Investigation into the effects of advanced technologies on overall aircraft performance in a collaborative design environment

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Investigation into the effects of advanced technologies on overall aircraft performance in a collaborative design environment

Master of Science Thesis

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The undersigned hereby certify that they have read and recommend to the Faculty of Aerospace Engineering for acceptance a thesis entitled “Investigation into the effects of advanced technologies on overall aircraft performance in a collaborative design environment” by Tristan Higgs in partial fulfillment of the requirements for the degree of Master of Science.

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For the past decades concerns over the effect of aviation on the local air quality have risen, with mitigation remaining a priority for industry. To meet the CO\textsubscript{2} reduction goal of 75\% compared to 2005 levels, set out by the European Commission report ‘Flightpath 2050’, more assessment on future aircraft technologies and their potential in meeting these goals is needed. Analysis of these technologies requires increased amount of disciplines being involved in the conceptual design stage through the use of physics-based methods. With the amount of computational budget and knowledge needed by specialists during this stage increasing, methods for effective management is needed. Multidisciplinary collaborative design aims at reducing the analysis burden placed on engineers by distributing computational load among numerous involved parties.

Collaboration comes with technical and non-technical issues. Work at DLR in the last few years has focused on tackling some of these issues with the development of the Remote Component Environment (RCE), an integration framework, and the Common Parametric Aircraft Configuration Scheme (CPACS). From projects, such as ”VAMP”, it has been shown that issues in effective communication between teams of experts with different specialists still exist in large collaborative design projects. Identifying common knowledge among the involved specialists, such as inter-disciplinary correlations, has shown to assist in this effective communication. In this project a visualisation tool has been developed in order to easily identify and present these correlations. This is accomplished through the use of Response Surface Modeling techniques in order to generate real-time functioning 2D and 3D plots from given data sets. The functionality of this tool is demonstrated throughout this report with the data obtained from analyses in this study.

In order to assess the potential of advanced technologies a study is performed. Fuel consumption can be assumed to be directly linked to CO\textsubscript{2} emissions, thus within this study analysis of fuel consumption is performed. Cost savings in future aircraft will also play a crucial role for airliners and passengers, and therefore is also analysed within this study. In order to perform this study an analysis workflow system was developed for the design of a mid-range conventional passenger aircraft from top-level requirements. This workflow was developed in the RCE collaborative integration environment and from joining tools from a physics-based toolkit developed at DLR. So-called adjustment modules were devel-
oped and integrated into this workflow in order to artificially adjust basic parameters at
different stages of the analysis workflow, thus mimicking the effects of certain technologies. 
These technologies included *retrofittable* technologies, such as winglets, geared-turbofans,
and lightweight cabin materials, as well as *non-retrofittable* technologies, including Natural
Laminar Flow (NLF), Active Load Alleviation (ALA), and composite structures.

Through these adjustments two analyses were performed. One in which the wing was
fixed to the reference aircraft planform, and another in which the wing area was adjusted
according to the reference wing loading and changes in MTOM from the artificial ad-
justments. From these analyses the potential fuel and cost savings of a number of case
studies were performed. For a case in which technologies were retrofitted onto an A320-
like aircraft, a potential fuel savings of 16-24% and cost savings of 4-6% was estimated.
For a case in which a number of both non-retrofittable and retrofittable technologies were
implemented at the start of development of the same aircraft, a potential fuel savings of
26-36% and cost savings of 9-13% was estimated.
Acknowledgments

To start with I would like to take this opportunity to thank Erwin Moerland and Till Pfeifer from DLR Institute of Air transportation System for the support they have shown me during my time there. Their knowledge helped me tremendously in completing this project. Without them I wouldn’t have been able to complete this work. I would also like to thank Gianfranco La Rocca, for his support and useful comments on my work. I would also like to thank Pier, Daniel, Jonas, Thomas and Bjorn for their invaluable input and assistance during my work. I appreciate all the time they spent on helping with issues that arose during the project and thank them for their feedback.

I would also like to thank the other members of my graduation committee: Leo Veldhuis and Richard Dwight, for giving their time. Finally I would like to thank my family and friends for supporting me.
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Nomenclature

Latin Symbols

\[
\begin{align*}
C_D & \quad \text{Drag coefficient} \quad [-] \\
C_{D0} & \quad \text{Zero-lift drag coefficient} \quad [-] \\
C_l & \quad \text{Lift coefficient} \quad [-] \\
D & \quad \text{Drag} \quad [N] \\
f & \quad \text{Objective function} \quad [-] \\
g & \quad \text{Gravitational constant} \quad [m/s^2] \\
L & \quad \text{Lift} \quad [N] \\
m_{\text{Engine}} & \quad \text{Engine mass} \quad [kg] \\
m_{\text{Fuselage}} & \quad \text{Fuselage mass} \quad [kg] \\
m_{\text{Systems}} & \quad \text{Systems mass} \quad [kg] \\
m_{\text{Wing}} & \quad \text{Wing mass} \quad [kg] \\
W & \quad \text{Weight} \quad [N] \\
x & \quad \text{Design variables} \quad [-] \\
y & \quad \text{Coupling variables} \quad [-] \\
z & \quad \text{Global variables} \quad [-] \\
\phi & \quad \text{Technology factor} \quad [-] \\
\rho & \quad \text{Air density} \quad [kg/m^3]
\end{align*}
\]

Abbreviations

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<tr>
<td>AAO</td>
<td>All-At-Once</td>
</tr>
<tr>
<td>ACARE</td>
<td>Advisory Council for Aeronautics Research in Europe</td>
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<tr>
<td>ALA</td>
<td>Active Load Alleviation</td>
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<tr>
<td>BLISS</td>
<td>Bi-Level Integrated System Synthesis</td>
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<tr>
<td>BWB</td>
<td>Blended-Wing-Body</td>
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<td>CO</td>
<td>Collaborative Optimisation</td>
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<td>CCD</td>
<td>Central Composite Design</td>
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<td>COC</td>
<td>Cash Operating Costs</td>
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<td>CPACS</td>
<td>Common Parametric Aircraft Configuration Scheme</td>
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<td>DOC</td>
<td>Direct Operating Costs</td>
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<td>DOE</td>
<td>Design Of Experiments</td>
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<td>International Air Transport Association</td>
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<td>Wireless Flight Control System</td>
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For the past decades concerns over the effect of aviation on the local air quality have risen, with mitigation remaining a priority for industry. Global warming has become one of the biggest challenges for modern life, and solving it has become an aim for all nations. Aviation contributes to 2% of the global CO₂ emissions [2]. Along with other environmental effects such as contrails and cirrus the total contribution of air transportation to the greenhouse effect is 3% [2].

Air transportation has been steadily growing for the past couple decades at a rate of approximately 5% (despite economic and political crises) and is predicted to continue at this rate in the coming decades [3]. Economic growth in less-developed countries is the biggest contributor to this continued growth. With this continued growth over the coming decades the contribution of the air transportation industry to the global CO₂ emissions is expected to grow to 3% by 2050, with a total contribution to the greenhouse effect of 5% [2]. In light of the negative effects of global warming on society today any growth in greenhouse gas emissions is not desired.

Figure 1.1 illustrates the decrease in fuel consumption of aircraft since the introduction of the De Havilland Comet 4 in the 1960s. As can be observed there was a period of large improvements in performance followed by a period of plateaued progress. Technological breakthroughs, such as the introduction of the jet engine on the De Havilland Comet, have led to jumps in aircraft performance. However, available improvement in performance from these technological breakthroughs reach a point where the effort put into the design of an aircraft is disproportionately large compared to the increase in performance gained. There is a limited amount of performance to be gained from each new technology. This is the stage the aviation industry has reached today, where the growth in efficiency in new aircraft designs with the existing aircraft and engine architecture is beginning to plateau. The European Commission within the Flightpath 2050 report, set out the goal to reduce CO₂ emissions by 75% by 2050 among other goals to assist in mitigating the global warming effect. In order to meet these goals, a new technological breakthrough is needed. In order to achieve this technological breakthrough increased investigation into the viability of future aircraft technologies in today’s global fleet is needed.
In order to assess the progress of the industry in meeting the FlightPath 2050 goals, numerous studies investigating the potential of future aircraft technologies have already been performed by multiple research institutions, including the International Air Transport Association’s (IATA) TEchnology Roadmap for Environmentally Sustainable Aviation (TERESA) study [3]. Other projects include the ACARE Goals Progress Evaluation (AGAPE) [5], the UK Committee on Climate Change (CCC) [6] and the Independent Expert Study within ICAOs Committee on Aviation Environmental Protection (CAEP) [4]. These studies have contributed to understanding the possible benefits of a number of individual technologies on the future of aircraft and engines. These technologies included among others, advanced wingtip devices, natural laminar flow, active load alleviation, composite structures, and health monitoring. However, many of these studies findings were predominantly based upon industry and research expert’s predictions, with the need for further quantitative investigation through physics-based analyses remaining.

Quantitative analysis of advanced technologies requires greater knowledge on the aircraft design at earlier stages in the design process than in previous development projects. As stated by the AIAA technical committee, it is this need for greater knowledge and the increasing complexity of aircraft design that has lead to the amount of disciplines involved in aircraft design to steadily increase [7]. Increases in computational power over the last decade, along with the development of multi-fidelity approaches (such as the one used in [8]), has allowed for increased detail of design knowledge in the early design phases. However, as a consequence of these developments an increased analysis burden is placed on the engineer as larger amounts of data are produced with increased detail [1]. Multidisciplinary collaborative design allows engineers to make development and research projects more affordable and to lower the financial risk associated with these projects by distributing computational load. With the ever increasing demands on the performance and afford-ability of flight by both the passenger and the industry as a whole, collaboration is becoming a necessity. However, collaboration presents a number
Due to the often distributed nature of collaborative design, many disciplinary specialists, mostly having diverse engineering and socio-cultural backgrounds, are involved in the early stages of the aircraft design process. New challenges in effective management and synchronization of knowledge and resources present themselves. Clear communication of disciplinary results from these often complex problems is crucial in establishing effective collaboration. In collaborative design projects, exchange of data and models between multiple locations and codes while maintaining protection of knowledge are just some of the technical issues encountered. Consequently engineers with the task of integrating multiple disciplinary analyses can at times find it a challenge to interpret all results. Interpretation of results should be collectively performed by these integrators and involved disciplinary experts. Methods aiding in the effective communication of data and results between engineers has been under investigation in the Integrated Design Lab (IDL) of the Institute of Air Transportation Systems. The IDL aims at establishing a means for this communication of results, by providing disciplinary specific output through visualisations and messages understandable for a wide audience [9]. However, a means to easily interpret analysis results for a wide range of design and research projects is needed.

1.1 Research Objectives and Questions

The need for further quantitative analysis of future technologies form the main motivation for this thesis work. Though some focus will be placed on mitigating the challenges of collaborative design, as discussed above. The motivations of this research work can be formulated into a main objective:

*Investigate, in a collaborative design environment, the potential of both retrofittable and non-retrofittable technologies currently under research on the overall design of a mid-range passenger conventional aircraft, from an operating cost and fuel consumption point of view.*

From this objective the end goal of this thesis would be to obtain quantitative estimations on the potential fuel and cost savings of the following technologies:

- Laminar Flow Control
- Active Load Alleviation (ALA)
- Advanced Composite structures
- Geared Turbofan Engines
- Wingtip devices
- Drag reducing coatings
- Wireless Flight Control System (WFCS)
- Lightweight Cabin Interiors
This portfolio of technologies, which includes both retrofittable and non-retrofittable technologies, were selected due to their estimated potential fuel savings in the TERESA project \[3\]. The quantitative estimations on fuel and cost savings should be made on cases involving the application of individual technologies from this portfolio on a conventional aircraft, as well as the application of a number of these technologies on the same aircraft. These cases should also allow for an investigation into the potential of retrofitting technologies onto an aircraft compared to the implementation of technologies at the start of an aircraft’s development. This quantitative analysis would allow the reader to gain an insight into the potential fuel and cost savings that can be made in the coming decades, with the technologies that are currently known, for both newly designed aircraft, and the existing global fleet. Another part of this goal is to develop a tool to make use of the results from this quantitative analysis in improving the design process of advanced technologies. This quantitative analysis will be achieved in a collaborative environment. Therefore this tool should also be designed to assist in tackling some of the remaining challenges in effective communication that still exist in multidisciplinary collaborative design projects. The results from this quantitative analysis of technologies can serve in demonstrating the use of this tool, which can be applied to results from other multidisciplinary collaborative design projects.

From knowing the goal of this thesis a number of sub-questions can be derived:

- Why should we collaborate on aircraft design projects and how can the process be improved?
- What is the fuel consumption of current state-of-the-art aircraft compared to industry targets?
- How do the retrofittable and non-retrofittable technologies that are currently under research aim to help in bridging the gap between current aircraft fuel consumption levels and industry targets?
- What method can be utilised to assess the fuel consumption and operating cost reduction potential of these wide ranges of technologies in a collaborative design environment?

These sub-questions can then be translated into sub-objectives, that if each are accomplished, should lead to the answering of these sub-questions and ultimately the main thesis objective. These sub-objective can be formulated as follows:

1. Investigate the benefits of collaborative design and the remaining issues in effective communication and knowledge transfer.

2. Develop a tool aimed at improving this effective communication and knowledge transfer between collaborating engineers.

3. Investigate the progress made in current state-of-the-art aircraft in reducing fuel consumption and operating cost and compare this to the CO$_2$ reduction goal set out in Flightpath 2050.
4. Investigate the technologies that are currently under research and determine in which ways these technologies improve aircraft performance.

5. Develop a method for designing/analysing a mid-range passenger conventional aircraft in terms of fuel consumption and operating cost in a collaborative design environment.

6. Develop a method for estimating the savings in fuel consumption and operating cost by implementing the previously investigated technologies into an aircraft design.

1.2 Methodology

From the sub-objectives outlined in the previous section a procedure in which to accomplish said objectives, and ultimately the main objective, was constructed.

1. The first stage of this project was to develop a tool aimed at improving knowledge transfer between collaborating engineers. In order to accomplish this goal an investigation into the benefits of distributed collaborative design as well as the lessons learned from previous collaborative projects, such as projects "TIVA" and "VAMP" [10], with respect to communication of analysis results was needed. In this way the issues that have already been addressed through methods or tools, and the issues still remaining can be addressed [10, 11, 8].

2. From the findings of the previous investigation into collaborative design, a tool aimed at improving some the remaining issues with collaborative design could be developed.

3. The next stage in this study is to determine by how much current state-of-the-art aircraft have reached fuel consumption goals of FlightPath 2050 and estimate what savings are needed to close the remaining gap. By doing so an idea of what sort of fuel savings are needed to reach the goal of reducing CO₂ emissions by 75% by 2050 (compared to 2005 levels) is obtained.

4. An investigation into a number of technologies currently under research, and showing promise in improving aircraft fuel economy and operating costs, was performed. From this investigation the analysis parameters affected by these technologies, and by how much, was estimated from literature. This information was then used in the method for estimating fuel and cost savings of these technologies, outlined in the subsequent stages of this thesis work.

5. The next stage was to develop an analysis workflow in a collaborative design environment. A workflow here defines a collection of interconnected design and analysis tools in order to design or analyse an aircraft configuration. This workflow is needed for designing/analysing a conventional aircraft configuration. In this case the workflow will be constructed in the collaborative design environment that has been developed at DLR. To this purpose the distributed design environment RCE [12] was used as a framework for constructing the analysis workflow, using the CPACS data exchange format [13, 14] as an interface. Thus a workflow of connected existing
statistical- and physics-based analysis tools on distributed servers was constructed to analyse a conventional passenger aircraft. The aircraft model used as a reference aircraft during this project is the D150, an A320-like aircraft.

6. From investigating technologies in the previous stage of this study it becomes clear that a small set of basic parameters can be used to mimic the effect of the technologies. For example, a wingtip device will provide improved lift-to-drag ratio at an increased wing weight, and geared turbofan engines provide improved engine performance but with a possible increase in engine weight. Therefore the parameters mentioned can be used to mimic the effect of these technologies. With this approach a wide range of technologies (such as those mentioned in section 1.1) can be mimicked. For this a number of weight, aerodynamic, and engine analysis parameters can be artificially adjusted by so-called technology factors, $\phi$, throughout the analysis workflow, and investigate the effects on fuel and operating cost results. These artificial adjustments can be likened to ‘what-if’ studies. If, by a certain technology, lift-to-drag ratio was increased by 10%, but wing weight increased by the same amount, what would its effect be on fuel and operating cost? In this case the so-called technology factor would be 1.1 and 0.9 for the lift-to-drag and wing weight parameters respectively. The 1.1 represents a lift-to-drag ratio 10% higher than the lift-to-drag ratio of an aircraft without this technology applied. The 0.9 represents the same but 10% lower. In this case a technology factor of 1 would represent a lift-to-drag ratio or wing weight of this aircraft without technology applied. In some cases this manipulation would entail a simple multiplication of the parameter in question by the corresponding technology factor constant. In other cases it comprises of slightly more complex methods in order to achieve the desired change in the observed parameter. This method was then incorporated into the analysis workflow from the previous stage.

1.3 Report Structure

In chapter 2 the benefits of distributed collaborative design and the remaining challenges will be discussed. Also the framework that has been developed at DLR to support distributed collaborative design will be discussed. This includes the dedicated workflow integration environment RCE, and the aircraft data exchange format CPACS, which facilitates the communication between design and analysis tools within RCE.

In chapter 3 a discussion into the current state-of-the-art aircraft when compared to the 'Flightpath 2050' CO$_2$ emissions reduction goal is given along with an investigation into possible future aircraft technologies.

In chapter 5 the description of the chosen disciplinary tools is given as well as the reasoning behind choosing them in the context of the thesis goals. Also in this chapter the modules developed to perform the artificial adjustments, discussed in section 1.2 (hereafter referred to as adjustment modules) will be presented.

In chapter 4 the developed analysis workflow is discussed, along with its validation. To validate the developed workflow it was used to design the D150, an A320-like aircraft, and compared to A320 data. Also within this chapter the outline as to how the adjustment
modules will be integrated into the analysis workflow will be discussed, along with the systems verification and validation. The validation is done by estimating the fuel savings for the A320neo, the next generation of the A320 family.

In chapter 6 a method for investigating the effect of technologies on aircraft performance is outlined. The verification of this method will also be performed.

Finally in chapter 7 an investigation into the potential of the technologies mentioned in section 1.1 from the analysis results is performed through a number of case studies. Also in this chapter the functionality of the developed tool from the second sub-objective in aiding the design process of advanced aircraft technologies will be demonstrated.
Chapter 2

Multidisciplinary Collaborative Design - What challenges still remain?

The first thesis sub-objective in section 1.1 states that an investigation into the benefits of collaborative design and the remaining issues in effective communication and knowledge transfer is needed. Therefore in this chapter this investigation is performed as well as an investigation into the tools and methods already developed by DLR, to address some of the technical issues with collaborative design. An overview of their functionality and required tasks for this project is beneficial in understanding the development of the workflows during this project.

The second thesis sub-objective states that the development of a tool aimed at improving this effective communication and knowledge transfer between collaborating engineers is required. Therefore methods aimed at tackling the issues found from the previous investigation will also be addressed in this chapter. Ultimately a tool was developed that implement these methods. In section 2.1 the investigation into the benefits and issues with collaborative design will be covered. In section 2.2 the framework developed at DLR for collaborative design so far will be addressed. Finally in section 2.3 the possible methods aimed at improving effective communication in collaborative design projects along with the developed tool that implements these methods will be outlined.

2.1 Distributed Collaboration - Benefits and Challenges

As mentioned before the changing complexity of aircraft design and increased number of disciplines involved has led to collaborative design methods to be more widely adopted. The most obvious benefits come from the reduced computational expense and required specialist knowledge of each institution involved in a project. The decentralized approach to the development of design and analysis workflows allows specialized software of experts
to be executed on their own hardware. The benefits of such an approach are threefold: Firstly much of the software involved in a complex design problem has specific hardware or licensing requirements. The effort required to implement and maintain all software on a centralized hardware outweighs the effort required to set up networked computing. Secondly, the owner of software controls its own utilization. This has the benefit that those who have specialist knowledge of a certain software will control its utilization, avoiding the risk of unrealistic results being produced by non-experts utilizing the software. Thirdly, the decentralized approach permits parallel execution of tasks, leading to reduced time required for a project. However this positive effects of this final benefit can be reduced if methods for effective data transfer and workflow construction and testing aren’t utilised.

