Jennings (2000) shows that ABMS techniques are particularly well suited to complex systems because: a) they provide an effective way of partitioning the problem space of a complex system; b) they provide a natural means of modelling complex systems through abstraction; and c) they capture the interactions and dependencies. In the same vein, (Burmeister et al. 1997) discuss the benefits of using an ABMS approach in domains that are functionally or geographically distributed into autonomous subsystems, where the subsystems exist in a dynamic environment, and the subsystems have to interact more flexibly. According to Burmeister, ABMS can be used to structure and appropriately combine the information into a comprehensible form. For a large complex system such as a traffic system, ABMS provide the tools for analyzing, modeling, and designing the whole system in terms of its subsystems, each with its own set of local tasks and capability. The integration can then be achieved by modeling the interactions among the subsystems. So ABMS provide abstraction levels that make it simpler and more natural to deal with the scale and complexity of problems in these systems. Agent components can be described at a high level of abstraction, yet the resulting systems are very efficient (Burmeister et al. 1997). (Burmeister et al. 1997) conclude that ABMS reduce the complexity in systems design by making available abstraction levels that lend themselves to a more natural way of modeling the problem domain. They enhance the robustness and adaptivity of systems by virtue of increasing the autonomy of subsystems and their self-organization.

1.2.4 ABMS Tools

Nikolai & Madey 2009 have examined the entire continuum of ABMS tools and created a corresponding page in Wikipedia (Wikipedia 2015b) based on their findings. In their examination, Nikoley & Madey (2009) compared 53 tools with regard to five basic criteria which are usually considered by users when selecting a specific tool. These criteria are 1) the language required to program the model and run the simulation; 2) the type of license; 3) the operating system required to run the tool; 4) the primary domain for which the tool is intended; and 5) the types of support available to users. In another review, Railsback et al (2006) have focused on four tools that have succeeded to a large extent in multi-agent systems. These include MASON, NetLogo, Repast, and Swarm. Through implementing example models in each of these tools, Railsback et al (2006) were able to compare some performance characteristics such as execution speed. In their conclusion, Railsback et al (2006) argue that the variety of tools and their objectives has its benefits, and that it is difficult to recommend which ABMS tool is best because: 1) the tools continue to evolve, some rapidly; 2) not all tools have been reviewed; and 3) there are more possible ways to implement the example models. In the air transportation domain, there has also been a number of highly specialized tools that were successfully used. For instance Brahms (Wolfe et al. 2009) was used to develop agent-based simulations of Collaborative Air Traffic Flow Management; LEADSTO (Sharpanskykh & Stroeve 2011) was used to study safety culture in Air Traffic Control, and TOPAZ (Blom et al. 2001, Blom et al 2003a-b, Blom et al 2009a, Stroeve et al 2009, Deoliveira et al 2010) was used to assess the safety risk in different ATM applications. Table 1.2 summarizes these widely used tools from both domains.

The two applications considered in this thesis have played a key role in selecting the most suitable tool. For the airport safety application, it was decided to choose TOPAZ because of two primary reasons: 1) because it enables the integration of highly specialized and complementary complexity science techniques dedicated to ATM safety risk analysis including: the Stochastically & Dynamically Coloured Petri Nets (SDCPN) (Everdij & Blom 2010) which provides formalisms for specifying and composing interacting agents and their stochastic analysis; rare event Monte Carlo simulations (Blom et al 2009b) and sensitivity analysis (Everdij et al 2006) for dealing with uncertainty that is inherent to safety risk analysis; and 2) the availability of direct support and trainings from the tool developers. For the airline resilience application, it was initially decided to either use Brahms or LEADSTO because the main purpose was to simulate coordination and collaboration processes in an AOC centre. Eventually, LEADSTO was used because of the availability of several example LEADSTO models in the areas of emergency response, organizational modelling, and behavioural dynamics (van den Broek et al. 2006, Bosse et al. 2007b, Sharpanskykh & Treur 2006, Hoogendoorn et al. 2008), all of which are closely related to the airline disruption management domain and therefore were very helpful learning examples. Table 1.3 provides more complex characteristics of the two tools that have been used in this research.

Table 1.2: Comparing some of the popular ABMS tools

Agent-based tool	**Primary Domain**	**License type**	**Programming language**	**User Support**
Brahms	Work practice modelling	Academic purposes (closed source)	Brahms language	User manual, tutorial, online forum, wiki
LEADSTO	Behavioural science, Organizational modelling	Academic purposes (closed source)	Prolog + Visual programming capability	User manual, tutorial, online forum, FAQ, bug list, example models, publications, Interviews with developers
MASON	General purpose agent-based	Academic free license (open source)	Java	User manual, turorial, online forums, APIs, publications, 3rd party extensions
NetLogo	Social and natural sciences, and education	Free (closed source)	Logo	User manual, tutorial, online forums, FAQ, bug list, publications, 3rd party extensions
Repast	Social sciences	BSD (open source)	Java + Visual programming capability	User manual, tutorial, online forums, FAQ, bug list, example models, publications, 3rd party extensions
Swarm	General purpose agent-based	GPL (open source)	Java	User manual, tutorial, FAQ, bug list, example models, publications, wiki,
TOPAZ	ATM safety	Conditionally free	Delphi (Visual programming capability currently in development)	Specialized training workshops, user manual, tutorial, example models, publications

Table 1.3: ABMS tools used throughout this thesis

Aspects	**ABMS Tools**	
	TOPAZ	LEADSTO
Application	Airport safety (active runway crossing)	Airline resilience (disruption management)
Modelling formalism	Stochastically and Dynamically Coloured Petri Nets (SDCPN)	Temporal Trace Language (TTL)
Development Environment	Delphi/TOPAZ	LEADSTO (Prolog like)
Ontology	Defined by the places and colours used in the petri nets	Defined using sorts, elements of sorts, and logical predicates.
Dynamics representation	Stochastic differential equations and petri nets transition	Time-based rules (predicates)
Rare event Monte Carlo simulation	yes	no
Computational load	Relatively low	Relatively high

1.3 Emergent Safety Risk

1.3.1 Motivation

In the literature, various safety assessment approaches have been proposed to analyse accidents. Everdij et al. (2010) give an extensive overview of safety methods. These approaches can be categorized into three main types, namely:

1. Sequential Accident Models: are widely used in safety assessment methodologies (Eurocontrol 2006, Damidau et al. 2010). In these models, the accident occurrence is described as the result of a sequence of events that occur in a specific order. The models assume that there are well-defined cause-effect links that propagate the effects of events leading to an accident. Recent views indicate that such models may not be adequate to represent the complexity of modern socio-technical systems (Hollnagel et al. 2006). This is because of the difficulty to represent the large number of interactions between humans, technical systems and the dynamics of these interactions. Other limitations of event-chain models which mostly use fault and event trees, are reflected in the fact that the focus is mainly on errors, whereas it should be shifted towards the circumstances and context in which the actions take place and decisions are made.
2. Epidemiological Accident Models: Motivated by the need to better understand accidents, a new class of epidemiological accident models began to gain popularity in the 1980's (Hollnagel 2004). These models consider events leading to accidents in analogy with spreading of a disease, i.e. combination of failures and latent / environmental conditions leading to degradation of barriers and defences. The latent conditions support the understanding of accident causation beyond the proximate

causes. However, epidemiological models still follow the principles of sequential models as they show the direction of causality in a linear fashion (Hollnagel 2004). Examples of epidemiological accidents models are the Swiss cheese model, and the Bayesian belief networks (Adusei-Poku 2005) which allow the inference of a future event based on prior evidence.

3. Systemic Accident Models: In systemic accident models, accidents are the result of unexpected and uncontrolled relations between system entities. Examples of systemic accident models include the System-Theoretic Accident Model and Processes (STAMP) developed by Leveson (2004) using concepts from system thinking and system dynamics, and the Traffic Organization and Perturbation-AnalyZer (TOPAZ) developed by Blom et al. (2001) using the agent-based paradigm. STAMP follows a top down approach and considers the technical, human and organizational factors, whereas TOPAZ follows a bottom-up approach and consider interactions between human operators and their environment.

Sequential and epidemiological safety approaches assume well defined cause-effect links that propagate the effects of events contributing to the safety risk. However, recent views indicate that such models may not be adequate to represent the complexity of modern socio-technical systems (Hollnagel et al. 2006). Instead, systemic accident approaches form a logical choice for the safety risk analysis from a socio-technical perspective. As illustrated before, such approaches can be either top-down or bottom-up approaches. For instance, an accident model using concepts from system dynamics would abstract from single entities and take an aggregate view by describing the global system behaviour e.g. in terms of interacting feedback loops. On the other hand, it would not be possible to define the global system behaviour in an accident model using an ABMS approach. Instead one needs to define behaviour at the individual level, and then global behaviour would emerge from the individuals and their interactions (bottom-up approach) (Borshchev & Filippov 2004).

Borshchev and Filippov 2004 have compared the major simulation paradigms including ABMS and system dynamics and have found that ABMS captures more real life phenomena than other approaches. However, this does not mean that ABMS is a replacement of other approaches. There are a lot of applications where system dynamics for instance is most suitable (see for instance Forrester 1971), and using ABMS does not make sense because of the nature of the problem. It is also possible to combine both top-down and bottom-up approaches which was shown to provide new insights in the assessment of future air transportation concepts (Lewe et al 2012). One of the main benefits of using an ABMS approach is the ability to model heterogeneous individual abilities and attributes such as agent's experience, memory, or intelligence all of which are hard to represent by the previous approaches (Gilbert 2008). Such attributes can represent a wide range of agent behaviours. Macal & North (2014) list several criteria where ABMS can offer distinct advantages to conventional simulation approaches such as discrete event simulation, system dynamics, and other quantitative modelling techniques. Some of these criteria are:

- When the problem has a natural representation as being comprised of agents.
- When there are decisions and behaviours that can be well-defined.
- When it is important that agents adapt and change their behaviours.

For the airport safety application, this thesis explores ABMS because it can be used at a low abstraction level in order to well capture the relevant agents who directly control the hazardous process. As such, an agent-based model would explicitly incorporate the complexity arising from the behaviour of individual agents and interactions that exist in the real world.

1.3.2 Problem Statement

Air transportation systems are facing the challenge to innovate air and ground infrastructures and ATM procedures to meet the levels of projected passenger volume and quality of services expected in the coming years. The most critical aspects of this challenge is to understand the impact of new designs on both safety and efficiency, since risks that were not known before might emerge. Following Bedau (2008), simulation is needed to capture yet unknown emergent behaviour. There are three established types of simulation tools available in air transportation (Blom et al 2015):

- Human-in-the-loop simulation; this works well for the identification of emergent behaviour that happens under normal conditions. For example to identify that a pilot or controller tends to use a technical system or procedure in a different way than intended by the developers.
- Network flow-based simulation: this works well for identifying how specific propagation patterns in the air transport network change as a result of a new design. For example to identify the impact of the design change on the traffic flows in case of a significant disturbance, such as a bad weather condition (e.g. Gong et al. 2012).
- Agent Based Modelling and Simulation: this works well in case of many interacting agents, in particular if these agents have intelligence, e.g. pilots and controllers. Shah et

al. (2005) explain that ABMS can identify emergent behaviour in air transportation in which human agents play a key role.

The problem is that these three simulation tools alone cannot capture emergent behaviours of exceptional safety critical events, nor can they be used to analyse the safety risk of a novel design. The gap between these established simulation approaches and what is required is depicted in Figure 1.1. At the bottom of the safety pyramid there are the controller and pilot actions, which may happen in the order of 10 to 100 events per flight hour. These events are well analysed by human-in-the-loop (HITL) simulation and ABMS. However, HITL and ABMS leave emergent behaviour unexplored that happens along the flank and at the top of the safety pyramid. Halfway the flank, there are incidents happening in the order of once per 10 thousand flight hours. Just below the top there are accidents, which happen in the order of once per ten million flight hours. At the top you have mid-air collisions which may happen in the order of once per billion flight hours. The ratio between the event frequencies at the top versus those at the bottom are in the order of 10 to the power 10. This is abridged by complementary techniques such as the ones used in TOPAZ which are explained in the next section.

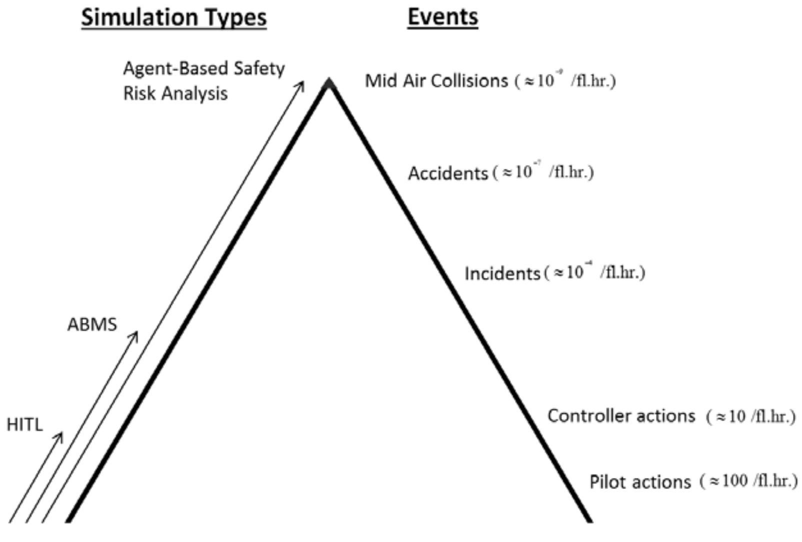

Figure 1.1: The Air Traffic Management Safety Pyramid (Blom 2013) showing that complementary simulation tools are required to evaluate weak emergent behaviour along the flank and at the top of the safety pyramid of (Heinrich 1931).

1.3.3 TOPAZ

Because the time scales of events at the top and bottom of the safety pyramid are widely separated, a straightforward MC simulation of an agent-based model might take a life time. A way out of this problem is to integrate ABMS with the power of dedicated mathematical tools. For this purpose, NLR has developed TOPAZ which makes use of several complementary mathematical methods including: The Stochastically & Dynamically Coloured Petri Nets (SDCPN) (Everdij & Blom 2010) which provides formalisms for specifying and composing interacting agents and their stochastic analysis; rare event Monte Carlo simulations (Blom et al 2009b) for estimating reach probabilities; and sensitivity analysis and uncertainty quantification (Everdij et al 2006) for dealing with uncertainty that is inherent to safety risk analysis.

Developing an agent-based model in TOPAZ is performed in a hierarchical way. At the highest hierarchical level, the relevant agents to be evaluated are distinguished depending on the operation involved. In a runway crossing operation for instance, where human operators and technical systems concurrently interact, the agents might include the runway controller, the ATC alerts, both crossing and taking-off aircraft, as well as their flight crew. In TOPAZ, these interactions include deterministic and stochastic relationships, as it is appropriate for the human performance or system considered. TOPAZ has many toolsets which have been used for accident risk evaluation in many applications such as opposite en-route lanes (Blom et al. 2003a), Simultaneous converging approaches (Blom et al. 2003b), active runway crossings (Stroeve et al. 2009), free flight equipped aircraft (Blom et al. 2009a), and ASAS-Interval Management (DeOliveira et al 2010).

1.3.4 Active Runway Crossings

In many airports around the world, runway crossings are used by taxiing aircraft from the apron area to the runway and vice versa. These crossings are attractive because they reduce the taxiing time and save fuel. However, they also have safety implications, namely the risk of having a runway incursion. A runway incursion is defined by the International Civil Aviation Organization (ICAO) (ICAO 2007) as “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”. While a runway incursion does not imply a collision, the probability of an accident is not nil. One of the most famous aviation accidents is the Tenerife airport disaster that occurred on March 1977. Two Boeing 747 aircraft, operated by KLM and Pan American World Airways, respectively collided. While the Pan American aircraft was taxiing, the KLM aircraft took off, resulting in a collision causing 583 fatalities. This accident is the deadliest aviation accident in history (Wikipedia 2015c). 38 years later, runway incursions are still frequently reported in many countries. In the United States alone, preliminary data (FAA 2015) shows a total number of 653 runway incursions in the first half of FY2015, a 17 percent increase over the same span in FY2014.

Researchers and planners operating from different perspectives have proposed many options to address this problem, such as new technology (e.g. in aircraft, ATC tower, or Airport) and new procedures such as ICAO compliant procedures. These proposals aim to reduce the probability of runway incursions, and reduce the accident risk in case runway incursions occur. However, assessing the safety of these proposals is a demanding task, given the complex interactions between the highly distributed multiple human operators, technical systems, and procedures. As explained before, this thesis proposes the integration of ABMS and Monte Carlo simulations to identify emergent safety risk for the active runway crossing application.

1.4 Resilience Modelling and Analysis

1.4.1 Motivation

The resilience of the current air transportation system is implicitly tested around the globe on a regular basis. Each day of operation, an airline's flight schedule is subject to a multitude of disruptions ranging from deteriorating weather, through passenger delays, up to aircraft or crew related problems. Each such disruption may be detrimental to the realisation of the daily fleet schedule of an airline and to the smooth and timely transportation of passengers from their origins to their destinations. Within AOC, Operators with different roles interact and coordinate in real-time to manage disruptions. Consideration of the aircraft routings, crew, maintenance, weather, customer needs, and turnaround processes complicate AOC. Current practice consists of coordination between humans who play a key role in recovering from disruptions and make sure airline operations adhere to the strategic plan (schedule) as closely as possible with minimum costs. Consequently most problems are adequately solved, and most of the disruptions pass without substantial inconvenience for passengers.

In some cases, however, the resilience of the air transportation system falls short resulting in tremendous costs to both airlines and passengers. A typical example is the JetBlue crisis that took place on Valentine's Day of 2007 when a snowstorm hit the Northeast and

Midwest, throwing JetBlue's operations into chaos (Brizek 2011, Wikipedia 2015d). Because AOC operators followed the policy of never cancelling flights, the airline was forced to keep several planes on the ground during the storm. As a result, passengers were kept waiting at airport for flights to take off. In some cases, passengers who had already boarded were not allowed to disembark, and ended up spending as many as 11 hours trapped on planes on a frozen tarmac in New York. Customer service was damaged for JetBlue, as most people were not happy with the long amount of time they spent on the planes. Even though JetBlue offered refunds to passengers, their reputation was still damaged as passengers compared these long delays as hostage situations (Brizek 2011). Eventually, the airline was forced to cancel most of its flights due to the on-going storm. The crisis reportedly cost JetBlue $30 million.

1.4.2 Problem Statement

Thanks to the influential work by Hollnagel and other researchers (2006), the value of resilience in air transportation has been well recognised in behaviour sciences. Qualitative modelling of resilience in air transportation started some six years ago (Eurocontrol 2009). A good illustration of the associated kind of results obtainable for ATM is provided by Woltjer et al. (2013). Despite these efforts, resilience still remains not well understood in terms of quantitative models. Efforts should be geared towards modelling and simulation in order to mitigate the negative impacts of disturbances and help design a resilient future air transportation system. To address this gap, this thesis proposes developing and evaluating multi-agent coordination models for airline disruption management. This was motivated by the central role that coordination plays in the resilience of air transportation.

Coordination is a unique capability by humans that plays an essential role in recovering from disruptions. Klein (2001) defines coordination as "the attempt by multiple entities to act in concert in order to achieve a common goal by carrying out a script they all understand." Within AOC for instance, many operators with different roles interact and coordinate in managing a large a variety of unforeseen disturbances that happen during the day of operation. Consideration of the aircraft routings, crew, maintenance, weather, customer needs, and turnaround processes complicate AOC. In order to start thinking about designing a resilient air transportation system, a prerequisite is to first develop an in-depth understanding of the current interaction and coordination processes and optimize them. Otherwise, decision-support systems could disrupt rather than support coordination and likely result in coordination breakdowns (Klein et al. 2005), and tremendous costs to aviation stakeholders.

1.4.3 LEADSTO

Developing the AOC agent-based model is performed in three major steps. In the first step, the agents and their attributes are identified (e.g. operators at the AOC centre and decision-support systems). Once the key agents have been defined, their behaviour is accurately specified in the next step and verified with experts. Subsequently, interactions between the agents are represented and the model is verified. In order to formally capture the dynamic properties of airline disruption management in the model, this thesis makes uses of the simulation environment LEADSTO (Bosse et al. 2009). LEADSTO proved its value in a number of projects in multi-agent systems research (e.g. in the areas of emergency response, organizational modelling, and behavioural dynamics (van den Broek et al. 2006, Bosse et al. 2007b, Sharpanskykh & Treur 2006, Hoogendoorn et al. 2008). In LEADSTO, one can specify both qualitative and quantitative aspects of complex socio-technical systems using the Temporal Trace Language (TTL). TTL has the semantics of order-sorted predicate logic (Manzano 1996) that is defined by a rich ontological base. This base includes sorts, constants within these sorts, functions, predicates, and variables. Relationships between system components can be expressed in a straightforward way. This provides wide means for the conceptualization of the airline disruption management domain. In addition, TTL is an extension of the standard multi-sorted predicate logic in the sense that it has explicit facilities to represent dynamic (temporal) properties of systems. Such a temporal expressivity is particularly important for the representation and analysis of processes over time.

1.4.4 Airline Disruption Management

Airline disruption management plays a central role in the resilience of the air transportation system. The goal of disruption management is to return to the published airline schedule while minimizing recovery costs. To date, studies on airline disruption management e.g. (Grandeau et al. 1998, Bratu & Barnhart 2006, Abdelghany et al 2008, Castro & Oliveira 2011, Castro et al. 2014) have mainly concentrated on developing decision-support systems rather than studying the socio-technical challenges of the operation. According to Clausen et al. (2005), there is a gap between the support offered by IT systems and the reality faced in AOC centres. There is also a very limited number of studies (Pujet & Feron 1998, Kohl et al. 2007, Feigh 2008, Bruce 2011a-b) that address AOC as a socio-technical system. Pujet and Feron (1998) have investigated the dynamic behaviour of an AOC centre of a major airline using a discrete event model. Kohl et al. 2007 have studied numerous aspects of airline disruption management, and argue that realistic approaches to disruption management must involve humans in the key parts of the process. Feigh 2008 has examined the work of airline controllers at four US airlines of varying sizes, and applied an ethnographic approach for the development of representative work models. Bruce (2011a-b) has examined many aspects of decision-making by airline controllers through conducting multiple case studies at six AOC centres. Although these socio-technical studies provide valuable insight into the challenges of an AOC centre, this has not yet led to a significant improvement in the performance of the socio-technical AOC system. In addition, none of the studies addresses coordination which plays a central role in recovering from disruptions and hence improving the resilience of the air transportation system. In order to address coordination, this thesis proposes using ABMS because it has been extensively used to model and analyse complex socio-technical systems, and address cases where agents need to coordinate and solve problems in a distributed fashion.

1.5 Thesis Overview

All chapters in this thesis except the introduction and conclusion chapters 1 and 7, have been published. The contents of each chapter have been preserved in their original format so that they can be read separately. Below a short description of each chapter is provided which explains how the chapters are related to each other and to the overall research.

Chapter 2 - Airport performance modelling using an agent-based approach: In this chapter, we study the large variety of actor types and Key Performance Areas (KPAs) at an airport and how these KPAs have different meanings for different actor types. These KPAs include safety, capacity, economy, and the environment. The chapter also identifies key airport challenges in terms of these different KPAs, and discuss potential conflicts that might arise due to differences in goal settings. The chapter proposes using the agent-based paradigm to model and analyse the complex socio-technical air transportation system to help increase the knowledge about the identified problems, and give insights on what actors should do to achieve their different goals.

Chapter 3 - Agent-based modelling and simulation of emergent behaviour in air transportation: This chapter applies ABMS to identify emergent safety risk at an airport. The specific application considered is the controlled crossing by a taxiing aircraft of a runway that is in use for controlled departures. The agent-based model is used to conduct rare event Monte Carlo (MC) simulations of both nominal and off-nominal scenarios. The chapter also explores the relation of the simulation results with various emergent behaviour types as defined and discussed in the literature. For this, a recent taxonomy for emergent behaviour has been used. This taxonomy identifies different types of emergent behaviour ranging from simple emergence, through weak emergence, up to strong emergence.

Chapter 4 - Resilience in air transportation In order to increase the resilience of the air transportation system, there is a need to identify, understand, and model system interdependencies of the complex socio-technical air transportation system and analyse its response to the large variety of possible disruptions. This chapter aims to show that a complexity science perspective can be a valuable asset in meeting this need. In particular, the chapter aims at answering the following questions: What is resilience and how is it measured? Why use complexity science to model and analyse resilience? And which complexity science approaches can be used?

Chapter 5 - A study into modelling coordination in disruption management by airline operation control: In this chapter we identify the potential of joint activity theory from the psychology research domain for AOC. In particular, we exploit a theoretical framework of coordination to analyse the current way of working at an AOC centre for a specific test case. The findings are then used in the next chapter to develop an agent-based model of AOC.

Chapter 6 - Agent-based modelling and simulation of coordination by airline operations control: This chapter demonstrates the benefits of applying ABMS to an airline problem. The specific application concerns airline operations control, which core functionality is one of providing resilience to a large variety of airline operational disruptions. Motivated by the need to improve resilience, this chapter implements and compares four coordination policies for disruption management. Three policies are based on established practices, whereas the fourth is based on the joint activity theory introduced in the preceding chapter. Each of these policies has been characterized in terms of the various coordination techniques that have been developed in the literature. In order to evaluate the four policies, an agent-based model of the AOC and crew processes has been developed. Subsequently, this agent-based model is used to evaluate the operational effects of the four AOC policies on a challenging airline disruption scenario.

Chapter 7 – Conclusion: This chapter provides a discussion of all research results obtained in this thesis and recommendations for future research

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2

Airport Performance Modeling Using an Agent-Based Approach

In this chapter, we study the large variety of actor types and Key Performance Areas (KPAs) at an airport and how these KPAs have different meanings for different actor types. These KPAs include safety, capacity, economy, and the environment. The chapter also identifies key airport challenges in terms of these different KPAs, and discuss potential conflicts that might arise due to differences in goal settings. The chapter proposes using the agent-based paradigm to model and analyse the complex socio-technical air transportation system to help increase the knowledge about the identified problems, and give insights on what actors should do to achieve their different goals.

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Airport Performance Modeling Using an Agent-Based Approach

Abstract: 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.

2.1 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 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.

2.2 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.

2.2.1 Airports 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 2.1 summarises airside models from the literature and maps them according to these three aspects.

Table 2.1: 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

2.3 Airport Performance Challenges

This paper focuses on four key challenges airports are facing in terms of safety, capacity, economy, and environment.

2.3.1 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 2.2 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 2.2: 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	Collision or near collision with obstacles/objects/terrain while	LALT

Operations	intentionally operating near the surface (excludes take-off or landing phases)	
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
Take-off 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

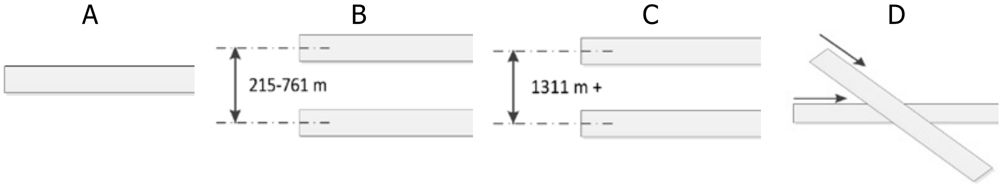
2.3.2 Capacity Challenge

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 2.3 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.

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.

Table 2.3: 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

2.3.3 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 2.4 shows a complete structure for the flight operating costs from an airline perspective.

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.

Table 2.4: 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

2.3.4 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 2.5 gives a qualitative description of typical effects of L_{dn} on nearby communities.

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 CO2 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 CO2, a little less than 30 percent of water vapor H2O, and less than 1 percent of emissions that have negative health impacts [49]. The last category includes nitrogen oxides NOx, carbon monoxide CO, oxides of sulfur SOx, 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 2.6 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 2.5: 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

Table 2.6: Significance of main effects of emissions (Source [51])

Pollutant	Health effects
Nitrogen Oxides NOx	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 SOx	Sulphur oxides include sulphur dioxide SO2, 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

2.4 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 2.1 identifies key actors including their hierarchical relationships across three levels.

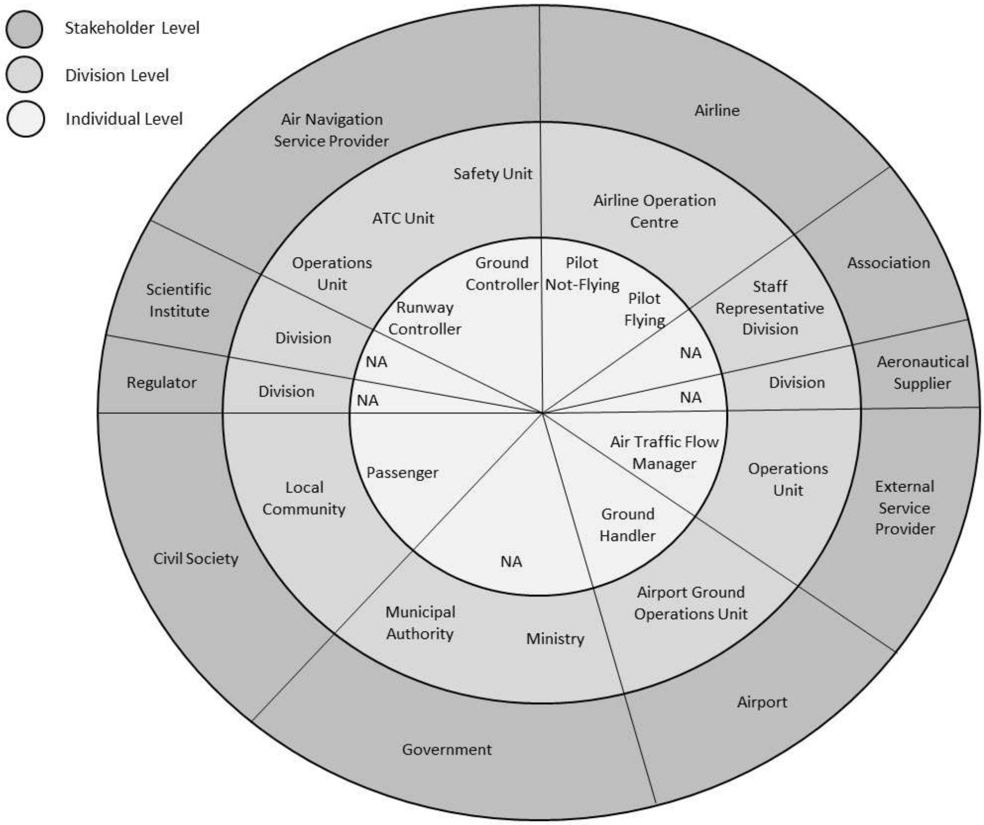


Figure 2.1: Key Actors in the air transport sector

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 figure 2.1 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.