The first technical challenge in connecting different disciplinary tools lies with data transfer. In order to interconnect a number of tools, in many cases based on different languages and data types, a centralized data exchange format is needed. This way the method of providing inputs and outputs in standardized, leading to the easy interconnection of tools developed to use this data exchange format. To solve this challenge DLR set up CPACS (see section 2.2.1). A framework to construct and run these workflows of tools is also needed for effective collaborative design. For this purpose the workflow integration environment RCE was developed at DLR (see section 2.2.2). The utilisation of these frameworks are showing large benefits, however, organizational issues for collaborative design remain.

From the experience gained during collaborative projects such as ”TIVA” and ”VAMP” focus has been placed on addressing challenges at the organizational level of collaborative design [10]. Issues with effective communication and interpretation of analysis results were some of the main challenges faced during these projects. Collaborative teams are mostly heterogeneous, i.e. teams involving experts from multiple specialisms, which means that they are built up of experts who are specialized in individual disciplines. This characteristic of collaborative teams in one respect can lead to the benefit of reduced specialist knowledge required by each involved expert, but in the other respect can hinder communication between these experts. Certain competencies prevalent in one discipline, in many cases are much less prevalent in another. Thus in heterogeneous teams this can often lead to limited overlaps in knowledge, causing challenges in understanding one another and each other’s disciplinary results. Extensive information libraries and reporting can mitigate this issue, but excessive amounts of data and information from these libraries can be damaging to comprehension [10]. A method for improving comprehension of the entire process is crucial in improving the efficiency and effectiveness of collaborative projects.

### 2.2 Framework to Support Multidisciplinary Collaborative Design

In order to build a workflow of multiple disciplinary tools located on distributed servers an integration tool, called RCE, along with the CPACS data exchange format have been developed at DLR. In this section this framework, set up at DLR to support collaborative aircraft design, will be discussed in respect to achieving the thesis goal. In section 2.2.1 the CPACS data exchange format will be addressed and in section 2.2.2 the RCE tool is discussed.
2.2 Framework to Support Multidisciplinary Collaborative Design

2.2.1 CPACS

For effective multidisciplinary collaborative design it was determined from previous projects, such as project "TIVA" and "VAMP" [10] that a "sharable common vehicle description to facilitate communication among all disciplines" [15] is needed. To fulfill this purpose the DLR has been developing the Common Parametric Aircraft Configuration Scheme (CPACS) [13, 14]. This central data exchange format was developed to transfer and load aircraft configuration and analysis data within multiple analysis and design tools. CPACS is a hierarchic XSD-Schema that contains detailed parametrized definitions of the aircraft geometry and the complete air transportation system along with data for various aircraft analyses.

For this project a multidisciplinary workflow to analyse a conventional passenger aircraft is needed. The workflow is to be built from a collection of low-fidelity tools, some developed at DLR during previous projects, others sourced externally, but almost all located on distributed servers. To easily transfer data between these many disciplines a central data exchange format, such as CPACS, is extremely beneficial. It allows for the easy changing of workflows as the implementation effort of integrating different tools into the workflow is reduced [14]. This allows for a reduced number of interfaces between disciplines (see figure 2.1) as communication is only between the discipline and the central database. That added onto the fact that the toolkit available, containing many tools from multiple disciplines, have been developed to work with the CPACS aircraft definition. This makes CPACS an optimal choice for the utilised data exchange format in constructing the analysis workflow.

Figure 2.1: CPACS advantage of unified data management in a multi-code framework: without a centralized data exchange format that has n to n interfaces (left), and with a centralized data exchange format that has n to 1 interfaces (right) [8]

In figure 2.1 the general structure of a CPACS definition is shown. As seen in the figure the definition comprises of a number of hierarchal levels with increasing detail of the aircraft description further down in the levels. This central data exchange format will allow for the structured exchange of data between analysis modules, however, an integration framework that will allow the coupling of these analysis modules was required. For this the integration framework RCE was utilised.

2.2.2 Remote Component Environment

To build the workflow required to design and analyse a mid-range conventional aircraft from top-level requirements, an engineering framework was required. This framework
should allow for the integration of various statistical- and physics-based analyses and design tools. The DLR developed its own workflow integration environment called the Remote Component Environment (RCE) [12]. RCE is built upon the Eclipse Rich Client Platform and allows for collaborative design in industries, such as aircraft and shipyard [16]. RCE allows for easily connecting different analysis and design tools for building the analysis workflow required to accomplish the thesis goal. The possibility to observe data at different stages in the constructed workflow also makes it a good choice for debugging. This function makes it easier to determine which disciplines aren’t providing reasonable results if the results of the entire workflow are in doubt.

In figure 2.3 the RCE interface is shown. There are four main panes. The center window is the workflow editor, this is where the multidisciplinary workflows are built. On the right is the tools palette which contains all the available analysis and design tools available on distributed servers. The window on the top left is the project explorer, which lists the workflows created. The window on the bottom is the Properties and Logs window showing certain properties and output of the workflow along with logs noting the errors and warnings that arose during execution.

A number of tools have already been implemented into RCE by so-called tool wrappers. These tool wrappers make it possible to connect different analysis tools written in different coding languages into a single workflow in the RCE environment. The wrapper performs this job by automating the generation of the input and output files. To accomplish this task the TIXI and TIGL interface libraries were developed in order to have an interface between the XML language used in CPACS files and the coding language used in the
2.3 Method for Effective Communication

As mentioned at the end of section 2.1, a method for improving comprehension of the entire design process in a multidisciplinary collaborative project is needed. Tools with varying data types can be interconnected relatively easily using the tools described in sections 2.2.1 and 2.2.2, but the challenge arises once errors occur, or workflows produce improper results and determining where these improper results originate becomes the task. To determine if specialist’s codes are producing reasonable results, expert knowledge is required. For the process integrator finding the source of improper results requires communication with disciplinary specialists. During project ”VAMP” it was experienced that gaining understanding of the entire over-all process is best realized during physical meetings. Within these meetings *depict* and *explicit* communication was found to be the most effective [10]. What is meant by *depict* and *explicit* communication is communicating results by providing disciplinary specific output through clear visualisations and messages understandable for a wide audience, such as workflow integrators. To aid in this *depict* and *explicit* communication the Integrated Design Lab (IDL) (see figure 2.4) was constructed [9].

Investigation into methods within the IDL for establishing effective communication have been performed at DLR for the past few years. It has been found that identification of multidisciplinary interactions and affinity for common disciplines can form a basis for communication within these teams of engineers [11]. This common affinity for disciplines can be enlarged by finding areas of knowledge that specialists of different disciplines both
possess. This area of common affinity can be defined by shared explicit knowledge, such as design parameters exchanged between disciplines, as well as the less obvious implicit knowledge, such as common theoretical methods applied within the included analysis codes. This area of common affinity is illustrated in figure 2.5 for the example of a pre-engine designer and aircraft pre-designer. Presenting clear visualisations of these implicit cross-disciplinary correlations in collaborative design teams can aid in understanding each other’s considerations and interests [11]. However, a means to easily interpret analysis results and identify these multidisciplinary interactions for a wide range of design and research projects is needed.

**Figure 2.4:** The Integrated Design Lab at DLR Hamburg

**Figure 2.5:** Area of common affinity (green) of two knowledge bearers: a pre-engine designer (blue), and aircraft pre-designer (orange) [11]
2.3 Method for Effective Communication

2.3.1 Visualisation Tool

In fulfilling one of the objectives of this thesis a tool to improve effective collaboration between involved engineers by allowing for improved communication of results, was developed. This tool would be used in the Integrated Design Lab (IDL) (see figure 2.4) and is aimed at to provide disciplinary specific output by generating clear and real-time functioning visualisations from large datasets of results. As discussed previously by providing a method to effectively convey inter-disciplinary correlations, some of the remaining organizational challenges of multidisciplinary collaborative design can be tackled and could ultimately lead to improved knowledge transfer between involved experts.

A way to clearly present these multidisciplinary interactions is through clear 2D and 3D plots. This tool should have the functionality to import large datasets and produce plots and/or computed results for different combinations of design parameters and outputs chosen by the user. With this task in mind the visualisation tool shown in figure 2.6 was developed in the MATLAB Graphical User Interface Design Environment (GUIDE).

As observed in figure 2.6 the developed tool has a number of functions to make generating and positioning 2D and 3D plots easy. The tool also has the Parameters box which includes sliders to allow the user to experiment with adjusting various input parameters and observe its effects. This includes observing the effect on the analysis results presented in the Results box and observing how these adjustments effect already generated plots in real-time. To accomplish this function it isn’t possible to run a full system evaluation (e.g. running an entire workflow) for every adjustment due to time constraints. For any adjustment on the sliders shown in figure 2.6 a re-calculation of the outputs is required. When analysis tool evaluations require minimal computation time (i.e. empirical-based tools that require less than a second for the analysis of one design point) this does not
create a problem. However, once more physics-based analysis tools are considered function evaluations can take from a couple minutes to 20-30 minutes (depending on the fidelity level and number of disciplines involved). For the workflow that was required in this project a full run would take approximately 20-25 minutes, with the majority of time required for the physics-based tools. Therefore if a number of adjustments are made with the visualisation tool this can become quite computationally expensive. This would defeat the whole purpose of the tool, to quickly analyse and identify cross-disciplinary correlations. To mitigate this issue the disciplines can be approximated by Response Surface Models (RSM) [18]. This would allow for a cheap and quick representation of the complete simulation from a number of response datum.

For a more detailed user guide into all the functionalities of the developed tool, including the import function, the reader is referred to appendix D.

2.3.2 Response Surface Modelling Methods

As discussed in section 2.3.1 for the proper functioning of the visualisation tool, RSM techniques were adopted. For these models to be created a number of response datum is needed. This data should be obtained by performing full system evaluations at certain sample data points. As mentioned in section 2.3.1 these function evaluations are quite computationally expensive for the analysis workflow of this project. Therefore the user will look to perform function evaluations at a minimal number of sample points in the design space. In order to cover the design space adequately, while keeping the number of sample points to a minimum, a so-called Design of Experiments (DOE) method was implemented. This not only allowed for the generation of clear visualisations, showing the multidisciplinary relations in the analysis system, but also made it possible to demonstrate the functionality of the developed tool with data obtained from the workflow analysis. The available methods for this DOE are discussed in appendix A.

For this study the Latin Hypercube Sampling method was used. It is the space-filling capabilities of the LHS method along with the ability to tailor the number of sample points to the computational budget that made this sampling technique the chosen DOE method for this thesis. In section 3.2.9 it will shown that seven technology factors were to be applied to the eventually developed analysis workflow (see chapter 4 for more detail). With this amount of parameters to be adjusted in the DOE it was advised from RSM specialists that at least 100 sample points are needed to sufficiently map the design space, with 150 sample points being the recommended amount. With the LHS method the number of sample points can be set to 150 sample points, regardless of the dimension of the design space, and will optimize the sample points to evenly fill the design space. One tool that allows for the generation of space-filling DOEs, including LHS, is the statistical discovery tool JMP [19]. For further information on this tool and its capabilities the reader is referred to section 6.3.1.

Once this response data is obtained a method of interpolation to generate the response surface is required. The possible interpolation methods are discussed in appendix B. For the visualisation tool two RSM techniques were used, Polynomial response surfaces and Kriging. The reasoning for using both of these methods in the tool becomes clear when comparing the advantages of the two methods. Polynomial response surface models have
the benefit of easy construction and is advantageous when it comes to smoothing out noisy data; however the disadvantages of this method appear when data that is highly nonlinear or exhibits irregular behaviour is modelled [20]. Kriging on the other hand is beneficial in modelling irregularly spaced data and is able to model surfaces with nonlinear behaviour [21]. For the visualisation tool to be applicable to a wide range of datasets it must be able to work with both linear data (or noisy data that needs smoothing) and highly nonlinear data. Therefore by giving the option for both RSM methods, the user can decide as to which method would work best with the data being analysed.

As just mentioned, Kriging is an advantageous interpolation method when sparse sample points are modelled; however if the sample points are too close together the method can become unstable [21]. An appropriate DOE to maximize the distance between sample points, such as the LHS method adopted for this study, solves this issue.

A popular tool for generating polynomial RSMs from sample data, and the tool used within the visualisation tool, is *Polyfitn*, an extension of the Matlab polynomial fit function *polyfit* [22]. A popular toolkit that makes use of the kriging method for generating RSMs is the DACE toolbox [23], based upon the MatLab coding language. It was this tool that was used to generate the Kriging models within the visualisation tool.
Multidisciplinary Collaborative Design - What challenges still remain?
The third thesis sub-objective in section 1.1 states that an investigation into the progress made in current state-of-the-art aircraft in reducing fuel consumption and operating cost and compare this to the CO$_2$ reduction goal set out in Flightpath 2050 is needed. Progress in performance of state-of-the-art aircraft has been steadily improving, helping towards reaching the CO$_2$ reduction goals of Flightpath 2050. In order to assess this progress so far an overview is given in this chapter. The fourth thesis sub-objective states that an investigation into the technologies that are currently under research is also needed and that this investigation should also determine in which ways these technologies improve aircraft performance. To this purpose an overview of these technologies aimed at improving aircraft performance is given in this chapter. In section 3.1 the feats so far in aircraft performance will be outlined. In section 3.2 an investigation is performed into future technologies currently being researched at varying levels of readiness.

3.1 State-of-the-art aircraft

In order to analyse the position that the aviation industry is currently in reaching the goal of reducing CO$_2$ by 75% by 2050, an investigation into the current state-of-the-art aircraft is needed. For this investigation a number of the latest aircraft designs will be presented and analysed in light of this CO$_2$ reduction goal.

The latest aircraft that Boeing has developed is the 787 dreamliner. The long-range, mid-size wide-body jet airliner is Boeing’s most fuel-efficient aircraft to date [24]. Designed to be 20% more fuel efficient than its predecessor, the 767, the 787 is the world’s first major airliner that uses composite materials as the primary material. The Dreamliner also implements the relatively new technology, raked wingtips, as well as increased use of electrical systems, implementation of an advanced computing environment for the aircrafts avionics, improved engines accompanied by a host of other improvements [25, 26].
Approximately 40% of its fuel savings over the 767 come from the more fuel efficient engines \([27]\).

The A350XWB, Airbus’ competitor to the Dreamliner, also has composite materials as the primary material in the fuselage and wing structure along with improved engines over the A330. These design features, along with the added 4.3m winglets that reduce lift induced drag, allowed for a 25% decrease in fuel consumption compared to its current competitor \([28]\).

In the regional jet market the state-of-the-art Bombardier CRJ900 NextGen aircraft has a 5.5% improvement in fuel efficiency over older NextGen aircraft, due to the implementation of advanced technology \([29]\). This includes its new conical engine nozzle for decreasing drag. It’s also claimed that due to the introduction of a carbon braking system in future CRJ900 aircraft a further 400 pounds of weight savings can be made \([30]\).

Aviation companies, such as Boeing and Airbus, are placing a greater focus on improving their existing families of aircraft. An example of this is the improvement of the successful Airbus A320 family, the A320neo. Improvements in the A320neo included improved aerodynamic efficiency with the placement of winglets on the wings. Improvements also came from the introduction of engines with improved efficiency such as the Pratt & Whitney 1100G geared turbofan engine, said to improve fuel efficiency by up to 15% over the existing A320 engines \([31]\).

As observed by these aircraft reasonable improvements in fuel efficiency have been achieved in the aviation industry. However, over the next 20 years air traffic is expected to triple and whether these increments in fuel efficiency will be able to provide a decrease in CO\(_2\) is still a question to be answered. CO\(_2\) emissions will also be decreased due to more efficient operations and infrastructure, however, as illustrated in the schematic shown in figure 3.1 to reach the CO\(_2\) emissions reduction goals radical strides in technological advancement in the industry are needed. The AGAPE project aimed at assessing the progress in reaching the 2020 and 2050 goals. In its final report it was concluded that progress has been made in terms of reaching the goals, however more effort is needed for them to be fully achieved \([5]\). It was also determined that improvements in fuel efficiency has the benefit of reducing the CO\(_2\) footprint for each passenger per 100km but at the same time has another effect opposing the goal of achieving reductions in global CO\(_2\) emissions. Namely the reduced cost of flying from reduced operating costs, thus increasing global air traffic. Thus it is still to be determined whether these improvements in fuel efficiency without implementing drastic operational restrictions, such as set CO\(_2\) quotas, will lead to the required reductions in global CO\(_2\) emissions. Despite this, further studies into the potential fuel efficiency of combining multiple technologies into the aircraft design is needed. This applies to technologies being implemented as retrofits onto existing aircraft designs, thus improving the existing global fleet, or implementation at the start of an aircraft’s development, for the future global fleet.

### 3.2 Future Technologies

A number of studies have been performed in order to assess the potential of future aircraft technologies in improving aircraft performance. These included studies such as the
3.2 Future Technologies

Figure 3.1: Projection for CO₂ emissions in reaching reduction goals [3]

previously mentioned AGAPE study, the UK Committee on Climate Change and the Independent Expert Study within ICAO’s Committee on Aviation Environmental Protection (CEAP). The TERESA project is a recent study, carried out in close cooperation between IATA, DLR and the Aircraft Systems and Design Laboratory (ASDL) [3].

TERESA project used a strict bottom-up approach, that consisted in starting with estimates of the fuel efficient improvements yielded by single technologies obtained from all relevant aviation stakeholders, namely manufacturers, scientists, government agencies, infrastructure providers and airliners. These estimates are included in an implementation roadmap into the world fleet, accounting for operational aspects. The study focused on gathering information on a number of different fuel-efficient technologies from the areas of aerodynamics, lightweight materials and structures, propulsion and equipment systems. The technologies were then assessed for their fuel saving capabilities and timeframe of implementation into the world’s fleets. The results showed that, after 2020, reductions in fuel savings can reach as much as 27-40% for new aircraft designs and 5-12% for retrofits, with technologies such as laminar flow control, active load alleviation, winglets, composite structures, and advanced engine architectures (such as geared turbofan and open-rotor engines) being identified as most promising. In the following sub-sections a number of these promising technologies (along with a few others) will be outlined including an explanation on how they influence the performance of an aircraft.

3.2.1 Laminar Flow Control

Natural Laminar flow (NLF) designs and materials pertain to optimised shapes and surfaces of an aircraft in order to delay the transition of a laminar boundary layer to one of a turbulent nature. This results in the reduction of skin friction drag, which in turn results in lower fuel consumption. The point at which a boundary layer becomes turbulent is dependent on the atmospheric conditions, pressure gradient along the surface and the surface’s qualities. For most cases atmospheric conditions are restricted by the set mission of the aircraft. Thus, NLF is predominately being achieved by developing
A number of airfoils have been designed with the goal of maximising laminar flow for certain atmospheric conditions, such as the NACA 6-series airfoils. For natural laminar flow wings a reduced sweep is required in order to reduce flow instabilities occurring from the flow component that exists along the leading edge of a swept wing. It has been found that certain weight penalties occur from implementing natural laminar flow wings into an aircraft’s design. One of the most extensive studies performed to date on NLF wings was performed by Boeing 36 years ago [33]. The study showed that by implementing natural laminar flow airfoils and increasing wing span an increase of up to 30% is achieved in L/D for a passenger aircraft carrying 196 passengers over a range of 3704km (2000 nmi). However much of this aerodynamic benefit was found to be outweighed by a similar increase in wing weight. This increased weight occurred mainly from a number of contributors: increased gust load factor due to reduction in sweep angle; increased wing area required for low-speed landing requirements without leading edge high-lift devices; reduction in thickness of the inner wing in order to achieve laminar flow. It must be noted that the results from this study are uncertain today as advances in aerodynamics, structures and materials since then counter many of these issues with increased weight. Advances in the use of carbon-fibre reinforced plastic in order to achieve a smooth surface and the use of articulated leading-edge devices to achieve landing requirements are just two measures that can be used in order to limit any increases in weight [34].

More extensive use of this technology has been researched and undertaken recently. One such example of its recent use in aircraft design is in the Boeing 787. Through the implementation of a natural laminar-flow nacelle, achieved through advances in composite construction, material joining techniques and smooth painted surfaces, airlines can expect to save 100,000 litres of fuel per 787 aircraft every year [35]. Research in this field is also being undertaken by the European Joint Technology Initiative (JTI) Clean Sky with the aim of maintaining natural laminar flow on the outer wings of an A340 aircraft through optimisation of the wing profile [36].

Another variant of achieving laminar flow over surfaces is with the use of surface suction or blowing in order to manipulate the boundary layer. This manipulation of the boundary layer, known as Hybrid Laminar Flow Control (HLFC), allows for increased portions of the aircraft maintaining laminar flow. NASA, the U.S. Air Force, and Boeing began a project in 1990 in which a 757-200 was used as a demonstrator for a number of technologies [37]. A HLFC wing glove was tested in order to demonstrate the potential of this technology. It was concluded from initial tests that with HLFC applied to both the wing and empennage a 15% reduction in fuel consumption can be achieved for a 300-passenger aircraft. The latest ecoDemonstrator test flights currently underway focus on further demonstrating the use of NLF and HLFC, as well as technologies aimed at reducing environmental effect on NLF, such as a Krueger shield with the goal of protecting the leading edge from insects.

Laminar flow control systems, be it natural or hybrid, are technologies that must be implemented within the conceptual design stage of an aircraft for its potential benefits in aerodynamic efficiency to be achieved. Implementation of technologies such as NLF are connected to drastic changes in sweep angle and possibly required High Lift Devices
3.2 Future Technologies

(HLD). These are design restraints that must be considered from the start of aircraft development. Thus chances of such a technology being implemented within an aircrafts design at later stages in its development or life are low. This is due to large-scale optimisation of the wing shape, systems layout and HLD design that is required for such technologies to be beneficial.

3.2.2 Active Load Alleviation

Active load alleviation (ALA) systems aim at improving the load distribution on a wing through active deflection of its control and flap surfaces in order to reduce wing structural weight [32]. The system would allow for the reduction of gust loads on the outboard sections of a wing thus reducing bending moments experienced inboard and allowing for wings with increased wing span and aspect ratio without increasing structural weight. Systems such as these have already been implemented into the Boeing 787 design (along with a number of other aircraft, including the A350XWB) by actively deflecting the ailerons during gusts and other manoeuvres [38].

ALA systems show great potential in reducing wing structural weight with little negative effects on other aircraft disciplines. NASA has proposed coupling both elevators and wing flaps with a load alleviation system in order to reduce gust loads by as much as 90% [39]. A study performed on the application of ALA on a Boeing 737-class airliner was performed at Stanford University [40]. The results showed that the reduction in loads experienced during gusts and manoeuvres allowed for a potential 25% reduction in wing weight while at the same time increasing wing span by 4.5 metres. The clear potential of ALA has led to it being involved in the current JTI clean sky project where further research into its fuel saving potential will be performed [36].

ALA is showing potential in reducing wing weight, but issues arise with certification of such systems, since assurance that the system will prevent structural failure from gust and maneuvre loads, without the additional structural strength, is still needed. ALA, similar to Laminar flow control, is a technology that must be implemented into an aircraft’s design early on for its fuel saving potential to be realized. Only once wing weight is reduced due to integration of an ALA system is the fuel consumption reduced. However, ALA can be retrofitted onto an existing aircraft design in order to reduce fatigue loads experienced by the wing. This in turn increases inspection intervals and reduces cost through the improvements in aircraft operation.

3.2.3 Advanced Composite Structure

A composite material consists of at least two different materials in the form of a fibre and matrix. The combination of the two materials usually leads to a greater strength-to-weight ratio than the standard all-metal structures. Examples of such materials finding wider use within aircraft structures are Carbon Fibre Reinforced Plastic (CFRP) and Glass Laminate Aluminium Reinforced Epoxy (GLARE). The use of composite materials in new aircraft structures has been steadily growing over the last couple decades. In the last decade the A380 has entered operation with its airframe comprising of 25% advanced materials, including CFRP and GLARE [41]. The A380 was the first commercial
aircraft to have its central wingbox made of carbon fibre, and the first major application of the material GLARE, used in the upper fuselage for its improved fatigue properties and stabilisers’ leading edges for its impact resistance.

More recently, the Boeing 787 has entered service as the first commercial mid-sized aircraft with composite primary structures [24]. The recently certified Airbus A350 is comprised of at least 50% composite materials [42]. With primary structures of a typical conventional configuration making up approximately 60-70% of the total airframe weight, and components made of composite materials saving around 20% weight, a total weight savings of approximately 15% could be made by switching to an all composite primary structure [43]. This possible weight savings makes composite primary structures an appealing prospect for fuel savings, despite their associated risks.

Composite materials not only have the benefit of weight reduction but in many cases have improved durability, damping characteristics, and the ability to form complex shapes when compared to metals. However, these benefits come with greater technical and monetary risks associated with development, certification, and repair of an all-composite primary structure.

The application of composite materials within an aircraft primary structure must obviously be decided in the conceptual stage of the design process. However, applications of composites to other non-primary components is possible at later stages of the aircraft development and life (depending on the component in question) and as such could be retrofitted onto an existing aircraft.

3.2.4 Advanced Engine technology

Of the improvements in aircraft performance made in the last few decades, a large part can be attributed to engines with greater fuel efficiency. The current jet engine architecture comprises of a single stage fan, a low-pressure compressor, and a high-pressure compressor powered by two or three directly linked turbines. A number of improvements on the current engine architecture have been achieved over the past decades, mainly from increases in engine bypass ratio, allowing for a 70% reduction in fuel consumption and 75% reduction in noise [32]. However, the greatest improvements in efficiency for the current architecture have already been achieved with the latest engines, and in order to achieve the emissions goals it may be necessary to make use of new engine architectures.

One of these new engine architectures under research is the Geared TurboFan (GTF). This architecture largely makes use of the existing turbofan architecture with a gearing system implemented in order to allow the fan and the low-pressure compressor to rotate at different speeds. This allows for the fan to increase in size, thus allowing for greater bypass ratios, while preventing the formation of shockwaves at the fan blades’ tips. This is achieved by allowing the compressor to operate at optimal rotational speeds while the fan rotates at a low rotational speed in order to keep the fan’s tip speed well below the speed of sound. This improved efficiency comes with a greater engine weight due to the presence of a gearbox, as well as the increased weight from increasing the fan diameter. However, this weight increase is reduced due to the fact that with a lower fan rotational speed the fan can contain fewer blades and the blades can have a lower weight. The gearbox, on the other end, allows the low-pressure compressor and the turbine to operate
at a higher rotational speed, which means fewer stages in the compressor and turbine are required for the same mass flow rating. This leads to further weight reductions.

An example of a recent GTF is the Pratt & Whitney 1100G, which has been claimed to achieved improvements in fuel efficiency of 15% over existing turbofan engines at the same mass flow rating [31]. Design decisions, similar to those just mentioned, have been made during the engine’s development to reduce any increase in engine weight from the increased mechanical complexity and engine diameter [31]. As to whether these design decisions has prevented any weight increase over its predecessor, the V2500, and if so, by how much, is yet to be confirmed. Airbus’ CEO has claimed that the PW1100G engine will lead to 20% lower maintenance costs for the engine compared with engines powering the A320 [45]. This is mainly due to the reduced number of compressor and turbine stages required. However, this claim is yet to be proven by airlines.

Another engine architecture under extensive research is the open rotor engine. This engine exhibits an unducted fan configuration where, as the name implies, the fan stage found in conventional turbofans is unducted and thus has an ultra-high bypass ratio. It is this ultra-high bypass ratio that allows for large improvements in engine performance to be achieved. Back in the late 70s, as a result of the oil crisis in the early 70s, NASA led an advanced turboprop (ATP) initiative with the goal of reducing fuel consumption by up to 50% [46]. As a result a GE36 open-rotor engine (see figure 3.2) was used to power an MD-80 and demonstrated a 30% reduction in fuel consumption while complying with noise and vibration requirements. In this design the unducted fans were counter-rotating in order to direct the flow closer to the direction of the free stream, thus increasing propulsive efficiency. However, due to McDonnel Douglas’ selection of the IAE V2500 for the MD-90 the prop fan concept was no longer commercially viable.

![Figure 3.2: GE36 open rotor concept](image)

The interest in open-rotor engines has been revived over the last years with Rolls-Royce stating that a 30% reduction in fuel consumption over the current turbofan design was possible [48]. However, these benefits come with technical challenges. One main challenge is the issue of noise, due to the fans being unducted [32]. The unducted nature of the fans also comes with the issue of having a larger diameter than conventional ducted fans. This leads to a heavier engine that requires greater spacing between the engine and airframe, leaving the rear of the fuselage being their only viable location. The addition of the unducted blades will also lead to issues with certification, with increased issues with vibration, maintenance, and blade containment regulations [32].
A study was performed by NASA into the performance and weight estimation for an open rotor engine and GTF engine [49]. The study showed that for a GTF with a thrust of 105kN 10-15% increase in fuel efficiency can be achieved. This improvement would come with an engine weight increase of approximately 5-10% compared to the current turbofan architecture. These values are confirmed by the PW1100G initial performance values [50]. For the open rotor engine a possible increase in fuel efficiency of 50% is achievable with an equal increase in engine weight [49].

Rolls-Royce demonstrated in the FP7 DREAM project the effectiveness of the open rotor concept and the possibility to minimise noise through scaled rig testing [51]. More recently both Rolls-Royce and Snecma are developing geared open rotor demonstrators under the Clean Sky’s Sustained and Green Engines (SAGE) project. Snecma’s SAGE 2 demonstrator is planned for delivery and ground testing by 2016 [52].

### 3.2.5 Wingtip Devices

A number of devices that are placed at the wingtips in order to improve the aerodynamic performance of an aircraft have been developed over the last decades. These include wingtip fences, blended winglets, raked wingtips and non-planar wingtip extensions. A wingtip device works to improve the aerodynamic efficiency of a wing by reducing the strength of the wingtip vortices. This reduces the induced drag of the wing and thus reduces fuel burn. A wingtip device can improve the performance of almost any wing, however, consideration into the increased bending moments placed on the wing with the implementation of a wingtip device is needed.

The wingtip device allows a wing’s aerodynamic performance to be improved while adhering to wingspan limits set for airport operations. Depending on the type of device, a retrofit of a wingtip device is possible, which provides aircraft manufacturers an attractive way to improve the performance of an existing aircraft without huge development costs.

The wingtip fence (see figure 3.3a) is the simplest to retrofit due to the minimal changes in wing bending moments, however, provides the least improvement in aircraft performance due to the interference drag that is formed by the sharp corner at the tip. Recently optimisation into the shape of a wingtip device have been performed and wingtip devices such as the blended winglet found on the Boeing 737 and the raked wingtip on the 787 dreamliner have been developed. It is claimed that the blended winglet found on the Boeing 737-800 provides a 3.0% to 3.5% improvement in fuel burn for a 980 nautical-mile mission [53]. The raked wingtip has also shown improvements in performance, an example being the Boeing 767-400 which showed an improvement of 5.5% reduction in induced drag [54]. Yet this reduced fuel burn comes with a larger wingspan and thus increased bending moments. This leaves retrofitting raked wingtips to aircraft with large structural reserves (i.e. large margins in structural strength to allow for increased bending loads).

A study performed by Elham [56] showed that for a Boeing 747 a reduction of 9-11% in induced drag during cruise is achievable by a winglet. For the D150 a reduction of 9-11% in induced drag in cruise conditions is equal to approximately 4-6% increase in maximum L/D. In the same study it was estimated that this increase in L/D would come with a 5-8% increase in wing weight, depending on the wingtip design. These numbers are similar to those for the Boeing 737-800 once winglets were implemented. The winglets
are claimed to improve total drag during cruise conditions by approximately 4-5% [57], which equates to around 4-6% improvement in lift-to-drag ratio (if lift from the wing is kept the same). The winglets are also claimed to add as little as 170kg to wing weight, and up to 235kg for the option to retrofit them onto existing 737 family aircraft [58]. This equates to approximately 3% weight increase for implementation at production and approximately 5% for a retrofit [59]. Thus from the results of both of these studies it can be assumed that for a retrofit the wing weight increases could be 5-8%, while the case that implementation occurs at production this increase goes down to 3-5%. The fuel reduction from winglets would reduce the fuel costs, however, any addition to the aircraft structural weight will affect landing fees, navigation fees, airframe maintenance cost, depreciation cost, insurance and interest costs. Thus when deciding on retrofitting a wingtip device these effects must be accounted for in order to assess its potential in reducing overall operating costs.

3.2.6 Drag Reducing Coatings

Manufacturers have been developing coatings that are retrofittable on aircraft designs in order to reduce skin friction drag. One example is laminar flow drag coatings, which aim at delaying laminar flow transitioning to turbulent flow. This is achieved by applying films that smooth out the skin of the aircraft and thus reduce the creation of small flow disturbances that lead to turbulent flows forming [60]. Coatings have also bee developed that aim to reduce the build up of occlusions (such as dead insects) on the aircraft skin, thus delaying transition to turbulent flow. It has been stated that a reduction of 20% in wing skin friction drag might be possible, leading to a reduction of 3-5% in total drag [60].

Another form of drag reducing coatings under development are turbulent-flow drag reducing coatings. These coatings aim at reducing the drag that occurs due to turbulent-flow over the aircraft’s skin. The best-known coating that performs this function are aerodynamic riblets [60]. These surfaces contain small grooves or protrusions aligned with the
local air flow, similar to the skin scales of sharks (see figure 3.4). The effect of these riblets on the turbulent boundary layer can reduce the skin friction drag. Studies into the effects of riblets indicate that with optimal sizing and spacing the savings in skin friction drag can reach 7-8\% [61]. Issues with these coatings include surface contamination, as well as insufficient ultraviolet radiation stability of adhesive films, which both require increased airframe maintenance to counter these issues. Misalignment of the riblets with the local airflow can also reduce the riblets effectiveness. Thus high-accuracy design of the coatings is required.

![Figure 3.4: Model of shark skin scales with small grooves](image)

3.2.7 Flight Control Systems

In recent decades flight control systems (FCS) have become lighter, safer, and more reliable since the aviation sector has embraced fly-by-wire (FBW) control systems. In a FBW system the movement of the flight controls are converted to electronic signals and transmitted to the appropriate actuators (e.g. the actuator to an aileron) by wire. Thus the traditional system with hydraulics run by manual flight controls is reduced in weight and the level of safety is increased. FBW also allows the natural stability of an aircraft to be relaxed as the FBW system’s response to any change in aircraft attitude will be much quicker than that of a pilot with manual flight controls.

Fly-by-wire has been steadily introduced into new aircraft designs, however a FCS that is yet to be applied to commercial passenger aircraft is a Wireless Flight Control System (WFCS). This would entail the same principle of a FBW system but with the electronic signals transmitted to the control surfaces wirelessly. This would ultimately reduce the FCS weight, size and cost as the required wiring is reduced. In 1997 NASA performed ground-based feasibility tests for a novel WFCS for the F-18 Iron Bird at the Dryden Flight Research Centre [62]. The tests had demonstrated that a wireless control system is feasible and provided data to develop a closed-loop WFCS. This system could be a redundancy system, acting as back-up to the current wired systems, or replace the wire system entirely. The main issue with this system is the possibility of radio-frequency
interference effecting the flight controls, as well as the security risks that come with the possibility for people to assess the wireless system and control the aircraft remotely.

In a recent study it was shown that by applying a WFCS to a Cessna 310R 90 lbs could be saved from the control systems [63]. This translates to a 15-20% reduction in the entire systems weight.

### 3.2.8 Lightweight Cabin Interiors

Cabin interiors make up a large part of the fuselage mass and reductions in weight in this area would be beneficial for future as well as existing aircraft. An example of a technology that provide savings in cabin and interior weight is the replacement of the current fibreglass sidewall and ceiling panels with carbon fibre panels. Savings of 40% in leather seat covers by using lightweight materials and savings of 15% in sidewall weight by using ductile polyetherimide based plastics are just two of the many ways weight savings in interiors can be made [32].

High strength Glass Microspheres (i.e. microscopic spheres of high strength glass) when incorporated into optimised plastic resins and rubber compounds can lead to: reduced mass, reduced resin consumption, improved dimensional stability of a part, reduced warpage and differential shrinkage [32].

If 11.5% of the volume of interior plastics is made up of glass microspheres, part weight can be reduced by as much as 10% [32]. For a Boeing 777, 5000kg of its weight is comprised of phenolic resins, resulting in a possible weight savings of 500kg. This correlates to approximately 1-2% savings in fuselage weight (i.e. structural and furnishings weight combined) These microspheres can also be utilised in rubber compounds to reduce weight further.

A key benefit of these technologies is that cabin interiors are constantly being updated throughout an aircrafts service life. Thus implementation of these technologies, be it early in development or later during service, is possible.

### 3.2.9 Overview of Technology Investigation

From analysing these technologies it becomes clear that technologies on a basic level affect (in most cases both positively and negatively) one to three analysis results. For example, a natural laminar flow wing will provide improved lift-to-drag ratio at an increased wing weight, and GTF engines provide improved engine performance but with a possible increase in engine weight depending on the final design. Therefore a small set of basic parameters can be used to mimic the affects of a wide range of technologies (such as those mentioned in the previous sections). These parameters are:

- Lift-to-Drag ratio
- Zero-lift drag
- Fuselage mass
In the tables 3.1 and 3.2 these analysis parameters and how they are effected by both retrofittable and non-retrofittable technologies are outlined. In this table fuselage mass includes both structural and furnishings masses. Therefore for the technologies effecting these parameters the corresponding effects are calculated for the entire fuselage weight (i.e. structural and furnishings weight combined). For example, for the advanced composite fuselage structure the possible 15-20% reduction in fuselage structural weight translates to approximately 10-15% in the total fuselage weight. The same is done for the lightweight cabin technology.

Table 3.1: Retrofittable technologies and their effect on analysis parameters

<table>
<thead>
<tr>
<th>Technology</th>
<th>Parameter</th>
<th>Adjustment [%]</th>
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<tbody>
<tr>
<td>Geared Turbofan [49]</td>
<td>Engine mass</td>
<td>+[5-10]</td>
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<td></td>
<td>SFC</td>
<td>-[10-15]</td>
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<tr>
<td>Winglet (retrofit) [56, 57]</td>
<td>Lift-to-Drag ratio</td>
<td>+[4-6]</td>
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<tr>
<td></td>
<td>Wing mass</td>
<td>+[5-8]</td>
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<tr>
<td>Winglet (in-production) [56, 57]</td>
<td>Lift-to-Drag ratio</td>
<td>+[4-6]</td>
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<tr>
<td></td>
<td>Wing mass</td>
<td>+[3-5]</td>
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<tr>
<td>Drag Reducing Coatings [60]</td>
<td>Zero-lift Drag</td>
<td>-[3-5]</td>
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<tr>
<td>Lightweight Cabin Interiors [32]</td>
<td>Fuselage mass</td>
<td>-[1-2]</td>
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Table 3.2: Non-retrofittable technologies and their effect on analysis parameters

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<tr>
<th>Technology</th>
<th>Parameter</th>
<th>Adjustment [%]</th>
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<tr>
<td>Natural Laminar Flow [33]</td>
<td>Lift-to-Drag ratio</td>
<td>+[20-30]</td>
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<td></td>
<td>Wing mass</td>
<td>+[20-25]</td>
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<td>Active Load Alleviation [40]</td>
<td>Wing mass</td>
<td>-[20-25]</td>
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<tr>
<td>Wing Composite Structure [43]</td>
<td>Wing mass</td>
<td>-[15-20]</td>
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<tr>
<td>Open Rotor Engine [49]</td>
<td>Engine mass</td>
<td>+[40-50]</td>
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<td></td>
<td>SFC</td>
<td>-[40-50]</td>
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The studies presented in tables 3.1 and 3.2 provide the estimations on the changes in parameters that they cause. However, its important to be critical with these estimations and to be aware of the uncertainties that arise from using these results. A number of
assumptions have been made in order to achieve these results in their respective studies. It would be out of the scope of this report to mention each of these limitations and assumptions made but it must be noted that these results only provide an indication of the potential of the technologies investigated. Hence each estimation is provided as a range of values in order to allow a tolerance for uncertainties in results. These uncertainties increase as the respective change in parameters increases. This is due to the fact that any effect of an assumption on results is accentuated as the effect on these parameters is greater.