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 2.7). 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 2.7: 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 2.8: 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	+	-	-	+

Table 2.8 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.

2.5 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' 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 2.9 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 2.9: 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

2.6 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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3

Agent-Based Modelling and Simulation of Emergent Behaviour in Air Transportation

This chapter applies ABMS to identify emergent safety risk at an airport. The specific application considered is the controlled crossing by a taxiing aircraft of a runway that is in use for controlled departures. The agent-based model is used to conduct rare event Monte Carlo (MC) simulations of both nominal and off-nominal scenarios. The chapter also explores the relation of the simulation results with various emergent behaviour types as defined and discussed in the literature. For this, a recent taxonomy for emergent behaviour has been used. This taxonomy identifies different types of emergent behaviour ranging from simple emergence, through weak emergence, up to strong emergence.

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Agent-Based Modelling and Simulation of Emergent Behaviour in Air Transportation

Abstract - Purpose: Commercial aviation is feasible thanks to the complex socio-technical air transportation system, which involves interactions between human operators, technical systems, and procedures. In view of the expected growth in commercial aviation, significant changes in this socio-technical system are in development both in the USA and Europe. Such a complex socio-technical system may generate various types of emergent behaviour, which may range from simple emergence, through weak emergence, up to strong emergence. The purpose of this paper is to demonstrate that agent-based modelling and simulation allows identifying changed and novel rare emergent behaviour in this complex socio-technical system. **Methods:** An agent based model of a specific operation at an airport has been developed. The specific operation considered is the controlled crossing by a taxiing aircraft of a runway that is in use for controlled departures. The agent-based model includes all relevant human and technical agents, such as the aircraft, the pilots, the controllers and the decision support systems involved. This agent-based model is used to conduct rare event Monte Carlo (MC) simulations. **Results:** The MC simulation results obtained confirm that agent based modelling and simulation of a socio-technical air transportation system allows to identify rare emergent behaviour that was not identified through earlier, non-agent-based simulations, including human-in-the-loop simulations of the same operation. A typical example of such emergent behaviour is the finding that alerting systems do not really reduce the safety risk. Conclusions: Agent based MC simulations of commercial aviation operations has been demonstrated as a viable way to be evaluated regarding rare emergent behaviour. This rare emergent behaviour could not have been found through the more traditional simulation approaches.

Keywords: Agent-based modelling and simulation, Complex socio-technical systems, Air transportation, Airport operations, Safety risk analysis

3.1 Introduction

THE Air Traffic Management (ATM) community is continuously seeking to improve ATM system performance and identify best practices (PRC & ATOS PBU 2009). Within the Single European Sky ATM Research program (SESAR), a performance framework for the future European ATM system has been proposed (SESAR Consortium 2006). This framework aims at improving ATM system performance, in particular with regard to the Key Performance Areas (KPAs) safety, capacity, cost efficiency, and environment. These KPAs are important to accommodate the expected air traffic growth and respond to user's concerns (Bouarfa et al. 2012; Fron 2001). As part of this framework, airport performance is considered to have an impact on the entire ATM system performance, as airports make up the fixed nodes on which the ATM system is built (Ball et al. 2007; PRC 2009).

Civil air transportation is an example of a complex socio-technical system. Each airport comprises of interactions between a variety of facilities, users, technical systems, human resources, rules, and procedures, and is embedded in a large network of other airports, multiple airlines, and ATM centers. This type of complex socio-technical systems is characterized by a large number of interconnected parts, the difficulty to predict the behavior, and the existence of many different stakeholders (Forrester 1971; Sussman 2007a-b). Moreover, in civil air transportation, different parties are involved in the operation of an airport with varying boundaries of responsibility per region or country. At Amsterdam Airport Schiphol for instance, the parties involved in air transport related operations include the airport operator, the airport authority, the ministry of infrastructure and environment, the slot coordinators, the air navigation service provider, the airlines, as well as the general public (Deregee 2006). All these stakeholders have a certain viewpoint on performance which adds to the airport complexity (Bouarfa et al. 2012). In addition, each airport is characterized by a number of runways, taxiways, navigational aids, stop-bars, markings, and so on. Technology plays a central role in the airport system as does the social context within which the system is operating. This makes major airports by their very own nature complex socio-technical systems.

Past experience has shown that improving airport and ATM performance is very difficult to achieve. For example, Bar-Yam (Bar-Yam 2005) discusses the failure of design and implementation of the Advanced Automation Systems (AAS) in the previous century. A centerpiece of AAS was the replacement of the air traffic control system near airports. This process faced so many problems in terms of cost overruns, program delays, and safety issues, that it could only be partially completed after an FAA emergence decree. Bar-Yam argues that due to the level of complexity, different parts of the AAS design are so interdependent that changes in one part may have unforeseen effects on other parts.

Holland (Holland 2006) argues that there are few points through which the behavior of complex socio-technical systems can be changed to a desired state. These points named "lever points" are not where designers typically expect them to be. They are points where an action has an amplifier effect on the entire performance. If these points can be discovered, designers can make best use of them. There is however no theory that tells where or how to look for these points (Holland 2006).

Airport operators are faced with different trade-offs every day. These trade-offs are created by the complexities inherent to the processes managed and the finite resources of operational systems (Hollnagel 2009). Potentially, there are conflicting goals leading to dilemmas and bottlenecks that must be dealt with. An example would be how to make sure that a new environmentally-oriented procedure is safe without putting aircraft and people at risk? The widely established system engineering approach has not been developed to capture the socio part of a socio-technical system well. Then it should not come as a surprise when this creates unforeseen behavior that goes unnoticed during the development and implementation of a complex socio-technical system. Instead, such socio-technical behavior should be identified early on in the development process. This requires an approach to identify emergent behavior early on in the development of changes in civil air transportation operations.

Emergent behavior by an air transportation system results from interactions between the various human operators, technical systems, and procedures. The emergence concept is central to complex socio-technical systems and refers to how collective properties arise from the properties of the parts. Examples in air transportation include the impact on air traffic safety by new air traffic control techniques such as time-based spacing, the impact on airport capacity or airline business by policies restricting airport noise, the propagation of delays through the air transportation network, or the consequences that multiple actors can have when coordinating together. The Tenerife airport disaster for instance resulted from an interruption of routines among aircraft crew and air traffic control, loss of communication accuracy, and low visibility conditions (Weick 1990). At the same time, one should be aware of the fact that current aviation also works thanks to the explicit use of emergent behavior for the better. Examples of this are the various control loops that are working in current ATM, within each aircraft itself and also those formed by the interplay between the aircraft crew and each ATM center on its path. And there is no doubt that the role of control loops will only increase for advanced ATM. Logically, one should expect that emergent behavior that is not well understood is often characterized by poor performance, missed opportunities, and the inability to quickly adapt to disturbances. Only once emergent behavior is well understood, it may be exploited for the better.

In (Shah et al. 2005), it is well explained that the key difficulty of evaluating advanced ATM operations is to address emergent behavior, i.e. behavior which emerges from the combined dynamic actions and reactions by individual systems and humans within the overall ATM system. This emergent behavior cannot be foreseen and evaluated by examining the individual behaviors alone. To understand the behavior of a complex socio-technical system we must understand how the parts act together to form the behavior of the whole (Bar-Yam 2003). It is the goal of this research to study the emergence concept in air transportation, and develop a deeper understanding of system-wide performance issues and/or benefits arising from a change in design. In this paper we aim to identify key lever points through which the safety of runway crossing operations at airports can be significantly affected. Our approach is to embrace Agent-Based Modeling and Simulation (ABMS) because it has been extensively used to: a) analyze complex socio-technical systems and their emergent behavior (Shah et al. 2005; Chen & Cheng 2010; Stroeve et al. 2003; Wolfe et al. 2009); and b) address cases where agents need to collaborate and solve problems in a distributed fashion (Klein et al. 2004). ABMS provides a platform to integrate multiple heterogeneous components at different levels. Models of actors, technological systems, and the operating environment as well as the interactions between them can be naturally covered. Therefore, it is expected that an ABMS approach will help: a) predicting airport system-wide behavior emerging from the interactions between individual components; b) identifying and understanding key lever points; and c) managing dependencies between the activities of multiple actors both at the organizational and operational level.

This paper is organized as follows. The next section (section 2) shortly discusses different perspectives on emergent behavior, and identifies examples in the air transportation domain using a comprehensive taxonomy. Section 3 introduces the agent-based modeling approach chosen to model emergent behavior. Section 4 positions the runway crossing application in the broader context of agent-based modeling. Here, the main agents, their entities, as well as their interactions are described. Section 5 presents the Monte Carlo Simulation results, and provides a discussion. Section 6 provides a conclusion. A short version of this paper has been published in (Bouarfa et al. 2013).

3.2 Emergent Behaviour in Air Transportation

There is a wide consensus that it is essential for future ATM developments to study and understand emergent behavior (Shah et al. 2005; SESAR Consortium 2007; European commission and Eurocontrol 2010; Everdij et al. 2011). In (European commission and Eurocontrol 2010), it is explained that with the introduction of advanced ATM concepts as considered in SESAR, yet unknown emergent risk may appear. Hazards that were not anticipated before could rise as a result of new concepts, tools, or procedures. Next to this negative aspect of emergence, positive emergent behavior would also be possible. (Woods et al. 2010) explain that as much as new concepts could give rise to new vulnerabilities, they could also remove existing ones. This positive aspect of emergence was also emphasized by Beart (2012) who claims that there are things that emergent systems can do that other systems cannot:

- They are robust and resilient: There is no single-point of failure, so if a single unit fails, becomes lost or is stolen, the system still works.
- They are well-suited to the messy real world: Human-engineered systems may be ‘optimal’ but often require a lot of effort to design and are fragile in the face of changing conditions. Importantly, they don’t need to have complete knowledge/understanding to achieve a goal.
- They find a reasonable solution quickly and then optimize: In the real world, time matters because decisions need to be taken while they are still relevant. Traditional computer algorithms tend to not produce a useful result until they are complete (which may be too late in case of avoiding an obstacle for instance)

3.2.1 Different Perspectives on Emergence

Philosophers have long been interested in the concept of emergence, and especially in trying to establish a common definition for this vague yet very useful concept. The term has been in use since at least the time of Aristotle (Wikipedia 2012b) who referred to emergence as “the whole is something over and above its parts, and not just the sum of them all”. Two thousand years later, (Mill 1872) used the example of water to illustrate the same idea. The term emergent was said to be coined by Lewes in his multi-volume problems of life and mind (Lewes 1874–1879). Lewes argued that certain phenomena produce “qualitative novelty”, or material changes that cannot be expressed in simple quantitative terms. Quoting Lewes: “The emergent is unlike its components insofar as these are incommensurable, and it cannot be reduced to their sum or their difference.” (Casti 1997), like Lewes associates emergence with dynamic systems whose behavior arises from the interaction among its parts and cannot be predicted from knowledge about the parts in isolation. Crick explains in (Crick 1994) that: “The scientific meaning of emergent, or at least the one I use, assumes that, while the whole may not be the simple sum of its separate parts, its behavior can, at least in principle, be understood from the nature and behavior of its parts plus the knowledge of how all these parts interact”.

(Bedau 1997) distinguishes between two types of emergence namely, strong and weak emergence. Strong emergence was defined as nominal emergence in which the emergent properties are supervenient properties with irreducible downward causal powers. In the second type “weak emergence,” the system’s global behavior derives from the operation of micro-level processes, but the micro-level interactions are interwoven in such a complicated network that the global behavior has no simple explanation. Bedau argues that ‘strong’ emergence has had a prominent place in the philosophical discussions but that its scientific credentials are very poor, whereas ‘weak emergence’ is consistent with materialism and scientifically useful. Bedau proceeds to defend one version of weak emergence (noting that there are other versions), which is: “A nominally emergent property of a locally reducible system is called weakly emergent if it is derivable from all of the micro facts of this system, but only by simulation.”

(Chalmers 2002) includes a notion of “unexpectedness” or “surprise” to the definition of emergence, when providing alternative definitions for strong and weak emergence. Other authors also refer to the notion of surprise, like (Sanz 2004) who defines emergence as “just systemic behavior — nothing more, nothing less— that is difficult to predict in advance.” (Bedau 2002) explains that he left the notion of surprise absent on purpose, due to it being rather subjective. Instead, Bedau claims that with his definition of weak emergence in terms of simulation he is presenting objectivist approaches to emergence, though he notes that his classification is not exhaustive.

The diverse writings on emergence show that the term emergence captures a broad spectrum of system behavior. (Goldstein 1999) notes that “emergence functions not much as an explanation but rather as a descriptive term pointing to the patterns, structures, or properties that are exhibited on the macro-scale”. Editor Lissack acknowledged in his inaugural article on emergence and complex systems theory that “it is less than an organized, rigorous theory than a collection of ideas that have in common the notion that within dynamic patterns there may be underlying simplicity that can, in part, be discovered through large quantities of computer power and through analytical, logical, and conceptual developments.”

3.2.2 Identifying Emergence in Air Transportation

Air transport operations are feasible thanks to a complex socio-technical system involving interactions between human operators, technical systems, and procedures. These interactions generate various types of emergent behavior, ranging from simple emergence up to strong emergence. Understanding these types of emergence is critical for effective decision-making. The more we learn about these types of emergence, the more opportunities we identify to improve the performance of the air transportation system, and prevent system failure. In this paper, we use the taxonomy proposed by (Fromm 2005; CAS wiki 2013) to illustrate various types of emergence in the air transportation system. This taxonomy builds upon a simplified formulation for cellular automata based on (Wolfram 1984). (Fromm 2005; CAS wiki 2013) distinguish between four primary classes (Types I-IV) based on the type of feedback observed in the phenomena. Table 3.1 shows that the stronger the emergence, the less predictable are the emergent properties, patterns, and structures. Type I corresponds to the simplest form of emergence whereas type IV corresponds to strongest form of emergence.

Table 3.1: Types of emergence identified by Fromm (Fromm 2005; Complex Adaptive Systems Wiki 2013)

Type of Emergence	**Name**	**Type of feedback**	**Predictability**
Type I	Nominal or Simple Emergence	No Feedback	Predictable
Type II	Weak Emergence	Top-down feedback	Predictable in principle
Type III	Multiple Emergence	Multiple feedback loops	Not Predictable (Chaotic)
Type IV	Strong Emergence	Multiple feedback loops	Not Predictable, even in principle

Type I - Nominal or Simple Emergence

This type of emergence is totally predictable due to the controlled and planned interaction of the individual components. A machine for instance has a function which is different from the function of its parts, but the overall function is well-known. In air transportation, one can think of the multitude of technical systems either on-board the aircraft or on the ground. There are no unpredicted or unexpected behavior patterns in these systems.

Type II – Weak Emergence

This type of emergence describes emergence with top-down feedback, which is predictable in principle, but not in every detail. The roles of the elements and agents are flexible. Coherent global structures appear and become visible on a higher level of organization through the local interaction of several autonomous agents. The top-down feedback from the group imposes constraints on the local interactions. Examples from air transportation include a sequence of flying aircraft, which limits the possible speed adjustments of individual aircraft. The agents (e.g. flight crew) adjust their behavior and their role in the group according to the actual context and situation (e.g. following an ATC instruction, or TCAS warning). Feedback from the environment or group to the agent is possible through this form of context dependency.

Type III – Multiple Emergence

This type of emergence is characterized by multiple positive and negative feedback loops appearing in complex systems with many agents. The behavior is not predictable and can be chaotic. Completely new roles can appear while old ones disappear. Although air transportation operations are feasible thanks to such feedback loops, chaotic behavior may arise following some exceptional events. There are two categories of such exceptional events: 1) catastrophic accidents involving one or two aircraft; and 2) events that push the dynamics of the air transportation system far away from its point of operation and therefore dramatically affect the performance of the system. Examples of the latter are a terror action causing closing down of air travel in large areas (e.g. 9/11 in 2001), a disease causing passengers to change their travel behaviour (e.g. SARS in 2003) or volcanic ashes blocking air travel in a large area (e.g. Iceland volcano in 2010). Examples of the former are fatal runway incursions (e.g. Linate runway collision in 2001), fatal mid-air collisions (e.g. Üeberlingen mid-air in 2002), loss of control of an aircraft flying through a hazardous weather system (e.g. Air France crash in Atlantic Ocean in 2009).

Type IV – Strong Emergence

This type of emergence is not predictable, even in principle, because it describes the appearance of a completely new system in a multi-level or multi-scale system with many levels. Combinatorial explosion renders any attempt of explaining emergent macroscopic phenomena in terms of microscopic low-level phenomena useless and futile. An intermediate or mesoscopic level often protects the macroscopic level from the microscopic level, i.e. the microscopic level is irrelevant to the behavior of the macroscopic level. Life is a strongly emergent property of genes, genetic code and nucleic/amino acids, as is culture a strongly emergent property of language and writing systems. In the air transportation domain, one can think of the safety culture which is described as the product of routine aspects of everyday practice as well as organizational structure and rules (Leveson et al. 2005; Ek et al. 2007). However the causal relations are not yet understood (Sharpanskykh & Stroeve 2011).

3.3 Agent-Based Modelling and Simulation

In order to understand complex socio-technical systems and their emergent behavior, rigorous models are needed that allow us exploring their properties (Holland 2006). One of these properties, is what Holland (Holland 2006) calls ‘lever points.’ These are points where a simple intervention causes an important effect on system performance. According to Holland, all complex systems that have been studied carefully exhibit such points. In the same article, Holland suggests using ABMS to study and analyze complex systems and capture their emergent behavior.

3.3.1 ABMS and Complex Socio-Technical Systems

The agent-based modeling paradigm is increasingly recognized as a powerful approach to model and simulate complex socio-technical systems exhibiting emergent behavior (Holland 1997). This is because it can represent important phenomena resulting from the characteristics and behaviors of individual agents and their interactions (Railsback & Grimm 2012). (Burmeister et al. 1997) discuss the benefits of using an agent-based approach in domains that are functionally or geographically distributed into autonomous subsystems, where the subsystems exist in a dynamic environment, and the subsystems have to interact more flexibly. According to Burmeister, agent-based modeling can be used to structure and appropriately combine the information into a comprehensible form. For a large complex system such as a traffic system, they provide the tools for analyzing, modeling, and designing the whole system in terms of its subsystems, each with its own set of local tasks and capability. The integration can then be achieved by modeling the interactions among the subsystems. So agent-based modeling provide abstraction levels that make it simpler and more natural to deal with the scale and complexity of problems in these systems. Agent components can be described at a high level of abstraction, yet the resulting systems are very efficient (Burmeister et al. 1997). (Burmeister et al. 1997) conclude that agent-based modeling reduce the complexity in systems design by making available abstraction levels that lend themselves to a more natural way of modeling the problem domain. They enhance the robustness and adaptivity of systems by virtue of increasing the autonomy of subsystems and their self-organization. In the same vein, Jennings (Jennings 2000) outlines that ABMS and complex system development requirements are highly compatible. (Jennings 2000) shows that agent-based modeling techniques are particularly well suited to complex systems because: a) they provide an effective way of partitioning the problem space of a complex system; b) they provide a natural means of modeling complex systems through abstraction; and c) they capture the interactions and dependencies.

3.3.2 Agents in Air Transportation

In the ABMS domain, although there is no widely agreed definition for an agent, there is general consensus that autonomy is central to the notion of agency. (Wooldridge 2009) explains that part of the difficulty is that beyond this autonomy point various attributes associated with agency are of different importance for different domains.

Among the various definitions in the literature for an agent are:

- An agent is anything that can be viewed as perceiving its environment through sensors and acting upon that environment through effectors (Russel & Norvig 2006).
- An autonomous agent is a system situated within a part of an environment, which senses that environment and acts upon on it, over time, in pursuit of its own agenda and so as to effect what it senses in the future (Franklin & Graesser 1997).
- An agent is a computer system that is situated in some environment, and that is capable of autonomous action in this environment in order to meet its delegated objectives (Wooldridge 2009).
- An agent is a system with the following properties (Tessier et al. 2002):
    - It lives in an artificial world *W*
    - It has facilities to sense *W* and to manipulate *W*
    - It has a (at least partial representation of *W*
    - It is goal-directed, and as a consequence it has the ability to plan its activities
    - It can communicate with other agents

In the context of air transportation, in particular where different actors, hardware, and software are interacting elements of a complex socio-technical system, we consider agents as autonomous entities that are able to perceive and act upon their environment. These agents may be humans, systems, organizations, and any other entity that pursues a certain goal. For instance, an air traffic controller can be viewed as an agent observing his/her environment (displays, alerting systems, runway availability, etc.) and acting upon this environment (e.g. through communicating with other agents like pilots/ other controllers, or turning off runway stop-bars remotely). The agent environment is understood as all surrounding human and non-human agents.

3.3.3 Agent-Based Safety Risk Analysis

The aim of this paper is to position an active runway crossing application in the broader context of agent-based modeling. This was motivated by the capability of this rather new approach to obtain known and unknown emergent behaviors (Chan et al. 2010). Traditional safety approaches assume well defined cause-effect links that propagate the effects of events contributing to the safety risk (e.g. sequential or epidemiological safety models). However, recent views indicate that such models may not be adequate to represent the complexity of modern socio-technical systems (Hollnagel et al. 2006). Instead, agent-based modeling forms a logical choice for the safety-risk analysis from a socio-technical perspective. By having distinguished a number of agents and their interactions, the overall process can be analyzed as emerging from the individual agent processes. This not only provides a transparent way of structuring the model, which supports the analysis both conceptually and computationally, but also makes the model easier to maintain, resulting in local model refinements instead of global changes. For the runway crossing operation, a systematic comparison of the agent-based approach against a sequence based approach has been made in (Stroeve et al. 2011). The study revealed many advantages of the former approach, including considerable differences in the risk results obtained. The only disadvantage however, is that the agent-based approach requires computational modeling experience that differs from the expertise of most current safety analysts. Finally, compared to the major simulation paradigms, agent-based modeling can be used across all abstraction levels (see Figure 3.1) which is necessary to cover all relevant agents who directly control the hazardous process in the context of the runway crossing application.

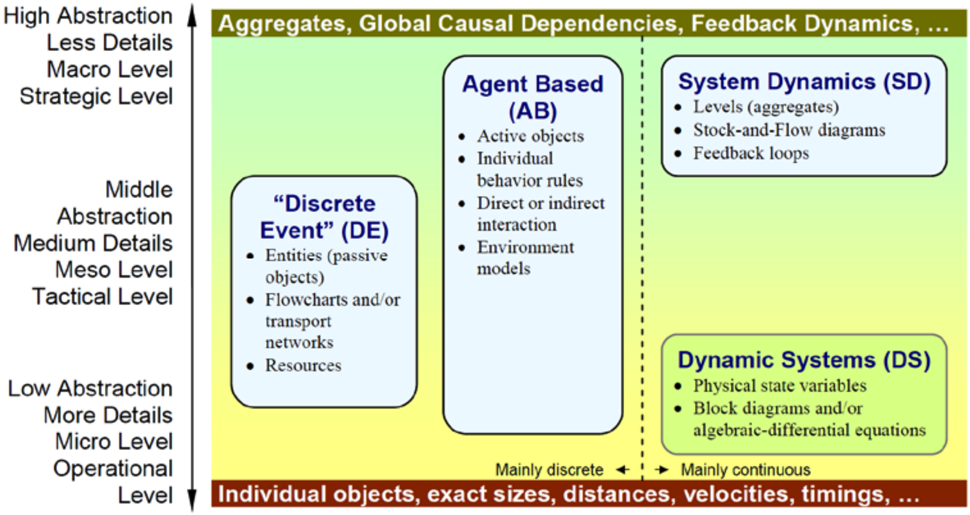


Figure 3.1: Approaches (Paradigms) in Simulation Modelling on Abstraction Level Scale (Borshchev & Filippov 2004)

3.3.4 TOPAZ Safety Risk Assessment Methodology

Motivated by the need to model the dynamics, the stochastic, and the interactions of safety critical multi-agent systems, NLR has developed the TOPAZ safety risk assessment methodology, e.g. (Blom et al. 2001a; Blom et al. 2006). The quantitative part of TOPAZ develops and evaluates an agent-based model through running Monte Carlo simulations (Blom et al. 2009) in combination with bias and uncertainty analysis (Everdij et al. 2006). Next to these techniques, TOPAZ also integrates human performance modeling (Blom et al. 2001b), and powerful petri net modeling syntax (Everdij & Blom 2010). Applications of these modeling techniques requires dedicated expertise from safety analysts. However, when the TOPAZ toolset is available, normal safety expertise is sufficient.

3.4 Case Study: ABMS of an Active Runway Crossing Operations

In this section we explore ABMS to study emergent behavior in an active runway crossing operation. Our study is performed in three main steps, namely:

1. Model the agents and their interactions with the environment: For example human performance models of pilots and controllers interacting with technical systems

2. Run Monte Carlo Simulations of both nominal and off-nominal scenarios: In order to assess the impact of agents' individual performance on system behavior
3. Analyze system behavior: Explore an array of behaviors or parameters of system performance to guide alternative selection and future development

3.4.1 Active Runway Crossings and Incursions

In many airports around the world, runway crossings are used by taxiing aircraft from the apron area to the runway and vice versa. These crossings are attractive because they reduce the taxiing time and save fuel. However, they also have safety implications, namely the risk of having a runway incursion. A runway incursion is defined by the International Civil Aviation Organization (ICAO) (ICAO 2007) as "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". While a runway incursion does not imply a collision, the probability of an accident is not nil. One of the most famous aviation accidents is the Tenerife airport disaster that occurred on March 1977. Two Boeing 747 aircraft, operated by KLM and Pan American World Airways, respectively collided. While the Pan American aircraft was taxiing, the KLM aircraft took off, resulting in a collision causing 583 fatalities. This accident is the deadliest aviation accident in history (Wikipedia 2012a). 35 years later, runway incursions are still frequently reported in many countries. In the united states alone, preliminary data (FAA 2012) through the end of August 2012 shows a total number of 1010 runway incursions in the year 2012, a 17 percent increase over the same span in 2011.

Researchers and planners operating from different perspectives have proposed many options to address this problem, such as new technology (e.g. in aircraft, ATC tower, or Airport) and new procedures such as ICAO compliant procedures. These proposals aim to reduce the probability of runway incursions, and reduce the accident risk in case runway incursions occur. However, evaluating the impact of these proposals is a demanding task, given the large number of human operators and technical systems that closely interact at the airport. This paper evaluates the safety risk of an active runway crossing operation from an agent-based modeling perspective.

3.4.2 Agent-Based Model of the Active Runway Crossing Operations

An agent-based model of the active runway crossing operation has been developed in a series of studies (Stroeve et al. 2011; Stroeve et al. 2013). The agents in this operation and their interactions are shown in Figure 3.2. The developed agent-based model considers accidents as emerging phenomena from the interactions between multiple agents involved. In these previous studies, it has been shown that the level of safety in sociotechnical systems depends on the interactions between organizational entities in their contextual conditions. In this paper we present the model in the wider context of socio-technical systems and run new Monte Carlo Simulations of non-nominal scenarios using this model.

In order to define the stochastic dynamics of the agents and their interactions unambiguously, the agent-based model has been specified in terms of Stochastically and Dynamically Colored Petri Nets (SDCPNs). SDCPNs are a powerful extension over normal Petri nets in that they are able to represent general stochastic hybrid processes in a form that supports powerful stochastic analysis (Everdij & Blom 2010). In view of the scope of the current paper, it suffices to describe this agent-based model in normal language rather than in SDCPN language.

At the highest hierarchical level, the relevant agents in the active runway crossing operation are identified. These agents are concurrently interacting with each other and include human and non-human agents. The human agents are the flight crew operating the aircraft, and the runway controller handling the traffic on the runway and its crossings. The non-human agents represent the aircraft and ATC system. In the context of the active runway crossing operation, the ATC system is comprised of three components where each component is performing a number of functions.

These components include: 1) the Radio/Telecommunication (R/T) system used for communication between the controller and flight crew; 2) the Surveillance system used for providing radar track data; and 3) the alerting system used to generate ATC alerts in safety critical situations.

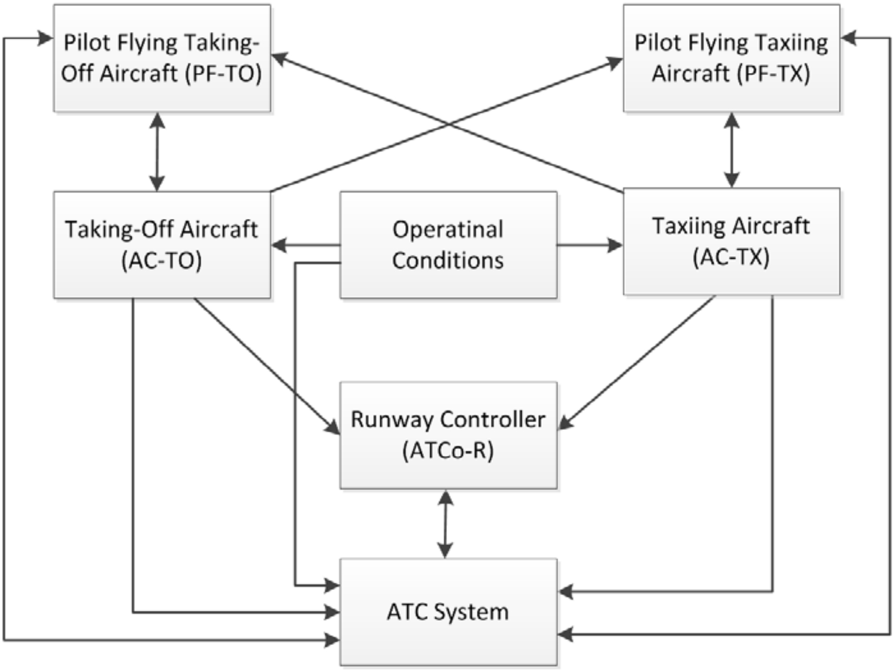


Figure 3.2 Agent-Based Model of the active runway crossing operation showing the interactions between the agents (Stroeve et al. 2011)

In Figure 3.2 we use the following abbreviations for the different agents:

- Human Agents
    - PF-TX: represents the Pilot Flying the Taxiing Aircraft
    - PF-TO: represents the Pilot Flying the Taking-Off Aircraft
    - ATCo-R: represents the Runway Controller
- Non-Human Agents
    - AC-TX: represents the Aircraft Taxiing
    - AC-TO: represents the Aircraft Taking-Off
    - ATC System: represents the ATC system

The main entities within these agents as well as their interactions are described below.

Human Agents

The human operators' function in the distributed air transportation system includes visual monitoring, perception, spatial reasoning, planning, decision-making, communication, procedure selection, and execution (Corker et al. 2008). In order to account for these cognitive and perceptual functions of the human operators, human performance modeling has been used as a complementary technology (Blom et al. 2001b). Figure 3.3 gives an overview of the main entities within the human agent's internal model in the context of advanced aviation concepts. This model applies to both the ATCo-R and pilots.

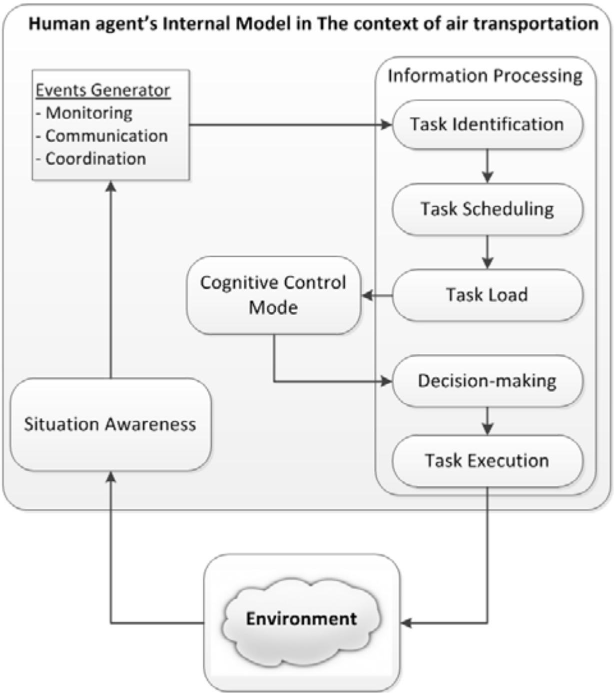


Figure 3.3 Overview of the internal model of a human agent and its interactions with its environment.

The concept of situation awareness (SA) addresses perception of elements in the environment, their interpretation, and the projection of their future status (Endsley 1995). Stroeve et al. (Stroeve et al. 2003) have captured these perception, interpretation, and project notions of SA mathematically in terms of three components namely, State SA, Mode SA, and Intent SA. The state SA represents the awareness by one agent of other agents. In the context of the active runway crossing operation, this might be the awareness of the flight crew about the state (position and speed) of their own aircraft and other aircraft, or the awareness of the controller about traffic state at the airport. The mode SA represents the awareness by one agent of the mode of other agents. This mode could be for instance the flight phase of an aircraft, or status of an ATC alert. The intent SA represents the awareness by one agent of the intent of other agents. The intent includes continuous states of agents as well as the related times at which these states are expected to be achieved. For example, intent SA may represent the expectations by a runway controller of aircraft destination, and the time it will arrive at a certain waypoint. The timing of the situation awareness updates depends on the initiation and duration of related tasks (e.g. monitoring, communication, coordination).

The information processing entity considers processing of information from the environment that leads to actions that may influence the environment. This entity is based on task analysis, which takes into account the multiple resources model (Wickens 1992). The idea reflected by this model is that humans have several different mental capacities with resource properties. In this view, task interference depends on the extent to which tasks use the same resources: two difficult tasks may be time-shared easily if they use different types of resources (Blom et al. 2001b). The principal idea behind the model is that human cognitive effort can be divided over several activities. This may account for failures in time-sharing between competing activities, since the human cognitive effort is limited. So, the underlying assumption is that the human is an information processing system with limited processing capacity. The human information processing entity focuses on how this limited processing capacity can be used to time-share several processing tasks. Its sub-entities include:

- Task Identification: Considers the ways the human operator identifies the tasks that need to be performed at a particular time instance
- Task Scheduling: Determines which tasks may be performed concurrently, as well as a priority among the tasks that cannot be performed concurrently
- Task Load: Describes the number of tasks to be performed and/or the resources required by tasks at the level of visual, auditory, cognitive and motor performance.
- Decision Making: Decision Making processes are based on decision rules dedicated to the scenario considered. In an active runway crossing operation, this could be how to react to a conflict situation.
- Task execution: Considers the dynamic and stochastic performance characteristics of tasks.

This Cognitive Control entity considers that humans can function in a number of cognitive control modes such as: Strategic, Tactical, Opportunistic, and Scrambled (Hollnagel 1993). The cognitive control mode may depend on the taskload sub-entity which describes the range of tasks to be done or the situation awareness of the human. It influences human aspects such as the planning horizon and the accuracy of task performance

Non-Human Agents

The model of the aircraft agent represents aircraft dynamics in different flight phases, which is a function of the aircraft type (see Figure 3.4). For AC-TX the model represents aircraft movement during taxiing, including braking as a means to avoid a collision. For AC-TO, it represents the ground run, airborne transition and airborne climb-out phases during takeoff. It also includes the possibility of a rejected takeoff by the pilot.

The main entities within the ATC system agent include the surveillance system, the alerting system, and R/T communication system (see Figure 3.5):

- The model of the surveillance system provides position and velocity estimates for both aircraft. The surveillance data is used by the alerting system.
- The alerting system generates two types of alerts in case surveillance data indicate a safety critical situation. The alerts include 1) a stopbar violation alert in case AC-TX has passed the stopbar, and 2) a runway incursion alert in case AC-TX is within a critical distance of the runway center- line and AC-TO has exceeded a velocity threshold in front of the runway crossing. There is a chance that the surveillance system is not available, resulting in track loss and no alerts being generated.
- The model for the R/T communication system between ATCo-R and pilots accounts for the communication system of the aircraft, the communication system of the ATCo-R, the tower communication system, and the frequency selection of the aircraft communication system. The nominal status of these communication systems accounts for direct non-delaying communication. The model accounts for the chance of delay or failure of the communication systems.

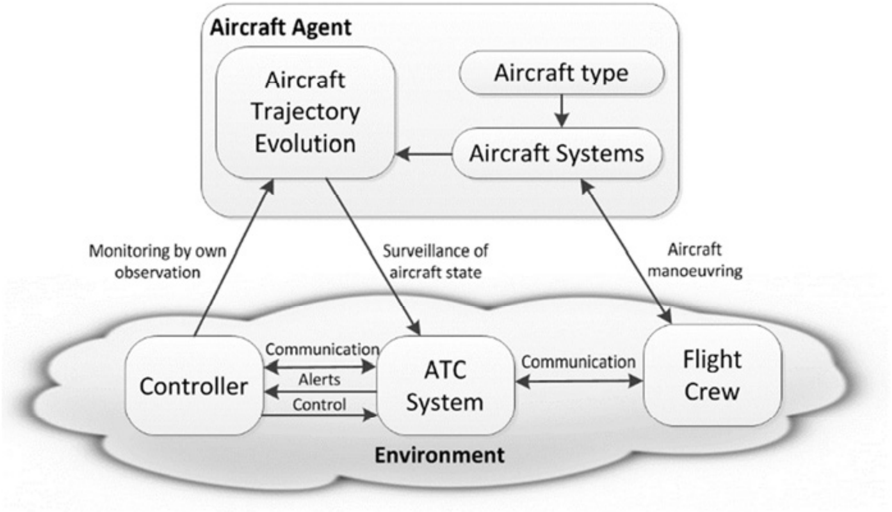


Figure 3.4 Overview of the internal model of the aircraft agent and its interactions with its environment

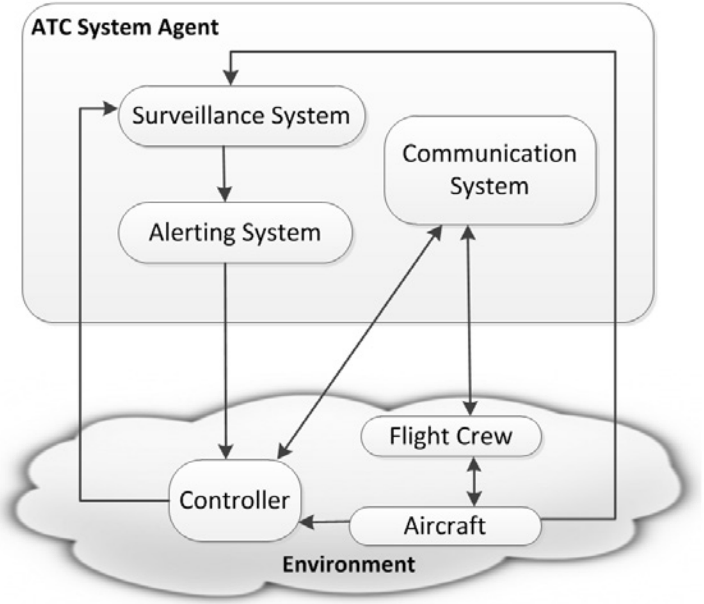


Figure 3.5 Overview of the internal model of the ATC system agent and its interactions with its environment

Operational Conditions

The operational conditions in the active runway crossing operation are characterized by two elements namely the runway configuration and visibility conditions. For the first element, runway characteristics such as runway length, width, location of stopbars, and number of branches are specified. Each branch is of the class holding, crossing, or exit. For the second element, four different visibility conditions are represented.

Environment of Each Agent

Each agent is situated in its environment, from which this agent perceives information and acts upon its environment (See Figures 3.4, 3.5, 3.6)

3.4.3 Active Runway Crossing Operation

In the active runway crossing operation, we consider a departure runway that is used by AC-TO and has a crossing taxiway at a distance of 1000 m from the runway threshold (see Figure 3.6). The runway crossing is used by the taxiing aircraft (AC-TX) to cross the active runway. In this experiment, we focus on the scenario that the taxiing aircraft is crossing the runway while it should not, due to a wrong intent situation awareness of its flight crew. Such condition has been shown in previous work to have a strong effect on accident risk (Stroeve et al. 2003; Stroeve et al. 2009). Evaluating the conditional collision risks associated with this condition provides more insight on the collision risk contributions.

In the active runway crossing operation, AC-TX enters the taxiway leading to the runway crossing at a position close to the stopbar, whereas AC-TO initiates take-off from a position near the runway threshold (Figure 3.6). The entrance time of AC-TX is uniformly distributed around the take-off time of AC-TO. In addition, both AC-TX and AC-TO may be medium-weight or heavy-weight. The operation is assumed to be without restricted visibility range in line with visibility condition 1 of ICAO (ICAO 2004). This implies that the involved human operators can visually observe the traffic situation.

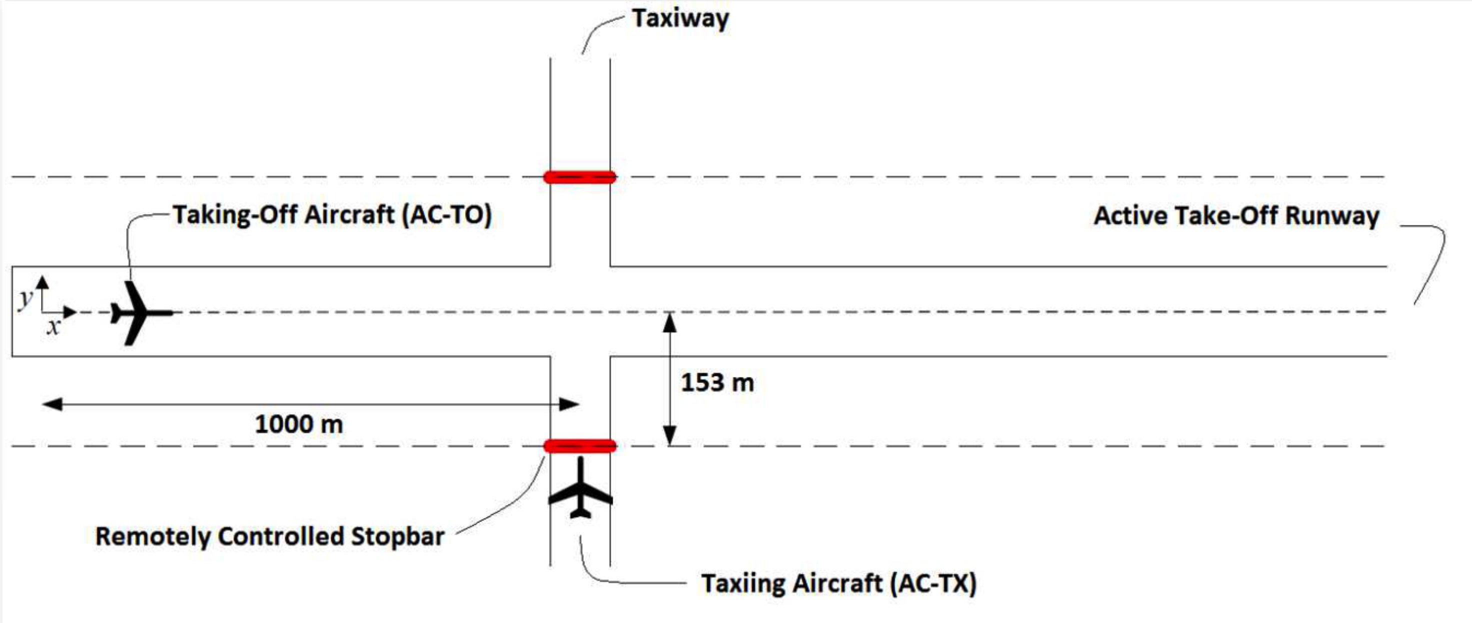


Figure 3.6 Schematic overview of the traffic situation considered. The taking-off aircraft accelerates along the runway while the crew of the taxiing aircraft intends to proceed along the taxiway towards the active runway (Stroeve et al. 2009).

The pilots PF-TO and PF-TX are both responsible for the safe conduct of the flight operations and should actively monitor for potential conflicting traffic situations. ATCo-R is responsible for the safe and efficient traffic handling on the runway and the runway crossings. During taxiing and take-off, both PF-TX and PF-TO visually monitor the traffic situation at stochastically distributed times. Both pilots may detect a safety critical situation by their own observation. PF-TO observes a conflict when AC-TX is observed to be within a critical distance to the runway centerline. PF-TX observes a conflict when AC-TO is observed to be approaching AC-TX with an increasing speed, and AC-TX is within a critical distance from the runway centerline.

Next to their own monitoring actions, pilots of both AC-TX and AC-TO may also detect a conflict following a call from ATCo-R. In this case, the R/T communication system is used for communication between ATCo-R and the flight crew. ATCo-R may detect a conflict during monitoring if AC-TX is observed to have passed the stopbar, or following an ATC alert. The ATC alerting system may generate two types of alerts to warn ATCo-R: 1) A runway incursion alert for the situation that AC-TX is crossing the runway in front of AC-TO that has initiated take-off; and 2) A stopbar violation alert for the situation that AC-TX crosses an active stopbar. These alerts consist of audible warnings and an indication on the ground surveillance display. The alerts are based on radar tracking data (Aircraft position and velocity estimates) provided by the surveillance system. Following conflict detection, PF-TX may decide to start a full braking action or continue crossing in case AC-TX is within a critical distance of the runway center line. Likewise, PF-TO may decide to start a full braking action or continue taking off if it is too late to brake.

3.5 Results and Discussion

3.5.1 Monte Carlo Simulation Results

To better understand the potential of agents to restrict the risk in cases where the performance of other agents is affected, one or more agents can be placed out of the monitoring role in the Monte Carlo simulations. This is done for all agents that are capable of detecting a conflict in the active runway crossing operation, namely PF-TO, PF-TX, ATCo-R, and the ATC alerting system. The conditions for placing these agents out of the monitoring role are:

- PF-TX does not actively monitor the traffic situation visually, such that he may only detect a conflict via a call of ATCo-R.

- PF-TO does not actively monitor the traffic situation visually, such that he may only detect a conflict via a call of ATCo-R.
- ATCo-R does not actively monitor the traffic situation visually, such that he may only detect a conflict through ATC alerts.
- The ATC alerting system does not generate any alerts.

The conditions above refer to the situation at the start and during the active runway crossing operation, and they are not assumed to hold prior to the occurrence of the crossing operation. Combining these conditions results in sixteen cases where agents are either monitoring or not monitoring the traffic situation. A total of 1 million Monte Carlo simulation runs were performed for each of the sixteen combinations. The Monte Carlo method was used to capture the stochastic nature of the various agents in the active runway crossing operation. The conditional collision risk was obtained by dividing the number of collisions by the number of performed simulations for each case.

Figure 3.7 shows the conditional collision risk results corresponding to the sixteen cases. The conditional collision risk lies between 1,7E-4 and 9,5E-2. The lowest value corresponds to the nominal case C1 where the performance of agents is not affected. Here all agents operate according to the active runway crossing operation described in the previous section. The highest collision risk corresponds to the hypothetical case C16 where none of the agents is actively involved in recognizing the conflict and avoiding a collision. In this case, the risk increases by a factor of 556 with respect to case C1.

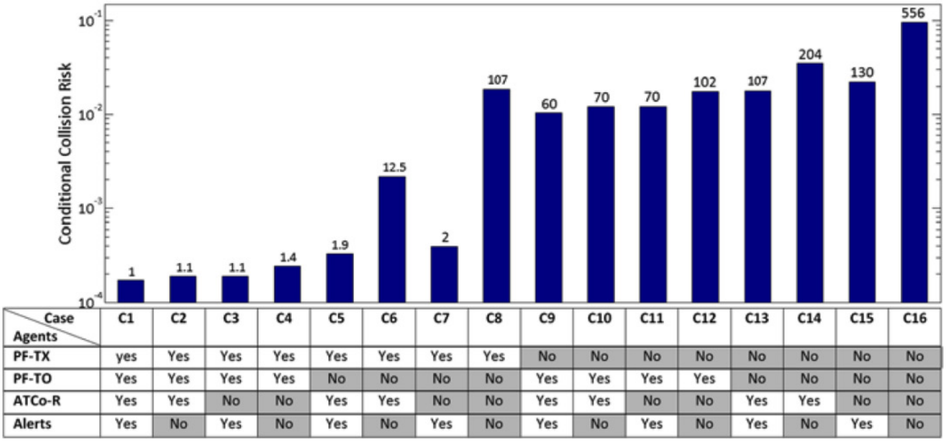
The conditional collision risk results in figure 3.7 can be divided into two main categories. The first category is characterized by low to medium risk increase factors and includes the first seven cases C1 to C7 on the left-hand side. The second category is characterized by high risk increase factors and includes cases C8 to C16 on the right-hand side.

In the first category, the risk increase factors are low for all cases except for case C6 which has a medium risk increase factor. The low factors are between 1.1 and 2. This means that agents can restrict the conditional collision risk in some cases where the performance of one or more agents is affected. These cases are:

- Case C2: ATC alerts are not generated
- Case C3: ATCo-R is not actively monitoring the traffic situation visually
- Case C4: ATC alerts are not generated and ATCo-R is not actively monitoring the traffic situation visually
- Case C5: PF-TO is not monitoring the traffic situation visually

- Case C7: Both PF-TO and ATCo-R are not actively monitoring the traffic situation visually

In the second category, the risk increase factor with respect to C1 is between 60 and 556. The risk levels are high and are in the range between 1.0E-2 (case C9) and 9.5E-2 (case C16). In almost all cases of the second category, PF-TX was not actively monitoring the traffic situation (cases C9-C16). The only exception is Case C8 where the conditional collision risk is around 1.8E-2. In this case however, the performance of all other agents was affected to attain similar risk levels corresponding to cases without active monitoring of PF-TX.



Case / Agents	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12	C13	C14	C15	C16
PF-TX	yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No	No	No	No	No	No	No	No
PF-TO	Yes	Yes	Yes	Yes	No	No	No	No	Yes	Yes	Yes	Yes	No	No	No	No
ATCo-R	Yes	Yes	No	No	Yes	Yes	No	No	Yes	Yes	No	No	Yes	Yes	No	No
Alerts	Yes	No	Yes	No	Yes	No	Yes	No	Yes	No	Yes	No	Yes	No	Yes	No

Figure 3.7 Conditional collision risk results corresponding to different cases where agents are monitoring (white cells with yes) or not monitoring (grey cells with no). The value on top of each bar represents the risk increase factor with respect to case C1[1]. PF-TX refers to Pilot-Flying Taxiing Aircraft. PF-TO refers to Pilot-Flying Taking-Off Aircraft. ATCo-R stands for Runway Controller.

Figure 3.7 gives some insights on the role of each agent in restricting the conditional collision risk in case the performance of other agents is affected. The role of each agent is explained below:

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[1] In this chapter, the aggregated simulation included extra combinations compared to (Stroeve et al. 2013). This way the role of ATC alerts in restricting the risk becomes clearer in cases where the controller is not actively monitoring the traffic situation visually (e.g. cases C3, C7, C11, and C15).

PF-TX

The results show that an actively monitoring PF-TX restricts the risk in cases where the performance of one or two agents is affected (cases C1 to C7). The risk increase factor with respect to case C1 is between 1.1 and 12.5. In addition, all cases without active monitoring of PF-TX, are characterized by a high conditional collision risk. The risk increase factor with respect to C1 varies between 60 and 556.

PF-TO

The conditional collision risk is increased by a factor of 1.9 in the hypothetical case C5 where PF-TO is the only agent not monitoring the traffic situation. In case C8, where no ATC alerts are generated and both PF-TO and ATCo-R are not monitoring, the risk is higher by a factor of 76 with respect to case C4. This indicates that an active monitoring of PF-TO considerably restricts the risk in cases that involve both the lack of monitoring of ATCo-R, and malfunctioning of ATC alerts (Case C4 versus C8). The risk is also reduced by the active monitoring of PF-TO (factor of 11) in case no ATC alerts are generated (Case C2 versus C6). The role of PF-TO in restricting the risk is however limited when PF-TX is not actively monitoring the traffic situation. This can be noticed when comparing cases C9 with C13, C10 with C14, C11 with C15, and C12 with C16.

ATCo-R

The comparison of cases with and without active traffic monitoring by ATCo-R indicate that in most cases, the controller's observation does not significantly restrict the risk. This can be noticed when comparing case C1 with case C3. The active monitoring by ATCo-R does reduce the risk with only a factor of 1.1. Close factors can be found when comparing cases C2 with C4, C5 with C7, C9 with C11, C10 with C12, C13 with C15, C14 with C16. However, an interesting remark can be made when comparing case C6 with C8. Here the controller's own visual observation does play a role in restricting the conditional collision risk when the PF-TO is not monitoring the traffic situation and the ATC alerts are not functioning.

ATC alerts

The comparison of cases with and without alerts indicates that in most cases ATC alerts barely reduce the collision risk. This can be noticed when comparing cases C1 and C2.

In case C1, ATC alerts are generated in case of safety-critical situations, and can be detected by ATCo-R. In case C2, No ATC alerts are generated as described in the experiment set-up. Looking at both cases, the risk increases by a factor of 1.1 meaning that ATC alerts do not significantly reduce the conditional collision risk. A similar remark can be made when comparing C3 with C4, C9 with C10, and C11 with C12. In all these cases, the presence of ATC alerts does reduce the risk by a factor no larger than 1.5. This indicates that alerts to ATCo-R are often too late resulting in late instructions to the PF-TX as manifest from C9 and C11. Only in cases without active monitoring of PF-TO and at the same time with active monitoring of PF-TX, do alerts restrict the risk by higher factors. This can be noticed when comparing cases C5 with C6, and C7 with C8. Here, the conditional collision risk is reduced by a factor of 6.5 and 46 respectively due to ATC alerts. However, if the PF-TX is out of the monitoring role, the contribution of ATC alerts in restricting the risk is reduced to a factor of 1.9 and 4.2 for the cases C13 versus C14, and C15 versus C16 respectively. These results indicate that ATC alerts are of little help to ATCo-R in cases where PF-TX is not actively monitoring the traffic situation. They are often too late to prevent collisions.

3.5.2 Monte Carlo Simulation Events

In the Monte Carlo simulation, a number of event occurrences was defined and recorded in order to have more insight regarding the interactions between agents and their relation to accident risk. These event occurrences included conflict detection by the agents, their actions, as well as the consequences of these actions. In a Monte Carlo simulation run, the time $\tau_q$of the first occurrence of event E_q together with the position of the aircraft at time $\tau_q$were recorded. This is helpful to understand how a collision emerges from the interactions between agents, through tracing back possible sequences of events preceding a collision. The authors came up with a novel method to visualize possible sequences of events resulting from the interactions between the agents (Figure 3.8). For instance, Figure 3.8 indicates that an ATC alert (event E4) may result in warnings specified by ATCo-R towards the flight crew of both taxiing and taking-off aircraft (event E8). The possible sequences of events with the corresponding simulated scenarios are summarized in table 3.2.

Figures 3.9 and 3.10 show probability distribution functions of relevant event times for case C1 described in Figure 7. Figure 3.9 corresponds to simulation runs that have resulted in a collision, whereas Figure 3.10 corresponds to simulation runs that have not resulted in a collision. Comparing the two figures show that, for the nominal case C1, early detection of a potential conflict by the human agents play a key role in restricting the accident risk.

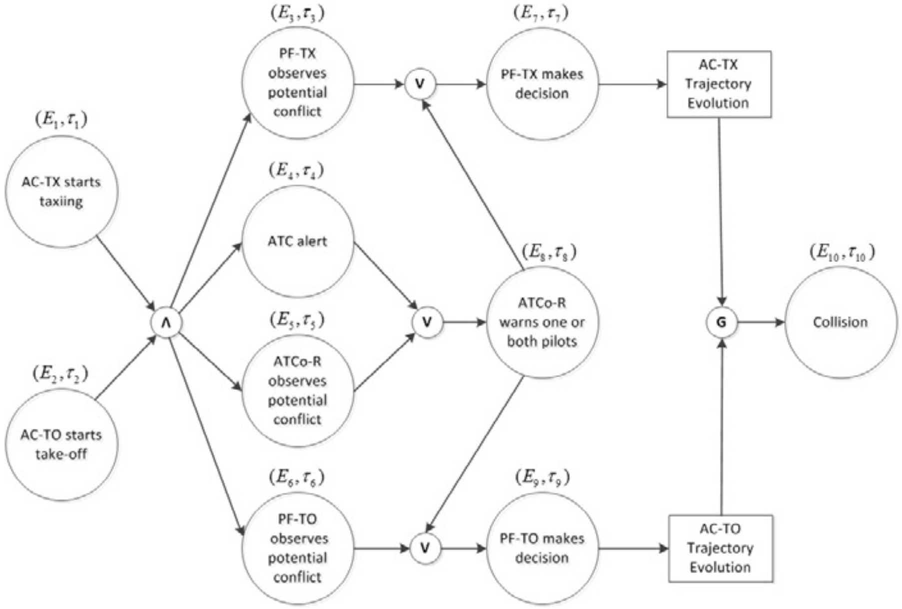

Figure 3.8 Recorded events in the Monte Carlo simulation and their relation with collision in the active runway crossing operation. E_q (q = 1,2,…,10) represents the event number, τ_q represents the time of the first occurrence of event E_q, '∧ ' means that both events E_i and E_j should have occurred in order for the next event to happen such that $\tau_i \wedge \tau_j = \max\{\tau_i, \tau_j\}$, '∨ ' means that as soon as one of the (competing) events occur, the next event will happen such that $\tau_i \vee \tau_j = \min\{\tau_i, \tau_j\}$, G is a guard function evaluating the first time τ_{10} that trajectories of AC-TO and of AC-TX are such close that the aircraft shapes hit each other.