Not only are the results obtained from the studies themselves uncertain but further uncertainties are created by assuming these values are representative for a mid-range conventional passenger aircraft over its entire mission. What is meant by this is that each value in tables 3.1 and 3.2 is assumed it can be applied to the A320-like reference aircraft and kept constant over its entire mission, when in many cases the estimation was made on an aircraft with differences to the A320 and at one specific flight condition, when conditions vary over the mission. For example, it isn’t possible to fix one value to the drag reducing potential of a winglet as it varies for each flight condition experienced over the mission. Also the fact that it is for a 747 aircraft, which is a larger long-range aircraft, could lead to further uncertainties to the validity of this value for an A320-like aircraft.

The values for the NLF technology were obtained from a 36 year old study on an aircraft with a 30% higher passenger capacity and 13% longer range. This study has been the most extensive to date that results for are available, making it the best option in providing representative values. More urgent studies are being performed, such as the JTI clean sky project [36], but results aren’t available for this study. The difference in aircraft can also cause uncertainties in the values stated in tables 3.1 and 3.1. The values for the WFCS were obtained from its application on a Cessna 310R, and the values for the lightweight cabin interiors from combining test results for lightweight plastics and the level of plastics in a B777 to find a percentage of fuselage weight.

The engine study was performed on a 105kN engine, similar to that on a D150, however, the study had shown that the savings from a GTF or open rotor engine varies for different flight conditions. Thus setting a fixed value for the entire mission adds additional uncertainties to the given values.

It can be seen that these studies aren’t ideal in providing accurate results on the performance enhancements from the technologies on an A320-like aircraft. Some studies are more applicable than others, such as the engines and ALA studies, both performed on engines and aircraft similar to the reference configuration in this study. However, an accurate estimation on the fuel saving potential of these technologies once applied on the D150 model is not the purpose of this study. As mentioned in chapter 1, the purpose of this study is twofold: firstly to provide an insight into the potential incorporating these technologies on a conventional aircraft configuration. Secondly, to develop a methodology in which it is possible to observe the interactions between disciplines in the conceptual design stage and possible to build upon with higher-fidelity disciplinary modules. These higher-fidelity analyses will ultimately allow for the more detailed investigation into these technologies and their implication on other aspects of the aircraft, thus allowing for the verification of the results obtained in this study.
Chapter 4

Design Workflow Development

The fifth thesis sub-objective in section 1.1 states that a method must be developed for designing/analysing a mid-range passenger conventional aircraft in terms of fuel consumption and operating cost in a collaborative design environment. To achieve this objective a analysis workflow is developed. In the previous chapter the integration tools and methods available for collaborative design, such as RCE and CPACS, were introduced. Using these tools along with a collection of analysis and design tools available on distributed DLR servers an analysis workflow with the capability of designing and analysing a conventional aircraft configuration is developed.

A multi-fidelity fixed-point iteration approach is adopted in the construction of the analysis workflow and is discussed in section 4.1 along with an outline of the tools used for each discipline. Finally in order to test whether the developed workflow is providing adequate results it needs to be validated by the chosen reference aircraft, the D150, an A320-like aircraft. An overview of D150 design parameters along with a comparison of the workflow results to A320 data is given in section 4.2.

4.1 The Analysis Workflow

The analysis workflow should allow for a complete configuration to be generated in CPACS along with a mass-breakdown and estimated operating costs. With this goal in mind an analysis chain of interconnected tools is established. With the required inputs and available outputs of each analysis tool the N2-chart aids in logically ordering the analysis chain. The N2-chart for the analysis chain of this project is shown in figure 4.1. The analysis chain comprises of multiple analysis modules which are performed by specific tools. For an overview of these tools as well as the reasoning behind their selection, the reader is referred to chapter 5.
### Figure 4.1: N2 chart for analysis workflow

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<td>Zero-lift drag Estimation</td>
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<td>Primary Wing Mass Estimation</td>
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<td>Secondary Wing Mass Estimation</td>
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<td>Engine Analysis</td>
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<td>Engine Performance Map</td>
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<td>Mission Analysis</td>
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<tr>
<td>Thrust Scaling</td>
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<td>Aircraft Synthesis Mass Breakdown</td>
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<td>A/C Cost Analysis</td>
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<tr>
<td>CPACS Output</td>
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</tbody>
</table>

L0 Initialization | L0 + L1 Multi-fidelity Analysis | L0 Aircraft Synthesis and Cost
4.1 The Analysis Workflow

As can be seen in figure 4.1 a multi-fidelity fixed-point iteration approach was adopted. This approach has been demonstrated in previous studies [8]. Within this approach low-level tools will perform the initialisation of the aircraft configuration while higher-level physics-based tools will perform analyses on the aircraft configuration. In order to understand this concept of levels in analysis and design tools the table 4.1 describes the different levels of classification of tools that exist.

Table 4.1: Tool level classification [1]

<table>
<thead>
<tr>
<th>Level</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>Consisting of typical conceptual OAD approaches, based on empirical relations and existing databases</td>
</tr>
<tr>
<td>1</td>
<td>Disciplinary analysis based on simplification on the modeling, and on the representation of the physics phenomena, mainly accounting for linear effects</td>
</tr>
<tr>
<td>2</td>
<td>Accurate modeling of the aircraft components, accounting for a higher level of details, and physics representation accounting for non-linear phenomena</td>
</tr>
<tr>
<td>3</td>
<td>Highest-fidelity physical simulations, mainly dedicated to non-linear local effects, and whose disciplinary models cannot be fully automated, as required for extensive MDAO applications</td>
</tr>
</tbody>
</table>

A low-level physics-based toolkit has been developed at DLR involving tools at different levels of fidelity and ranging all disciplines of aircraft design. In the low-level toolkit tools in both levels 0 (L0) and level 1 (L1) are available.

As seen in figure 4.1 L0 empirical-based tools perform the initialisation of the aircraft configuration. A tool that could initialize the design processes was needed in order to provide the inputs required for higher-fidelity analyses further down the design chain. In this stage of the workflow the aircraft geometry is initialized in CPACS-format and an initial estimation for the mass-breakdown is given as well as various performance indices. As input a CPACS file is given, providing the top-level aircraft requirements, design parameters and choice of engines available in the TWDat database. The required top-level requirements are:

- Design range
- Cruise altitude
- Cruise mach Number
- Number of passengers
- Cargo mass
- Wing planform parameters and position
• Htp and Vtp planform parameters
• Engine selection

At DLR a conceptual design module based on handbook methods, named VAMPzero (see section 5.1.1), was developed in order to perform this task. The initialisation of the workflow will also be performed by the cabin design tool FuCD. During this initialisation phase L0 tools are utilised for fast initialisation of the aircraft design. The initialisation phase passes the aircraft geometry and mass-breakdown to all the higher-fidelity tools in the multi-fidelity phase.

After the L0 initialisation stage comes the multi-fidelity analysis segment in which L0 and L1 physics-based tools are combined to perform higher-fidelity analysis on the initial aircraft design. The aim of this higher-fidelity analysis is to calculate an improved wing and block fuel mass. This segment is comprised of four components:

• Aerodynamic analysis
• Wing structural mass estimation
• Propulsion analysis
• Mission analysis

In order to determine the fuel mass from the mission analysis, aerodynamic performance data for the aircraft is required for all flight conditions throughout the prescribed mission. Similarly to determine the wing structural mass, a lift distribution on the wing for the critical load case is needed. Therefore, the first required step in the multi-fidelity segment is to generate the load case for the wing weight estimation. For this task the LCGplus tool is used. Then the aerodynamic analysis is performed with the L1 tool, Tornado. The tool is executed twice, once for each of the two tasks of the aerodynamic analysis just mentioned. Continuing down the workflow the wing mass estimation is performed using the load distribution estimated by Tornado. For the wing mass estimation the primary structural masses are computed with the help of the L1 Aeroelastic tool AAE. The secondary masses are computed by the L0 tool PESTsewi to assemble the complete mass of the main wing.

For the mission analysis segment of the workflow the engine performance and aerodynamic performance maps of the complete aircraft are needed. Since the aerodynamic performance data given by Tornado only includes the induced drag, the zero-lift drag coefficient must be computed. The L0 tool VRAero, performs this task, and combines the computed zero-lift drag coefficient with the existing aerodynamic performance maps generated by Tornado. The engine performance maps are extracted from the TWDat engine database for the selected engine. These performance maps along with the aircraft mass-breakdown from the initialisation phase are then fed into the L1 tool FSMS for a mission analysis, in which an updated mission block fuel mass and required take-off thrust is estimated.

The final phase in the analysis workflow is the aircraft synthesis. In this stage the L0 tool, VAMPzero, re-calculates the mass-breakdown with the physics-based values for the
4.2 Design Workflow Validation

block fuel mass and wing mass fixed as constants. Since many of these disciplinary
tools are mutually dependent, a procedure is required that coordinates how information
is exchanged between them, and assures that coherence in the disciplines is achieved.
Therefore, at this point in the analysis chain a fixed-point iteration procedure is adopted.
In this procedure the updated mass-breakdown provided as output by the multi-fidelity
analysis phase is fed back into it and the procedure is repeated until convergence in the
global masses is achieved. The convergence criteria was set for this analysis as:

\[
\left| \frac{OEM_{i-1} - OEM_i}{OEM_i} \right| \leq 0.01 \land \left| \frac{MTOM_{i-1} - MTOM_i}{MTOM_i} \right| \leq 0.01
\] (4.1)

With this process the results from the physics-based analyses enhance the low-fidelity
results from the initialisation phase. Once convergence in the global masses is achieved
the mass-breakdown, along with other aircraft performance and geometry data, is passed
onto the cost analysis tool. This analysis is performed by the L0 cost module of the
Initiator design tool. The complete aircraft configuration along with mass-breakdown
and operating costs are provided as output.

From this procedure, presented in the N2-chart in figure 4.1, a workflow of the chosen
analysis tools is constructed. This workflow is outlined in the flow diagram shown in
figure 4.2.

As can be observed in figure 4.2 the wing mass estimation and mission analysis are
performed simultaneously. The decision to have the mission analysis and wing sizing run
simultaneously is made in order to reduce computation time. Since both these analyses
involved physics-based methods, the run times of the tools are relatively high. Thus by
running them in parallel the computation time is reduced. The issue with using this
method is that when the wing mass is estimated by the physics-based tools at least two
convergence cycles are required in the fixed-point iteration cycle in order to obtain a valid
result. The reason behind this is that any changes in wing mass compared to the initial
estimation by VAMPzero isn’t captured in the mission analysis until the following analysis
loop.

The workflow as was implemented in RCE can be seen in figure 4.3. For further in-
formation on the purpose of some of the additional tools seen in figure 4.3 and on the
integration process in general, along with the validation of certain tools, the reader is
referred to appendix C.

4.2 Design Workflow Validation

In order to check whether the analysis workflow is giving accurate results a test-case
was chosen in order to validate it. For this study the D150 model was used as reference
aircraft, which is an A320-like aircraft (see figure 4.4). The design parameters of the D150
are given in table 4.2. The standard mission profile used for analyzing the D150 is given
in figure 4.5.
Figure 4.2: Flow chart of the analysis workflow

Choice of Critical Loadcase for Estimation of Primary Wing Mass

For this study the wing’s primary structural weight is computed using only one critical load case. This decision was made for two reasons. Firstly, the computation of the
primary structural weight using the AAE tool takes a decent amount of time due to the physics-based nature of the tool’s analysis. Reducing the number of load cases requires less computation time which reduced the computational time for one sample points analysis considerably. Secondly, the tool available for use in this analysis was an earlier version of the AAE tool, and due to a number of issues existing in this version, analysis of multiple load cases was not possible within the projects timeframe. Thus a critical load case had to be determined through analysis.
Table 4.2: Design parameters for the D150

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Tool</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Design range</td>
<td>3704</td>
<td>km</td>
</tr>
<tr>
<td>Cruise altitude</td>
<td>12000</td>
<td>m</td>
</tr>
<tr>
<td>Cruise Mach number</td>
<td>0.78</td>
<td></td>
</tr>
<tr>
<td>Wing area</td>
<td>122.4</td>
<td>m²</td>
</tr>
<tr>
<td>Aspect ratio</td>
<td>9.396</td>
<td></td>
</tr>
<tr>
<td>Taper ratio</td>
<td>0.24</td>
<td></td>
</tr>
<tr>
<td>Sweep angle</td>
<td>25</td>
<td>deg</td>
</tr>
<tr>
<td>Nr. of engines</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>Nr. of pax (2 class)</td>
<td>150</td>
<td></td>
</tr>
<tr>
<td>Cargo mass</td>
<td>5000</td>
<td>kg</td>
</tr>
</tbody>
</table>

In order to decide on a critical loadcase a selected number of loadcases were generated using the loadcase generation tool LCGplus. From this tool six loadcases were generated, an overview of these loadcases can be found in table 4.3.

All loadcases were at cruising altitude and without flaps extended. The fuel was set at a level such that with maximum payload the mass is equal to MTOM. The fuel was distributed such that the least amount of fuel is in the outboard tanks, thus reducing the relief on bending loads from the fuel. In order to obtain wing masses for the specified load case definitions the workflow shown in figure 4.2 is used without performing secondary wing mass estimation, the mission analysis and aircraft synthesis. With this method only the primary wing masses are computed. It was determined that load case 5 was the critical load case as it produced the highest primary wing mass. This makes sense since load case 5 is the highest speed and load factor out of all the load cases.
### Table 4.3: Overview loadcases generated by LCGplus

<table>
<thead>
<tr>
<th>Loadcase</th>
<th>Speed</th>
<th>Load factor</th>
<th>Mass</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Stall</td>
<td>1</td>
<td>MTOM (maximum payload)</td>
</tr>
<tr>
<td>2</td>
<td>Stall</td>
<td>-1</td>
<td>MTOM (maximum payload)</td>
</tr>
<tr>
<td>3</td>
<td>Maneuver</td>
<td>2.5</td>
<td>MTOM (maximum payload)</td>
</tr>
<tr>
<td>4</td>
<td>Cruise</td>
<td>-1</td>
<td>MTOM (maximum payload)</td>
</tr>
<tr>
<td>5</td>
<td>Dive</td>
<td>2.5</td>
<td>MTOM (maximum payload)</td>
</tr>
<tr>
<td>6</td>
<td>Dive</td>
<td>0</td>
<td>MTOM (maximum payload)</td>
</tr>
</tbody>
</table>

### Results

Thus by running the analysis workflow described in previous sections with the design parameters given in table 4.2 the results as shown in table 4.4 were produced. Table 4.4 also contains original A320 data for comparison.

As can be observed from table 4.4 the workflow results are all within 3% of the A320 data. This indicates that the analysis workflow is reliable enough to perform the technology factors study (see section 5.8) on the D150 reference aircraft.

### Table 4.4: D150 workflow results compared to A320 data [64]

<table>
<thead>
<tr>
<th>Parameter</th>
<th>A320 [kg] [64]</th>
<th>D150 [kg]</th>
<th>Difference [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>MTOM</td>
<td>73500</td>
<td>73465</td>
<td>-0.05</td>
</tr>
<tr>
<td>OEM</td>
<td>40023</td>
<td>40324</td>
<td>+0.75</td>
</tr>
<tr>
<td>Wing mass</td>
<td>8801</td>
<td>8865</td>
<td>+0.72</td>
</tr>
<tr>
<td>Block fuel</td>
<td>-</td>
<td>13891</td>
<td>-</td>
</tr>
</tbody>
</table>
In chapter 4 the analysis workflow was presented. Within the analysis workflow a number of tools were used in order to design and analyse a conventional aircraft configuration from top-level requirements. In this chapter descriptions of the these tools and justifications for the choice of using these tools for each relevant discipline are given. In section 5.1 the tools used in the initialisation are covered and in section 5.2 the aerodynamic analysis tools will be outlined. In section 5.3 the structural sizing tools are described. Then in sections 5.5 and 5.6 the propulsion and mission analysis are covered. In section 5.7 the cost analysis tool is outlined. Finally in section 5.8 the developed adjustment modules as mentioned in section 1.2 will be shown.

5.1 Initialisation

During the initialisation stage the initial estimations for the overall aircraft geometry, mass-breakdown, engine performance, and aircraft performance is to be obtained through empirical-based methods or available databases. The main tool available to perform these estimations is the VAMPzero conceptual design tool. Other empirical-based or database method tools such as the FuCD cabin design tool and TWDat engine performance database tool are also utilised in this stage of the aircraft design and analysis process. These tools will be discussed in the subsequent sections.

5.1.1 VAMPzero

VAMPzero is a level 0 conceptual design tool for aircraft, based upon well known handbook methods. VAMPzero designs new configurations including outer geometry as well as structures, engines, and systems. It also performs a mission analysis and cost estimation, all from top level requirements and certain design parameters. The tool is written in python, which is easy to use and is based on an object oriented structure, thus leading to a highly flexible tool. VAMPzero accepts an CPACS based XML-file as input.
in which the top level requirements are given and provides an output CPACS file with the aircraft geometry along with the aircraft’s mass-breakdown and other performance outputs.

VAMPzero was chosen for the initialisation phase of the multi-fidelity workflow shown in figure 4.2 as it had been purpose built to close the gap between top-level requirements and preliminary design [8]. It is also the ability of VAMPzero to provide the outputted aircraft definition in CPACS format that makes it an advantageous choice in providing the initial aircraft configuration details required for the subsequent physics-based analyses.

It is the tools robustness that made it a good choice for the aircraft synthesis stage shown in figure 4.2. The tool can accept any given value as a fixed parameter and will attempt to design an aircraft based on the provided values. However, there are limitations to the minimum number of inputs and the ranges of values given for convergence in the tool to be achieved. It is this function that will be used to fix the values determined from low-fidelity physics-based analyses in the mass-breakdown synthesis.

Within the developed analysis workflow VAMPzero played two main roles:

- Provide an aircraft geometry in CPACS-format with top level requirements and design variables given as inputs.
- Analyse the aircraft configuration for OEM mass-breakdown and performance parameters including fuel mass for a specified mission.

The VAMPzero process is a black-box to the user. Therefore to help clarify the role that VAMPzero played in the developed analysis workflow the flow chart in figure 5.1 is provided in order to illustrate the inputs required for convergence and the provided outputs for a typical tool execution.

5.1.2 FuCD

VAMPzero provides an initial estimation of the fuselage weight from statistics, however, a tool that provides a more accurate and detailed breakdown of the fuselage masses and layout has been developed at DLR. The Fuselage and Cabin Design tool (FuCD) was developed in order to estimate fuselage weights and cabin layout. This tool was developed from using hand book methods and by analysing a multitude of existing aircraft configurations, including complete cabin layouts [63]. The tool is able to produce detailed mass-breakdowns of the fuselage structural weight and operator items. The tool provides an improved estimation of the fuselage outer dimensions in comparison to those provided by VAMPzero by determining the required layout of seats and galley equipment for the payload and mission requirements. Therefore FuCD was implemented into the analysis workflow in order to provide this improved estimation of the fuselage structural weight and dimensions as well as the operator items weight. In order perform this task the tool requires a number of inputs:

- Number of passengers
5.2 Aerodynamic Analysis

Within the analysis workflow the aerodynamic analysis is a crucial aspect of the overall aircraft performance. The aerodynamic analysis performs two main functions:

- Produce aerodynamic performance maps containing lift and drag coefficients for varying values of Reynolds number, angle of attack, and Mach number. These maps will be utilised in the mission analysis.
- Determine the aerodynamic wing loading for structural analysis purposes.

VAMPzero performs an aerodynamic analysis at cruise condition using handbook equations, however, for this analysis it is desired to implement physics-based higher-fidelity analyses. This allows for improved accuracy in the derived aerodynamic parameters and allows for the aerodynamic polars to be generated for multiple flight conditions.

The total drag of an aircraft is comprised of three main components, as shown in the following equation:

\[
C_D = C_{D_0} + C_{D_{\text{induced}}} + C_{D_{\text{wave}}}
\]  

(5.1)
As observed in equation 5.1, the total aircraft drag is comprised of the zero-lift drag $C_{D_0}$ (formed from viscous effects), the induced drag $C_{D_{induced}}$ and the wave drag $C_{D_{wave}}$ caused by the formation of shock waves in transonic flow. To compute the zero-lift drag and wave drag, a level 0 tool has been developed as discussed in section 5.2.2. To compute the induced drag in the conceptual design stage, an algorithm that produces accurate predictions of the aerodynamic forces with relatively small computational effort was needed.

There are different levels in the hierarchical order of flow analysis models. The flow solvers with the highest level of fidelity in computational fluid dynamics are ones based on the Reynolds-averaged Navier-Stokes equations (RANS). There are simplifications leading to Euler codes and Full potential solvers, with the simplest solvers adopting the linear potential method. The linear potential solvers are the least accurate while neglecting the rotational, viscous and non-linear terms of the Navier-Stokes equations. However, this reduced accuracy comes with reduced computational expense. For this project, the aerodynamic analysis is performed on a conventional set of lifting surfaces. With this task, the linearized potential flow provides sufficient accuracy to capture the physical properties of the flow over the lifting surfaces but with minimal computational time. As mentioned in section 2.3.1 in order to use the developed analysis workflow to demonstrate the visualisation tool, a DOE of 150 sample point will be required. The minimised time by making use of a linearized potential solver is key when such a large amount of full simulation evaluations, including physics-based analyses, is required. Not only will 150 runs of the solver be required, but possibly 3 times that amount since for each DOE sample point a number of convergence loops will be required in the fixed-iteration process shown in figure 4.2. Table 5.1 illustrates the potential savings in time obtained when adopting a linearized potential solver.

<table>
<thead>
<tr>
<th>Method</th>
<th>Computational time</th>
</tr>
</thead>
<tbody>
<tr>
<td>Linear Potential solver</td>
<td>5 sec - 15 min</td>
</tr>
<tr>
<td>Full Potential solver</td>
<td>5 min - 1 hr</td>
</tr>
<tr>
<td>Euler solver</td>
<td>1 - 15 hr</td>
</tr>
<tr>
<td>RANS solver</td>
<td>Multiple days</td>
</tr>
</tbody>
</table>

5.2.1 Tornado Vortex lattice method

One method for solving the linearised potential flow equations is the vortex lattice method (VLM). In this numerical approach, the lifting surface of a finite length wing is subdivided into a finite number of panels spread over the entire surface spanwise as well as chordwise with a horseshoe vortices superimposed on each panel. Several VLM solvers exist including the Athena Vortex Lattice tool (AVL). However, for this thesis, the open-source Tornado vortex lattice tool was utilised. The decision to use Tornado is the fact that in previous projects Tornado has been connected to CPACS and implemented into RCE as well as being tested in multiple DLR projects.
The panel geometry produced by Tornado can be observed in figure 5.2. The aerodynamic analysis tool Tornado is a level 1 tool, written in Matlab. The tool wrapper developed for Tornado extracts the geometrical properties of the lifting surfaces (i.e. the main wing and empennage) and provides them to Tornado in the required format. The Tornado tool is then executed and provides the force coefficients of the aircraft in all three directions.

In order to compute the aerodynamic loads for all flight conditions of the prescribed mission Tornado is executed a number of times in order to build a performance map. A set of prescribed Mach numbers, Reynolds numbers and angles of attack at which the aerodynamic loads are needed are provided as input to the tool. In order to reduce the computational load further, only a few angles of attack are analysed using Tornado for each combination of set Mach number and Reynolds number in the performance map. The aerodynamic properties are computed for the highest and lowest values of the prescribed set of angles of attack along with a value in between these two. The aerodynamic properties are then computed for all angles of attack within the set range of values by interpolating the drag polar from the three analysed flight conditions with a quadratic trend. For example, assume that \([0,0.5,0.8], [1\cdot10^7,5\cdot10^7,7\cdot10^7], \text{ and } [-2,0,2,4,6,8,10,12]\) are the prescribed sets of Mach numbers, Reynolds numbers, and angles of attack respectively. The first combination of Mach and Reynolds numbers would be 0 and 1\cdot10^7. The aerodynamic loads would then be computed with these Mach and Reynolds numbers at angles of attack of -2°, 6°, and 12°. The aerodynamic loads of the remaining angles of attack would then be computed by interpolating the results of these three flight conditions. This interpolation process is illustrated in figure 5.3. This process is then repeated for all 27 combinations of Mach and Reynolds numbers from the prescribed sets for this example.

Using this method the tool is able to determine the aerodynamic loads for all combinations of Mach number, Reynolds number and angle of attack with minimal computational effort. In the example presented only 81 executions of Tornado would be required instead of 2.8\cdot10^{11} (i.e. 3\cdot8). These sets of discrete points in the aerodynamic performance map could then be used in the mission analysis for interpolation purposes. The tool wrapper then goes on to computing the wing load distribution for a given load case, which is needed for later wing mass estimations.

### 5.2.2 Viscous Drag

The results from the Tornado analysis provide the induced drag components for the lifting surfaces, however, the other two drag components shown in equation 5.1 must be computed for an accurate aerodynamic performance map. The viscous drag components can be computed using the class II equations set out by Raymer. These methods have been implemented into a tool called VRaero at DLR which computes the zero-lift drag coefficients to be added to the inviscid drag coefficients computed from Tornado. These zero-lift drag coefficients are computed for the wing, empennage, fuselage, and engines, and then summed up for the overall aircraft drag.
5.2.3 LCGplus

In order to determine the load distribution on the wing for the wing mass estimation a critical load case definition is needed. The load case definitions were generated by the Load Case Generator LCGplus [69]. This tool develops load case definitions using the European Aviation Safety Agency (EASA) certification specifications for large aircraft, i.e. CS-25. The tool generates the flight conditions, lift coefficient during the manoeuvre, mass definitions, and configuration settings for a number of cases. It also sets the distribution of fuel in the available fuel tanks.
5.3 Structural Analysis

For the structural analysis a method for determining the wing structural mass from the aerodynamic load distribution, which was computed in the aerodynamic analysis, is needed. The wing structural mass is divided into two components, namely the primary and secondary masses. To compute the primary masses a method by which the stresses in the wing, occurring due to the applied aerodynamic loads, are computed. The wing is then sized in such a way as to withstand these stresses. Thus to compute the primary masses a physics-based tool is required.

The aircraft performance is sensitive to the aircraft weight. A reduction in weight for a fixed aerodynamic performance can improve the fuel consumption and range of an aircraft. Thus an accurate prediction of the wing weight is crucial for a reliable multidisciplinary design/analysis workflow.

A number of methods with varying levels of fidelity are available to determine the wing primary masses. The highest-fidelity method is the Class III method, which involves the Finite Element Method (FEM) to calculate the weight of the aircraft primary structure. For the current study the FEM will be utilised in order to capture and accurately the structural trends of a configuration, thus effectively capturing changes in the design of the aircraft and analysis results. However, the method requires a reliable load set, increased computational budget, and a detailed geometry model of the aircraft structure, including structural details, such as cross-sectional shapes of spars, ribs and skins [70]. To reduce computational time a simplified FEM model will be applied, in which the wings are modeled as equivalent cantilever beams.

5.3.1 Aeroelastic Engine

The Aeroelastic Engine (AAE) is an aeroelastic Finite Element (FE) level 1 solver that takes into account flexibility effects [71]. The AAE tool requires the wing geometry and aerodynamic loads computed using the aerodynamic analysis tool for a given load case as input. A geometrical preprocessor extracts the structural information from the CPACS input file and generates a stick model representation of the aircraft. The solver first passes the stick geometry and loads through a static structural sizing FE tool. Coupling schemas then map the aerodynamic loads onto the produced structural mesh which is then passed through the aeroelastic engine where flexibility effects are applied. The computed deformations of a D150 model stick model can be observed in figure 5.4. The tool finally provides the primary structural weight.

This tool was chosen for estimating the primary wing mass since it has been tested and proven in numerous DLR projects to provide results with sufficient accuracy for this project at a reduced computation time when compared to more advanced FEM solvers [71] [73] [72]. That added onto the work that has already gone into connecting it to CPACS and implementing it into RCE made this a good choice for the primary wing mass estimation tool for the analysis workflow.
5.4 Secondary Structure

The AAE tool will perform an FE analysis to estimate the wing’s primary structural weights, however, another method will be applied for the secondary masses. In the past, at DLR, secondary masses were computed using a fixed ratio of the primary structural mass. This method didn’t provide the most accurate results as the ratio of secondary weight to primary weight for different aircraft types varies widely. Thus a tool called PESTsewi was developed that computed the secondary masses through the application of empirical relations. The tool has been used in prior DLR projects [1, 11] and has proven to provide improved results compared to the fixed ratio approach, as the weights adjust for varying aircraft layouts.

5.5 TWDat

In order to perform the mission analysis in figure 4.2 the performance map of the selected engine is required. The performance of the engines required to perform the desired mission is estimated for cruise conditions by VAMPzero. However, in order to perform a mission analysis the engine performance at a range of flight conditions is needed. For this purpose the TWDat engine performance database tool is utilised. Through this tool the performance data for a number of existing engines is available. The database includes performance indices including thrust, Specific Fuel Consumption (SFC) and emissions and can provide these indices for all flight conditions that the aircraft is expected to fly. This database was created using thermodynamic analyses for varying operating conditions. A number of the engines are ‘scalable’ in which performance data can be adjusted according to a thrust scaling factor within narrow bounds. This scaling factor specifies the ratio
between the maximum required thrust (determined by VAMPzero in the first iteration loop and the mission analysis thereafter) and the maximum thrust of existing engine in the database.

Thus by specifying the name of engine that the performance data is required for and the corresponding scaling factor the following outputs are provided:

- Thrust, SFC, and emission data for a number of flight conditions with varying Mach number and altitude.
- Engine geometry according to thrust scaling factor.

This performance index data for different flight conditions throughout the flight envelope are called the *engine performance maps*. With the scaling factor the thrust, SFC, emission data, and geometry of the engine can be scaled within 80% to 120% of the existing engine geometry with respect to the required maximum thrust.

## 5.6 Mission Analysis

In order to improve upon the estimation of the required fuel mass to perform the desired mission that VAMPzero predicts, a physics-based mission analysis is required. This analysis would entail simulating the aircraft’s flight through each stage of the mission (i.e. take-off, climb, cruise, decent, and fly to alternate airport) with the use of physical relations and values determined from physical analyses. This analysis would provide an improved estimation of the fuel burn throughout the mission, as well as provide additional information such as emissions and required thrust scaling factor for later use in the TWDat database tool. The approach would also allow artificial changes in the aerodynamic performance map and mass-breakdown to be effectively captured in the prediction of the required fuel mass.

### 5.6.1 FSMS

The fast and simple mission simulator (FSMS) allows for the simulation of the two-dimensional aircraft design mission for initial aircraft design purposes [1]. FSMS is a level 1 tool and requires the aerodynamic, engine, weight and geometrical data in CPACS as input. The tool then determines whether the aircraft is able to fly the mission and the required fuel by representing the aircraft by a discrete mass point and applying the standard equations of motion. The FSMS tool is also able to determine a re-calculated thrust scaling factor for the engine performance map. A mission profile produced by FSMS for a D150 model aircraft is provided in figure [5.5].

Since this tool provides information on the fuel needed for flying a specified mission, it provides a means to measure the performance in the analysis workflow. Since aerodynamic performance maps of the aircraft are likely to be artificially adjusted by technology factors in the analysis, fuel is the most promising in providing a sufficient metric for performance. In analysing the potential CO₂ emissions, fuel can be assumed to be directly related to
CO₂ emissions. Thus any savings in block fuel mass will also be an indicative the possible reduction in CO₂ emissions. Cost can also play a role in determining the performance of an aircraft and thus methods for the costs analysis were required.

### 5.7 Cost Analysis

As just mentioned, a method for computing the operating costs for a given aircraft configurations was needed in order to assess its efficiency. The operating costs of an aircraft can be divided into two components, the Direct Operating Cost (DOC) and the Indirect Operating Cost (IOC). DOC are specified as all costs that are aircraft type dependent which include [74]:

1. Flight operations
   - Flight crew salaries and expenses.
   - Fuel and Oil.
   - Airport and en-route charges.
   - Aircraft insurance.
   - Rental/lease of flight equipment/crews.

2. Maintenance and overhaul
   - Engineering staff costs.
   - Spare parts consumed.
5.7 Cost Analysis

- Maintenance administration

3. Depreciation and amortization
  - Flight equipment.
  - Ground equipment and property.
  - Extra depreciation.
  - Amortization of development costs and crew training

IOC are specified as the remaining operating costs, which include [74]:

1. Station and ground expenses
  - Ground staff.
  - Building, equipment, transport.
  - Handling fees paid to others.

2. Passenger services
  - Cabin crew salaries and expenses.
  - Other passenger service costs.
  - Passenger insurance.

3. Ticketing, sales, and promotion
  - General and administration.

4. Other operating costs

The Total Operating Cost (TOC) is the combination of both the DOC and IOC. The TOC therefore not only takes into account any changes in block fuel mass when determining any changes in cost, but the changes in mass and aerodynamic performance are included. This makes TOC another important performance index along with block fuel mass, as total cost is a performance index important, not only for the aircraft operator who wants to make the largest profit possible, but for the passenger as lower operating costs usually leads to reduced ticket prices. However, this reduced cost of flying can lead to a negative effect on total CO₂ emissions, this will be explained further in section 3.1.

A number of empirical-based methods exist for estimating the life cycle costs of a design. One of which is a statistical-based method provided by Roskam based on the aircraft geometry, performance, mission profile, and massbreakdown [59]. It is this method that the cost module of the Initiator design tool uses to determine the life cycle costs of both conventional and unconventional configurations [75, 76]. Therefore this module of the Initiator can be considered a level 0 tool. This module was chosen as it takes a number of factors relating to all aspects of the aircraft configuration when determining the operating cost. Therefore any changes in both OEM and fuel mass are captured in the calculated operating cost. The only downside to using this tool is that it required a wrapper to connect it to CPACS and implement it into RCE. The Initiator itself uses a hierarchical xml file as input but in a different format to the CPACS structure. Thus an interface between the two structures was needed and is explained in appendix C.
5.8 CPACS Adjustment Module

In order to achieve the last sub-objective outlined in section 1.1 a number of key analysis parameters are artificially adjusted in order to assess the effects on other disciplines and overall aircraft performance. In this way insight into the potential of a vast array of technologies on overall aircraft design can be gained. In order to perform these artificial adjustments so-called CPACS adjustment modules were developed in order to manipulate basic parameters at different points in the analysis workflow. For the analysis performed the module should be able to specify which parameters to adjust at varying locations in the analysis workflow. As mentioned in section 3.2.9 seven key parameters can be used in order to mimic the technology portfolio of this study. These parameters are shown in table 5.2 along with the technologies that are simulated by adjusting them.

Table 5.2: Parameters to be adjusted in the adjustment module

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Technologies Simulated</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wing mass</td>
<td>NLF, ALA, Wing Composite Structure, and Winglet</td>
</tr>
<tr>
<td>Fuselage mass</td>
<td>Fuselage Composite Structure and Lightweight Cabin Interiors</td>
</tr>
<tr>
<td>Systems mass</td>
<td>Wireless Flight Control Systems</td>
</tr>
<tr>
<td>Engine mass</td>
<td>Geared Turbofan and Open Rotor Engine</td>
</tr>
<tr>
<td>Engine SFC</td>
<td>Geared Turbofan and Open Rotor Engine</td>
</tr>
<tr>
<td>Lift-to-drag ratio</td>
<td>NLF and Winglet</td>
</tr>
<tr>
<td>Zero-lift drag coefficient</td>
<td>Drag Reducing Coatings</td>
</tr>
</tbody>
</table>

In table 5.2 the fuselage mass includes both structural and furnishings masses. Systems masses includes: APU, hydraulics, air conditioning, de-icing, fire protection, flight controls, instrument panels, navigation, communication and electrics masses. Engine mass includes: equipped engine (i.e. including nacelle structure), bleed air system, engine control system, fuel system, and inert gas system masses. These parameter adjustments can be divided into four main modules, namely the:

- Fuselage, systems and engine weight adjustment module
- Aerodynamic parameters adjustment module
- Wing weight adjustment module
- Engine SFC adjustment module

For the adjustment of the weights (i.e. fuselage, systems, engine, and wing) a simple multiplication by a constant called the technology factor in order to mimic a reduction or increase in that specific weight is required. These adjustments can be given as:

\[ M_{\text{adjusted}} = \phi \cdot M \]  \hspace{1cm} (5.2)

where \( M_{\text{adjusted}} \) is the adjusted mass, \( \phi \) is the corresponding technology factor and \( M \) is the unadjusted mass of the reference aircraft. This same procedure is applied to the
engine SFC, with the entire performance map being multiplied by a factor. However, this procedure is not possible for the aerodynamic parameters. For these adjustments a specific process is applied in order to manipulate the aerodynamic performance maps. This process can be seen in the flow diagram shown in figure 5.6 As shown in figure 5.6 the process takes a number of steps:

1. The process starts by extracting the data from the format that the aerodynamic performance maps are stored in the CPACS file. Currently the aerodynamic performance maps are stored as a single array. Within this single array the drag polars are contained for all combinations of Mach number and Reynolds number specified for the aerodynamic analysis. Equations 5.3 to 5.6 illustrate how these arrays are organized. The data is thus re-formatted to separate the drag polars for each combination of Mach and Reynolds number in preparation for adjustment process that follows.

\[
M = (M_1 M_2 \cdots M_l) \quad (5.3)
\]

\[
Re = (Re_1 \, Re_2 \cdots \, Re_m) \quad (5.4)
\]

\[
A = (\alpha_1 \, \alpha_2 \cdots \, \alpha_n) \quad (5.5)
\]

\[
C = \begin{pmatrix}
\begin{array}{cccc}
Re_1 & Re_2 & \cdots & Re_m \\
C_{111} & C_{112} & \cdots & C_{11m} \\
C_{121} & C_{122} & \cdots & C_{12m} \\
\vdots & \vdots & \ddots & \vdots \\
C_{l11} & C_{l12} & \cdots & C_{l1m}
\end{array}
\end{pmatrix}
\begin{pmatrix}
M_1 \\
\alpha_1 \\
\vdots \\
\alpha_n \\
M_2
\end{pmatrix}
\quad (5.6)
\]

2. The axes used for the force coefficients computed by Tornado are the body axes (i.e. x-axis along the fuselage orientation). Thus a transformation around the angle of attack is required in order to obtain the drag polars.

3. The zero-lift drag coefficients for each atmospheric condition are determined as the minimum drag coefficients in the drag polars.

4. The zero-lift coefficient is then artificially adjusted by displacing the drag polar in the direction of the drag coefficient axis. This is accomplished by adding or subtracting a calculated amount from the drag coefficient for each data point.

5. In order to adjust the lift-to-drag ratio a quadratic trend is fitted to the data points of each drag polar.

6. The maximum lift-to-drag ratios are then determined from these trends.

7. The polynomial coefficients are adjusted in such a way as to create an adjustment in the lift-to-drag ratios equal to the technology factor being applied.

8. The trend is transformed back into data points at the same angles of attack as the input data.

9. The aerodynamic forces are then transformed back into the body axes.

10. Finally the data is transferred back into the CPACS file in the required array format.
1. Data extraction
Formulate aerodynamic performance maps from data contained in CPACS format

2. Transformation to aerodynamic axes
Transform force coefficients from body axes to aerodynamic axes

3. Determine zero-lift drag coefficient
Determine the minimum drag coefficient from the drag polars

4. Adjust zero-lift drag coefficient
Apply technology factor for zero-lift drag coefficient by vertically displacing drag polars

5. Fit quadratic trend to data
Fit a quadratic trend to the drag polar data

6. Determine maximum L/D ratio
Determine the maximum lift-to-drag ratio from quadratic fit

7. Adjust quadratic trend
Adjust the polynomial coefficients of the quadratic trend in order to adjust the maximum lift-to-drag coefficient by the specified technology factor

8. Discretize quadratic trend
Extract adjusted values for the data points from the adjusted quadratic trend

9. Transformation to body axes
Transform data to body axes from aerodynamic axes

10. Data output
Set transformed data into required CPACS format

**Figure 5.6:** Flow diagram of aerodynamic parameter adjustment process within the CPACS adjustment module

(a) Technology factor of 0.8 and 1.2 for \( C_{D_0} \) and \( L/D \) respectively

(b) Technology factor of 1.1 and 0.9 for \( C_{D_0} \) and \( L/D \) respectively

**Figure 5.7:** Adjusted drag polars for the D150 at a Mach number of 0.78 and Reynolds number of \( 50 \cdot 10^6 \)
Chapter 6

Development of a Methodology to Assess the Potential of Technologies

The final thesis sub-objective in section 1.1 states that a method must be developed for estimating the savings in fuel consumption and operating cost by implementing the previously investigated technologies into an aircraft design. To accomplish this objective the developed CPACS adjustment modules were implemented into the basic analysis workflow shown in chapter 4. This workflow with CPACS adjustment modules implemented was then tested by running it at the sample points in the DOE discussed in section 2.3.2. The RSM techniques discussed in sections 2.3.2 were then utilised in order to develop visualisations for observing trends in the performance indices with changes in key analysis results. Here the functionality of the visualisation tool shown in 2.3.1 is demonstrated with the results of this DOE.