Table 3.2 Possible sequences of events before a collision. The table maps different possible sequences of events with corresponding cases as defined in figure 3.8

Seq. nr.	Possible sequences of events	High risk restriction cases	Low risk restriction cases
1	(E1 ∧ E2) → E3 → E7 → E10	C1-C7	C8
2	(E1 ∧ E2) → E6 → E9 → E10	C1-C4	C9-C12
3	(E1 ∧ E2) → E4 → E8 → E7 → E10	C1, C3, C5, C7	C9, C11, C13, C15
4	(E1 ∧ E2) → E5 → E8 → E7 → E10	C1, C2, C5, C6	C9, C10, C13, C14
5	(E1 ∧ E2) → E4 → E8 → E9 → E10	C1, C3, C5, C7	C9, C11, C13, C15
6	(E1 ∧ E2) → E5 → E8 → E9 → E10	C1, C2, C5, C6	C9, C10, C13, C14
7	(E1 ∧ E2) → E4 → E8 → (E7 ∧ E9) → E10	C1, C3, C5, C7	C9, C11, C13, C15
8	(E1 ∧ E2) → E5 → E8 → (E7 ∧ E9) → E10	C1, C2, C5, C6	C9, C10, C13, C14
9	(E1 ∧ E2) → E10	NA	C16

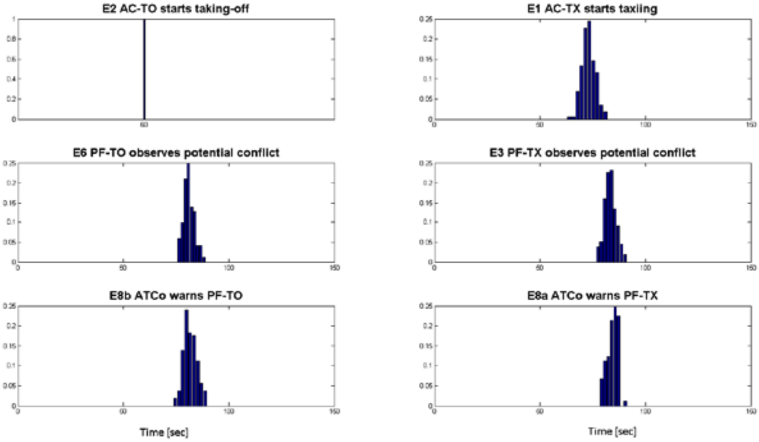

Figure 3.9 Conditional probability Distribution functions of relevant event times for runs corresponding to case C1 that have resulted in a collision

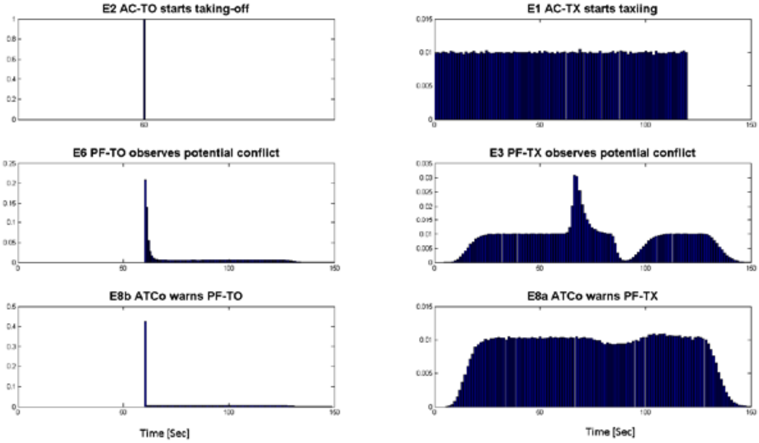

Figure 3.10 Conditional probability distribution Functions of relevant Event times for runs corresponding to case C1 that have not resulted in a collision

3.2.5 Results Discussion

The results suggest that if PF-TX is not actively monitoring the traffic situation, then the conditional collision risk is high, and then the role of PF-TO, ATCo-R, and alerts in restricting the risk is rather limited. This can be explained by the condition considered in this experiment regarding the intent situation awareness of PF-TX. Here, PF-TX crosses the runway without contacting ATCo-R because he is not aware about the runway crossing. PF-TX can only detect a conflict in two cases: 1) when PF-TX observes that AC-TO is approaching AC-TX (Event E3 in figure 3.8) or 2) when PF-TX timely receive an R/T call from ATCo-R (Event 8 in figure 3.8). This means that if PF-TX is not actively monitoring the traffic situation, the only way to detect a conflict is through an R/T call from ATCo-R (Event E8). For PF-TX, this call often comes too late because AC-TX has already started crossing. A similar evaluation of the results for the PF-TO shows another picture. For PF-TO, the call from ATCo-R does restrict the collision risk considerably. This can be noticed by comparing cases C5 and C8. This is mainly because PF-TO has more time compared to PF-TX to start a collision avoidance braking action, as is manifest from the recorded aircraft positions. The comparison of both of these cases also shows that the call from ATCo-R was mainly triggered by the ATC alerting system.

Identifying weak emergence of type II (see table 3.1) was revealed due to the development and simulation of the agent-based model in the wider context of socio-technical systems. The ABMS approach covered both the socio and technical parts through: a) developing the internal model of both human operators and technical systems; and b) capturing the totality of their interactions through Monte Carlo simulations. This is an example where emergent behavior of type II has been predicted thanks to agent-based modelling and simulation (Figure 3.7). In addition, the events recorded in the Monte Carlo simulation revealed unpredicted behavior regarding the sequence of conflict detection by the agents. Normally, in the context of the runway crossing operation, one would expect according to the ConOps, that conflicts would be first detected by ATCo-R who will then warn the pilots. However, this might not necessarily always be the case. It was shown that PF-TX might detect a conflict even before ATCo-R which could lead to an accident if detection by the pilot is too late (e.g. Figure 3.9). Such unpredictable behavior can be chaotic and falls under the category multiple emergence type III. In such type of emergence, complete new roles can appear while old ones disappear.

3.6 Conclusion

Emergent behavior in the open socio-technical air transportation system results from the interactions between the constituent elements and the operating environment. For an airport, these elements include human operators and their organizations, working procedures, technical systems, and weather. Changing the characteristics of these elements or the way they interact may have an impact on the overall system behavior.

Both the operating environment and the socio-technical system elements influence the evolution over time. On the one hand, weather conditions for instance may be a factor in deciding which flight plan to file or which runway configuration to use. On the other hand, flight progress may change as a result of pilots and controller's decisions. In order to identify which changes at the "elements" level do have a significant impact on the emergent behaviour of the socio-technical system, models of constituent elements and their interactions are required.

In this paper, Monte Carlo Simulations of an agent-based model were performed to assess the safety risk of an active runway crossing operation. The safety performance of such an operation depends on the coordination between the runway controller, pilots, and technology all functioning together. The agent-based model has been developed in a hierarchical way. At the highest level, the relevant agents including human operators and technical systems were identified. Then the interactions between these agents were captured and included deterministic and stochastic relationships, as is appropriate for the human performance or the technical systems considered. The impact on the emergent safety behavior was studied through running simulations of both nominal and off-nominal scenarios.

It has been explained that ATM is a complex socio-technical system that exhibits various types of emergent behavior ranging from simple emergence, through weak emergence, up to strong emergence. It has been demonstrated that agent-based modeling and Monte Carlo analysis provide a platform to integrate and simulate multiple heterogeneous components at different levels, and identify different types of emergence through modeling the interactions between technical systems, human operators, working procedures, and environment.

One of the main findings is that the role of alerting systems in restricting the conditional collision risk is limited in cases without active monitoring of the PF-TX. Another interesting result is that although the role of the controller's own observation does not restrict the risk in some cases, it plays a significant role in cases without active monitoring of PF-TO and no ATC alerts being generated. These findings are revealed due to the development and simulation of the agent-based model that covers the totality of interactions of components and their variability in performance over time. The Monte Carlo simulations make it possible to understand the potential of agents in restricting the risk in off-nominal scenarios, through capturing their stochastic nature.

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4

Resilience

In order to increase the resilience of the air transportation system, there is a need to identify, understand, and model system interdependencies of the complex socio-technical air transportation system and analyse its response to the large variety of possible disruptions. This chapter aims to show that a complexity science perspective can be a valuable asset in meeting this need. In particular, the chapter aims at answering the following questions: What is resilience and how is it measured? Why use complexity science to model and analyse resilience? And which complexity science approaches can be used?

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Resilience

Abstract - Thanks to the influential work by Hollnagel and other researchers (2006), the value of resilience in air transportation has been well recognised in behaviour sciences. The objective of this chapter is to show that air transportation can benefit significantly by studying resilience from the complementary complexity science perspective. This allows to combine the knowledge from behavioural sciences with the systematic modelling and analysis approach of complexity science.

Keywords: Resilience, Resilience Metrics, Complexity Science

4.1 Introduction

CIVIL air transportation is an example of a large complex socio-technical system. It comprises interactions between different types of entities, including technical systems, operational stakeholders, regulators, and consumers (DeLaurentis and Ayyalasomayajula, 2009). Technology plays a central role as does the social context within which the various parties operate. This complex socio-technical air transportation system copes with many internal and external disruptions of different nature that implicitly test its resilience on a regular basis. These events may interact with each other, potentially creating a cascade of other events that may span over different spatial as well as time scales, ranging from affecting only one aircraft or crew, up to a group of aircraft. In current air transportation, disruptions are managed by operators at airlines, airports, and ATC centres, and may impact the overall performance of the socio-technical system, e.g. some flights are rerouted, some aircraft or crew are exchanged, and some passengers are rebooked. Managing disruptions involves trade-offs which are created by the complexities inherent to the processes managed and the finite resources of operational systems (Hollnagel, 2009). For instance, in the case of congested airspace, air traffic controllers might ask airlines to reroute their flights. In such a situation, improving the key performance area (KPA) 'safety' comes at the cost of the KPA 'economy'. Potentially, there are conflicting goals leading to dilemmas and bottlenecks that must be dealt with. Nevertheless most problems are adequately solved, and most of these events pass without substantial inconvenience for passengers.

In some cases, however, the resilience of the air transportation system falls short resulting in significant flight delays. A typical example is bad weather, which may jeopardise the normal operation of an airport or a sector and induces 'ripple' effects (propagation) throughout the air transportation network. Another example is that of a malfunctioning aircraft being stuck with its passengers at a distant airport, as a result of which all passengers are delayed many hours.

In addition to regular cases with limited consequences, also rare cases happen with very severe consequences. These severe consequences are of two categories: catastrophic accidents involving one or more aircraft; and network-wide consequences that may push the dynamics of the air transportation system far away from its point of operation, and therefore dramatically affect the performance of the system. The latter happens in case of external events for which the air transport network is vulnerable, such as outbreak of a viral disease causing passengers and airlines to change their travel behaviour (e.g. SARS in 2003 and Ebola in 2014) or volcanic ash impacting air travel in a large area (e.g. the Icelandic volcano in 2010). Cases of the former are fatal runway incursions (e.g. the Linate runway collision in 2001), fatal mid-air collisions (e.g. the Überlingen mid-air event in 2002), and loss of control of an aircraft flying through a hazardous weather system (e.g. the Air France crash in the Atlantic Ocean in 2009). Some external events belong to both categories, e.g. the 9/11 terrorist action in 2001 led to fatal accidents and caused closing down of air travel in a large area.

The examples above show a wide variety of significant events with major consequences. However, thanks to the resilience of the air transportation system, there also are many significant events having negligible consequences. In order to increase the resilience of the air transportation system, there is a need to identify, understand, and model system interdependencies of the complex socio-technical air transportation system and analyse its response to the large variety of possible disruptions. This chapter aims to show that a complexity science perspective can be a valuable asset in meeting this need. In particular, the chapter aims at answering the following questions: What is resilience and how is it measured? Why use complexity science to model and analyse resilience? Which complexity science approaches can be used?

This chapter is organized as follows. Section 4.2 addresses resilience capacities. Section 4.3 examines various resilience metrics from the literature. Section 4.4 introduces complexity science approaches for studying resilience. Section 4.5 provides conclusions.

4.2 Resilience Capacities

Resilience comes from the Latin word resilio, meaning ‘to jump back’, and is increasingly used in various disciplines to denote the ability to absorb strain and bounce back from unfavorable events. The term was initially used in the field of mechanics as "the ability of a metal to absorb energy when elastically deformed and then to release it upon unloading", e.g. Hoffman (1948). Holling (1973) extended the resilience concept to ecological systems as the "persistence of systems and of their ability to absorb change and disturbance and still maintain the same relationships between populations or state variables". Since then, various other extensions of resilience have been introduced in other domains, such as economics, organisational science and safety science.

Recently, Francis and Bekera (2014) conducted a systematic review of the complementary resilience developments across multiple domains, and identified the following three resilience capacities: (i) absorptive capacity, (ii) adaptive capacity, and (iii) restorative capacity. Absorptive capacity is the degree to which a system can absorb the impacts of system disruptions and minimise consequences with little effort (Vugrin et al., 2010). The practice of incorporating adequate buffer capacity in anticipation of increased stress on the system is for example an absorptive endowment. It is considered to be a proactive measure to absorb potential shocks. Adaptive capacity is the ability of a system to adjust to undesirable situations by undergoing some internal changes. Adaptive capacity is distinguished from absorptive capacity in that an adaptive system can change its response. A system's adaptive capacity includes the ability to forecast adverse events, recognise threats, and reorganise after the occurrence of an adverse event. Finally, restorative capacity is the ability to recover or bounce back from disruptive events and return to normal or improved operations.

Table 4.1 shows what the three resilience capacities mean for resilience related concepts like robustness and dependability. Robustness is defined as the ability of elements, systems, and other units of analysis to withstand a given level of stress or demand without suffering degradation or loss of function (MCEER, 2006). This definition is consistent with the absorptive capacity described by Francis and Bekera (2014). Hence, a socio-technical system that has absorptive capacity only is robust. System dependability is the collective term used in system engineering to describe a system's availability performance and its influencing factors: reliability[2] performance,

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[2] In system engineering, reliability is the ability of a system or component to perform its required functions under stated conditions for a specified period of time. One should note that this system engineering definition of reliability is more restricted than what is meant when we refer to a 'reliable' airline. Such an airline is indeed reliable in the sense of the system engineering definition. However, an airline also needs to be adaptive in response to unexpected adverse conditions, in order to perform in a competitive market. This entails getting passengers (and their bags) to their destinations (reasonably on time) and, indeed, having a reputation for doing so. Successful airlines thus have an adaptive capacity, rendering them resilient.

maintainability performance and maintenance support performance (IEC, 1990). Thus, a dependable system has both absorptive and restorative capacities. In comparison to dependability, resilience is an endowed or enriched property of a system that is capable of effectively combating (absorbing, adapting to, and rapidly recovering from) potentially disruptive events.

Table 4.1: Resilience capacities in relation to robustness and dependability

Related System properties	**Resilience Capacities**		
	Absorptive	**Restorative**	**Adaptive**
Robustness	+	-	-
Dependability	+	+	-
Resilience	+	+	+

Robustness and dependability are system properties that are well addressed through system engineering. For air transportation this means that the key resilience challenges are not only to address a complex socio-technical system rather than a complex technical system, though also to learn improving the adaptive capacities. These adaptive capacities of the socio-technical air transportation system concern both the phase of disruption absorption and the phase of recovering from a system performance degradation due to disruptions.

Placing emphasis on improving the adaptive capacity in absorbing disruptions concurs with the **resilience engineering** definition of Hollnagel et al. (2009) for use in air traffic management research: “a system is called to be resilient if it has the intrinsic ability to adjust its functioning prior to, during, or following changes and disturbances, and thereby sustain required operations under both expected and unexpected conditions”. In the safety domain, Hollnagel (2014) explains that this resilience engineering view reveals a need to study “what may go right”, rather than the traditional approach of studying “what may go wrong” only. The traditional and novel approaches are referred to as Safety-I and Safety-II respectively.

4.3 Resilience metrics

This section examines resilience metrics from the literature, covering different domains including ecosystems, critical infrastructure systems, networks, organizations, information systems, psychology, and transportation systems.

4.3.1 Ecosystems

For ecosystems, Gunderson et al. (2002) distinguished between two resilience measures: **ecological resilience** and **engineering resilience**. The latter considers resilience as the ability to return to the steady state following a perturbation (Pimm, 1984; Varian, 1992; Tilman, 1996; Scheffer, 2009), i.e. it implies only one stable state and global equilibrium. The former concept, considers resilience as the amount of disturbance that a system can absorb before it changes state (Holling, 1996; Gunderson et al., 2002; Scheffer, 2009), i.e. it emphasises conditions far from any stable steady-state, where instabilities can 'flip' a system into another regime of behaviour (Gunderson et al., 2002). So, ecological resilience is measured by the magnitude of disturbance that can be absorbed before the system redefines its structure by changing the variables and processes that control behaviour (Gunderson et al., 2002). For engineering resilience, the only possible measures for resilience are near-equilibrium ones, such as a characteristic return time to a global equilibrium following a disruptions, or the time difference between the moments of disruption and of full recovery.

4.3.2 Critical Infrastructure Systems

The earthquake engineering community (Tierney and Bruneau, 2007) suggested measuring resilience by the functionality of an infrastructure system after a disaster has occurred, and also by the time it takes for a system to return to pre-disaster level. Their suggestion was based on the observation that resilient systems reduce the probabilities of failure, the consequences of failure, and the time for recovery. This concept is illustrated by the 'resilience triangle' in figure 4.1, which represents the performance degradation due to damage caused by earthquake disruption(s), as well as the pattern of restoration and recovery over time.

The higher the resilience of a system, the smaller the size (depth and duration) of the triangle. Bruneau et al. (2003) expressed resilience as follows: $R_e = \int_{t_d}^{t_r} \left[100 - Q(t)\right] dt$, where $Q(t)$ is the performance level percentage at moment t, t_d is the moment of disruption, and t_r is the moment of recovery.

In a later earthquake engineering community work (Renschler et al. 2010), a framework was proposed to measure resilience at the community scale, integrating several dimensions such as population, environment, physical infrastructure, and economic development into one resilience index.

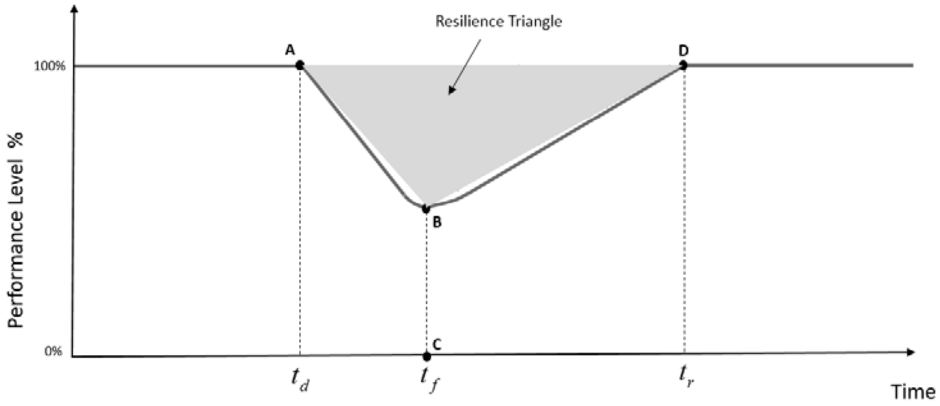

Figure 4.1: Resilience Triangle adapted from Tierney and Bruneau (2007), with disruption moment t_d, moment of full performance impact t_f and moment of full recovery t_r.

Li and Lence (2007) defined resilience $R_e(t_f, t_r)$ as the conditional probability that given full performance impact at time t_f, the system is fully recovered at time t_r, i.e.

$$R_e\left(t_f, t_r\right) = P\left[\left(F(t_r) \geq F_0\right) \middle| \left(F(t_f) < F_0\right)\right]$$

where $F\left(t_f\right)$ and $F\left(t_r\right)$ are the performance levels at t_f and t_r respectively, and F_0 is the original stable system performance level (100% level in figure 4.1). Attoh-Okine et al. (2009) extended the conditional probability approach of Li & Lence (2007) with a 'belief' function to capture incomplete data in urban infrastructure systems.

Francis and Bekera (2014) have proposed quantifying resilience R_e as follows:

$$R_e = S_P \frac{F(t_r)}{F_0} \frac{F(t_f)}{F_0}$$

where F_0 is the original stable system performance level (100% level in figure 4.1); $F(t_f)$ is the post-disruption performance level (at point B in figure 4.1); $F(t_r)$ is the performance at a new stable level after recovery efforts have been exhausted (at point D in figure 4.1); and S_P is the speed recovery factor (slope of BD).

Ayyub (2014) proposed to express the resilience R_e metric as follows:

$$R_e = \frac{t_d + \alpha\left(t_f - t_d\right) + \beta\left(t_r - t_f\right)}{t_r}$$

where α and β are the ratios of mean performance levels during periods $\left(t_d, t_f\right)$ and $\left(t_f, t_r\right)$ respectively versus the pre-disruption performance level.

Musman and Agbolosu-Amison (2014) proposed to capture resilience in terms of mission risk. According to their definition, resilience can be computed as being either: (1) a utility-based performance metric that indicates how well the system responds in the face of one or more incidents (where incidents are assumed to have occurred); (2) a probability that some events might occur to bring the system to some specified unacceptable level of performance; or (3) a risk estimate that combines the probability of incidents with the system utility-based measure of performance changes that result when the incidents occur.

4.3.3 Networks

In the area of networks, Najjar and Gaudiot (1990) proposed network resilience $R_N(p)$ and relative network resilience $R_{NR}(p)$, where $R_N(p)$ is defined as the number of node failures a network can sustain while remaining connected with a probability $(1-p)$, and $R_{NR}(p)$ is defined as the ratio of network resilience $R_N(p)$ to the number N of nodes in the network.

Garbin and Shortle (2007) generalised this to a network resilience metric in the form of actual network performance (or percentage of the normal network performance) as a function of the network damage (see figure 4.2). Examples of parameters that characterise networks are demand, topology, capacity, and routing. Garbin and Shortle (2007) also proposed to use the area under the curve in figure 4.2 as a resilience index metric for a network.

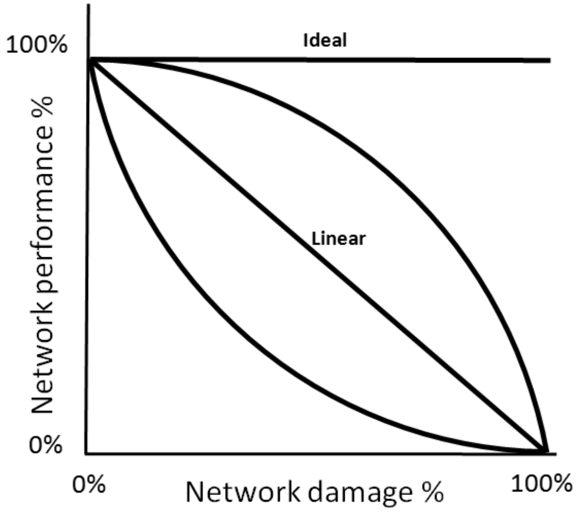

Figure 4.2: Examples of network resilience curves, showing network performance percentage as a function of network damage percentage; adapted from Garbin and Shortle (2007).

Rosenkrantz et al. (2009) proposed metrics to quantify the resilience of service-oriented networks under node and edge failures. The metrics are based on the topological structure of the network and the manner in which services are distributed over the network. They made a distinction between network edge resilience and network node resilience. A network is said to be k-edge failure resilient if no matter which subset of k or fewer edges fails, each resulting sub-network is self-sufficient. A network is said to be k-node failure resilient if no matter which subset of k or fewer nodes fails, each resulting sub-network is self-sufficient. In the same work, Rosenkrantz et al. (2009) presented algorithms to determine the maximum number of node and edge failures that can be tolerated by a given service-oriented network, and to optimally allocate services over a given network so that the resulting service-oriented network can tolerate single node or edge failures.

Henry and Ramirez-Marquez (2012) expressed resilience as the ratio of recovery to loss suffered by the system. This means that if the recovery is equal to the loss, then the system is fully resilient, and if there is no recovery, then no resilience is exhibited. They acknowledged that quantifying resilience requires identification of a quantifiable and time-dependent system-level delivery function, also called a ‘figure-of-merit’ (such as delay, connectivity, flow, etc.). In systems where multiple figures-of-merit are considered, an event could be disruptive with respect to one figure-of-merit but not disruptive with respect to another figure-of-merit. Therefore for a holistic analysis of system resilience, the system must be analysed with respect to all figures-of-merit that are relevant and important (Henry and Ramirez-Marquez, 2012).

4.3.4 Organizations and Information Systems

Dalziell and McManus (2004) suggested measuring resilience through assessing the total impact on Key Performance Indicators (KPIs) between the time of disruption and the recovery time, where the KPIs are real-valued measures at a certain moment in time for the corresponding KPAs. The variation of a specific KPI is measured and plotted against time from the start of the disruption t_d until full recovery t_r. The resilience then represents a weighted sum of the areas under the KPI curves.

Zobel and Khansa (2012) introduced a general approach for characterizing cyber infrastructure resilience in the face of multiple malicious cyber-attacks. Their proposed technique accounts for the amount of loss incurred by an information system in the face of multiple cyber-attacks, and it captures the strength and timing of these attacks.

4.3.5 Psychology

In psychology, various psychometric scales have been developed to assess the resilience of individuals, i.e. Likert scales. For instance, Wagnild and Young (1993) developed a resilience scale, the purpose of which was to identify the degree of individual resilience, considering a positive personality characteristic that enhances individual adaptation. The scale consists of 25 items each rated with a 7-point agreement scale. Smith et al. (2008) proposed a ‘brief resilience scale’ to assess the ability to bounce back or recover from stress.

Other Likert scales include the Baruth protective factors inventory, the Connor-Davidson scale, and the resilience scale for adults (see Ahern et al. (2006) for a detailed review).

4.3.6 Transportation Systems

Chen and Miller-Hooks (2012) defined a resilience indicator that considers the ability of the freight transportation network to cope with the negative consequences of disruptions. The indicator explicitly accounts for the network topology, operational attributes, and the impact of potential recovery activities. Such activities might be taken in the immediate aftermath of the disruption to meet target operational service levels while adhering to a fixed budget.

Omer et al. (2013) identified three resilience metrics to measure the impact of disruptions on the performance of a road-based transportation system. The three identified metrics were the travel time resilience, environmental resilience, and cost resilience. The resilience values were measured by introducing hypothetical disruptions to a network model of a regional transportation network.

Gluchshenko and Foerster (2013) proposed a qualitative measure for resilience in air transportation based on recovery time. They introduced three degrees of resilience, namely: (i) high resilience, when the time of deviation is considerably longer than recovery time; (ii) medium resilience, when the time of deviation and recovery time are approximately equal; and (iii) low resilience, when the time of deviation is considerably shorter than the recovery time.

Hughes and Healy (2014) proposed a qualitative framework to measure the resilience of road and rail transport system, through dedicated measurement categories for technical and organisational dimensions. The framework involves an initial determination of the context of the resilience assessment, followed by a detailed assessment of resilience measures, which combine to generate a resilience score ranging from 4 (very high resilience) to 1 (low resilience).

Janic (2015) provides an alternative resilience indicator for air transport network analogous to the indicator proposed by Chen and Miller-Hooks (2012) for intermodal freight transport. Such indicator considers the network's inherent properties and the set of actions for mitigating costs and maintaining the required safety level. Because mitigating actions include delaying, rerouting and/or cancelling flights, Janic (2015) defines this indicator as the ratio of the actually realized on-time and delayed flights to the total number of scheduled flights during specific time period. Janic (2015) also proposed to measure the resilience of an air transport network consisting of N airports by estimating the sum of the weighted resilience of each individual airport.

Following the proposal of Musman and Agbolosu-Amison (2014) resilience can be expressed in terms of mission risk. In air transportation, a well-studied mission risk metric is the reach probability for an aircraft trajectory (Prandini and Hu, 2006, 2008; Blom et al., 2007b, 2009). Let $P_{\mathrm{Re}ach}^{i,j}(h,d,T)$ be the probability that the difference in

3-dimensional position $(s_t^i - s_t^j)$ of aircraft pair *(i,j)* hits or enters a disk $D(h,d)$ of height *h* and diameter *d*, on a finite time interval $[0,T]$, i.e.

$$P_{\mathrm{Re}ach}^{i,j}(h,d,T) = \Pr ob\{\exists t \in [0,T] \text{ such that } (s_t^i - s_t^j) \in D(h,d)\}$$

Then the reach probability $P_{\mathrm{Re}ach}^{i}(h,d,T)$ for aircraft *i* is obtained by a summation over these $P_{\mathrm{Re}ach}^{i,j}(h,d,T)$'s for all $j \neq i$, i.e.

$$P_{\mathrm{Re}ach}^{i}(h,d,T) = \sum_{j \neq i} P_{\mathrm{Re}ach}^{i,j}(h,d,T)$$

In Blom et al. (2015) this reach probability is evaluated for an air traffic application with $h = 0$ and *d* ranging from 0.1 NM till 6 Nm. Hence $P_{\mathrm{Re}ach}^{i}(h,d,T)$ is here a metric for the probability that the mission fails in realizing a horizontal miss distance of *d* or higher between aircraft *i* and all other aircraft. Similarly, the complement $1 - P_{\mathrm{Re}ach}^{i}(h,d,T)$ is the probability that the mission succeeds in realizing a horizontal miss distance of *d* or higher between aircraft *i* and all other aircraft.

4.3.7 Usability in Air Transportation

From the literature review of resilience metrics one may conclude that there are multiple approaches to measuring resilience. Hence, the key question is which of these resilience metrics from various domains are most appropriate for air transportation? In order to make some progress we address this for the possible types of consequences identified in the introduction:

i. Negligible consequences.
ii. Catastrophic accidents involving one or more aircraft;
iii. Significant local performance consequences
iv. Network wide performance consequences.

For the latter types (iii) and (iv) consequences, it is tempting to use the triangle in figure 4.1 as a measure of the lack of resilience of the system considered in response to the disruption(s). Then **engineering resilience** is very effective in measuring the duration

(A-D) of the resilience triangle in figure 4.1. Typically, this duration is a measure for the extra time needed to implement and realise a (safe) recovery from the disturbance. However, the real difficulty is how to measure the depth (A-B) of the immediate post-disruption performance degradation in the resilience triangle. The resilience metrics developed in various domains form an illustration of the difficulty in measuring this depth. As suggested by Dalziell and McManus (2004), a possible approach would be to measure this depth in terms of a weighted sum of multi-dimensional KPIs that are commonly in use by the air transportation community.