6.1 Development of an Adjustment Workflow

The locations of the adjustment modules in the design workflow are important in order for the changes to be captured by the subsequent disciplinary analyses. An overview of the location of the four main divisions of adjustments mentioned earlier can be seen in the extended N2-chart shown in figure 6.1. The implementation of the design workflow with adjustment modules included in RCE is shown in figure 6.3. For more information on the integration of this workflow into RCE the reader is referred to appendix C.
### Figure 6.1: N2-chart of the design workflow with adjustment modules implemented
The CPACS file given as output during the validation of the design workflow was used as input for this workflow. This is illustrated in figure 6.2 as the bottom right corner of the D150 analysis workflow N2-chart being the top left corner of the adjustment workflow N2-chart. With the D150 reference CPACS input file the first stage of adjustments are made to the fuselage, systems and engine weights. By adjusting these parameters at the start of the multi-fidelity analysis they are captured in the aerodynamic analysis through the adjustment of OEM. Following the aerodynamic analysis the aerodynamic parameters adjustments are made through the process outlined previously. The wing weight and SFC adjustments are made after the wing sizing and engine performance analysis respectively. At the end of the analysis loop both the wing weight and fuel mass are affected by the adjustments made previously in the workflow. The mass-breakdown is then updated, however, the systems and engine weights are re-calculated from statistics by VAMPzero. Thus following the aircraft synthesis the technology factors must be applied again. Since the passenger requirements remain unchanged throughout this study the fuselage weight and dimensions are kept constant as the values determined by FuCD during the initialisation phase. Since the fuselage characteristics are unaffected by changes in MTOM throughout the fixed-point iteration the technology factor for the fuselage weight is only applied on the first iteration of the convergence loop.

![Diagram of D150 Analysis Workflow and Adjustment Workflow](image)

**Figure 6.2:** Illustration of the bottom right corner of the D150 analysis workflow N2-chart being the top left corner of the adjustment workflow N2-chart

The wing mass is being artificially adjusted during the analysis which causes a problem for the aircraft synthesis with VAMPzero. VAMPzero performs analysis and design on statistics from existing aircraft configurations. Providing a fixed wing mass that is artificially lowered while keeping the wing planform the same would cause VAMPzero not to converge. The methods used in VAMPzero would expect a higher wing mass. Thus in order to achieve convergence the provided wing reference area is adjusted according to the MTOM and the reference wing loading during each fixed-point iteration as follows:
$S = \frac{MTOM \cdot g}{(W/S)_{ref}} \quad (6.1)$

Where $(W/S)_{ref}$ is the wing loading of the reference area. This not only allows VAMPzero to converge but provides a method to analyse the potential of reducing the wing size with changes in MTOM. With a reduced MTOM the required wing size for the take-off, climb to cruise altitude, and landing segments of the mission is reduced. This change in wing area is determined by the reference wing loading as it is important to keep the wing loading equal to this value. This assures that take-off, climb, and landing certification specifications are met by the aircraft with the adjusted wing area. Another constraint is that the wing must still be able to contain all the required fuel. A simple calculation is performed for the required fuel tank volume in order to check this constraint is met by the adjusted wing area. This calculation is made in the Wing Area Adjustment module using the ratio of fuel mass to wing area of the reference aircraft as an upper limit for the same ratio for the adjusted aircraft wing. This reduction in wing area can lead to a snowball effect on reductions in MTOM, as a reduced wing area would result in a reduced wing mass and ultimately in a further reduced MTOM. This process can continue until the whole process converges.
6.2 Fixed Aircraft Configuration Analysis

As mentioned in section 3.2, a number of technologies can only be integrated into an aircraft’s configuration early on in its development. Therefore experiencing the benefits of being able to adjust the aircraft configurations according to changes in fuel mass and OEM originating from these technologies during the design iterative process. However, a number of technologies can be included at a later stage in the aircraft’s life as a retrofit, without making major changes to the aircraft design. These technologies include wingtip devices and drag reducing coatings, among others. The design workflow with the adjustment modules included allows a snowball effect in changes in MTOM to occur for the reasons discussed at the end of section 5.8.

Another workflow was developed, in which the aircraft configuration was fixed during the fixed-point iteration process, i.e. the wing area was kept constant. The N2 chart for this workflow including the CPACS adjustment modules can be observed in figure 6.4. Its implementation into RCE is shown in figure 6.5. The workflow for this analysis was similar to the initial design workflow with adjustment modules. However, since the wing structure is unaffected, there was no change in the wing mass (except for those made by the adjustment modules themselves). Therefore the wing mass estimation tools were not needed in this workflow. In addition, the aircraft synthesis with VAMPzero is no longer needed as none of the aircraft configuration is adapted. This meant that for this analysis only the fuel mass and cost would be affected by the adjustments made in the adjustment modules. As with other adjustment workflow the CPACS file given as output during the validation of the design workflow (without adjustment modules implemented) was used as input to this fixed aircraft configuration workflow (see figure 6.2).
### Figure 6.4: N2-chart of the design workflow with adjustment modules implemented and the aircraft configuration fixed
6.3 Design Workflow with Adjustment Module Verification

As discussed in section 2.3.2 RSM techniques were utilised in order to demonstrate the functionality of the visualisation tool shown in section 2.3.1. By using these RSM techniques the proper functioning of the system discussed so far in this chapter can also be verified by observing the inter-disciplinary trends. Therefore, by using the design workflow with adjustment module implemented an analysis was performed using these technology factors, in order to verify its proper functioning.

6.3.1 Generating the DOE Sample Points

A DOE is performed in which sample points where the technology factors discussed previously are varied. These sample points are generated using the LHS technique by making use of the tool JMP which is discussed in the following sub-section.

JMP

As mentioned in section 2.3.2 the statistical discovery software, JMP from SAS, was used to generate the DOE. JMP is able to create a space-filling DOE, including the Latin-Hypercube sampling technique. The tool also allows for statistical analysis of data.

Figure 6.5: The design workflow with adjustment modules implemented and the aircraft configuration fixed in RCE
through interactive dynamic graphics \[^{19}\]. JMP is able to perform sensitivity analyses, Gaussian model fitting and many other statistical functions for a given set of data. The screening functionality of JMP allows for the determination of design parameters that affect the performance indices the greatest. This function is therefore able to identify parameters that will play a key role in improving aircraft performance and consequently the technologies that are most associated with varying these certain parameters. Therefore technologies showing promise for reaching the CO\(_2\) reduction goals of flightpath 2050 can be identified.

**Technology Factor Ranges**

As discussed in section \[^{3.2.9}\] there are seven parameters to adjust, thus there will be seven technology factors that will be defined by each DOE sample point. As discussed in section \[^{2.3.2}\] 150 sample points were generated. The ranges in which the sample points were selected are presented in table \[^{6.1}\].

**Table 6.1: DOE design variable ranges**

<table>
<thead>
<tr>
<th>Design variable</th>
<th>Parameter Adjusted</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\phi_{mWing})</td>
<td>Wing Mass</td>
<td>0.8-1.1</td>
</tr>
<tr>
<td>(\phi_{mFuselage})</td>
<td>Fuselage Mass</td>
<td>0.8-1.1</td>
</tr>
<tr>
<td>(\phi_{mSystems})</td>
<td>Systems Mass</td>
<td>0.8-1.1</td>
</tr>
<tr>
<td>(\phi_{mEngine})</td>
<td>Engine Mass</td>
<td>0.8-1.1</td>
</tr>
<tr>
<td>(\phi_{CD0})</td>
<td>Zero-lift Drag</td>
<td>0.8-1.1</td>
</tr>
<tr>
<td>(\phi_{L/D})</td>
<td>Lift-to-Drag Ratio</td>
<td>0.9-1.2</td>
</tr>
<tr>
<td>(\phi_{SFC})</td>
<td>SFC</td>
<td>0.8-1.1</td>
</tr>
</tbody>
</table>

For these technology factors a 1 refers to being equal to reference values. Thus values below 1 refer to adjusting the parameter below reference values and values above 1 refer to adjusting the parameter above reference values. A range of 20% in the positive direction (i.e. improving performance) and 10% in the negative direction (i.e. decreasing performance) from the reference values was selected. The reasoning behind these values is that from tables \[^{3.1}\] and \[^{3.2}\] it was shown that the range in which the majority of technologies effect certain parameters is between 5% and 20%, with only more drastic technologies, such as open rotor engines, passing 20%.

Something to observe from tables \[^{3.1}\] and \[^{3.2}\] is that not all of the seven parameters shown in table \[^{6.1}\] are negatively effected by the technologies included in this study. Examples of this are systems mass, zero-lift drag, lift-to-drag ratio, and SFC. Likewise, not all of the seven parameters being positively effected by the technologies included in this study. Thus the question arises, why have all parameters been varied in both directions? The reason for this is twofold: Firstly by varying all parameters in both directions the inter-disciplinary trends and correlations can be observed through the use of the visualisation tool. The use of the tool for this purpose can be observed in section \[^{6.3.6}\]. Secondly, in this study only a number of the main current technologies under research are being investigated. However, the results from this study would not only provide an
indication into the potential of these technologies but also improve the design process of new currently unknown technologies. The results from this study can provide information into the effect of varying multiple key analysis parameters at different locations in the design workflow. Through the visualisation tool it will be possible to perform so-called reverse engineering. This process can assist in determining conceptual design goals for a certain technology being researched. For further information on how this process can happen using the results from this study and the visualisation tool the reader is referred to section 7.3.

As seen in table 3.2 the NLF technology could increase wing mass by as much as 25%, however, the technologies were limited to 10% in the negative direction (i.e. decreasing performance). The reason to limit the negative effects to 10% was due to the limitations of the analysis tools available, specifically the mission analysis tool FSMS. By applying a less restrictive limit on the negative effects, DOE sample points located at the extreme corners of the design space i.e. all technology factors were set at values causing the lowest aircraft performance possible. So if the negative effects were not limited to 10%, but to 20%, this would entail the technology factors being close to the values shown in table 6.2 i.e. all weights, fuel consumption, and zero-lift drag set to 20% above reference values and the lift-to-drag ratio set at 20% below reference values.

Table 6.2: Values of technology factors in extreme negative corner of design space

<table>
<thead>
<tr>
<th>Design variable</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \phi_{mWing} )</td>
<td>1.2</td>
</tr>
<tr>
<td>( \phi_{mFuselage} )</td>
<td>1.2</td>
</tr>
<tr>
<td>( \phi_{mSystems} )</td>
<td>1.2</td>
</tr>
<tr>
<td>( \phi_{mEngine} )</td>
<td>1.2</td>
</tr>
<tr>
<td>( \phi_{CD} )</td>
<td>0.8</td>
</tr>
<tr>
<td>( \phi_{L/D} )</td>
<td>0.8</td>
</tr>
<tr>
<td>( \phi_{SFC} )</td>
<td>1.2</td>
</tr>
</tbody>
</table>

Running the workflow with technology factors such as these lead to the FSMS tool being unable to analyse such a configuration as the tool decided such a design would not be able to fly the prescribed mission. This is understandable as the aircraft would be too aerodynamically inefficient and heavy. Thus a more modest range in the negative direction was chosen in order for the FSMS tool to converge for each sample point in the DOE.

6.3.2 Sensitivity Analysis

By running the design workflow for each sample point in the DOE with the reference mission requirements and design parameters given as input the fuel consumption and operating costs for each sample point were determined. With this data two RSM methods were used in analysing the data. In figure 6.6 there are plots illustrating the sensitivity of the fuel mass to changes in the various technology factors using a kriging and polynomial model. The curves were generated with all technology factors, other then the one being adjusted, set to reference values i.e. all set to the value of 1. For example, for the first
Development of a Methodology to Assess the Potential of Technologies

In Figure 6.6, all technology factors were kept constant at 1 while $\phi_{m\text{Wing}}$ was adjusted in the range of 0.8-1.1.

![Figure 6.6: Sensitivity of fuel mass to technology factors for adjustment workflow with adjustable wing area](image)

The plots in Figure 6.6 show that the fuel mass is largely affected by the aerodynamic and engine SFC parameters, seen in the plots by the steeper gradients in the curves. The curves follow the trends that would be expected, with the fuel mass increasing for increasing weights, engine consumption, and drag, while decreasing for decreasing values of the same parameters. The opposite happens for the case of L/D, as fuel mass decreases for increasing L/D ratio and increases for decreasing values of L/D. These results were expected, as a change in the aerodynamic performance map and engine performance would have a more direct impact on the mission analysis, and consequently the fuel mass for a D150 aircraft. Changes in masses have a reduced impact on the fuel mass, due to the less direct impact changes in these parameters have on mission performance.

The aerodynamic parameters also play a key role in the fuel consumption as the required thrust during cruise is set as equal to the total drag. Thus the effect of changes in the aerodynamic parameters is lower than that of SFC but still much greater than the masses. Another reason for this reduced effect of the OEM on fuel consumption is that, although reductions in OEM overall cause a reduction in block fuel mass, for certain mission segments the required fuel mass is increased. This is shown in Figure 6.7, where a 10% decrease in OEM leads to reductions in fuel burn for all segments except the descent phase. This makes sense as a reduced mass would lead to a larger required thrust to perform a descent in a given time. This opposite effect on fuel burn during the descent phase reduces the potential reductions in overall mission fuel burn. The changes in fuel
burn from changes in SFC or the aerodynamic parameters are consistent for all mission profile segments. However, this effect on the reduced impact of changes in OEM is minimal compared to the other reasons specified previously.

One final observation would be that the wing and fuselage masses have a slightly greater impact on the required fuel mass compared to the other masses because these components together make up around 45% of the OEM.

By using the tool JMP it was also possible to investigate the sensitivity of performance and cost indices to changes in the seven parameters with the screening function. This function provides a t-ratio for each parameter, which is a measure for the level of linear correlation between the parameter and the relevant output variable (for more information on this parameter the reader is referred to [?]). In figure 6.8 the t-ratios of all seven technology factors for the output variables fuel mass and total operating cost (TOC) are presented. As can be observed, SFC along with $C_{D_0}$ and L/D have the strongest correlations with the fuel mass, which is in-line with the previous observations. This observation holds for the TOC as well, however, the masses start to play a larger role as the MTOM plays a key role in determining maintenance costs as well as station and ground expenses. From figure 6.8c it can be seen that MTOM is more sensitive to changes in the masses than the fuel mass. Two conclusions can be made from these plots: Firstly that engine SFC has a strong correlation to fuel mass, TOC, and MTOM. Secondly, that the engine and systems masses have the least effect on fuel mass, TOC, and MTOM.

Thus from these analyses it becomes clear that technologies that improve the engine and aerodynamic performance of an aircraft show the greatest potential in reducing fuel burn and consequently emissions. However, from a cost point of view, technologies that reduce
OEM have an important role to play as well. In light of the flightpath 2050 CO₂ reduction goals, the goal is to reduce fuel burn, however, for airliners and passengers, total savings in cost plays an equally important role. Lower cost equates to higher profit margins for the airliners and lower flight costs for the passenger.

6.3.3 Comparison of RSM techniques

As observed in figure 6.6, both RSM techniques produce similar models, since both display the same trends with only moderate differences between their results. However, there remain differences in their accuracy. For the purpose of using this data in assisting the design of technologies through reverse engineering (which is demonstrated in section 7.3) it is of importance to determine how good these models are in accurately modeling the analysis data. In order to do this another DOE was performed with a reduced amount of variables involved. In this DOE the five parameters with the largest effect on the output variables shown in figure 6.8 were chosen (i.e. SFC, $C_{D0}$, $L/D$, and $m_{Wing}$) to be
adjusted by the technology factors. In this DOE, unlike the previous DOE of 150 sample points, only two variables are adjusted for each sample point. For example, for the first 30 sample points a two variable LHS DOE is performed where only $\phi_{SFC}$ and $\phi_{CD0}$ are varied while the other technology factors remain constant at value 1. In the next 30 sample points a similar DOE is performed but with only $\phi_{SFC}$ and $\phi_{L/D}$ being varied. This is repeated until a LHS DOE is performed for each combination of the technology factors of the five parameters mentioned previously. In total this amounts to a DOE of 180 sample points made up of six combinations of technology factors (i.e. $\phi_{SFC}$-$\phi_{CD0}$, $\phi_{SFC}$-$\phi_{L/D}$, $\phi_{SFC}$-$\phi_{mWing}$, $\phi_{CD0}$-$\phi_{L/D}$, $\phi_{CD0}$-$\phi_{mWing}$, and $\phi_{L/D}$-$\phi_{mWing}$).

The purpose for this DOE is to allow analysis of the accuracy of the generated RSM models, through the use of $R^2$ values. It will also allow proper visualisation of how well the models fit the data as it is not possible to properly visualize a model of seven variables.

By running this second DOE a set of data was produced that was utilised in a statistical analysis of the goodness of fit of the RSM models to the data from the full simulation. In figure 6.9 the Kriging models (with a zero order polynomial regression model) for the change in TOC, $\Delta TOC$, along with the data generated from the second DOE can be seen. In table 6.3 the $R^2$ values, an index for goodness of fit, are shown. For some areas of the design space the kriging model sufficiently fits the data. However, towards the corners of the design space the model deviates from the data, quite substantially for some cases (e.g. $\phi_{CD0}$ vs $\phi_{L/D}$). These deviations caused one of the $R^2$ values to be unacceptably low at 0.5348. These discrepancies at the corners are a common issue with using kriging as an RSM technique when a zero order polynomial regression is applied to the model. These discrepancies in the corners can be mitigated by increasing the total number of sample points, thus increasing the number of samples in these areas. This was not an option as increasing the sample size would take too much time to perform the DOE for this project. Also, data points in some of the corners would cause issues with the FSMS tool for the reason mentioned in section 6.3.1.

<table>
<thead>
<tr>
<th></th>
<th>$\phi_{SFC}$</th>
<th>$\phi_{CD0}$</th>
<th>$\phi_{L/D}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\phi_{mWing}$</td>
<td>0.972</td>
<td>0.922</td>
<td>0.960</td>
</tr>
<tr>
<td>$\phi_{SFC}$</td>
<td>-</td>
<td>0.963</td>
<td>0.957</td>
</tr>
<tr>
<td>$\phi_{CD0}$</td>
<td>-</td>
<td>-</td>
<td>0.535</td>
</tr>
</tbody>
</table>

In figure 6.10 the polynomial response surfaces are shown. The corresponding $R^2$ values can be seen in table 6.4. Observing the surface plots and $R^2$ values it becomes clear that the data in question follows a predominantly quadratic trend and as such a second order polynomial would produce the most accurate RSM. The polynomial response surfaces have discrepancies from the data but from observing the plots and $R^2$ values it becomes clear that these models in general have a better goodness of fit than the Kriging models. This better goodness of fit is clearly seen in figure 6.10c with the model being closer to the data points in the right corner and thus having as significantly higher corresponding $R^2$ value. A couple of the $R^2$ values are lower for the polynomial models compared to the Kriging, but the overall goodness of fit has increased. Other than the improved fit
Figure 6.9: Kriging response surface models of $\Delta$TOC with adjustable wing area for different design variables with sample data points from second DOE
to the data, a benefit to using a polynomial response surface over Kriging is the reduced computational effort required to generate the model. This benefit is advantageous when numerous evaluations of a model are needed, which can be the case when using the visualisation tool developed during this project. The reader is referred to section 2.3.1 for further information on this tool.

Table 6.4: $R^2$ values for Polynomial models of order 2

<table>
<thead>
<tr>
<th>$\phi_{mWing}$</th>
<th>$\phi_{SFC}$</th>
<th>$\phi_{CD0}$</th>
<th>$\phi_{L/D}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.981</td>
<td>0.958</td>
<td>0.921</td>
<td></td>
</tr>
<tr>
<td>$\phi_{SFC}$</td>
<td>-</td>
<td>0.968</td>
<td>0.946</td>
</tr>
<tr>
<td>$\phi_{CD0}$</td>
<td>-</td>
<td>-</td>
<td>0.878</td>
</tr>
</tbody>
</table>

Thus from comparing the generated models to the data points from the second DOE it can be concluded that in general the polynomial models show the interdisciplinary trends sufficiently and is therefore the ideal RSM technique for this data. The Kriging technique is able to provide a model including a regression model of order two, which improves the surfaces accuracy in modeling the data. However, there are little or no improvements in using the Kriging method over polynomial response surfaces since the data in question follows predominantly quadratic trends. To improve the models further, the data set from the second DOE will be added to the model in order to improve the goodness of fit of the polynomial models. By doing so the improved $R^2$ values are shown in table 6.5.

Table 6.5: $R^2$ values for Polynomial models of order 2 with second verification DOE response data added

<table>
<thead>
<tr>
<th>$\phi_{mWing}$</th>
<th>$\phi_{SFC}$</th>
<th>$\phi_{CD0}$</th>
<th>$\phi_{L/D}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.990</td>
<td>0.981</td>
<td>0.963</td>
<td></td>
</tr>
<tr>
<td>$\phi_{SFC}$</td>
<td>-</td>
<td>0.984</td>
<td>0.978</td>
</tr>
<tr>
<td>$\phi_{CD0}$</td>
<td>-</td>
<td>-</td>
<td>0.962</td>
</tr>
</tbody>
</table>

It can be seen that by adding the data points the $R^2$ values are improved, especially the value for the $\phi_{CD0}$ vs $\phi_{L/D}$ case.

### 6.3.4 The Snowball Effect of Adjusting Wing Area

With this study two analyses were performed: one with the wing area adjusted according to changes in MTOM, and one with a fixed wing. In figure 6.11 the results of both analyses are compared for the block fuel mass.

Results show that for the analysis with an adjustable wing, reductions and increases in fuel mass from variations in technology factors are accentuated. The masses in the fixed-wing analysis have very little effect on the fuel mass for the same reasons as mentioned previously in section 6.3.2. The biggest increase in fuel savings by implementing changes in the wing area can be found at $\phi_{mWing}=0.8$ with a difference of approximately 8%
Figure 6.10: Polynomial response surface models of $\Delta TOC$ with adjustable wing area for different design variables with sample data points from second DOE.
between the results of the two analyses. However, some of this increase in fuel savings would have come from discrepancies between the polynomial model and the results of the full simulation. As seen in section 6.3.3 the model has a reasonably good fit to the data but still has $R^2$ values of 0.962. Thus these discrepancies will occur. The results for the TOC and MTOM are shown in figures 6.12 and 6.13.

As shown in the plots the analysis with varied wing area creates larger decreases and increases in TOC and MTOM for when the parameters are reduced or increased respectively. The differences in analyses increases for all technology factors as the design moves further from the reference aircraft. This is consistent with the snowball principle, that an initial decrease in weight will create a larger decrease overall, and the larger the initial decrease the larger the added decrease in weight from design iterations.

The snowball effect in mass that occurs from changing the wing area have the greatest effect for technologies that provide a larger initial adjustment in a parameter. For technologies that only provide a small improvement in a certain analysis parameter the benefits gained from the snowball effect is minimal. Thus a trade-off on the effort required in developing a new aircraft design for a particular technology, against the added benefits is needed for each case. For certain technologies an entire redesign is required, such as NLF wings or open rotor engines, but for other technologies a retrofit would be the most beneficial route in implementing a technology into the current airliner fleet. An example for such a technology is winglets. For this technology the added benefit of redesigning an aircraft for added performance, if only this technology is being applied, would be minimal, and therefore possibly not worth the extra effort of a redesign. Other technologies that could fall under this category would be drag reducing coating, WFCS, and GTFs.
For an aircraft manufacturer the following process can be made when deciding if a portfolio
of technologies is more feasible as a retrofit option for one of their existing aircraft already in the global aircraft fleet or implemented into a newly designed aircraft. At the start of a project the potential operating cost savings can be estimated for two different cases, a case in which the technology portfolio is retrofitted and one that is implemented on a newly designed aircraft. From these operating cost savings estimates the aircraft manufacturer can estimate the potential increase in unit price that they can ask for in each case, along with an estimate of the potential number of sales. These values can then be compared to the associated estimated development costs for each case. With the methodology of the technology factor initial estimates into these operating costs savings can be made early on in the design and implementation of a technology. It allows for case studies in which the potential of technology portfolios is easily assessed. These sorts of case studies are carried out in chapter 7.

6.3.5 Workflow Verification Overview

In this section the results of the verification of the adjustment module workflow system was presented. A number of observations were made concerning the effect of certain parameters on dependent disciplines. From the results it was first shown that, by analysing the sensitivity of fuel mass to the technology factors, the parameters that predominantly effected fuel mass were SFC and the aerodynamic parameters. For MTOM the masses started to become influential, which resulted in wing mass and fuselage mass having more influence in operating costs. However, still marginally lower influence than SFC. In terms of fuel and operating cost, technologies that effect SFC and \(C_D\) show the most promise for future aircraft designs. In this study only the potential fuel savings were analysed, but these savings will be similar to the savings in emissions. Slight differences will occur but the fuel savings can be assumed representative of the associated emissions savings for this study. Therefore in light of the FlightPath 2050 goals, it can be concluded that SFC and the aerodynamic parameters will lead the way (according to these results) in technological advancement.

From comparing RSM techniques, both models generally interpolated the data with a sufficient goodness of fit. However, some of the Kriging model had low \(R^2\) values, some being lower than 0.6. This is not sufficiently accurate. Polynomial models of the order two seemed to improve upon the kriging models, with higher overall \(R^2\) values. This was attributed to the data following a largely quadratic trend. Kriging has the ability to include a polynomial regression model, but the improvement in goodness of fit gained was miniscule and was unnecessary as the data did not follow an irregular trend. To further improve the model, the set of sample points from the second verification DOE of 180 sample points were included in it.

6.3.6 Plot Generation Using Visualisation Tool

The main purpose of the visualisation tool is to allow the user to easily produce 2D and 3D plots that can help identify and communicate inter-disciplinary correlations. In order to demonstrate how this may work, the data obtained from this verification process can be used in an example. In figure 6.14 the annotated view of the main GUI of the visualisation tool is shown again. For this example the Polynomial RSM method with order two was
selected. As shown in figure 6.15 there are options for choosing a Kriging RSM model and adjusting parameters for both models. Further explanation of these options can be found in appendix [D].

![Diagram of a GUI for a visualisation tool](image)

**Figure 6.14:** The main GUI of the visualisation tool

### 3D Plot generation

In order to generate a 3D plot the options in the *3D Plot options* panel can be used (see figure 6.16). The desired inputs and outputs for each plot can be chosen from the drop-down menus, as shown in figure 6.16 and the plots will be generated by pressing the *3D plots* button. The generated plot for this example can be seen in figure 6.17. The '1' in some of the names in the variables is due to limitations of the data importer tool, which is described further in appendix [D].

By generating plots such as these the combined interaction between three key parameters from different disciplines can be observed. In this case two 3D plots are shown. One showing the interaction between $\phi_{CD0}$, $\phi_{mWing}$ and the fuel mass. The other showing the interaction between $\phi_{SFC}$, $\phi_{L/D}$ and MTOM. For these plots all other input variables (other than the ones selected for the plot) are kept constant to the values shown in the *Parameters* panel, as shown in figure 6.18.

The *plot DOE points* option shown in figure 6.16 gives the user the option to plot the data points used to generate the plots. This option is useful in showing how well the RSM models fit the data in a problem where only two variables are varied at one time. However, for this example, in which seven variables are varied at one time, this option has little use.
2D Plot generation

In order to generate a 2D plot the options in the 2D Plot options panel can be used (see figure 6.19). In order to generate a 2D plot the user must first select the main output
Figure 6.17: 3D plots of $\phi_{CD0}$ vs. $\phi_{mWing}$ vs. fuel mass, and $\phi_{SFC}$ vs. $\phi_{L/D}$ vs. MTOM

![3D plots](image)

Figure 6.18: Parameters panel of the visualisation tool

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Value</th>
<th>Value</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>mLWing</td>
<td>1</td>
<td>0.8</td>
<td></td>
</tr>
<tr>
<td>mFuselage</td>
<td>1</td>
<td>0.8</td>
<td></td>
</tr>
<tr>
<td>mSystems</td>
<td>1</td>
<td>0.8</td>
<td></td>
</tr>
<tr>
<td>mEngine</td>
<td>1</td>
<td>0.8</td>
<td></td>
</tr>
<tr>
<td>CD01</td>
<td>1</td>
<td>0.8</td>
<td></td>
</tr>
<tr>
<td>SFC1</td>
<td>1</td>
<td>0.8</td>
<td></td>
</tr>
<tr>
<td>LiftDrag</td>
<td>1</td>
<td>0.9</td>
<td></td>
</tr>
</tbody>
</table>

variables from the Output 1 drop-down menu. The user then has the option as to which
input he/she would like to be shown in the plot by multi-selecting (with the \textit{ctrl} key) the desired input from the \textit{Inputs} list. In the example shown in figure 6.19 the fuel mass output was chosen along with the inputs $\phi_{m\text{Wing}}$, $\phi_{m\text{Fuselage}}$, $\phi_{m\text{Engine}}$, $\phi_{C\text{D}0}$, and $\phi_{S\text{FC}}$. By pressing the \textit{2D plots} button the 2D plot is generated. The generated plot for this example can be seen in figure 6.20. These 2D plots are the same as those shown in section 6.3.2 where, as with the 3D plots, the parameters (other than the input parameter in question) are kept constant at the values specified in the \textit{Parameters} panel shown in figure 6.18.

![2D Plots options panel on visualisation tool](image1)

**Figure 6.19:** 2D Plots options panel on visualisation tool

![2D plots of fuel mass vs. $\phi_{m\text{Wing}}$, $\phi_{m\text{Fuselage}}$, $\phi_{m\text{Engine}}$, $\phi_{C\text{D}0}$, and $\phi_{S\text{FC}}$](image2)

**Figure 6.20:** 2D plots of fuel mass vs. $\phi_{m\text{Wing}}$, $\phi_{m\text{Fuselage}}$, $\phi_{m\text{Engine}}$, $\phi_{C\text{D}0}$, and $\phi_{S\text{FC}}$.

There are two additional options for the 2D plots: the first option is to generate a plot with two output variables. The second output variable is chosen from the \textit{Output 2} drop-down menu. This option can be selecting through the \textit{2nd output} check-box and the plot generated by the \textit{2D plots} button. For this example TOC was chosen as the second output and the generated plots can be seen in figure 6.21. The second option is to add a reference line to the plot. This option places a line in the plot in which all parameters (except the input variable in question) are set at reference values. An example of this is shown in figure 6.22 where $\phi_{S\text{FC}}$ was set at 0.9 (for all plots except for fuel mass vs $\phi_{S\text{FC}}$) to illustrate how the reference line works. As can be observed in this plot, the reference line for fuel mass vs $\phi_{S\text{FC}}$ is the same as the line with adjusted $\phi_{S\text{FC}}$. This
is expected as all other parameters in the Parameters panel, other than $\phi_{SFC}$, were kept at reference values in this example.

Figure 6.21: 2D plots of fuel mass and TOC vs. $\phi_{m\text{Wing}}$, $\phi_{m\text{Fuselage}}$, $\phi_{m\text{Engine}}$, $\phi_{CD0}$, and $\phi_{SFC}$

![Figure 6.21: 2D plots of fuel mass and TOC vs. $\phi_{m\text{Wing}}$, $\phi_{m\text{Fuselage}}$, $\phi_{m\text{Engine}}$, $\phi_{CD0}$, and $\phi_{SFC}$](image)

Figure 6.22: 2D plots of fuel mass vs. $\phi_{m\text{Wing}}$, $\phi_{m\text{Fuselage}}$, $\phi_{m\text{Engine}}$, $\phi_{CD0}$, and $\phi_{SFC}$ with reference line and $\phi_{SFC}$ set at 0.9

![Figure 6.22: 2D plots of fuel mass vs. $\phi_{m\text{Wing}}$, $\phi_{m\text{Fuselage}}$, $\phi_{m\text{Engine}}$, $\phi_{CD0}$, and $\phi_{SFC}$ with reference line and $\phi_{SFC}$ set at 0.9](image)

From plots such as these the sensitivity of output parameters to changes in inputs parameters can be quickly observed. This way it can be identified if an output and an input parameter each from different disciplines have a strong, weak, or no correlation. Comparisons of the correlations between an output and different input parameters can be made, as well as those for a second output variable. When making changes to the parameters in the Parameters panel from reference values the effects on these correlations can also be observed by comparing the plots to the reference line. There are limitations to the use of this 2D plotting function, which are explained further in appendix D.
Other plot options

There are other functions embedded within the tool for plotting, as shown in figure 6.23. Once a change is made to the parameters in the Parameters panel (as shown in figure 6.18), the already generated plots can be manually updated with the adjusted values by pressing the Update plots button. This function can be automated by selecting the auto update check-box. With this option selected the plots will be automatically updated every time a value is adjusted in the Parameters panel. The Close all plots closes all generated plots and the Position Figures opens up a panel that allows the user to easily position plots on a large screen (such as the one in the IDL). For further information on this function as well as other functions of the visualisation tool (such as importing data) the reader is referred to the user guide in appendix D.

6.4 Adjustment Workflow Validation

In order to see if the adjustment methodology presented in this chapter gives reasonable results a validations was performed. This process would not only test the accuracy of the technology factor method, but also some of the values stated in table 3.1. This validation consists of using the adjustment workflow to assess the potential fuel savings of the D150 with winglets and GTFs implemented. The estimated fuel savings can then be compared to those claimed for the A320neo. As mentioned in section 3.1 the A320neo is the enhanced version of the A320, with most notably the option for the new GTF PW1100G engine as well as winglets. The aircraft geometry will remain the same as the A320, therefore the fixed-wing adjustment workflow shown in figure 6.4 will be used to estimate the fuel savings. For this test case the technology factors shown in table 6.6 were used. The corresponding results for this test case are shown in table 6.7.

For the A320neo it is claimed that a potential fuel savings of 15% can be achieved per aircraft [7]. Comparing this value to those shown in table 6.7 it can be said that the 15% fuel savings of the A320neo is within the range of fuel savings estimated from the adjustment workflow. The actual value is closer to the lower end of this range. It is unclear from the 15% fuel savings claim for what specific mission this estimate is for, and for how much payload, as the A320neo is able to hold up to 20 additional passengers due to a rearranged cabin. Thus deviations from the adjustment workflow results could originate from these uncertainties. The range of around 6% in the adjustment workflow results
Table 6.6: Technology factors for the adjustment workflow validation test case

<table>
<thead>
<tr>
<th>Technology</th>
<th>Parameter</th>
<th>Adjustment [%]</th>
<th>Technology Factor [-]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Geared Turbofan</td>
<td>mEngine</td>
<td>+[5-10]</td>
<td>1.05-1.1</td>
</tr>
<tr>
<td></td>
<td>SFC</td>
<td>-[10-15]</td>
<td>0.85-0.9</td>
</tr>
<tr>
<td>Wingtip Devices</td>
<td>L/D</td>
<td>+[4-6]</td>
<td>1.04-1.06</td>
</tr>
<tr>
<td></td>
<td>mWing</td>
<td>+[5-8]</td>
<td>1.05-1.08</td>
</tr>
</tbody>
</table>

Table 6.7: Changes in performance indices for the adjustment workflow validation test case

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Min [%]</th>
<th>Max [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>∆mFuel</td>
<td>-13.6</td>
<td>-19.9</td>
</tr>
<tr>
<td>∆MTOM</td>
<td>-1.0</td>
<td>-2.9</td>
</tr>
<tr>
<td>∆TOC</td>
<td>-2.9</td>
<td>-4.8</td>
</tr>
</tbody>
</table>

come from the uncertainties in the values shown in tables 3.1 and 3.2. Therefore until concrete estimations are available for the effects that these technologies have on these basic parameters, these large ranges in values will exist. Another aspect to take note of, is that for the GTF technology, is that a large part of the improved SFC comes from allowing for a greater bypass ratio. This leads to a larger engine diameter, and therefore a greater aircraft zero-lift drag coefficient. This would ultimately lead to lower fuel savings from this technology. Thus the results in table 6.7 would be slightly overestimated. The reason that this effect was not included was that information on the diameter increase of a GTF was unavailable. Its effect would also be minimal compared to the reductions in fuel consumption from these engines. This must be taken into account when observing the results of the case studies performed in chapter 7 involving the GTF technology.
Chapter 7

Results and Discussion

Using the workflow set-up and tested in chapters 4 and 6 a number of case studies involving different combinations of the technology portfolio discussed in section 3.2. Within each of these studies the fuel and cost saving potential of these technologies is estimated and assessed in light of the CO$_2$ reduction goals set out in Flightpath 2050. In section 7.1 the case studies are outlined along with the results and in section 7.2 an overview of the results is given. Finally in section 7.3 the power of the developed technology factor system combined with the visualisation tool in the assessment of future technologies, will be demonstrated.

7.1 Case Studies

In order to achieve the objective stated in section 1.1 an investigation into the potential increases in performance and reductions in cost that technologies can achieve is needed. In this section a number of case studies will be investigated that will assess the potential of a number of technologies, and outline possibilities to combine them into an aircraft design. In these assessments the fuel and cost savings are obtained through full runs of the adjustment workflows shown in chapter 6. The impact of allowing the wing area to change on aircraft performance will also be investigated for cases where it is relevant, such as for technologies where it is possible to retrofit.

7.1.1 Natural Laminar Flow Wing

This technology was discussed in section 3.2 and from studies performed by NASA on NLF airfoils it was determined that a potential increase of 20-30% in L/D is achievable while increasing the wing weight by as much as 20-25% [33]. In table 7.1 these adjustments along with their associated technology factors are shown. By implementing these technology factors, the results with wing area adjusted are shown in table 7.2 were obtained.
Table 7.1: NLF case parameter adjustments and associated technology factors

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Adjustment [%]</th>
<th>Technology Factor [-]</th>
</tr>
</thead>
<tbody>
<tr>
<td>L/D</td>
<td>+[20-30]</td>
<td>1.2-1.3</td>
</tr>
<tr>
<td>Wing Mass</td>
<td>+[20-25]</td>
<td>1.2-1.25</td>
</tr>
</tbody>
</table>

Table 7.2: Changes in performance indices for NLF wing analysis

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Min [%]</th>
<th>Max [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>ΔmFuel</td>
<td>-10.1</td>
<td>-13.8</td>
</tr>
<tr>
<td>ΔMTOM</td>
<td>1.4</td>
<td>-0.2</td>
</tr>
<tr>
<td>ΔTOC</td>
<td>-1.4</td>
<td>-2.7</td>
</tr>
</tbody>
</table>

From observing these results it shows that for the best case scenario a NLF wing with no other technology applied could achieve a savings of 13.8% in fuel burn. The MTOM actually increases from the increased wing mass but by 1.4% for the best case scenario (i.e. in this case, the technology factors would be set to $\phi_{L/D}=1.3$ and $\phi_{m_{Wing}}=1.2$). Overall TOC reduces but due to the increase in MTOM, not by as much as the fuel mass.

### 7.1.2 Winglets

This technology was discussed in section 3.2 and from the study performed by Elham [56] it was estimated that for a Boeing 747 a reduction of 9-11% in induced drag during cruise is achievable by a winglet. For the D150 a reduction of 9-11% in induced drag in cruise conditions is equal to approximately 4-6% increase in maximum L/D. In the same study it was estimated that this increase in L/D would come with a 5-8% increase in wing weight. In table 7.3 these adjustments along with their associated technology factors are shown. By implementing these technology factors, the results with wing area adjusted are shown in table 7.4.