Types (i) and (ii) consequences are not well captured by the resilience triangle interpretation. Consequence (i) means that there is no triangle at all. Consequence (ii) simply implies that there may be loss of aircraft hull(s) and passenger lives, rather than recovery. The measure needed for type (i) consequences is of **ecological resilience** type, i.e. which characterises the (amount of) disruptions that can be handled in such a way that the consequences are negligible. This leads to a shortlist of two remaining metrics: the psychological metrics (e.g. Likert scales) and the mission risk metric (e.g. reach probability). Because resilience metrics for individual humans only are insufficient for the complex socio-technical air transportation system, the mission risk metric seems to be the best candidate. A complementary advantage of the mission risk metric is that its complement forms a metric for mission success.

It should be noted that none of the metrics measures the individual contribution of the adaptive capacity separately from measuring the contributions of the absorptive and restorative capacities. This means that in order to capture the effect of adaptive capacities, one has to conduct two measurements: one for the full complex system, and another one for the complex system in which the adaptive capacities have been nullified.

A complementary problem is the challenge of collecting real resilience data from the complex socio-technical air transportation system. To do so, one has to await particular disruptions to happen in reality. Even for the existing air transportation system this is a challenge, let alone for the design of a novel operational concept. This asks for the use of appropriate complexity science modelling and analysis approaches.

4.4 Complexity Science Perspective

4.4.1 Complex Systems Interdependencies

In order to improve the resilience of the complex socio-technical air transportation system, it is critical to identify, understand, and model system interdependencies (Ouyang, 2014). Today, the performance of air transport operations, particularly under disruptive events, is dependent upon a set of highly interdependent subsystems including airlines, airports, and ATC centres. These subsystems are often connected at multiple levels through a wide variety of mechanisms, such that an interdependency exists between the states of any given pair of subsystems or components. Rinaldi et al. (2001) defined an interdependency as a bidirectional relationship between two infrastructures through which the state of each infrastructure influences or is correlated to the state of the other. As a simple example, airlines and airports are interdependent. An airport closure (e.g. due to weather, limited capacity, or ATC strike) might cause airlines to cancel or divert their flights. At the same time, decisions made at an airline operations control centre influence and depend on airport processes (e.g. gate change, passenger luggage). In normal air transport operations, some interdependencies are invisible, but under disruptive scenarios they emerge and become obvious. An illustration of this is the 2010 Eyjafjallajökull volcano eruption in Iceland which caused the closure of airspace of many European countries, and millions of passengers to be stranded at airports around the world.

Rinaldi (2004) identified four primary classes of interdependencies in critical infrastructure systems; these are presented in table 4.2. An infrastructure system is defined by the US President's commission on critical infrastructure protection (1997) as a network of independent, mostly privately-owned, man-made systems and processes that function collaboratively and synergistically to produce and distribute a continuous flow of essential goods and services. Such a system is considered to be critical when its incapacity or destruction would have a debilitating impact on defence and economic security.

Table 4.2 Interdependency types in critical infrastructure systems

Interdependency type	Definition
Physical interdependence	When the state of two systems are each dependent on the material output(s) of the other.
Cyber interdependency	When the state of a system depends on information transmitted through the information infrastructure.
Geographic interdependency	When the state of a system can change due to a local environmental event.
Logical interdependency	When the state of two systems are each dependent on the state of the other *via* another mechanism than one of the three above.

Modelling interdependencies in air transportation is a complex, multidimensional, multidisciplinary problem. Table 4.3 lists some of the dimensions associated with system interdependencies that complicate resilience analysis. To model such interdependencies, there is a need for the systematic application, validation, and integration of modelling approaches. This view aligns with a common view in the literature that for the analysis of the resilience of complex critical infrastructure systems, various modelling and simulation approaches need to be integrated into a unifying framework that accounts for various dimensions (Ouyang, 2014). Each approach is appropriate for a certain number of resilience applications, depending on the components being modelled. Overall, the unifying framework can be used to assess the effectiveness of various resilience improvement strategies, and therefore supporting both strategic and tactical decision-making.

Table 4.3 Dimensions and their implications for resilience analysis of the air transportation system.

Dimension	Implications for Resilience Analysis
Multiple stakeholders	Stakeholders have different motivations and problems that drive the modelling requirements.
Multiple spatial scales	Scopes of scenarios range from airports to the whole European airspace or to the global scale. Scale affects the resolution and quantity of interdependency data required for models.
Multiple time scales	Different events have varying time scales of relevance. The dynamics of the impacts vary from minutes (e.g. normal activities by the operators), to days (e.g. bad weather), up to years or even decades (e.g. catastrophic accidents).
Multiple KPAs	Multiple competing KPAs exist in air transportation; e.g. safety, capacity, economy, environment. Resilience analysis should be performed with respect to the full spectrum of these KPAs.
Cascading and higher order effects	Disruptions at one airport can propagate to other airports, creating second and higher order disruptions.
Socio-technical perspective	The air transportation system is a socio-technical system. Behavioural responses can influence the efficiency and safety of operations (e.g. situation awareness of operators, or passenger response to an infectious disease).
Disruption management plans	Recovery procedures influence the state of a system during a disruption and may affect coordination among various stakeholders; e.g., disruption management by airline operations control (AOC).
Regulations	Regulations influence operational behaviours as well as the response to and recovery from disruptions (e.g. cancelling a flight due to curfew at a destination airport).
Growing demand	Constant growth in the number of flights, aircraft and airports. Rapid change of the market (from a small number of national airlines to the recent appearance of many companies with new business models).

4.4.2 Complexity Science Approaches

Ouyang (2014) provided a comprehensive review of various complexity science modelling approaches and grouped them into several broad types: agent-based approaches, network-based approaches, empirical approaches, systems dynamics-based approaches, economic theory based approaches, and other approaches such as hierarchical holographic modelling, the high level architecture based method, Petri-nets, dynamic control system theory, and Bayesian networks. These approaches have subsequently been systematically assessed against several resilience improvement strategies for critical infrastructure systems, and the types of interdependencies they cover (Ouyang, 2014). Overall, agent-based methods and network flow-based methods appear to have the widest and proven applicability, since they cover most of resilience improvement strategies corresponding to the three resilience capacities when compared to other approaches. Complementary to this, viability theory and stochastic reachability analysis (Bujorianu, 2012; Martin et al., 2011) are particularly adept at allowing researchers to model and analyse the various forms of uncertainty in air transportation, and can be applied in both agent-based and network-based models. These four complementary modelling and analysis approaches are discussed in subsequent sections.

4.4.3 Agent-Based Modelling and Simulation

Agent-based modelling and simulation (ABMS) is increasingly recognised as a powerful approach to model complex socio-technical systems and to capture their emergent behaviour (Chan et al., 2010; Holland, 1998). This is because it can represent important phenomena resulting from the characteristics and behaviours of individual agents and their interactions (Railsback and Grimm, 2011). Burmeister et al. (1997) discuss the benefits of using an ABMS approach in domains that are functionally or geographically composed of autonomous subsystems, where the subsystems exist in a dynamic environment, and the subsystems have to interact flexibly. According to (Burmeister et al. 1997), ABMS can be used to structure and appropriately combine the information into a comprehensible form. For a complex socio-technical system, ABMS provides the tools for analysing, modelling, and designing the whole system in terms of its agents, each with its own set of local tasks, capability, and interactions with the other agents. Agents can be described at a high level of abstraction, yet the resulting composition is very efficient. Burmeister et al. (1997) conclude that ABMS reduces the complexity in systems design by making available abstraction levels that lend themselves to a more natural way of modelling in the problem domain. In the same vein, Jennings (2000) outlines that ABMS and complex system development requirements are highly compatible. He shows that ABMS techniques are particularly well suited to complex systems because: (a) they provide an effective way of partitioning the problem space of a complex system; (b) they provide a natural means to modelling complex systems through abstraction; and (c) they capture the interactions and dependencies.

4.4.4 Network-Based Methods

Network theory is used to investigate the structure and topology of networks, and it has applications in many disciplines including computer science, economics, sociology and operations research. Network-based methods are particularly useful for analysing the complex structure of large-scale systems. For instance, centrality measures can quantify the relative importance of network nodes and links (Newman, 2004). Dependency analysis between the nodes can calculate higher-order and cascading effects. Ouyang (2014) has classified network-based methods into two main categories namely topology-based methods, and flow-based methods. The former category models a network based on its topology, and the latter takes into account the service or flow made and delivered by the system. According to Ouyang (2014), network flow-based methods cover all three resilience capacities, in contrast to topology-based methods which cover the absorptive capacity only. In air transportation, both types of methods are of relevance. Complementary examples of topology-based methods are presented by the work of Guimerà et al. (2005) who analysed the worldwide air transportation network topology, Chi and Cai (2004) who analysed how topological properties of the US airport network are affected when few airports are no longer operational (e.g. due to failures or attacks), and Li and Cai (2004) who studied the airport network of China. A complementary example of results obtainable by network-flow based approaches is the analysis of delay in the US airspace system (Meyn et al., 2004) using the airspace concept evaluation system (ACES) simulator.

4.4.5 Stochastic Reachability Analysis

The primary aim of stochastic reachability analysis is to evaluate the probability that a system can reach a target set starting from a given initial state. This is especially of interest in air transportation where the system should be kept outside an unsafe region of the state space, and the control input can be chosen so as to avoid this unsafe region. Modern applications of stochastic reachability analysis have become increasingly complex. This complexity is due to the rich interactions, complicated dynamics, randomness of environment, uncertainty of measurements and tolerance to faults (Bujorianu, 2012). Examples of illustrative applications in air transportation include the work of Prandini and Hu (2006, 2008), who use stochastic reachability analysis to study aircraft conflict detection, and of Blom et al. (2007b, 2009), who use stochastic reachability analysis to study collision risk in air traffic management.

4.4.6 Viability Theory

Viability theory (Aubin, 1991) was originally developed to study dynamical systems which collapse or badly deteriorate if they leave a given subset of the state space. Therefore the objective is to keep the system in the part of the state space where it can survive, i.e. where it is viable. In follow-up research by Aubin et al. (2002), viability theory has been extended to hybrid dynamical systems. Recently, Martin et al. (2011) have explained that viability theory provides a natural mathematical framework for the modelling and analysis of resilience in complex systems. In general, viability theory can be applied to a wide range of applications ranging from cognitive sciences and finance, to economics and the sociological sciences. An example application in air transportation is obstacle avoidance, which also appears in numerous application fields. Other examples include using viability algorithms to compute wind optimal routes to reach an airport in minimal time, or computing safety envelopes of an aircraft in different phases of flight (Aubin et al., 2011).

4.4.7 Use in Air Transportation

The use of these methods in resilience modelling and analysis in air transportation may depend on the specific kind of application in mind. Below and in table 4.4 we make this more precise for the four types of consequences addressed earlier, i.e. (i) Negligible consequences; (ii) Catastrophic accidents involving one or more aircraft; (iii) Significant local performance consequences; and (iv) Network wide performance consequences.

Table 4.4 Ability in modelling and analysis of types of consequences due to disruptions.

Modelling and analysis approach	Types of consequences due to disruptions			
	(i)	(ii)	(iii)	(iv)
Agent-based modelling and simulation	+	+	+	-
Network flow-based methods	+	-	+	+
Stochastic reachability analysis	+	+	+	-
Viability theory	+	-	+	-

For types (i), (ii) and (iii) consequences, pilots and controllers may play a key role in reacting in a proper way to various events. In such cases agent-based modelling and simulation seems the most appropriate approach. For type (ii) consequences, it is explained in Blom et al. (2015) that agent-based modelling and analysis has to be combined with mathematical methods from the stochastic reachability domain; without these mathematical methods the MC simulation of an agent-based model might take too long. In contrast with traditional safety risk analysis, an ABMS approach can cover both Hollnagel's (2014) Safety-I (i.e. "what can go wrong") and Safety-II (i.e. "what can go right"). This dual capability of ABMS is clearly illustrated in Blom et al. (2015) for an advanced airborne self-separation concept of operations.

For types (i), (iii) and (iv) consequences, the network-flow-based methods seem to be the most logical fit as long as human involvement does not play a key role. Otherwise here also agent-based modelling and simulation might be the better choice. In this respect, it is of help to note that the earlier mentioned airspace concept evaluation system, used by Meyn et al. (2004), is a network flow-based method that uses an agent-based architecture, which reflects that, in practice, the network and agent-based methods tend to be integrated. If an agent-based or a network flow-based model has been developed in a proper mathematical setting, then this model can also be used to mobilise viability and reachability analyses for the specific application considered.

4.5 Conclusions

Thanks to scholars from behavioural sciences, it has become clear that for the future development of air transportation, resilience regarding various types of possible disruptions should be studied. The possible consequences of such disruptions may range from (i) negligible consequences, to significant consequences such as (ii) catastrophic accidents, (iii) significant local consequences, and (iv) very severe network-wide consequences. This chapter has conducted a systematic study of what complexity science has to offer to resilience in future air transportation for the various types of consequences.

A socio-technical system is said to be resilient when it has adaptive capacities in addition to absorptive and restorative capacities. A socio-technical system that has absorptive capacity only is called robust. A socio-technical system that has absorptive and restorative capacities is called dependable. Because system engineering is well developed regarding robustness and dependability, the main resilience research challenge is to significantly improve the adaptive capacities of the complex socio-technical air transportation system.

Robustness and dependability are system properties that are well addressed through system engineering. For air transportation this means that the key resilience challenges are not only to address a complex socio-technical system rather than a complex technical system, though also to learn improving the adaptive capacities. These adaptive capacities of the socio-technical air transportation system concern both the phase of disruption absorption and the phase of recovering from a system performance degradation due to disruptions.

Placing emphasis on improving the adaptive capacity in absorbing disruptions concurs with the **resilience engineering** definition of Hollnagel et al. (2009) for use in air traffic management research: “a system is called to be resilient if it has the intrinsic ability to adjust its functioning prior to, during, or following changes and disturbances, and thereby sustain required operations under both expected and unexpected conditions”. In the safety domain, Hollnagel (2014) explains that this resilience engineering view reveals a need to study “what may go right”, rather than the traditional approach of studying “what may go wrong” only. The traditional and novel approaches are referred to as Safety-I and Safety-II respectively.

In the literature several resilience metrics have been developed in various domains, both of qualitative and quantitative nature. The qualitative measures are of two types: **Ecological resilience** and **Engineering resilience**. Ecological resilience is a measure for the amount of disruptions that the socio-technical air transport system can absorb before it leads to significant changes in its KPAs. Engineering resilience is a measure for the duration of the period between the moment of significant reduction in its KPIs and the moment of recovery.

Most resilience metrics are of engineering resilience type, i.e. they address recovery rather than avoidance of significant consequences. Exceptions are the psychological metrics (e.g. Likert scales) for individual human performance (Ahern et al., 2006), and mission risk, such as reach probability for conflict and collision risk in air traffic management (Prandini & Hu, 2008; Blom et al., 2009).

None of the resilience metrics from literature is able to capture the effect of adaptive capacities of a socio-technical system in a separate way from capturing the effects of absorptive and restorative capacities. An effective way to address this problem is developing a proper model of the socio-technical system considered, and subsequently perform two measurements: one for the full model, and the other for a version of the model in which the adaptive capacities are nullified.

Complexity science provides powerful modelling and analysis means, the most important of which are agent-based modelling and simulation, network flow-based methods, stochastic reachability, and viability theory. When human operators play a key role in the specific resilience aspect to be studied, then agent-based modelling is the logical choice. When the resilience issue to be studied is concerned with propagation of disruption effects through a network, then a network flow-based method is the preferred choice. When both aspects play a role, then a network-flow based approach that uses agent-based architecture might be used. Once a proper agent-based or network-flow based model has been developed this may be used as a basis to mobilise stochastic reachability analysis or viability theory. These complexity science approaches allow making a model of the socio-technical air transportation system considered, and then use this model to assess the effects upon KPIs by increasing the size of disruptions and by varying disruption management strategies in each of the three capacities. The practical working of this approach is demonstrated in chapter 6 by quantifying the impact of adopting changes in coordination policies by airline operations control (AOC), e.g. by making them more or less adaptive.

In conclusion, this chapter has shown that the complexity science approach towards resilience in future air transportation has significant potential in both strengthening and broadening the resilience engineering approach of Hollnagel et al. (2006, 2009, 2014). This great potential of complexity science for the development of air transportation brings with it several valuable directions for follow up research, such as:

- To further develop and apply mission risk metrics that capture the effect of absorptive and adaptive capacities of the socio-technical air transportation system to both separation related and non-separation related disruptions.
- To further develop metrics that are directed to the recovery and adaptation of the socio-technical air transportation system from performance degradation due to disruptions.
- To further the development and application of ABMS for the evaluation of both positive as well as negative impacts of potential resilience improvements in the future designs in Air Traffic Management and Air Transport Operations.
- To further the development of network flow-based modelling and its integration with ABMS for the evaluation of recovery from network wide performance degradation in the air transportation system.
- To further develop the application of reachability and viability theories to the socio-technical air transportation system, by taking advantage of the above mentioned network-flow and agent-based model developments.

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5

A Study into Modelling Coordination in Disruption Management by Airline Operations Control

In this chapter we identify the potential of joint activity theory from the psychology research domain for AOC. In particular, we exploit a theoretical framework of coordination to analyse the current way of working at an AOC centre for a specific test case. The findings are then used in the next chapter to develop an agent-based model of AOC.

This chapter is a slightly improved version of:

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A Study into Modelling Coordination in Disruption Management by Airline Operations Control

Abstract - The resilience of the current air transportation system is implicitly tested around the globe on a regular basis. Each day of operation, the system is perturbed by disturbances of different nature ranging from severe weather conditions, through airport congestion, up to an aircraft mechanical failure. In most of these cases, humans operating at the sharp edge assure efficient and safe air transportation amidst various uncertainties and disturbances. Motivated by the need to understand such a human-invoked resilience, this paper explores a multi-agent systems approach to model part of the socio-technical air transportation system. The focus is on Airline Operations Control (AOC) where decision-making by the human operators facilitate disruption recovery. In particular, the paper integrates advances in research on coordination to understand its nature in AOC

Keywords: Resilience; Airline Operations Control; Disruption Management; Multi-Agent Coordination; Common Ground; Information Management

5.1 Introduction

THE resilience of the current air transportation system is implicitly tested around the globe on a regular basis. Each day of operation, the system is subject to a multitude of disruptions ranging from deteriorating weather, through passenger delays, up to aircraft or crew related problems. In most of these cases, operators at Airline Operations Control (AOC) take corrective actions in real-time in order to recover from disruptions. Such actions include cancelling or delaying flights, and swapping aircraft or crew, and are often the result of a coordination process that involve many operators at AOC. A good understanding of this coordination process is therefore important for analysing resilience in air transportation; which was defined by [1] as the Intrinsic ability of a system to adjust its functioning prior to, during, or following changes and disturbances, so that it can sustain required operations under both expected and unexpected conditions.

Coordination is a unique capability by humans that plays an essential role in the resilience of the complex socio-technical air transportation system; [2] defines coordination as “the attempt by multiple entities to act in concert in order to achieve a common goal.” Within AOC, many operators with different roles interact and coordinate at the sharp edge towards achieving a common goal, namely making sure their airline operations adhere to the plan as close as possible. Consideration of the aircraft routings, crew, maintenance, weather, customer needs, and turnaround processes complicate AOC. Current practice consists of coordination between humans who play a key role in recovering from disruptions. In order to start thinking about a further optimization of AOC resilience, a prerequisite is to first develop an in-depth understanding of the current interaction and coordination processes.

Recently, [2] has identified three coordination types that are required for a joint human-agent activity. These include the criteria, requirements, and choreography. The criteria are that the parties intend to work together and that their work is interdependent. If these criteria are to be satisfied, the parties have to fulfil certain requirements in order to have an effective coordination in the joint activity. E.g. the team members have to sustain common ground, and let themselves be directed by the actions of others. The form for achieving these requirements (the choreography) is a series of stages that are guided by various signals and coordination devices, in order to reduce the coordination costs of the coordination.

This paper aims at integrating advances in research on coordination to understand its types and stages in AOC. Application of the theoretical framework is illustrated using a scenario of an aircraft breakdown. The study focuses on European flight operations where aircraft operate a high number of flights in a day and have a short turnaround time. AOCC operators handle disruptions and therefore make numerous decisions within short timeframes. In contrast, intercontinental flights are long, aircraft may only operate a small number of flights per day, and have larger turnaround times. Decision-making therefore is generally less intense [3].

To date, the focus of research on coordination in aviation has been predominantly on pilots and air traffic controllers. Only few however have studied AOC (e.g. see the work of [4] and [5]). Yet, the AOC working environment is extremely intense and the outcomes of decisions made are critical to achieving desired performance targets. Furthermore, most of the research related to AOC focus on developing tools for solving operational problems [6]. However these tools could be of more assistance if coordination processes are considered by designers during the early development phase. Otherwise they could disrupt rather than support coordination and likely result in coordination breakdowns.

This paper is organized as follows. Section 2 gives a brief overview of the challenges faced during the day of operation. Section 3 provides relevant background on the disruption management process that is in use in many airlines. Section 4 presents the scenario as well as the multi-agent systems approach used to analyze coordination. Section 5 provides a conclusion.

5.2 Problems during the day of operations

It is important to develop a thorough understanding of typical problems that might appear during the day of operations. In many cases, these problems can have a significant impact on the airline's operations, resulting in substantial deviation from the planned schedule of services. Problems originating because of a local event (e.g. aircraft mechanical failure) can trigger other problems and easily propagate to other flights. A summary of these problems is provided below based on the literature [7-9].

- ATC restrictions
- Weather related: Wind, thunderstorm, low visibility conditions, etc.
- Equipment related such as aircraft mechanical failure or ATC system outage
- Crew related
- Misconnect violation: When a connecting crewmember is unable to connect on time to the next flight because of late arrival
- Rest violation: when crew layover is less than the legal layover e.g. due a late arrival preceding duty period
- Duty limit violation: when the actual duty period exceeds the duty period limit due to delay of one or more flights in the duty period
- Open position: it occurs in case of no show of a crew member due to illness or any other emergency, or when the up-line flight is cancelled such that the crewmember is not available to fly his next assignment.
- Passenger delays (longer than expected embarking and disembarking times) or delayed connecting passengers mainly due to late in-bound aircraft [10].
- Delay in ground handling operations: e.g. Cargo/baggage loading delays caused by lack of ground resources
- Airport capacity shortage at a given time due to traffic volume or runway unavailability (e.g. because of construction, surface repair, or disabled aircraft)

In order to deal with these disruptive events and reduce their impact, major airlines have established Airline Operations Control Centres (see Figure 5.1). These centres gather an extensive array of operational information and data, with the purpose to maintain the safety of operations, and efficiently manage aircraft, crew, and passenger operations. When disruptions occur, operators at AOCC adjust in real-time the flight operations by delaying departures, cancelling flights, re-routing aircraft, re-assigning crews, and accommodating disrupted passengers. This is known as disruption management and is explained in the next section.

Figure 5.1: A view of KLM's AOC centre

5.3 Disruption Management by AOC

The main objective of the disruption management process is to ensure that operations adhere to the airline published schedule through monitoring the progress of flights, identifying operational problems, and taking corrective actions in response to disruptions. The airline schedule is usually the outcome of a long-term and short-term planning process which is presented below.

5.3.1 The Airline Planning Process

Based on [4, 11-14], the airline planning process can be composed into different phases ranging from schedule development, through fleet assignment, up to aircraft routing and crew assignment (see Figure 5.2). These phases are shortly explained.

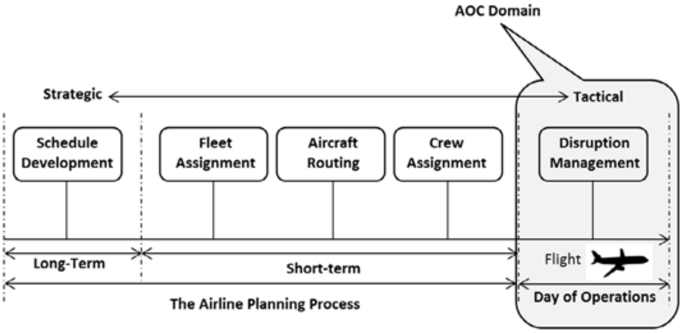

Figure 5.2: Airline planning and disruption management

Schedule Development: The airline scheduling process usually starts with the schedule development phase where (long-term) decisions are made by the airline regarding which cities to be served, the timing and the frequency of the flights. Such decisions are usually based on a market demand forecast, available resources, regulations, and the behaviour of competing airlines. The main objective is to generate a schedule that maximizes revenue.

Fleet assignment: Once the flight schedule has been generated, the next phase is the fleet assignment phase which is about matching each aircraft type in the fleet with a particular route in the schedule. The main goal is to maximize profit while meeting different operational constraints, since each aircraft type has different characteristics such as operating costs, seating capacity, crew, fuel, and maintenance. It should be noted that maintenance is a major process that causes airlines to be less diverse when planning their fleet. It requires to have skilled crew for each fleet type, different maintenance check plans, and thus less flexibility in replacing an aircraft in case of disruptions.

Aircraft Routing: Also referred to as aircraft rotation, aircraft assignment, or tail assignment is about assigning individual aircraft (referred to as tail number) to operate flight legs. The main goal is to minimize the operating costs, while satisfying mandatory maintenance requirements. The maintenance consideration is to ensure that aircraft are flown through the network in a manner that allows them to receive the required maintenance checks at the right time and at the right airport, since not all airports have the capability to perform maintenance on all fleet types.

Crew Assignment: This involves the process of identifying sequences of flight legs and assigning both cockpit and cabin crews to these sequences. Because of its complexity, the crew assignment problem is typically solved in two phases, namely flight leg sequencing and crew rostering:

- Flight leg sequencing: This is the process of sequencing flight legs within the same fleet that start and ends at the same crew home airport. The sequence typically spans from one to five days depending on the airline, and are subject to a set of rigid legality requirements imposed by unions and governments. The objective of this phase is to find a set of flight legs that covers all flights and minimizes the total crew cost.
- Crew rostering: Once the flight leg sequencing problem is solved, the next phase is crew rostering which is about assigning individual qualified crew members to crew pairings.

5.3.2 Disruption Management Process

Castro & Oliveira [12] present the current Disruption Management process that is in use by many airlines (see Figure 5.3). The process has 5 steps namely:

1. Operation monitoring: In this step, the flights are monitored to see if anything is not going according to the plan. The same in relation to crew members, passenger check-in, and boarding, cargo and baggage loading.
2. Take action: If an event happens, like, for example a crew member is delayed or an aircraft malfunction, a quick assessment is performed to see if an action is required. If not, the monitoring continues. If an action is necessary, then there is a problem that needs to be solved.
3. Generate and evaluate solutions: Having all the information regarding the problem AOCC needs to find and evaluate candidate solutions. It is current practice in the airline industry to recover from disruptions in a sequential manner, first recovering aircraft, then crew, and then passengers. Such approach is adopted because of the complexity of the problem (3 dimensions). AOCCs rely heavily on the experience of their controllers and on some rules-of-thumb (A kind of hidden knowledge) that exist in AOCC.
4. Take decision: Having the candidate solutions, a decision needs to be taken
5. Apply decision: After the decision, the final solution needs to be applied in the environment, that is, the operational plan needs to be updated accordingly.

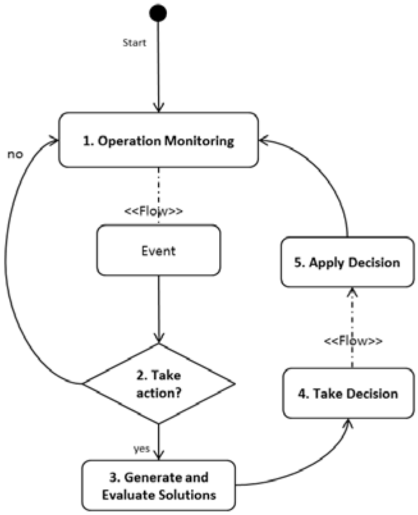

Figure 5.3: The disruption management process [12]

5.4 Analysing Coordination in an Aircraft Breakdown Scenario

In this section we explore the recent framework from [2] to investigate coordination in AOC. For this analysis we assume that the airline has a similar disruption management process to the one presented in the previous section.

5.4.1 Scenario Description

The scenario considered is from [15]. The pilot of aircraft PHBDT at Barcelona airport reports that there is a hole in the body of his aircraft. A luggage tractor has taken a turn too sharply and damaged the aircraft's aluminium skin. The Operations Controller organizes a telephone conference to discuss the problem. This way, he is able to talk simultaneously to the pilot, the engineers and the Service Manager in Barcelona and the KLM maintenance unit who are sitting behind him at AOCC. Below is a script of the initial communication activities.

> **Service Manager:** We have the Bravo Delta Tango here, and it has a very deep stretch with a hole in it. We would like to have maintenance here.
> **Operations Controller:** Clear, I think I have the captain on the other line. I will put you on hold for a second and then come back to you. Hold the line please. Bravo Delta Tango – is on departure from Barcelona. I now have the engineer and the captain on the other line
> **Pilot:** Hello

> **Operations Controller:** I will switch to the engineer in a moment, I have him on the other line. Hold on please.
> **Maintenance Engineer at AOCC:** This is Ben speaking
> **Operations Controller:** Jan here, I'm going to switch now: Bravo Delta Tango in Barcelona with a scratch and a hole. Everyone is switched on now, captain, engineer, and maintenance.
> **Barcelona Engineer:** There is a deep scratch of about 30 centimetres long, and in the middle of this there is a hole through the body.
> **Operations Controller:** Maintenance?
> **Maintenance Engineer at AOCC:** We can seal the scratches with high speed tape and then fly back to Amsterdam unpressurized

To better illustrate this scenario, we add a representation of the original schedule that involves 3 aircraft, twelve flights, and four airports (AMS, CDG, BCN, and HAM). A turnaround time of 40 minutes is assumed (see Figure 5.4).

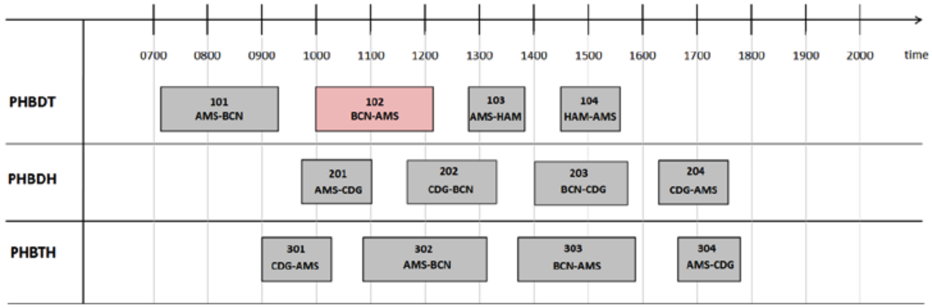

Figure 5.4: Original schedule showing the disrupted flight in red. The flight durations were obtained from the website of the airline.

The mechanical problem of aircraft PHBDT is serious enough to cancel flight 102. This will create different problems the OC must resolve: a) he needs to arrange a reserve aircraft for the subsequent flights that were originally planned to be flown by aircraft PHBDT; b) he needs to arrange both flight and cabin crew as it is probable that the delay of flight 102 will mean that they will exceed the number of hours they are legally permitted to work; and c) reroute all passengers to Amsterdam.

5.4.2 Agent-Based View of AOC

In order to examine the scenario, it is important to identify the human agents at AOCC and their behavior. There exist several types of AOCCs of which the organization depends on multiple factors. These factors include the airline size, the type of airline operations, location, and airline culture. However, despite the different organization types, it is possible to identify human agents that are common to all AOCCs [5, 8, 12, 16] (see Figure 5):

Supervisor: Also known as the Airline Operations Controller or Manager make the final operational decisions. His responsibility is to maintain the airline's published schedule and manage disruptions. Airline Operations Controllers are highly experienced, often having risen through the ranks at an airline over several years. They are known to be very decisive even when limited information is available, and work in a high pressure and time-critical environment. Airline Operations Controllers do not work in isolation, but function as part of a larger operations team in which they play the coordinating role. In case of disruptions, they work closely with the aircraft routers and crew schedulers. If no recovery is found within a reasonable time window, the only available option is to cancel the flight and rebook its passengers on next flights. However, before coming to this costly solution, all possible recovery options are thoroughly investigated.

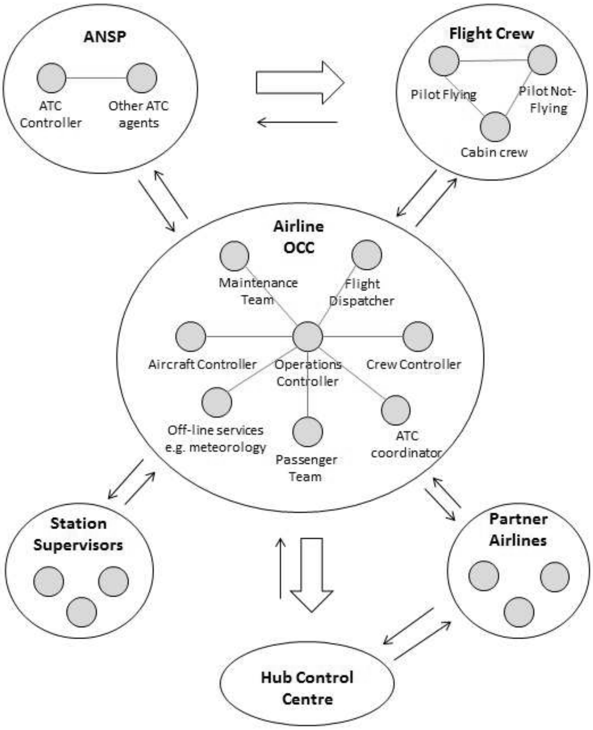

Figure 5.5: AOCC agents and their interactions

Flight Dispatcher: Prepares flight plans and requests new flight slots to ATC entities (FAA in North America and EUROCONTROL in Europe). Next to planning, the flight dispatcher also monitors the progress of an aircraft journey and advises its flight crew of any circumstances that might affect flight safety (e.g. weather conditions)

Aircraft Controller: Specialized in monitoring and adjusting the routing of aircraft through the network of flights while complying with maintenance requirements, operational restrictions, night curfews and other preferences. In case of violations, the aircraft router might swap, ferry, or use reserve aircraft. The aircraft router assures coordinated information flow among maintenance services, field stations, as well as within AOCC regarding aircraft availability.

Crew Controller: To ensure the staffing of flights, crew controllers continuously monitor the check-in and check-out of crew members as they move throughout the airline's route network. They update and change the crew roster in case of delays or cancellations, and check the legalities of proposed decisions with respect to affected crews. In case of violations, crew control might swap crew or use a reserve crew. The reserve crew can be at the same station or could deadheaded from another station. The newly assigned crew must have the same qualifications as the crew being replaced. In most airlines, crew control is divided into cockpit and cabin crew.

Maintenance Team: The maintenance group is responsible for the unplanned maintenance services as well as for short-term maintenance scheduling. Changes in aircraft rotations might impact short-term maintenance, since maintenance cannot be performed at all stations.

Passenger Team: Decisions taken at AOCC will typically affect passengers. The passenger team coordinates with the operations controller to provide an assessment of the impact of AOC decisions on passengers with the purpose to find efficient solutions from a passengers perspective (e.g. minimizing the number of passenger delay minutes and passenger dissatisfaction). Part of this role is performed at airports. In case of delays or cancellations, the passenger team rebooks disrupted passengers, and in some cases, provide them with meals and/or accommodation.

ATC coordinator: ATC coordination is increasingly becoming important both in Europe and the US, in order for airline controllers to deal with ATC advisories (e.g. GDP by the FAA based on the CDM initiative).

Off-line support: Off-line services such as meteorology or operational engineering (flight technical services) are usually located at AOCC, and serve to provide supporting resources for all AOC operators. In addition, a crisis centre which coordinates activities after an accident or incident is often an integrated part of the airline's AOCC.

5.4.3 Multi-Agent Coordination Framework

This section introduces the multi-agent coordination framework applied to analyse the current way of working for the selected test case. The framework identifies three coordination types that are required for joint activity namely criteria, requirements, and choreography of joint activity (see Figure 5.6). These types are explained below.

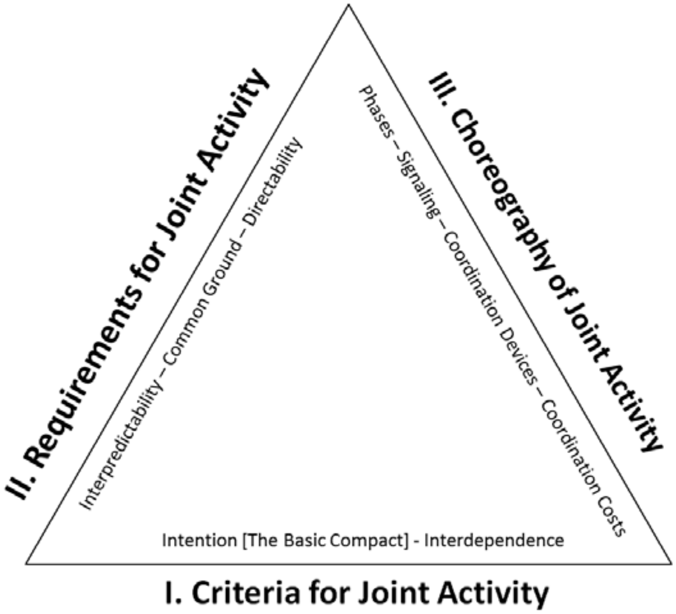

Figure 5.6: Description of Joint Activity [2]

I. Criteria for Joint Activity

There are two primary criteria for a joint activity: the parties have to intend work together (basic compact), and their work has to be interdependent

Intention (Basic Compact): is an agreement (usually tacit) to participate in the joint activity and to carry out the required coordination responsibilities. There are two aspects of basic compact: 1) the commitment to some degree of goal alignment. i.e. one or more participants relax their shorter-term local goals in order to permit more global and long-term goals to be addressed, and 2) commitment to try to detect and correct any loss of common ground that might disrupt the joint activity.

Interdependence: Joint activity emphasises how the activities of the parties interweave and interact. What party A does must depend in some significant way on what party B does and vice versa.

II. Requirements for Joint Activity

There are three primary requirements for effective coordination in joint activity: the team members have to be interpredictable, they have to have sufficient common ground, and they have to be able to redirect each other.

Interpredictability: Coordination depends on the ability to predict the actions of other parties with a reasonable degree of accuracy. Predictability includes accurate estimates of many features of the situation. E.g. the time needed by all of the participants to complete their actions, the skill needed, and the difficulty of the action. Shared scripts aid interpredictability because they allow participants in joint activities to form expectations about how and when other will behave.

Common Ground: refers to the pertinent mutual knowledge, mutual beliefs and mutual assumptions that support interdependent actions in some joint activity, more specifically about:

- The roles and functions of each participant
- The routines that the team is capable of executing
- The skills and competencies of each participant
- The goals of the participants
- The stance of each participant (e.g. his or her perception of time pressure, level of fatigue, and competing priorities)

It should be noted that common ground is not a state of having the same knowledge, data, and goals. Rather, common ground refers to a process of communicating, testing, updating, tailoring, and repairing mutual understandings.

Directability: refers to deliberate attempts to modify the actions of the other partners as conditions and priorities change.

III. Choreography for Joint Activity

The choreography of a joint activity centers on the phases (stages) of the activity. The choreography is also influenced by the opportunities the parties have to signal to each other and to use coordination devices. Coordination costs refer to the burden on joint action participants that is due to choreographing their efforts.

Phases: Coordination is accomplished one phase at a time in a joint activity. A phase is a joint action with an entry, a body, and an exit.

Signaling: The choreography of joint activity depends on the way the participants signal to each other about transitions within and between phases. The participants may signal their intentions, the difficulties they are facing, and their desires to redirect the way they are performing the task.

Coordination Devices: The choreography of joint activity is shaped by the use of coordination devices. These devices include highly diverse mechanisms of signalling. Examples include:

- Agreement: Coordinating parties can explicitly communicate their intentions.
- Convention: Often prescriptions of various types apply to how parties interact (e.g. established practices in a workplace)
- Precedent: Similar to coordination by convention, except that it applies to norms and expectations developed within an episode of the on-going process of a joint activity (or across repeated episodes of such activity): "that's the way we did it last time"
- Salience: has to do with how the ongoing work arranges the workspace so that next move becomes apparent within the many moves that could conceivably be chosen. Coordination by salience is a sophisticated kind of coordination produced by the very conduct of the joint activity itself. It required little or no overt communication and is likely the predominant mode of coordination among long standing highly practiced teams

Coordination Costs: Fundamental to coordination is the willingness to do additional work and to narrowly downplay one's immediate goals in order to contribute to the joint activity. Such effort to choreograph joint activity is one type of coordination costs.

Other types include synchronization overhead, communication overhead, redirection overhead, and diagnosis overhead

5.4.4 Identifying Coordination Types

Figure 5.7 gives an overview of AOCC's response to the disruption considered in the aircraft breakdown scenario. The following assumptions were made:

- No cooperation between airlines is accounted for[3].
- Following a disruption, the problem is solved in a sequential order: first aircraft, then crew, then passengers; as it is the case in many airlines.
- There are no VIP flights.
- There are no connecting passengers on board the disrupted flight.
- The schedule needs to be restored by the following day.
- Each minute of delay on any flights has an associated cost.
- A hierarchical structure was assumed for AOCC.

1. PF reports problem to OC
2. OC organizes conference call to assess problem
3. Joint conference call where stakeholders discuss problem and generate different solutions
4. MT suggest solution to OC: fly aircraft back empty
5. OC calls AC to arrange reserve aircraft
6. Joint call between OC and AC to arrange reserve aircraft for flights 103 and 104
7. AC calls MT after finding only one aircraft which is being scheduled for maintenance
8. Joint call between AC and MT to check if maintenance can be postponed
9. MT confirms that maintenance can be postponed
10. AC reports back to OC about arranging reserve aircraft
11. OC calls CS to check impact on crew
12. Joint call between OC and CS to discuss the situation for crew of flight 102
13. After finding violations in crew schedule, CS arranges reserve crew and reports back to OC
14. OC calls PT to solve the passengers problem
15. Joint call between OC and PT to reroute disrupted passengers of flight 102.
16. After finding available itineraries eligible for assignment, PT reroutes all disrupted passengers and reports back to OC

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[3] There exist several bilateral agreements within airline alliances which are a strong function of several airline types (full-service, low-cost, regional, charter).

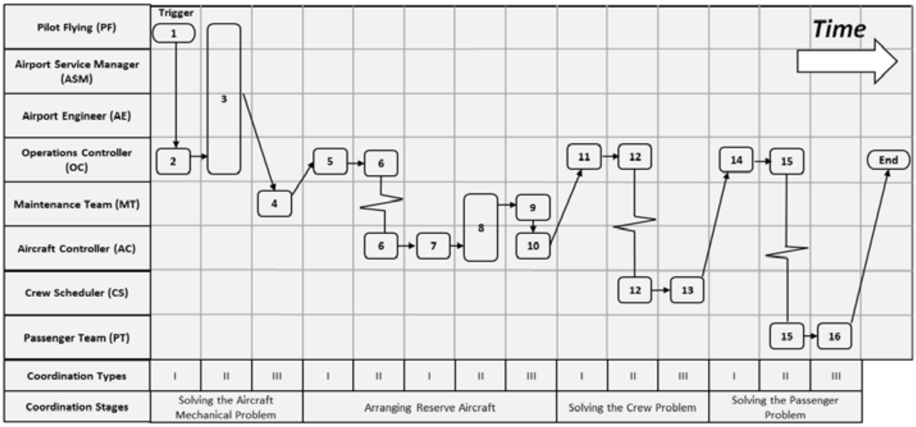

Figure 5.7: Identifying types and stages of coordination in the disruption management process for the test case

Figure 5.7 identifies various stages and types of coordination during the disruption management process. The coordination stages are characterized by the entry, actions, and exits. The exiting of a phase can be difficult to coordinate. Therefore passive team members at AOCC have a role in signalling to direct the operations controller attention to the cue that a certain task has been completed (e.g. step 4 or 10 in Figure 5.7). Figure 5.7, also shows that for each coordination stage, the three types of coordination are required. I) signing on the basic compact (e.g. intention of the operations controller to coordinate with his team); II) fulfilling the requirements (e.g. sustaining common ground through a conference call); and III) choreographing joint activity through signalling and coordination devices.

5.5 Conclusion

Within commercial aviation, the resilience role is largely concentrated within AOCC's. In this paper we have exploited the recent theoretical framework of coordination for joint activity [2] to analyse the current way of working of an AOCC for a specific test case. This has led to a systematic decomposition of the AOC process into three types of coordination, and into a series of well recognizable coordination stages.

In follow up work this systematic decomposition of the AOC process will be extended to additional test cases, and then be exploited for the development of an agent based model of AOC. Subsequently this model will be used in studying the further optimization of the resilience of AOC.

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6

Agent-Based Modeling and Simulation of Coordination by Airline Operations Control

This chapter demonstrates the benefits of applying ABMS to an airline problem. The specific application concerns airline operations control, which core functionality is one of providing resilience to a large variety of airline operational disruptions. Motivated by the need to improve resilience, this chapter implements and compares four coordination policies for disruption management. Three policies are based on established practices, whereas the fourth is based on the joint activity theory introduced in the preceding chapter. Each of these policies has been characterized in terms of the various coordination techniques that have been developed in the literature. In order to evaluate the four policies, an agent-based model of the AOC and crew processes has been developed. Subsequently, this agent-based model is used to evaluate the operational effects of the four AOC policies on a challenging airline disruption scenario.

This is a preprint of a forthcoming journal article including additional footnotes

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Agent-Based Modeling and Simulation of Coordination by Airline Operations Control

Abstract - This paper implements and compares four coordination policies through agent based modelling and simulation (ABMS), motivated by the need to understand and further optimize coordination processes in the highly complex socio-technical air transportation system. Three policies are based on established practices, while a fourth is based on the joint activity coordination theory from the psychology research domain. For each of these four policies, the relation with the literature on coordination is identified. The specific application of the four policies concerns Airline Operations Control (AOC), which core's functionality is one of coordination and taking corrective actions in response to a large variety of airline operational disruptions. In order to evaluate the four policies, an agent based model of the AOC and crew processes has been developed. Subsequently, this agent based model is used to assess the effects of the four AOC policies on a challenging airline disruption scenario. For the specific scenario considered, the joint-activity coordination based AOC policy outperforms the other three policies. More importantly, the simulation results provide novel insight in operational effects of each of the four AOC policies, which demonstrates that ABMS allows to analyze the effectiveness of different coordination policies in the complex socio-technical air transportation system.

Keywords: Airline Operations Control, Coordination, Joint Activity, Complex Socio-Technical Systems, Agent-Based Modelling and Simulation, Disruption Management, Decision-Making.

6.1 Introduction

COORDINATION is well developed in multi-agent systems research [1-6], with prominent application examples that include the framework for environment centered analysis and design of coordination mechanisms of Decker [7], the programmable coordination architecture for mobile agents of Cabri et al. [8], and the decentralized Markov decision process framework of Bernstein et al. [9]. Despite all these advances, important aspects that a human team can handle are not yet well understood in terms of multi-agent coordination models [10, 11]. A deeper, formal understanding of coordination in human teams could help researchers develop new insights and more efficient coordination strategies.

In order to contribute to this development, the aim of this paper is to conduct an Agent-Based Modelling and Simulation (ABMS) study of coordination in the highly complex socio-technical air transportation system. ABMS has proven to be of great use in identifying emergent behavior in the complex socio-technical air transport system [12]. Key ABMS application examples are in non-nominal air traffic response to air traffic control instructions [13], network-wide air traffic delay analysis [14, 15], agent-based safety risk analysis [16, 17], and artificial phase transitions in air traffic [18]. However, to the best of the author's knowledge, using ABMS for gaining a better understanding of the role of coordination in the socio-technical air transport system is novel.

Due to its open nature, the air transportation system is subject to daily disruptions from outside such as severe weather or volcano eruption. These external events may add to or interfere with various internal disruptions, such as an aircraft mechanical failure during operation. The management of these unforeseen airline disruptions requires ample coordination by the Airline Operations Control (AOC) centre.

Pujet and Feron [19] have investigated the dynamic behavior of an AOC center of a major airline using a discrete event model. In their model, each agent was represented as a multi-class queuing server, and the AOC as a multi-agent, multi-class queuing system. Since then several other AOC studies, e.g. [20-24], have focused on developing decision-support tools rather than studying the socio-technical challenges of the operation.

There are also a few studies addressing AOC as a socio-technical system [25-28]. Kohl et al. [25] have studied numerous aspects of airline disruption management, and argue that realistic approaches to disruption management must involve humans in the key parts of the process. Feigh [26] has examined the work of airline controllers at four US airlines of varying sizes, and applied an ethnographic approach for the development of representative work models. Bruce [27, 28] has examined many aspects of decision-making by airline controllers through conducting multiple case studies at six AOC centers. Although these socio-technical studies provide valuable insight into the challenges of an AOC center, this has not yet led to a significant improvement in the performance of the socio-technical AOC system.

The current paper studies how well multi-agent coordination. models for socio-technical systems compare to established AOC practices. To accomplish this, the paper uses agent-based modelling and simulation to compare four specific AOC disruption management policies P1-P4 for a challenging airline disruption scenario. Policies P1-P3 are based on established AOC practices [27, 28], and policy P4 is based on the joint activity coordination theory of Klein et al. [29]. Policy P1 forms the basis for P2-P4 and makes use of several approaches from the general coordination literature, such as organization, planning, supervision, routines and protocols. Complementary to the coordination approaches of P1, policy P2 also makes use of negotiation protocols between team members. Policy P3 is similar to Policy P2, though makes use of team meetings instead of negotiation protocols. Policy P4 is an extension of Policy P3 with Team Situation Awareness [30, 31] and with the higher level coordination elements of Klein et al. [29] replacing the dedicated routines and protocols of P3.

Section 2 of the paper reviews the literature on coordination approaches for teams of software agents and human agents respectively. Section 3 provides an overview of AOC, its embedding in the larger air transportation system, and its disruption management challenges. Section 4 develops the four policies P1-P4 and explains their relation with the coordination approaches reviewed in Section 2. Section 5 describes the challenging airline disruption scenario considered. Section 6 explains the development of the ABMS environment. Section 7 provides the simulation results obtained for the considered airline disruption scenario and finally, Section 8 draws some key conclusions of the work.

6.2 Coordination Approaches in the Literature

This section first gives an overview of coordination approaches in software agent systems, followed by a review of complementary coordination approaches in human teams.

6.2.1 Coordination by Software Agents

One of the classic coordination approaches is the **master/ slave technique** that is typically used for task and resource allocation among slave agents by a master agent [2]. The master agent plans and distributes fragments of the plans to the slaves. The slaves may or may not communicate among themselves, but must ultimately report their results to the master agent. Another classic coordination technique is the **contract net protocol** [32]. In this approach, agents assume two roles: 1) A manager who breaks a problem into sub-problems and searches for contractors to solve them, as well as to monitor the problem's overall solution, and 2) A contractor who does a sub-task. However, contractors may recursively become managers and further decompose the sub-task and sub-contract them to other agents.

Other coordination approaches include, **multi-agent planning** [2], **negotiation protocols** [33, 34], and **voting methods** [35]. In multi-agent planning, agents build and maintain a multi-agent plan that details all of the future actions and interactions required to achieve their goals, and furthermore interleave execution with more planning and re-planning. Due to the re-planning feature, multi-agent planning is particularly useful in dynamic situations. Negotiation is defined by Bussmann and Muller [34] as the communication process of a group of agents in order to reach a mutually accepted agreement on some matter. Sycara [33] has explained that to negotiate effectively, agents must reason about beliefs, desires, and other agents. Voting methods refer to various techniques that are used to describe decision-making processes involving multiple agents. Although originating from political science, they are currently used within a number of domains such as gaming theory and pattern recognition.

The various coordination approaches presented have their relative advantages and disadvantages and there is no universally best method. In general, the theoretical methods produce good results for narrowly defined coordination problems but many of their underpinning assumptions have limitations in developing real-world systems [11].

6.2.2 Complementary Approaches in Human Teams

Various complementary coordination approaches are of use in human teams, ranging from routine and psychological approaches, to ecological, socio-technical and integrative approaches; i.e. a fusion of multiple different approaches [36].

Thompson [37] identified two basic complementary coordination approaches in human teams, namely **routines/protocols** and **mutual adjustment**. The first approach involves the establishment of rules which constrain the action of each unit or position into paths consistent with those taken by others in the interdependent relationship. An important assumption in coordination by routine is that the set of rules be internally consistent, and this requires that the situations to which they apply must be relatively stable, repetitive, and few enough to permit matching of situations with the appropriate rules. The second approach, mutual adjustment, involves the transmission of new information during the process of action. March & Simon [38] refer to this as “coordination by feedback”. The more variable and unpredictable the situation, the greater the reliance on coordination by mutual adjustment [38].

Gittell [39] identified two other approaches, namely **team meetings** and **supervision**. Team meetings give participants the opportunity to coordinate tasks directly with one another. According to organization theory, they increase the performance of interdependent work processes by facilitating interaction among participants and are increasingly effective under conditions of high uncertainty. Supervisors, also known as boundary spanners, are individuals whose primary task is to integrate the work of other people.

Socio-technical coordination approaches include the **team situation awareness** model by Endsley & Jones [30, 31], and the **joint activity model** by Klein et al. [29]. The team situation awareness model conceptualizes how teams develop high levels of situation awareness (SA) across members and includes four crucial elements on which team SA is built. These include an understanding of what constitutes SA requirements in team settings, devices, and mechanisms that are important for achieving high levels of shared SA and the processes that effective teams use.

The joint activity model [29] identifies three types of process phases that are required for effective coordination namely: 1) **Criteria for joint activity**; 2) **Requirements for joint activity**, and 3) **Choreography of joint activity** (see Figure 6.1). The criteria for joint activity are that participants intend to work together (known as the basic compact) and their work has to be interdependent. The basic compact constitutes a level of commitment for all parties to support the coordination process, e.g. the commitment to some degree of goal alignment, and commitment to try and detect and correct any loss of common ground that might disrupt the joint activity. If these criteria are satisfied, the parties have to fulfill certain requirements such as making their actions predictable, sustaining common ground, and being able to redirect each other. The form for achieving these requirements (the choreography) is a series of activities that are guided by various signals and coordination devices.

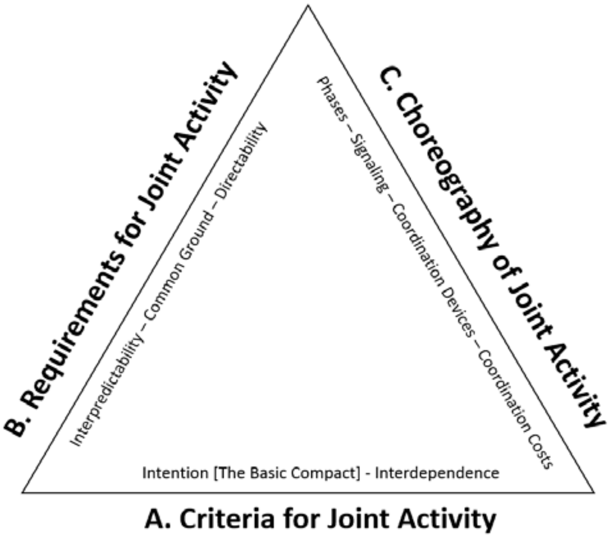


Figure 6.1: Joint activity theory of Klein et al. [29]

6.3 Airline Operations Control

6.3.1 AOC Embedded in the Larger Air Transportation System

Each airline comprises of interactions between a variety of facilities, human operators, technical systems, regulations and procedures, and is embedded in the larger air transportation system that is comprised of airports, other airlines, and ATC centers. Each day of operation, the system is subject to a multitude of disruptions ranging from deteriorating weather, late in-bound aircraft, to aircraft and crew-related problems. The current practice of recovering from disruptions in commercial aviation involves multiple teams of collaborating human operators, such as:

- Flight crews on board of each commercial aircraft, who work together with teams in ATC centers, AOC centers and at airports.
- Air traffic controller teams in various ATC centers working together to allow aircraft to safely and efficiently share the same airspace.
- Airline operational controller teams working together in one of the many AOC centers and collaborating with other partner airlines to resolve any disruption affecting the schedules and plans, and to facilitate in the delivery of passengers at their destinations.
- Ground-side teams at each airport, who are responsible for handling a wide variety of ground based operations to ensure an efficient and safe boarding and debarkation

of passengers and their luggage.

If a disruption affects flight plans, then human operators at the AOC center take corrective actions in real-time in order to manage the disruption. Possible actions include the cancelling or delaying of flights and swapping aircraft or crew, and are often the result of a coordination process that involves many AOC operators.

Current AOC practice consists of a coordination process between many human operators, each of which plays an essential role in disruption management. The specific organization of an AOC center depends on multiple factors. These factors include the airline size, type of airline operations, location, and airline culture. However, despite the different organization types, it is possible to identify human agents that are common to AOC centers [19, 23, 25, 40]. Figure 6.2 gives an overview of a typical AOC center showing the human agents, the technical systems, and the interactions between the AOC agents and their external world (while the exact terminologies may vary per airline). It should be noted that in addition to the agents shown in Figure 6.2, there exist other services in AOC centers which provide support for AOC operators (e.g. operational engineering). In addition, a crisis center which coordinates activities after an accident or incident is often an integrated part of an airline's AOC center.

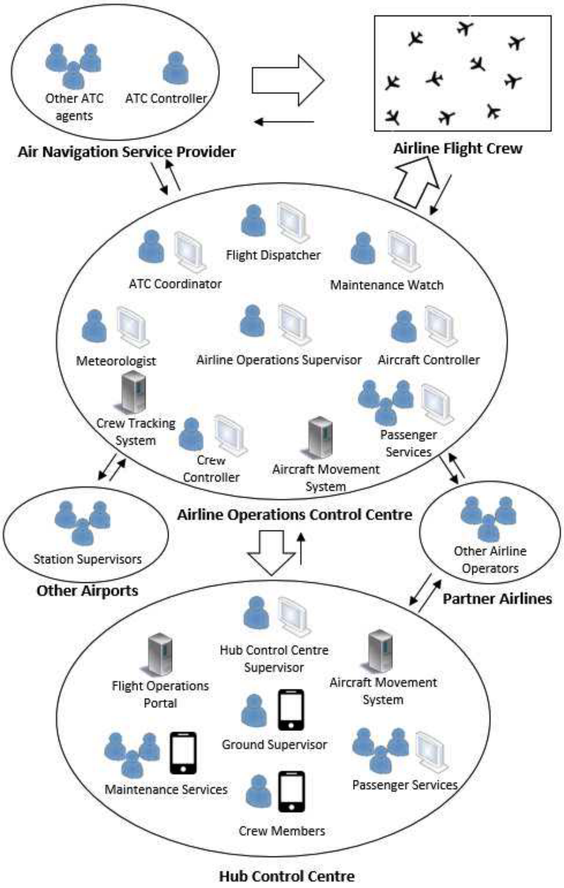


Figure 6.2: AOC agents and their interactions.

6.3.2 Disruption Management by an AOC Centre

It is important to develop a basic understanding of typical operational problems that might arise for an airline. In many cases, these problems can have a significant impact on the airline's operations, resulting in substantial deviation from the planned schedule of services. Problems originating because of a local event (e.g. aircraft mechanical failure) can trigger other problems and easily propagate to other flights [22, 40, 41]. Examples of such problems are:

- General ATC restriction related.
- Weather related: Wind, thunderstorm, low visibility, ATC restrictions.
- Equipment related: Aircraft mechanical failure or ATC system outage.

- Crew related: Misconnect violation, rest violation, duty limit violation, open position.
- Long embarking/disembarking times or delayed connecting passengers.
- Delay in ground handling operations: Cargo/baggage loading delays due to lack of resources.
- Airport capacity shortage at a given time due to traffic volume or runway unavailability, e.g. due to construction, surface repair, or broken aircraft.

In order to deal with disruptive events and reduce their impact, major airlines have established AOC centers, an example of which is shown in Figure 6.3. These centers gather an extensive array of operational information and data, with the purpose of maintaining the safety of operations, and efficiently managing aircraft, crew, and passenger operations. When disruptions occur operators at the AOC centers adjust in real-time the flight operations by selecting and implementing the best possible actions (See table 6.1). This is known as airline disruption management.

Table 6.1: Possible AOC Actions

Problem dimension	Possible actions
Aircraft	Exchange aircraft Combine flights to free up aircraft Delay flight Ferry aircraft from nearby airport Lease aircraft Request high cruise speed to compensate for delay Reroute flight Cancel flight
Crew	Use crew at airport Use nearest crew to airport Exchange crew from other flights Seek extensions to crew duty time Use crew with free time Position crew from other airport Delay crew for signing in duty Use crew with vacation/ day-off Proceed without crew Propose aircraft change Accept delay/ await crew from inbound aircraft Cancel flight
Passenger	Rebook pax. to other flight at own airline Rebook pax. to other flight at other airline Keep pax. on delayed flight Cancel pax. Itinerary and return to origin

The main objective of airline disruption management is to ensure that operations adhere as closely as possible to the airline published schedule and the shorter-term planning of fleet assignment, aircraft routing and crew assignment (see Figure 6.4). Kohl et al. [25] present the airline disruption management process that is in use by many airlines. The process has six steps namely:

1. *Operation monitoring:* in this step, the operations are monitored to check if there is anything that is not going according to plan. The state of operations is defined by the planned events (time table, fleet and tail assignment, crew scheduling, etc.)
2. *Assessment:* if an event happens (e.g. departure delay) a quick assessment is performed to see if an action is required. If not, the monitoring continues. If an action is necessary, then there is a problem that needs to be solved.
3. *Identify possible solutions:* having all the information regarding the problem, AOC operators need to identify solutions that are most appropriate for the problem (see table 6.1).
4. *Evaluate possible solutions:* This phase involves evaluations from the passenger, crew, and aircraft perspective and possibly other perspectives. These evaluations may result in proposed changes to the solutions.
5. *Take decision:* Based on the agreed solution, one can decide whether it is necessary to implement it directly or postpone taking the decision.
6. *Implement decision:* Once a decision has been taken, it must be implemented. Consequently the operational plan needs to be updated accordingly, and the monitoring must continue.

According to Castro and Oliveira [23], for steps 2-5, AOC centres rely heavily on the experience of their controllers who use some rules-of-thumb (a kind of hidden or tacit knowledge) that exist in the AOC centres.

Figure 6.3: A view of KLM's AOC centre

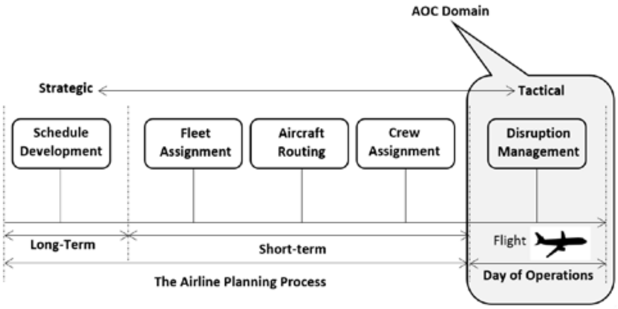


Figure 6.4: Airline planning and airline disruption management

6.4 AOC Disruption Management Policies

In this section we define four specific AOC disruption management policies P1-P4. Policies P1-P3 are based on established AOC practices [27, 28]. Policy P4 is based on the joint activity coordination theory of Klein et al. [29]. It is also explained how these four policies are related to the coordination approaches reviewed in Section 6.2.

6.4.1 Established AOC Policies P1-P3

In order to select representative AOC policies and make a clear distinction between them, a critical element is the understanding of how AOC operators make their decisions in relation to various aspects during disruption management. Bruce [27] has systematically studied the decision-making processes of 52 controllers in six AOC centers. Advice was sought from an expert panel of AOC management staff to ensure that: a) the considered AOC centers were representative of airline AOC centers around the world; and 2) the participating controllers were representative of AOC operators (e.g. in terms of gender, age, years of experience in the airline industry, years of experience in the AOC domain, and previous occupation). Simulations of real life airline disruptions were conducted with each individual controller and data was collected using think-aloud protocol and observation. All comments made were recorded and transcribed verbatim. The data was classified into categories by Bruce [28] with support from an expert panel. The findings indicate that airline controllers use policies with different levels of performance. In this study, we distinguish between three AOC policies P1-P3 that correspond to these three performance levels. The details of these three policies are given in table 6.2 and explained below:

AOC policy P1 – Elementary level of performance: airline controllers identify various basic level considerations such as aircraft patterns and availability, crew commitments and maintenance limitations. For example, when a maintenance problem is reported, controllers at this level appear to acknowledge the information provided and begin considering the basic consequences of the scenario. They also identify opportunities to replace the aircraft or rebook passengers on alternative flights.

AOC policy P2 – Core level of performance: airline controllers have a greater comprehension of the problem. They take into account the more complex consequences of the problem than those evident at the elementary level. Several constraints such as crew restrictions, slot times, and curfews are identified at this level. Controllers, would for instance negotiate maintenance requirements and crew limitations in order to overcome the risk of breaching the curfew.

AOC policy P3 – Advanced level of performance: airline controllers demonstrate thinking beyond the immediacy of the problem. They examine creative ways to manage the disruption. For instance, controllers at this level would consider more complex crewing alternatives such as positioning a crew from one airport to another airport where the flight crew is needed. Also, in the case of a maintenance problem, controllers at this level would seek alternative information and recheck the reliability of information, e.g. through organizing a conference call with the maintenance watch people.

Table 6.2: Overview of the three AOC policies P1-P3 in relation to various disruption management aspects

Aspect	AOC policy P1	AOC policy P2	AOC policy P3
Maintenance Information	Accept information source and content and act on information given about a maintenance situation	Challenge/ query information about a maintenance situation	Seek alternative information and recheck source and reliability.
Crewing	Await crew from inbound aircraft	Challenge crew limits/ Seek extensions to crew duty time	Seek alternative crew (e.g. from nearby base or other aircraft)
Curfews	Curfews are not taken into account	Identify curfews and work within them	Seek curfew dispension
Aircraft	Seek first available aircraft	Request high speed cruise	Combine flights to free up aircraft

6.4.2 AOC Joint Activity Policy P4

The fourth AOC policy P4 is based on the joint activity framework developed by Klein et al. [29]. As depicted in Figure 6.1, this framework identifies three types of process phases that are required for effective coordination, namely: (1) criteria for joint activity processes; (2) satisfying requirements for joint activity, and (3) choreography of joint activity. The criteria for joint activity are that the participants in the joint activity agree to support the coordination process and prevent its breakdown. If these criteria are satisfied, the parties have to fulfill certain requirements such as making their actions predictable, sustaining common ground, and being directable. The way of achieving these requirements (the choreography) is a series of activities that are guided by various signals and coordination devices. In a preceding study the potential of this joint activity theory for AOC has been identified [42].

In order to apply the joint activity based approach to AOC disruption management, table 6.3 presents a more specific sets of rules that are defined for each of the three types of joint activity process phases [29]; which AOC agents should adhere to in order to have effective coordination.

Table 6.3: Coordination rules for each of the three types of joint activity process phases (A,B,C) of AOC policy P4

ID	Informal Coordination Rules
A 1	▪ All AOC agents are committed to support the coordination process, and carry out the required responsibilities: - Acknowledging the receipt of signals. - Transmitting construal of the signal back to sender and indicating preparation for consequent acts. - Repairing common ground. ▪ AOC agents should relax their local goals in order to permit more global (shared) goals to be addressed.
A 2	If agent A does something, it must depend in some way on what agent B does.
B 1	Each AOC agent has to make his actions predictable, e.g. estimates of time needed to complete a certain task.
B 2	To support common ground AOC agents have to: ▪ Establish routines for use during execution. ▪ Insert various clarifications and remainders, whether just to be sure of something or to give team members a chance to challenge assumptions. ▪ Update others about changes that occurred outside their view or when they were engaged. ▪ Monitor other team members to gauge whether common ground is breaking down. ▪ Detect and repair loss of common ground.
B 3	As priorities and conditions change a team member should be able to change the actions of other partners.
C 1	AOC agents should accomplish coordination one phase at a time in a joint activity, each phase having an entry, body of action, and an exit.
C2	AOC agents should constantly provide cues for coordination, e.g. they should signal to each other about a phase completion. They may also signal their understanding of a situation, their intentions, and the difficulties they are facing.
C3	▪ AOC agents should explicitly communicate their intentions (Coordination by Agreement). ▪ AOC agents should act according to rules and regulations (Coordination by Convention). ▪ As conditions change, AOC agents should decide about the interpretation of events, and adopt new norms if necessary (Coordination by Precedent). ▪ AOC Agents should observe how the ongoing work is unfolding so that the next action becomes apparent within the many actions that could conceivably be chosen (Coordination by Salience).
C4	To reduce coordination costs, AOC agents should improve their common ground and invest in adequate signaling and coordination devices (e.g. using abbreviated forms of communication while still being confident that signals will be understood).

6.4.3 Coordination Approaches of P1-P4

In table 6.4 an overview is given of which coordination approaches reviewed in Section 6.2 apply for each of the four policies P1-P4. This shows that almost all coordination approaches of Section 6.2 (except Voting methods) are used within one or more of the four AOC policies P1-P4.

Table 6.4: Approaches from the coordination literature used by AOC policies P1-P4

Coordination Approach	Simulated Coordination Policies			
	P1	P2	P3	P4
Master/ Slave technique	+	+	+	+
Contract net protocol	+	+	+	+
Multi-agent planning	+	+	+	+
Negotiation protocol	-	+	-	-
Voting methods	-	-	-	-
Routines/ protocols	+	+	+	+
Mutual adjustment	+	+	+	+
Supervision	+	+	+	+
Team meetings	-	-	+	+
Criteria for joint activity	+	+	+	+
Requirements for joint activity	-	-	-	+
Choreography of joint activity	-	-	-	+
Team Situation Awareness	-	-	-	+

The four AOC policies P1-P4 have several of the coordination approaches from Section 6.2 in common, i.e. master/slave, contract net protocol, multi-agent planning, routines/protocols, mutual adjustment, supervision and criteria for joint activity. This commonality stems from the typical airline manner of flight planning (Figure 6.4) and their AOC organization (Figure 6.2). Policy P1 has only one coordination approach complementary to this common set, i.e. dedicated routines/protocols in resolving a disruption. Policy P2 also makes use of negotiation protocols between team members as a complementary approach. Policy P3 is similar to Policy P2, though makes use of team meetings instead of negotiation protocols. Policy P4 is an extension of Policy P3 with Team Situation Awareness [30, 31] and a replacement of the dedicated routines/protocols of P3 by the higher-level rules in table 6.3.

6.5 Airline Disruption Scenario

In order to assess the impact of the four policies (P1-P4) we will consider a challenging AOC scenario that is well described and evaluated in [27], and includes details of other ongoing flights (see Figure 6.6). The scenario concerns a mechanical problem with an aircraft at Charles de Gaulle (CDG) airport, aiming for a long-haul flight (flight number 705) to a fictitious airport in the Pacific, which is indicated by the code PCF. The scenario is briefly described below:

The time is 0655. Flight 705 is unserviceable in Paris (CDG). The engineers report that it has a hydraulic leak such that it may require a hydraulic pump change. If so, then they expect the pump change to take two hours. On this advice, the staff at CDG have stopped checking passengers in for Flight 705. After participants were given time to consider this situation, subsequent information was provided that confirmed the hydraulic pump change and advised that due to inclement weather, the maintenance work would be done in the hangar, delaying a possible departure considerably more than initial advice.

This scenario requires participants to consider strategies and consequences to resolve the delay caused by the unserviceable aircraft. The flight was progressively delayed at CDG for 3 hours due to mechanical unserviceabilities, to the extent that the operating crew were eventually unable to complete the flight within their legal duty time.

In [27], this scenario was considered by a panel of AOC management experts. They developed several alternatives, and subsequently identified the best solution, which was to re-route the flight from CDG to PCF and to include a stop-over in Mumbai (BOM). In parallel, a replacement flight crew was flown in as passengers on a scheduled flight from PCF to BOM in order to replace the delayed crew on the flight part from CDG to PCF (see Figure 6.5). The question therefore is how well the outcome of the agent-based modelling and simulation of the AOC centre compared to the expert panel in finding a best solution?

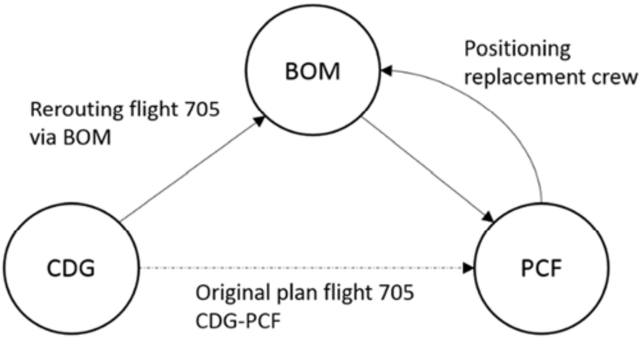


Figure 6.5: The expert panel identified best solution of the scenario considered

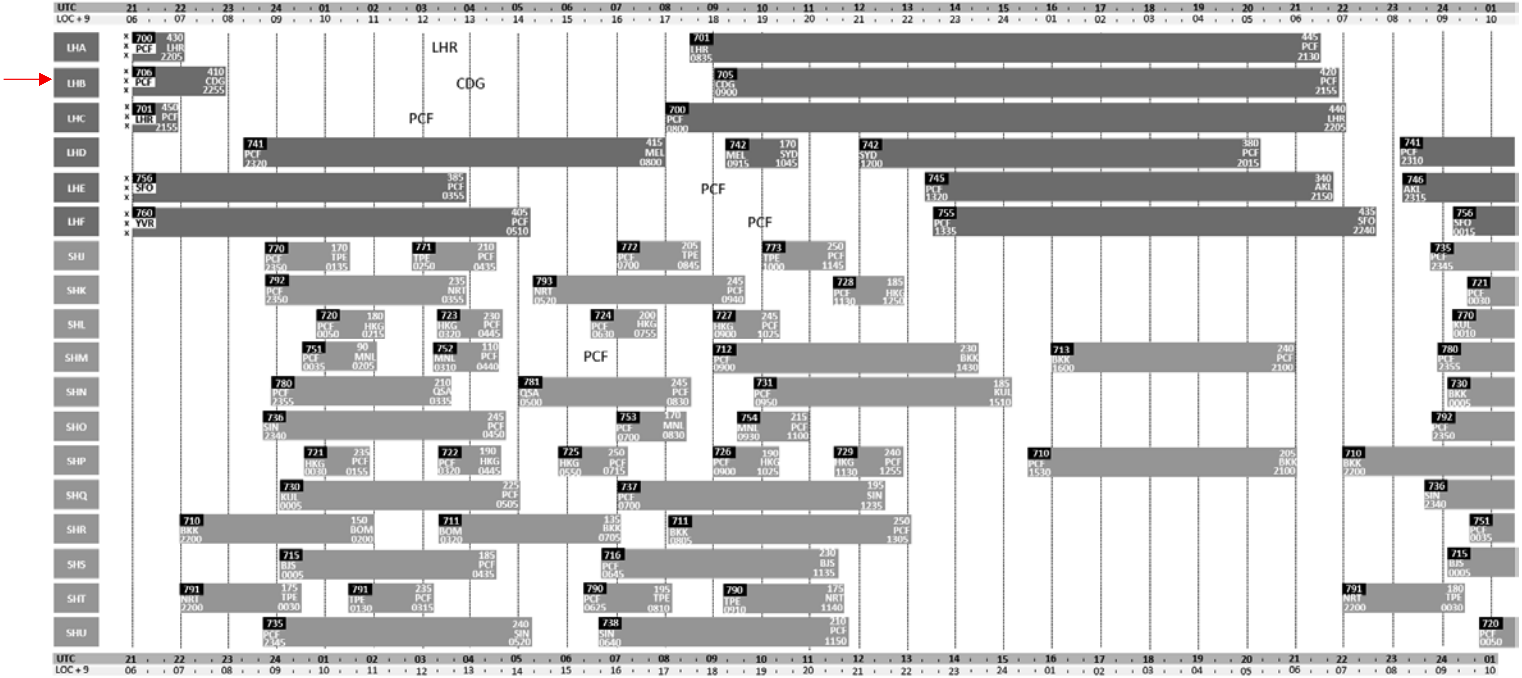


Figure 6.6: A printout of the screen image at the time of disruption 06:55 Coordinated Universal Time (see top horizontal UTC time-scale). A secondary horizontal time-scale showed local time (UTC + 9 hours). The horizontal blocks (called puks) represent the flights and include relevant information such as the flight number, actual passenger loading, departure and arrival airport, and departure and arrival time. The background color of each flight block was designed to represent a type of aircraft (a darker block represents a large aircraft and a light block represents a medium sized aircraft. The longer the flight duration, the larger the size of the block. The vertical axis on the left side shows the aircraft registrations that identify each aircraft in the fleet. In this scenario the aircraft with the mechanical problem is designated by registration code LHB 'Lima Hotel Bravo' to the left of the second row highlighted by the arrow.

6.6 Agent-Based Modelling

6.6.1 Identifying the Agents and their Interactions

In order to develop the agent-based model, a first step is to identify the main agents involved and their role in the disruption management process. The agents involved in the aircraft mechanical breakdown scenario and captured in the ABM are presented in table 6.5.

Table 6.5: Agents captured in the ABM

Agent	Abbreviation
Airline Operations Supervisor	AOS
Aircraft Controller	ACo
Crew Controller	CCo
Maintenance Services	MS
Airport Engineer	AE
Station Supervisor	SS
Aircraft Movement System	AMS
Crew Tracking System	CTS
Flight Crew	FC

6.6.2 Workflow Schemes and Communication Prescripts

The rules of each policy are captured in the ABM through two approaches: workflow schemes and communication prescripts. Workflow models capture the role of agents, communication paths, and authority relationships between agents in the ABM. The workflows corresponding to the four policies are distinctive in terms of the agents involved, information being exchanged, and sequence of activities. For instance, when the airline operations supervisor receives a message about the aircraft mechanical problem, he can either accept the information received and seek the first available aircraft using support from the aircraft controller (Policy P1); challenge and query the information about the mechanical breakdown (Policy P2); or consult maintenance services about the mechanical breakdown (Policy P3); or apply the joint activity framework (Policy P4). Figure 6.7 shows an example of the workflow corresponding to AOC policy P3.

To formally capture the dynamic properties of socio-technical systems in an agent-based model, a formal agent-based modelling language is needed. For this purpose, the Temporal Trace Language (TTL) [43] is used. TTL has been developed for the purpose

of specifying and analysing dynamic properties in multi-agent systems. Within TTL communication between two agents R_{src} and R_{dst} is expressed in the following type of predicate:
where:

- R_{src} models the source.
- R_{dst} models the destination.
- C_{type} models the type of communication (e.g. request, inform, declare, approve, etc.).
- $I_{content}$ indicates the content of the information being communicated.

As an example the predicate $communication\_from\_to\_(AE, SS, inform, leak)$ states that the Airport Engineer (AE) informs the Station Supervisor about a hydraulic leak, as a means to formalizing the communication

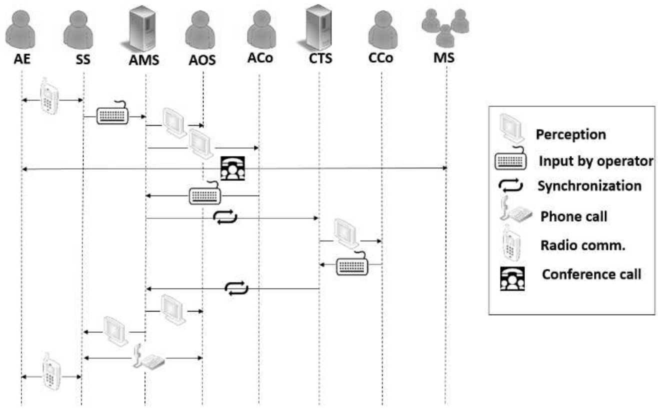


Figure 6.7: Operational workflow for AOC policy P3

$$communication\_from\_to\_(R_{src}, R_{dst}, C_{type}, I_{content})$$

6.6.3 Rule-Based Multi-Agent Modeling Environment

To implement interaction rules using the TTL communication prescripts, the authors made use of the LEADSTO simulation environment [44, 45]. LEADSTO consists of two programs: a Property editor and a Simulation tool (see Figure 6.8). The first is a graphical editor for constructing and editing LEADSTO specifications, and the second is for performing simulations of the LEADSTO specifications; generating data-files containing traces for further analysis, and visualizing these traces. Figure 6.8 gives an overview of the simulation tool architecture and shows its interactions with the property editor. The bold rectangular borders define the two separate tools while the arrows represent the data flow, with the dashed arrows representing control.

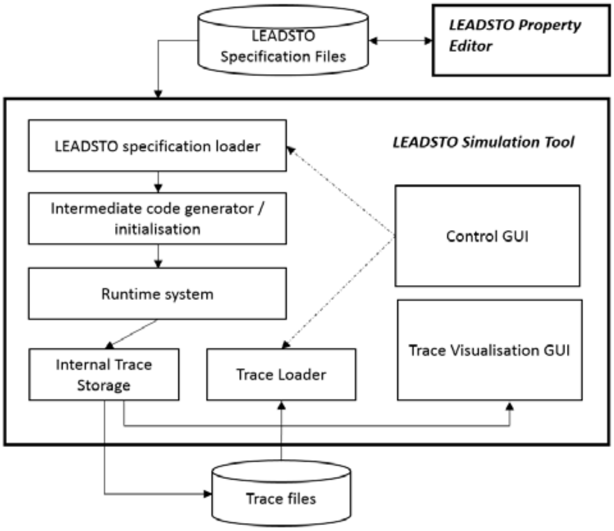
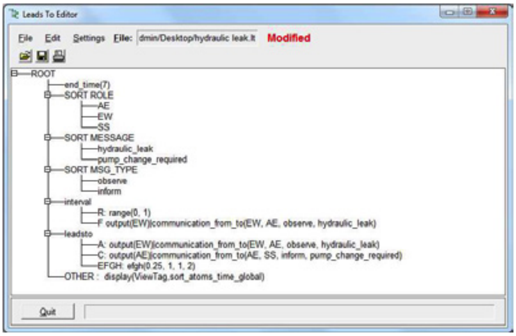


Figure 6.8: LEADSTO architecture [45]

LEADSTO enables one to model direct temporal dependencies between two state properties in successive states (i.e. dynamic properties). The LEADSTO format is defined as follows: let α and β be predicates, and e, f, g, h be non-negative real numbers. Then $\alpha \rightarrow_{e,f,g,h} \beta$ means:

> *If predicate α holds for a certain time interval with duration g , then after some delay (between e and f) predicate β will hold for a certain time interval of length h*

An example of a dynamic property in the LEADSTO format is $\alpha \rightarrow_{0.25,1,1,2} \beta$ where α represents the predicate $\mathit{communication\_from\_to\_(external\_world, AE, observe, leak)}$ and β represents the predicate $\mathit{communication\_from\_to\_(AE, SS, inform, pump\_change\_required)}$. This property expresses the fact that, if the airport engineer AE observes that there is a hydraulic leak during 1 time unit, then after a delay between 0.25 and 1 time unit, AE will inform the station supervisor R_{SS} about the problem during 2 time units. Such a rule can be implemented using LEADSTO editor as illustrated in Figure 6.9.



```
ROOT
    end_time(7)
    SORT ROLE
        AE
        EW
        SS
    SORT MESSAGE
        hydraulic_leak
        pump_change_required
    SORT MSG_TYPE
        observe
        inform
    interval
        R: range(0, 1)
        F output(EW)|communication_from_to(EW, AE, observe, hydraulic_leak)
    leadsto
        A: output(EW)|communication_from_to(EW, AE, observe, hydraulic_leak)
        C: output(AE)|communication_from_to(AE, SS, inform, pump_change_required)
        EFGH: efgh(0.25, 1, 1, 2)
    OTHER :  display(ViewTag.sort_atoms_time_global)
```

Figure 6.9: LEADSTO editing

By executing this rule a trace of predicates holding true or false can be generated and visualized as can be seen in Figure 6.10. In this example trace, the horizontal axis depicts the time frame while the vertical axis depicts the predicates. A blue box on each line indicates that the predicate is true.

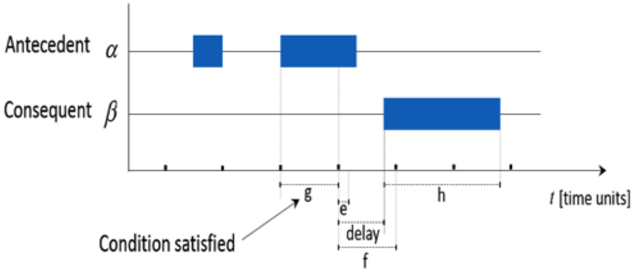


Figure 6.10: Visualizing traces in LEADSTO

6.6.4 Model Verification

After implementing all the rules corresponding to the various AOC policies in LEADSTO, the next step is to test if these rules are implemented correctly. For this purpose, a special software environment named the TTL checker [43] was used. The TTL checker takes a rule and one or more (empirical or simulated) traces as an input and checks[4] whether the rule holds for the trace(s). Using this environment, the formal rules can be automatically checked against the simulated trace. Traces are represented by sets of PROLOG facts of the form: $\text{holds}(\text{state}(m_1, t_2), a, \text{true})$. Here, m_1 is the trace name, t_2 time point 2, and a is a state formula in the ontology of the component's input. The above holds-statement indicates that state formula a is true in the component's input state at t_2 . The programme for temporal formula checking uses PROLOG rules that reduce the satisfaction of the temporal formula to the satisfaction of the atomic state formulae at certain time points, which can be read from the trace representation.

6.7 Simulation Results

The four AOC policies introduced in Section 6.3 have been implemented and simulated in the presented agent-based model. For each of these four policies various results have been collected such as related to aircraft, crew, passengers, and the minimum time needed to manage the disruption. Table 6.6 presents the simulation results obtained for the four AOC policies.

The outcome of policy P3 concurs with the best solution identified by the expert panel. However the outcomes of P1 and P2 are significantly worse, and the outcome of P4 even outperforms the expert panel result. In order to understand the background of these differences, the agent-based simulation results have carefully been analyzed.

Under policies P1 and P2, AOC operators make decisions based on limited coordination, as a result of which the disruption considered is not efficiently managed. The aircraft mechanical problem was eventually fixed, however the flight was

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[4] In addition to checking rules, TTL can check more complex emergent temporal properties. E.g. when reasoning about many time points and time intervals, and establishing relations between them.

cancelled. As a result, the 420 passengers were accommodated in hotels (i.e. greatly inconvenienced). This unfavorable outcome can be explained as a result of the possible actions identified by the crew controller i.e. "await crew from inbound aircraft" and "see extensions to crew duty time." Crew controllers mainly considered crew sign-on time and duty time limitations and tried to work within these constraints. In this scenario, none of the possible actions solves the crew problem.

Under policy P3, AOC controllers consider complex crewing alternatives such as flying-in a replacement crew from another airport. Therefore, under P3 the decision was made to reroute the flight via BOM and fly-in a replacement crew from PCF into BOM. Here, both the delayed crew and replacement crew were able to operate in one tour of crew duty time. In comparison to policies P1 and P2, policy P3 is much better from both the airline and the passenger's perspectives. Regarding the minimum time required for managing the disruption policy, P3 takes more time than P1 and P2.

Under policy P4, AOC agents make lower level decisions, like P1-P2, though under the joint-activity coordination regime. Therefore the aircraft, crew, and passenger problems were resolved with minimum disruption. The main difference between P4 and the other policies P1-P3 is that the AOC agents now act according to joint activity coordination rules (Table 6.3). Thus, for instance, when the crew controller can't find a crew, he signals his understanding about the situation and the difficulties he is facing. Likewise, the airline operations supervisor signals his understanding back to the crew controller just to be sure of the crew situation, or to give the crew controller a chance to challenge his assumptions. Such a process of communicating, testing, updating, tailoring, and repairing mutual understandings is aimed at building common ground prior to starting the choreography phase [29]. By updating the crew controller on changes outside their information base, and coordinating by agreement (precedent and salience) they managed together with the crew controller to solve the crew problem before moving to the next coordination phase. In the scenario considered, P4 was therefore able to identify a possibility that had not been identified by any of the other three policies, and neither by the expert panel. The flight crew that had landed the aircraft at CDG had received sufficient rest to fly the delayed aircraft directly to PCF instead of enjoying their scheduled day-off in Paris. Passengers had a minimum delay compared to the previous policies (P1-P3) as they only had to wait for the aircraft to be fixed. Another relevant difference between P4 and the other policies P1-P3 is the shorter minimum time needed to manage the disruption, because human agents work more in parallel under P4 than under P1-P3. .

Table 6.6: Simulation Results[5]

AOC policy	Flight	Aircraft mechanical problem	Crew problem	Passengers problem	Minimum disruption mgmt time	Costs for the airline [Euros]		Costs for the passengers: time lost
						Operating costs	Legal pax. compensation	
P1	Cancelled	Fixed	Not resolved	Pax. accommodated in hotel (i.e. distressed)	26 min	326 kEUR	168kEUR	24h
P2	Cancelled	Fixed	Not resolved	Pax. accommodated in hotel (i.e. distressed)	30 min	326 kEUR	168 kEUR	24h
P3	Diverted	Fixed	Resolved	Pax. significantly delayed due to fixing aircraft and diverting	33 min	360 kEUR	126 kEUR	8h
P4	Delayed	Fixed	Resolved	Pax. delayed until aircraft is fixed	20 min	326 kEUR	0 kEUR	3h

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[5] To calculate the costs for the airline, we used cost data from Air France KLM corresponding to FY 2013 to calculate the operating costs (source: www.airfranceklm-finance.com); and EU regulations to include passenger compensation rights (Source: http://europa.eu/youreurope/citizens/travel/passenger-rights/air/index_en.htm)

6.8 Conclusion

Coordination is well developed in multi-agent systems research. Despite all these advances, important aspects that a human team can handle are not yet well understood in terms of multi-agent coordination models. This raised the question how well coordination methods from the literature compare to established coordination policies in a complex socio-technical system like air transportation. This question has been studied in this paper for the problem of airline disruption management by an airline operational control (AOC) center.

The approach taken has been to run agent-based simulations for agent-based models of four airline disruption management policies P1-P4. The policies P1-P3 were based on established AOC practices, and policy P4 was based on the joint activity coordination theory of Klein et al. [29]. Each of these four policies has been characterized in terms of the various coordination techniques that have been developed in the literature. This characterization showed that all but one coordination techniques identified in the literature apply to one or more of the four policies P1-P4. This supports the view that coordination techniques in the literature have reached a remarkably high level of development.

For each of the four policies an agent-based model simulation has been conducted on a challenging airline disruption scenario. This challenging scenario had previously been evaluated by an expert panel. The outcomes of the agent-based simulations showed that the performance of policy P3 was the same as the best possible outcome identified by the expert panel. The outcomes of policies P1 and P2 were significantly less good than P3. Quite unexpectedly, policy P4 even had a better outcome then policy P3. Hence P4 outperformed both the three established policies P1-P3, and the best outcome identified by the expert panel. This leads to the following three conclusions:

There are disruptions for which established AOC coordination policies as well as expert panels may fail to identify the best solution.

Airline disruption management can learn from the insight that is gained through taking an ABMS approach.

For the challenging airline disruption scenario considered it would be best to make use of policy P4, i.e. the policy that is from the psychology domain.

In view of these three findings, there also are three directions for follow-up research. The first direction is to also evaluate some other airline disruption management policies through an ABMS approach, e.g. the fully automated policy of Castro et al. [24]. The second follow-up research direction is to test the different AOC policies also on other challenging airline disruption scenarios. The third follow-up research direction is to support AOC centers in improving their AOC disruption management policies.

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7

Conclusion

This chapter provides a discussion of all research results obtained in this thesis and recommendations for future research

7.1 Discussion of Results

The main objective of this thesis was to understand emergent behaviour in the complex socio-technical air transportation system. The motivation for doing so is the necessity to understand the effects of novel designs that are in development both in the USA and Europe in order to accommodate the expected traffic growth. In realizing this objective, ABMS has emerged as a key method because it is widely used in complexity science for understanding how interactions give rise to emergent behaviour. The thesis demonstrates that ABMS of air transport operations is a viable approach in gaining knowledge about emergent behaviour which was unknown before. This knowledge includes both bottlenecks of system designs and identified opportunities, and hence can be used to avoid undesired negative emergent behaviours and promote positive ones. This section discusses the results obtained for the applications considered in this thesis.

7.1.1 Emergent Safety Risk

Chapter 2 has identified key airports challenges and showed that airport safety performance continue to be a serious safety concern in aviation. For instance, the accident rate for ground operations is not improving and runway incursions are still frequently reported worldwide. In the United States alone, preliminary data (FAA 2015) shows a total number of 653 runway incursions in the first half of FY2015, a 17 percent increase over the same span in FY2014. To better understand runway incursions and their contributing factors, **chapter 3** views runway safety as an emergent property. This is because it is not a property of any constituting element, yet it is the resultant of the interactions between the constituting elements including pilots, their aircraft, ATC, technical systems, and procedures.

Chapter 3 has first introduced the challenges regarding the identification and analysis of emergent behaviour in the socio-technical air transportation system. This has been accomplished in three steps. First an outline has been given of different perspectives on emergence in the literature. This started with explaining that a property is emergent if it is not a property of the constituting elements of the system, though it results from the interactions between its constituting elements. In an airport for instance, emergent behaviour results from the interactions between human operators, technical systems, working procedures, organizations, and weather. Changing how these elements interact can have an impact on the overall system behaviour. Next, it was outlined that a recent taxonomy in the literature identifies four types of emergence ranging from nominal or simple emergence (type I) that can be identified through analysis, through weak emergence (type II) and multiple emergence (type III) that can be identified through simulation, to strong emergence (type IV) which cannot be identified in principle. Subsequently, it was shown through numerous examples that the air transportation system exhibits all these types of emergence.

Chapter 3 has also identified and analysed emergent safety risk of an active runway crossing operation. For this purpose, an existing agent-based model of the active runway crossing operation was used. The agent-based model has been developed in a hierarchical way. At the highest level, the relevant agents including human operators and technical systems were identified. Then the interactions between these agents were captured and included deterministic and stochastic relationships, as is appropriate for the human performance or the technical systems considered. The impact on the emergent safety risk was studied through running a complete set of rare event Monte Carlo simulations of both nominal and off-nominal scenarios.

The results clearly show that the active runway crossing yields various types of emergent behaviours that were not explored before. Weak emergence (type II) was revealed due to the development and simulation of the agent-based model in the wider context of socio-technical systems. In addition, multiple emergence (type III) was also revealed during the analysis of the Monte Carlo simulation results. Such type of behaviour is characterized by being unpredictable and counterintuitive. An example of type III result was the role of ATC Alerting systems in reducing the accident risk of a runway incursion scenario. Normally one would expect according to the ConOps that such alerts would have a large effect on reducing the accident risk. However, the findings show that the role of ATC alerts is very limited. The events recorded in the Monte Carlo simulation show that pilots might detect the conflict before the controller warning. This significant and novel result was not found through the traditional event-sequence based approach of the same operation. This means that the findings are revealed due to the development and simulation of the agent-based model that covers the totality of interactions of components and their variability in performance over time (e.g. equipment failure, non-nominal actions of pilots and controllers) which is key to safety risk. The Monte Carlo simulations make it possible to understand the potential of agents in restricting the risk in off-nominal scenarios, through capturing their stochastic nature and accounting for uncertainty.

Taking all together, chapter 3 has demonstrated that the emergence types that have been developed by philosophers are of great use in getting hold on the early identification and analysis of novel emergent properties and behaviours of a socio-technical air traffic design. Chapter 3 has also demonstrated that ABMS and Monte Carlo techniques provide a platform to integrate and simulate multiple heterogeneous components including human operators, technical systems, and working procedures, and identify different types of emergence which could not have been found through the more traditional simulation approaches. The MC simulation results obtained confirm that ABMS of a socio-technical air transportation system allows the identification of emergent properties that are not identified through earlier, non-agent-based simulations, including human-in-the-loop simulations of the same operation.

7.1.2 Resilience from a Complexity Science Perspective

Thanks to the influential work by Hollnagel and other researchers (2006), the value of resilience in air transportation has been well recognised in behaviour sciences. It has become clear that for the future development of air transportation, resilience regarding various types of possible disruptions should be studied. The possible consequences of such disruptions may range from (i) negligible consequences, to significant consequences such as (ii) catastrophic accidents, (iii) significant local consequences, and (iv) very severe network-wide consequences. Complementary to the behaviour science oriented approaches for studying resilience, **chapter 4** has explored the complexity science perspective in order to develop a better understanding of resilience in the socio-technical air transportation system. This allows to combine the knowledge from behavioural sciences with the systematic modelling and analysis power of complexity science. Subsequently this might enable the mitigation of negative impacts of disturbances and help designing a resilient future air transportation system. Both for the air transport sector, as well as for complexity science the resilience theme is rather new. This makes a full study of complexity techniques on their applicability to resilience in air transportation demanding. In order to simplify this, chapter 4 addresses several questions related to the resilience definition, resilience metrics, and complexity science approaches towards resilience.

Based on resilience developments across multiple domains, three key resilience capacities have been identified: absorptive capacity, restorative capacity, and adaptive capacity. A socio-technical system is said to be resilient when it has adaptive capacities in addition to absorptive and restorative capacities. A socio-technical system that has absorptive capacity only is called robust. A socio-technical system that has absorptive and restorative capacities is called dependable. In the literature several resilience metrics have been developed in various domains, both of qualitative and quantitative nature. The qualitative measures are of two types: Ecological resilience and Engineering resilience. Ecological resilience is a measure for the amount of disruptions that the socio-technical air transport system can absorb before it leads to significant changes in its KPAs. Engineering resilience is a measure for the duration of the period between the moment of significant reduction in its KPIs and the moment of recovery. Most resilience metrics are of engineering resilience type, i.e. they address recovery rather than avoidance of significant consequences. Exceptions are the psychological metrics (e.g. Likert scales) for individual human performance (Ahern et al., 2006), and mission risk, such as reach probability for conflict and collision risk in air traffic management (Prandini & Hu, 2008; Blom et al., 2009). None of the resilience metrics from literature is able to capture the effect of adaptive capacities of a socio-technical system in a separate way from capturing the effects of absorptive and restorative capacities. An effective way to address this problem is developing a proper model of the socio-technical system considered, and subsequently perform two measurements: one for the full model, and the other for a version of the model in which the adaptive capacities are nullified.

In order to improve the resilience of the complex socio-technical air transportation system, it is critical to identify, understand, and model system interdependencies (Ouyang, 2014). Today, the performance of air transport operations, particularly under disruptive events, is dependent upon a set of highly interdependent subsystems including airlines, airports, and ATC centres. These subsystems are often connected at multiple levels through a wide variety of mechanisms, such that an interdependency exists between the states of any given pair of subsystems or components. Chapter 4 has shown that modelling interdependencies in air transportation is a complex, multidimensional, multidisciplinary problem, and listed some of the dimensions associated with system interdependencies that complicate resilience analysis. To capture the various resilience dimensions, chapter 4 proposed using complexity science approaches for modelling system interdependencies and capturing all three resilience capacities. The most important of these approaches are agent-based modelling and simulation, network flow-based methods, stochastic reachability, and viability theory. When human operators play a key role in the specific resilience aspect to be studied, then agent-based modelling is the logical choice. When the resilience issue to be studied is concerned with propagation of disruption effects through a network, then a network flow-based method is the preferred choice. When both aspects play a role, then a network-flow based approach that uses agent-based architecture might be used. Once a proper agent-based or network-flow based model has been developed this may be used as a basis to mobilise stochastic reachability analysis or viability theory. These complexity science approaches allow making a model of the socio-technical air transportation system considered, and then use this model to assess the effects upon KPIs by increasing the size of disruptions and by varying disruption management strategies in each of the three capacities.

In conclusion, chapter 4 has conducted a systematic study of what complexity science has to offer to resilience in future air transportation for the various types of consequences. Chapter 4 has shown that the complexity science approach powerful modelling and analysis means, and therefore has significant potential in both strengthening and broadening the resilience engineering approach of Hollnagel et al. (2006, 2009).

7.1.3 Evaluation of AOC Coordination Policies

One of the core functionalities of Airline Operations Control (AOC) is providing resilience to a large variety of unforeseen disturbances that happen during the day of operation. In AOC, coordination between human operators play a key role in recovering from disturbances in the socio-technical air transportation system. In order to get insights about the role of coordination in the resilience of the socio-technical air transportation system, **chapter 5** has analysed coordination processes for a specific test case and identified the potential of joint activity theory from the psychology research domain for AOC. This has led to the development of an agent-based model for AOC and crew processes, which was used in **chapter 6** to evaluate the operational effects of four AOC coordination policies on a challenging airline disruption management scenario. Three of the simulated policies are based on established airline practices, whereas the fourth is based on the joint activity coordination theory.

Each of the four policies has also been characterized in terms of the various coordination techniques that have been developed in the literature. Policy P1 forms the basis for P2-P4 and makes use of several approaches from the general coordination literature, such as organization, planning, supervision, routines and protocols. Complementary to the coordination approaches of P1, policy P2 also makes use of negotiation protocols between team members. Policy P3 is similar to Policy P2, though makes use of team meetings instead of negotiation protocols. Policy P4 is an extension of Policy P3 with Team Situation Awareness [30, 31] and with the higher level coordination elements of Klein et al. [29] replacing the dedicated routines and protocols of P3. This characterization shows that all but one coordination techniques identified in the literature apply to one or more of the four policies P1-P4. This supports the view that coordination techniques in the literature have reached a remarkably high level of development.

For each of the four policies an agent-based model simulation has been conducted on a challenging aircraft mechanical breakdown scenario. This challenging scenario had previously been evaluated by an expert panel. The outcomes of the agent-based simulations showed that the performance of policy P3 was the same as the best possible outcome identified by the expert panel. The outcomes of policies P1 and P2 were significantly less good than P3. Quite unexpectedly, policy P4 even had a better outcome then policy P3. Hence P4 outperformed both the three established policies P1-P3, and the best outcome identified by the expert panel. This leads to the following four conclusions:

1. There are disruptions for which established AOC coordination policies as well as expert panels may fail to identify the best solution.
2. Airline disruption management can learn from the insight that is gained through taking an ABMS approach.
3. For the challenging airline disruption scenario considered it would be best to make use of policy P4, i.e. the policy that is from the psychology domain.
4. The simulation results provide novel insights into the operational effects of each of the four AOC policies, which demonstrates that ABMS allows to analyse the effectiveness of different coordination policies in the complex socio-technical air transportation system, and hence improve its performance.

To summarize, while chapter 4 has identified the significant potential of complexity science in studying resilience in air transportation, chapter 6 has demonstrated that applying a complementary complexity science approach yields practical results for improving the resilience of the socio-technical air transportation system. Through combining knowledge from behavioural sciences with the systematic ABMS approach from complexity science, the chapter measured the resilience effect of four coordination policies in Airline Operations Control (AOC), which core functionality is one of providing resilience to a large variety of unforeseen disturbances that happen during the day of operation.

7.2 Future Research

Based on the research conducted in this thesis, this section presents the following recommendations for future research:

- **Generalization:** Although this work demonstrated through two different applications that ABMS is a useful approach for understanding emergent behaviour in air transportation, more applications need to be tried before it can be widely accepted as a useful approach in identifying emergence and evaluating system designs in aviation.
- **ABMS tools:** In general, developing an agent-based model takes significant time. Including a visual editor functionality that automatically create the underlying program code would significantly improve efficiency, and enable domain experts to verify and create models without the need to have programming experience.
- **Integration with other complexity science approaches:** Integrate ABMS with other approaches from complexity science to reveal new types of emergent behaviour. E.g. develop the application of reachability and viability theories to the socio-technical air transportation system by taking advantage of agent-based model developments, or combine ABMS with other complementary approaches such as system dynamics.
- **Resilience metrics:** This line of research aims at developing resilience metrics that capture the effect of the three resilience capacities in the socio-technical air transportation system. i.e. absorptive, adaptive, and restorative capacities.

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Appendix A

Appendix A: TOPAZ-TAXIR agents and their sub-entities

This appendix gives an overview of the agents modelled in TOPAZ and their corresponding sub-entities. Tables A.1 and A.2 provide a detailed overview of the human agents and technical system agents respectively. The full mathematical model description can be found in:

Stroeve, S.H., van der Park, M.N.J., Blom, H.A.P., Klompstra, M.B., Bakker, G.J., 2002. Accident Rrunway Crossing Procedure. Version 2.0. NLR Technical Report, NLR-TR-2001-527, Version 2.0.

Table A.1: Human Agents

Agent	Local Petri Net	Description
Pilot Flying	Pilot actions	Crossing actions, Take-off actions, Runway taxiing actions, Taxiway taxiing actions
	Conflict resolution	Problem solving in response to detected conflict
	Task performance	Auditory and visual monitoring, Coordination with pilot not flying, Aircraft manoeuvring, Conflict detection
	State situation awareness (State SA)	Represents the pilot state SA. The SA could be for instance about the state of own aircraft or other aircraft. The model includes the possibility of observation errors depending on the cognitive mode of the pilot. There is also a chance that the situation awareness is not updated, for instance due to misunderstanding a call from the controller
	Intent situation awareness (Intent SA)	Represents the pilot awareness of destination and path mode. A pilot crossing for instance may have the intent SA that he is taxiing on a regular taxiway not leading to a crossing
	Conflict detection	Pilot detection of a conflict by own observation. An example would be that a pilot crossing detects a conflict when he is aware that his aircraft is within a critical distance from the runway centreline and that taking off aircraft is approaching the runway crossing with a velocity exceeding a threshold value
	Cognitive mode	Represents two cognitive modes in which the pilot

		might be. (1) *tactical control mode,* when there is low/medium workload resulting in low error probability or (2) *Opportunistic control mode*, when there is a high workload resulting in high error probability
	Monitoring generator	Events generation based on SA updates resulting from visual or auditory information
	Coordination generator	Coordination between pilot flying and pilot not flying
	Task scheduling	List of tasks to be run by the pilot
Runway Controller	Task performance	Includes monitoring by the controller, coordination with other controllers, communication clearance to an aircraft following an alert or own observation, general communication such as during take-off or crossing, and general complementary communication
	State situation awareness	Represents the controller awareness of traffic state based on monitoring actions or alerts. There is a chance that awareness about aircraft position may be erroneous for instance as a result of high workload
	Intent situation awareness	Controller awareness of the aircraft destination and path mode
	Controller Instructions	Crossing instructions, Take-off instructions, Runway taxiing instructions
	Conflict Resolution	Controller decision on a conflict resolution strategy as well as its communication to the flight crew
	Cognitive mode	Similar to the pilot, the controller may be either in a tactical mode or opportunistic mode depending on his workload
	Monitoring generator	Events generation when a monitoring action of the controller such as a visual observation has to be executed
	Coordination generator	Represents coordination with other runway and/or ground controllers
	Complementary communication generator	General complementary communication between pilots and runway controller
	Task scheduling	List of tasks to be run by the controller

Table A.2: Technical System Agents

Agent	Local Petri Net	Description
Aircraft	Aircraft Type	The model includes two aircraft types namely a B747 and A320
	Aircraft Evolution	Represents the aircraft evolution from the entry to the exit point of the runway crossing operation. The model incorporates aircraft dynamics during taxiing and take-off such as uniform motion, acceleration and

		deceleration, turn, airborne transition, airborne climb-out phases, rejected take-off, and hold status
	Aircraft Systems	Represents two different modes of aircraft systems namely a nominal mode and non-nominal mode
Communication system	VHF com aircraft	Represents three possible modes of the aircraft communication system. These modes are (1) *nominal*, when the system functions nominally (2) *delaying*, when the communication between the controller and flight crew is delayed, and (3) *down*, when the system is not functioning and communication is blocked
	VHF com controller	Similar to the aircraft communication system, the controller communication system could also be in three modes namely: nominal, delaying, or down
	VHF com airport	Represents two possible modes of the airport communication system. These modes are (1) *Up*, when the system functions nominally, and (2) *Down*, in case of a system failure. In the latter case, all communications systems of controllers will be down as well.
	VHF com frequency	Represents the controller frequency as chosen by the flight crew
	Message transfer	Transfers controller communication to aircraft crew through the R/T communication system
Surveillance system	Advanced Surface Movement Guidance and Control System (A-SMGCS) tracking availability	Represents two possible modes regarding the availability of A-SMGCS tracking. These modes are (1) *Up*, in case A-SMGCS tracking is working, and (2) *Down*, in case A-SMGCS tracking is not working. The latter case implies that no aircraft state will be provided
	A-SMGCS tracking	Represents two modes of A-SMGCS tracking. These modes are (1) *Track info*, when current aircraft position and heading are estimated based on processed sensor data, and (2) *Track loss* in case of a track loss
	A-SMGCS tracking ID	Represents two possible modes regarding the A-SMGCS tracking ID. These modes are (1) *Correct*, when the label is correct, and (2) *Erroneous*, when the label is not correct
	Runway Incursion Alerting System (RIAS) availability	Represents two possible modes regarding the availability of RIAS . These modes are (1) *Working*, in case of nominal functioning of RIAS and (2) *Not working*, in case of a RIAS failure
	RIAS alerting	Represents two modes of RIAS alerting. These modes are (1) *RIA* in case of Runway Incursion Alert, and (2) *No RIA* when no RIA alerts are generated
	Stopbar Violation Alerting System (SVAS) availability	Represents two modes regarding the availability of SVAS. These modes are (1) *Working,* in case of nominal functioning of SVAS, and (2) *Not working*, in case of a SVAS failure
	SVAS mode	Represents two modes of SVAS. These modes are (1) *SVA*, when a stopbar violation alert is generated , and (2) *No SVA*, when no stopbar violation alert is

		generated
Airport manoeuvre control system	Ground Navigation Support (GNS)	Represents two modes of GNS. These modes are (1) *Good*, when good ground navigation aids are available, and (2) *Poor*, in case of poor ground navigation aids
	Lighting system availability	Represents two possible modes regarding the availability of lighting systems. These modes are (1) *Working*, when the lighting systems are available, and (2) *Not Working* when the lighting systems are not available
	Lighting system mode	Represents different modes of the lighting systems which be off, set for take-off, or set for landing
	Remotely Controlled (RC) stopbar availability	Represents two possible modes regarding the availability of the RC stopbar. These modes are (1) *Working*, when the RC stopbar is available, and (2) *Not Working*, when the RC stopbar is not available
	RC stopbar mode	Represents two possible modes of the RC stopbar. These modes are (1) *Light,* when the has to stop, and (2) *No Lights*, when the aircraft may proceed
	Flight strips	Represents two possibilities regarding the flight strips, namely the information about aircraft destination could be available or not

Appendix B

Appendix B: AOC Modelling in LEADSTO

This appendix describes the formal ontology that was developed for the AOC case study. Table B.1 and B.2 give an overview of the logical predicates and sorts respectively. The LEADSTO simulation files can be downloaded from the following URL:

https://drive.google.com/folderview?id=0BzAje4T-cNWTUDZubmJaWGFQS00&usp=sharing

Table B.1: Domain Ontology - Logical Predicates

PREDICATE	DESCRIPTION
Internal states and communication activities of the agents	
Observation (A,I)	Agent A observes information I from the world
Belief (A, I)	Agent A believes that information element I is true in the world
Incoming_communication(A, C, I)	Agent A receives message type C with content I
Communicate_from_to(A, B, C, I)	Agent A communicates to agent B message type C with content I
Other predicates used for this scenario	
Disruption(DT,AC,AP)	Describes a disruption of type DT, concerning aircraft with registration code AC, at airport AP
Query(A, B, I)	Query by agent A to agent B about Information I
Query_disruption(DT,AC,AP)	Query about disruption (DT,AC,AP)
Flight_crew(AC)	Flight crew of aircraft with registration code AC
Reserve_aircraft(amount)	To denote the number of reserve aircraft available
Aircraft_available_for_swap(amount)	Number of aircraft within the same type available for swap
Crew_inbound_aircraft(amount)	To denote the number of crew available from inbound flights
Aircraft_problem(AS)	Proposed solution to the aircraft problem
Crew_problem(CS)	Proposed solution to the crew problem
extend_crew_hours(y/n)	Possibility to extend crew hours (yes/no)
Check_disruption(DT,AC,AP)	Checking information reliability about a disruption of type DT, concerning aircraft with registration code AC, at airport AP
Disruption(t/f)	Confirmation whether there is a disruption or not by local agents
Conf_call(O,D,A,B,…,N)	Conference call organized by agent O about a certain disruption D with N+1 participants in alphabetical order.
Early_serviceability(AC,DT,AP)	Request for earlier serviceability for aircraft AC with problem DT at airport AP
early_serviceability(AC,DT,AP,y/n)	Possibility for earlier serviceability of aircraft AC with problem DT at airport AP (yes/no)
Start_conf_call(O,D,A,B,…,N)	Start of conference call

End_conf_call(O,D,A,B,…,N)	End of conference call
Transmit_construal(DT,AC,AP,RT,F)	Transmitting construal of the meaning of the signal back to the sender
Construal(DT,AC,AP,RT,F)	Content of a signal being sent
Exit_reporting(DT,AC,AP,RT,F)	Signal of exiting a coordination phase (reporting) about a certain type of disruption with various attributes
Start_aircraft_problem_solving(DT,AC, AP,RT,F)	Signal of starting a new coordination phase (solving crew problem) for a certain type of disruption with various attributes
Renew_compact(AS)	Renewing the basic compact about a particular information element
crew_day_off(AP,y/n)	Possibility to use crew with day off at airport AP
Verify_disruption(DT,AC,AP,RT,F)	Verifiying a certain disruption with different attributes

Table B.2: Domain Ontology - Sorts and elements

SORT	ELEMENTS
DISRUPTION_TYPE	{mechanical_failure}
AGENT	{AE,SS,AMS,AOS,ACo,CTS,CCo,FC,MWE}
MESSAGE	{fix_aircraft, hydaulikc_leak, no_reserve_aircraft, no_crew_available, delayed_crew, crew_hours, extend_crew_hours, no, yes, true, none, exit_AOC_disruption_management, start_crew_problem_solving}
MESSAGE_TYPE	{inform, request, permit, ask, declare, report, synchronize, confirm, answer, negotiate , check, consult, transmit, verify}
AIRPORT	{CDG}
AIRCRAFT	{LHB}
AIRCRAFT_SOLUTION	{cancel_flight, fix_aircraft, no_reserve_aircraft, no_aircraft_available, pump_change}
CREW_SOLUTION	{no_crew_available, reroute_via_BOM, use_day_off_crew}
REPAIR_TIME	{three_hours}

Curriculum Vitae

Soufiane Bouarfa was born on 24 December 1984 in Meknes, Morocco. From 1998 to 2001 he attended the Omar Ibn Al Khattab Lyceum “ثانوية عمر ابن الخطاب” in Meknes, obtaining the Baccalauréat in Experimental Sciences “Bac Sciences Expérimentales”. In 2002 he joined the faculty of Aerospace Engineering at Delft University of Technology in the Netherlands and received his MSc degree in 2007. He followed an MSc program in Avionics, Human Machine Interface, and Air Traffic Management. His final thesis was about evaluating an advanced time-based separation concept in busy TMAs. This work was conducted at the Netherlands National Aerospace Laboratory NLR in Amsterdam under supervision of Ir. Nico de Gelder and Prof.dr.ir. Max Mulder. In 2006, Bouarfa was rewarded for his study progress with a scholarship from the ISTAT foundation.

After his graduation in 2007, Bouarfa joined Accenture in Amsterdam, The Netherlands, and worked as a cyber-security consultant. During his appointment at Accenture, Bouarfa worked for several international clients across multiple domains including energy, telecommunication, and financial services with the aim to protect IT assets. He also followed various trainings including the Accenture core analyst training in Saint-Charles, IL, USA. In 2009, he joined EUROCONTROL Experimental Centre in Brétigny-sur-Orge, France and worked as a research assistant under supervision of Prof. Vu Duong. His research topic was about exploring potential theory to model airspace dynamics.

In 2011, Bouarfa won a SESAR WP-E PhD grant, and started as a Ph.D. student at the Air Transport Operations chair at Delft University of Technology under supervision of Prof.dr.ir. Henk Blom and Prof.dr. Richard Curran. During his PhD, Bouarfa undertook research in the air transportation field from the complex socio-technical perspective and applied agent-based modelling and simulation to improve ATM safety and airline resilience. Next to his research activities, Bouarfa enrolled at the doctoral training programme of TU Delft and was an active member of the European research network

ComplexWorld. In addition, he was a reviewer of the Complex Adaptive Systems Modelling Journal; he supervised MSc and BSc students in both areas of airline and airport operations; gave guest lectures at MSc level; contributed to European research proposals; collaborated with airlines; was a member of the ATO MSc examination committee; and was involved in the organization of various PhD events.

List of Publications:

- Bouarfa, S., 2015. Agent-Based Modelling and Simulation of Safety and Resilience in Air Transportation. PhD thesis, Delft University of Technology, ISBN/EAN 978-94-6259-924-6.
- Bouarfa, S., Blom, H.A.P., Curran, R., 2015. Agent-Based Modelling and Simulation of Coordination by Airline Operations Control. IEEE Transactions on Emerging Topics in Computing, DOI 10.1109/TETC.2015.2439633. *(Forthcoming)*
- Blom, H.A.P., Bouarfa, S., 2015. Resilience. In Complexity Science in Air Traffic Management, eds. Cook, A., & Rivas, D., Ashgate publishing, Chapter 5, ISBN 978-1-4724-6037-0. *(Forthcoming)*
- Blom, H.A.P., Everdij, M.H.C., Bouarfa, S. 2015. Emergent Behaviour. In Complexity Science in Air Traffic Management, eds. Cook, A., & Rivas, D., Ashgate publishing, Chapter 6, ISBN 978-1-4724-6037-0. *(Forthcoming)*
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