Table 7.3: Winglet case parameter adjustments and associated technology factors

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Adjustment [%]</th>
<th>Technology Factor [-]</th>
</tr>
</thead>
<tbody>
<tr>
<td>L/D</td>
<td>+[4-6]</td>
<td>1.04-1.06</td>
</tr>
<tr>
<td>Wing Mass (in-production)</td>
<td>+[3-5]</td>
<td>1.03-1.05</td>
</tr>
<tr>
<td>Wing Mass (retrofit)</td>
<td>+[5-8]</td>
<td>1.05-1.08</td>
</tr>
</tbody>
</table>

As can be seen in table 7.4 the fuel savings of a winglet design is considerably less than an NLF wing, but this comes with less redesign work required to implement the technology. Again the MTOM increases, however, savings in TOC are low for the lower end of the TOC range. Thus in order for the technology to make a reasonable financial savings the increases in lift-to-drag would have to be approximately 6% and the wing mass increase...
Table 7.4: Changes in performance indices for retrofitted winglet analysis

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Min [%]</th>
<th>Max [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Delta m_{Fuel}$</td>
<td>-4.2</td>
<td>-5.6</td>
</tr>
<tr>
<td>$\Delta MTOM$</td>
<td>-0.2</td>
<td>-0.8</td>
</tr>
<tr>
<td>$\Delta TOC$</td>
<td>-0.9</td>
<td>-1.4</td>
</tr>
</tbody>
</table>

approximately 3%. Winglets have the possibility to be implemented as a retrofit into an existing aircraft design. Thus it would be of interest to look at the potential improvements in performance from the fixed-wing analysis. The results of which are shown in Table 7.5.

Table 7.5: Changes in performance indices for winglet analysis with fixed wing area

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Min [%]</th>
<th>Max [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Delta m_{Fuel}$</td>
<td>-4.0</td>
<td>-5.4</td>
</tr>
<tr>
<td>$\Delta MTOM$</td>
<td>0.2</td>
<td>-0.4</td>
</tr>
<tr>
<td>$\Delta TOC$</td>
<td>-0.7</td>
<td>-1.2</td>
</tr>
</tbody>
</table>

From the results it becomes clear that allowing the wing area to change with MTOM does positively effect the performance and cost of an aircraft with a technology implemented. However, the differences in results for the two analyses for fuel and cost savings is 0.2%. Thus for this technology, retrofitting could be a promising possibility for improvements in performance with reduced development costs. This is due to the fact that the changes in parameters are minimal for this technology and are close to the reference values. The results of the study performed by Elham showed that a potential savings of 3.8% in fuel can be achieved by retrofitting an optimised winglet design onto a Boeing 747 aircraft [56]. Comparing this value with those obtained from the analysis it shows that the Elham’s result is just below the lower end of the adjustment workflow results.

7.1.3 Geared Turbofan

This technology was discussed in section 3.2 and from the study performed by NASA [49] it was determined that for a Geared TurboFan (GTF) the engine fuel consumption can be reduced by 10-15% with an increase in weight of around 5-10%. In Table 7.6 these adjustments along with their associated technology factors are shown. By implementing these technology factors, the results with wing area adjusted are shown in Table 7.7.

As shown table 7.7 quite significant fuel and cost savings can be made from implementing such a technology. A savings of 17.7% in fuel and 4.6% in TOC is possible due to the fact that GTFs would reduce SFC, which has the strongest effect on required fuel mass. Also, these values would be slightly overestimated due to the reason mentioned in section 6.4. A GTF can be implemented as a retrofit if the wings on an existing aircraft has sufficient structural strength reserve for the heavier engines during taxi to the runway and landing. During flight the extra engine weight would provide bending relief. However, when the
Table 7.6: Geared Turbofan case parameter adjustments and associated technology factors

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Adjustment [%]</th>
<th>Technology Factor [-]</th>
</tr>
</thead>
<tbody>
<tr>
<td>SFC</td>
<td>-[10-15]</td>
<td>1.1-1.15</td>
</tr>
<tr>
<td>Engine Mass</td>
<td>+[5-10]</td>
<td>1.05-1.1</td>
</tr>
</tbody>
</table>

Table 7.7: Changes in performance indices for Geared Turbofan analysis with adjusted wing area

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Min [%]</th>
<th>Max [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>∆mFuel</td>
<td>-11.8</td>
<td>-17.7</td>
</tr>
<tr>
<td>∆MTOM</td>
<td>-1.5</td>
<td>-3.5</td>
</tr>
<tr>
<td>∆TOC</td>
<td>-2.8</td>
<td>-4.6</td>
</tr>
</tbody>
</table>

wing is not loaded by aerodynamic lift, and downward forces are experienced (e.g. during taxi to the runway with full fuel tanks and landing) the wing must be able to withstand these greater loads from the heavier engines. Therefore if the wing has the required structural strength and ground clearance for the increased bypass ratio, GTFs can be implemented as replacements to engines with the current turbofan architecture. Thus it would be of interest to look at the results with a fixed-wing, which are shown in table 7.8.

Table 7.8: Changes in performance indices for Geared Turbofan analysis with fixed wing

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Min [%]</th>
<th>Max [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>∆mFuel</td>
<td>-11.7</td>
<td>-17.1</td>
</tr>
<tr>
<td>∆MTOM</td>
<td>-1.3</td>
<td>-2.8</td>
</tr>
<tr>
<td>∆TOC</td>
<td>-2.7</td>
<td>-4.3</td>
</tr>
</tbody>
</table>

As seen in the results applying a GTF engine into an aircraft design early on in its development has a benefit in fuel savings over a retrofit of approximately 0.6%, and in TOC savings over a retrofit of 0.3%. This slightly increased difference over the winglet technology is due to the fact that the parameter adjustments made for this technology are further away from reference values. Thus the snowball effect on reductions in mass from adjusting the wing area is slightly accentuated.

7.1.4 Retrofittable Technologies Case

For this case all technologies that are retrofittable in the technology portfolio of this study will be applied and the results for the fixed-wing analysis will be analysed. This case would give an insight into the potential fuel and costs savings that can be made on currently operating aircraft with retrofitted technologies. This is important as newly designed aircraft that are more efficient are gradually implemented into the larger global
fleet over time. It is therefore of interest to observe the potential fuel and costs savings that can be made with the already existing fleet that is expected to still be operating for decades to come. For this case five technologies were included, which are shown in table 7.9. By applying the relevant technology factors the results shown in table 7.9 were obtained.

Table 7.9: Parameters affected by retrofittable technologies

<table>
<thead>
<tr>
<th>Technology</th>
<th>Parameter</th>
<th>Adjustment [%]</th>
<th>Technology Factor [-]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Geared Turbofan</td>
<td>mEngine</td>
<td>+[5-10]</td>
<td>1.05-1.1</td>
</tr>
<tr>
<td></td>
<td>SFC</td>
<td>-[10-15]</td>
<td>0.85-0.9</td>
</tr>
<tr>
<td>Wingtip Devices</td>
<td>L/D</td>
<td>+[4-6]</td>
<td>1.04-1.06</td>
</tr>
<tr>
<td></td>
<td>mWing</td>
<td>+[5-8]</td>
<td>1.05-1.08</td>
</tr>
<tr>
<td>Drag Reducing Coatings</td>
<td>C\textsubscript{Do}</td>
<td>-[3-5]</td>
<td>0.95-0.97</td>
</tr>
<tr>
<td>WFCS</td>
<td>mSystems</td>
<td>-[15-20]</td>
<td>0.8-0.85</td>
</tr>
<tr>
<td>Lightweight Cabin</td>
<td>mFuselage</td>
<td>-[1-2]</td>
<td>0.98-0.99</td>
</tr>
</tbody>
</table>

Table 7.10: Changes in performance indices for retrofittable technologies analysis

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Min [%]</th>
<th>Max [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\Delta m_{\text{Fuel}})</td>
<td>-16.0</td>
<td>-23.6</td>
</tr>
<tr>
<td>(\Delta MTOM)</td>
<td>-2.2</td>
<td>-4.9</td>
</tr>
<tr>
<td>(\Delta TOC)</td>
<td>-3.8</td>
<td>-6.3</td>
</tr>
</tbody>
</table>

As seen in the results for this case a potential fuel savings of 23.2% and cost savings of 6.3% is possible. In the TERESA project this case was performed without the GTFs included. Thus in order to have a proper comparison this case was performed again but with the GTF technology excluded. The results can be seen in table 7.11.

Table 7.11: Changes in performance indices for retrofittable technologies analysis without geared turbofan technology

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Min [%]</th>
<th>Max [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\Delta m_{\text{Fuel}})</td>
<td>-6.9</td>
<td>-9.9</td>
</tr>
<tr>
<td>(\Delta MTOM)</td>
<td>-1.4</td>
<td>-2.8</td>
</tr>
<tr>
<td>(\Delta TOC)</td>
<td>-1.8</td>
<td>-2.9</td>
</tr>
</tbody>
</table>

As can be seen the GTF has a considerable impact on the potential fuel and cost savings adding around 13% to the potential fuel savings from this case.
7.1.5 In-Design Technologies Case

In many cases by combining technologies in one aircraft design the negative effects of one of the technologies can be reduced or mitigated entirely. An example of such a combination would be combining an NLF wing with ALA. The added wing weight that comes with an NLF wing can be reduced by an ALA system. The final case that will be analysed is the combination of all technologies mentioned in this thesis, determining the potential performance improvements for a newly designed future aircraft configuration. For this case eight different technologies were included, however, the composite structure technology can be applied to both the wing and the fuselage. These technologies along with the remaining technology portfolio are shown in table 7.12.

<table>
<thead>
<tr>
<th>Technology</th>
<th>Parameter</th>
<th>Adjustment [%]</th>
<th>Technology Factor [-]</th>
</tr>
</thead>
<tbody>
<tr>
<td>NLF</td>
<td>L/D</td>
<td>+[20-30]</td>
<td>1.2-1.3</td>
</tr>
<tr>
<td></td>
<td>mWing</td>
<td>+[20-25]</td>
<td>1.2-1.25</td>
</tr>
<tr>
<td>ALA</td>
<td>mWing</td>
<td>-[20-25]</td>
<td>0.75-0.8</td>
</tr>
<tr>
<td>Wing Composite Structure</td>
<td>mWing</td>
<td>-[15-20]</td>
<td>0.8-0.85</td>
</tr>
<tr>
<td>Fuselage Composite Structure</td>
<td>mFuselage</td>
<td>-[10-15]</td>
<td>0.85-0.9</td>
</tr>
<tr>
<td>Geared Turbofan</td>
<td>mEngine</td>
<td>+[5-10]</td>
<td>1.05-1.1</td>
</tr>
<tr>
<td></td>
<td>SFC</td>
<td>-[10-15]</td>
<td>0.85-0.9</td>
</tr>
<tr>
<td>Wingtip Devices</td>
<td>L/D</td>
<td>-[4-6]</td>
<td>1.04-1.06</td>
</tr>
<tr>
<td></td>
<td>mWing</td>
<td>+[3-5]</td>
<td>1.03-1.05</td>
</tr>
<tr>
<td>Drag Reducing Coatings</td>
<td>$C_{D_0}$</td>
<td>-[3-5]</td>
<td>0.95-0.97</td>
</tr>
<tr>
<td>WFCS</td>
<td>mSystems</td>
<td>-[15-20]</td>
<td>0.8-0.85</td>
</tr>
<tr>
<td>Lightweight Cabin</td>
<td>mFuselage</td>
<td>-[1-2]</td>
<td>0.98-0.99</td>
</tr>
</tbody>
</table>

In this case the open rotor technology was left out. This decision was made due to the fact that by deviating analysis parameters so far from reference values the validity of the results, would be in doubt. By applying the relevant technology factors the results shown in table 7.13 were obtained.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Min [%]</th>
<th>Max [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Delta m_{Fuel}$</td>
<td>-26.4</td>
<td>-35.6</td>
</tr>
<tr>
<td>$\Delta MTOM$</td>
<td>-9.3</td>
<td>-15.0</td>
</tr>
<tr>
<td>$\Delta TOC$</td>
<td>-8.5</td>
<td>-12.4</td>
</tr>
</tbody>
</table>

As seen in table 7.13 the technologies within the portfolio of this project have the potential to save 35.6% fuel mass and 12.4% in operating costs. As can be seen a reasonably large improvement in fuel and cost economy can be achieved from just a few technologies that
could be implemented into aircraft design certified close to the year 2020. However, the question remains how far these fuel savings would go in achieving the 2050 CO\textsubscript{2} reduction goals.

### 7.2 Results Overview

An overview of the results from the case studies performed in this chapter is presented in table 7.14.

<table>
<thead>
<tr>
<th>Case</th>
<th>Fuel Savings [%]</th>
<th>TOC Savings [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Natural Laminar Flow</td>
<td>10.1 - 13.8</td>
<td>1.4 - 2.7</td>
</tr>
<tr>
<td>Winglet (retrofit)</td>
<td>4.0 - 5.4</td>
<td>0.7 - 1.2</td>
</tr>
<tr>
<td>Geared Turbofan (retrofit)</td>
<td>11.7 - 17.1</td>
<td>2.7 - 4.3</td>
</tr>
<tr>
<td>Retrofittable Technologies</td>
<td>16.0 - 23.6</td>
<td>3.8 - 6.3</td>
</tr>
<tr>
<td>Retrofittable Technologies (excluding GTF)</td>
<td>6.9 - 9.9</td>
<td>1.8 - 2.9</td>
</tr>
<tr>
<td>In-Design Technologies</td>
<td>26.4 - 35.6</td>
<td>8.5 - 12.4</td>
</tr>
</tbody>
</table>

Comparing these values to those obtained in the TERESA project the results can be seen as close to each other. In the TERESA project 5-12\% fuel savings was estimated for retrofits (excluding GTFs). The 6.9-9.9\% estimate from this study is located right in the middle of the estimate of TERESA. However, the TERESA results are considerably lower than the 23.6\% savings estimated for the retrofit case including GTFs. The difference of 9-14\% in fuel savings and 2-3\% in cost savings between the two cases shows the potential of implemented GTFs as retrofits. By comparing the results of including all technologies from the TERESA project and this study it can be seen that the results are close. The 26.4-35.6\% estimates from this study are at the lower end of the 27-48\% estimate for a newly designed aircraft post 2020 (also excluding open rotor technology) from the TERESA project. In this case for the TERESA project, additional technologies, such as fuel cells for secondary power, were implemented. Thus the greater fuel savings could originate from this additional technology. The savings from the different case studies as well as those from the TERESA project are shown in figure 7.1.

In light of the Flightpath 2050 goals these results show that technologies under development have the potential to save up to 35\% in fuel consumption, and thus similar figures in CO\textsubscript{2} emissions. However, these savings are unlikely to be enough to curve the increasing emissions caused by the ever-increasing amount of air traffic. Figure 7.2 illustrates the projected CO\textsubscript{2} levels up until 2050 if only these fuel savings of 35\% were achieved till then. In this projection, IATA’s estimation of the projected global air traffic growth level of 4.1\% was used and assumed constant up to 2050. The fuel savings of 35\% was assumed to be gradually achieved by 2022 (the earliest that all these technologies are estimated to be applicable to aircraft). As can be seen the CO\textsubscript{2} emissions would temporarily decrease but the continued global growth in air traffic quickly counteracts these
savings and ends up increasing CO$_2$ emissions by a factor of at least 2.5. This projection is simplistic in assuming all aircraft missions make the same savings (both long, mid-, and short range) and the air traffic expands equally for each of these aircraft missions up until 2050. However, it still illustrates that more radical changes in aircraft design are needed, such as open rotor engines and unconventional aircraft configurations, including among others the blended-wing-body and box-wing configuration.

Although these measures will go a long way in reducing CO$_2$ levels, there are issues with only relying on technological advancements to reduce global CO$_2$ levels. With reduced fuel and MTOM comes a reduced TOC, as seen in this study. This reduced operating cost would ultimately lead to further reductions in flight prices for the passenger. This would then lead to further increases in air traffic, additional to those coming from emerging economies. It would also lead to increased amount of long range travel, further adding to CO$_2$ emissions. Therefore it becomes clear that improvements in aircraft performance cannot be the only measures taken to reduce CO$_2$ levels. As shown in figure 3.1, the use of bio-fuels, with lower CO$_2$ emissions, along with other operation and infrastructure measures, such as CO$_2$ quotas, will be needed in reaching the FlightPath 2050 goals. Only with continued use of radical operational measures and technological advancements will it be potentially possible to bridge the remaining gap towards the radical reduction of CO$_2$ emissions needed in order to combat global warming.

It is important to recognize the limitations of this study. One of them being that the empennage geometry is kept constant throughout the analysis. With changes in masses

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**Figure 7.1**: Overview of case study results (dotted lines represent the corresponding results of the TERESA project)
7.2 Results Overview

![Graph showing passengers and CO₂ emissions](image)

**Figure 7.2:** Growth of passengers and CO₂ emissions with 35% improvement in fuel consumption achieved by 2022 (adapted from [3, 77])

comes a change in centre of gravity location. This undoubtedly would affect the stability of the aircraft and therefore a stability and balance analysis would be required to size the horizontal and vertical stabilizers. This change in empennage geometry could positively or negatively effect the performance of the aircraft. Another limitation of this study is the use of the NLF technology in the technology portfolio, but the wing planform (except for the area) remained unchanged. With implementation of NLF a drastic change in sweep, airfoil, and HLD will be required in order to achieve laminar flow over the wing [32]. Without making these changes the full effect of this technology on the aerodynamic performance of the aircraft remain uncertain. Changes in drag divergence Mach number from the change in sweep and airfoil are just one of the effects not accounted for in this study. Another limitation is with the analysis process itself. Artificial adjustment of parameters gives insight into a technologies potential, however, results are dependent on knowing by how much a certain technology effects analysis parameters. This can be dependent on a number of factors, and the effect of technologies can vary for each segment of a prescribed mission. Further higher-fidelity simulation of these technologies are required to get a complete overview of their potential. Despite these limitations the method of artificially adjusting parameters within the analysis workflow does have the advantage of giving an insight into the potential of these technologies as well as the interactions between disciplines and their corresponding analysis results.
7.3 Visualisation Tool in Assisting in Advanced Technology Design

As mentioned in section 6.3, the results from the verification process outlined can be used along with the visualisation tool to assist in the design of technologies. If a certain technology is known to improve a certain parameter by a certain amount but has a negative effect on another, the engineer is able to make an estimation of by how much the technology can negatively effect that parameter while reaching performance goals. An example of this process with an engine technology is outlined below.

1. A certain engine technology is known to reduce SFC by at most 5%. Therefore this value is set in the Parameters panel by a technology factor of 0.95, as shown in figure 7.3.

![Figure 7.3: Set SFC technology factor to 0.95 in visualisation tool](image)

2. Compute results for fuel mass by selecting fuel mass from the drop-down menu in the Results panel and pressing the Compute results button. By selecting the reference check-box the results are shown with respect to the reference values, as shown in figure 7.4.

![Figure 7.4: Compute fuel mass with respect to reference values in visualisation tool](image)
3. The engine technology is known to increase engine weight along with its reduction in SFC. In order to make the technology worth the required development costs the technology must create a total fuel savings of at least 5%. Therefore by adjusting the engine mass technology factor and re-computing the fuel mass, the maximum allowable change in engine mass while still achieving fuel savings goals can be found, as shown in figure 7.5. For this case an maximum increase in engine mass of 6% is possible. The 2D plotting function shown in section 6.3.6 could also be used in estimating the maximum allowable engine weight by plotting changes in fuel mass against changes in $\phi_m\text{Engine}$ and find the point at which the curve achieves 5% fuel savings.

![Figure 7.5: Determine maximum increase in engine mass at which fuel savings goals are still achieved with visualisation tool](image)

This sort of process can improve the design process of a technology, by determining estimates for design goals and knowing whether a certain technology will be beneficial for overall aircraft performance at the conceptual stage of its design.
From the work done in this thesis a number of conclusions can be drawn along with a number of recommendations for future work. First a summary of the conclusions made concerning the thesis objective will be made, followed by a summary of the limitations of this study and recommendation for future work.

8.1 Conclusions

This thesis project started with the main objective to:

Investigate, in a collaborative design environment, the potential of both retrofittable and non-retrofittable technologies currently under research on the overall design of a mid-range passenger conventional aircraft, from an operating cost and fuel consumption point of view.

To achieve this objective a number of case studies were analysed in which the potential of a number of different technologies were investigated. The results of these case studies can be seen again in table 8.1.

<table>
<thead>
<tr>
<th>Case</th>
<th>Fuel Savings [%]</th>
<th>TOC Savings [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Natural Laminar Flow</td>
<td>10.1 - 13.8</td>
<td>1.4 - 2.7</td>
</tr>
<tr>
<td>Winglet (retrofit)</td>
<td>4.0 - 5.4</td>
<td>0.7 - 1.2</td>
</tr>
<tr>
<td>Geared Turbofan (retrofit)</td>
<td>11.7 - 17.1</td>
<td>2.7 - 4.3</td>
</tr>
<tr>
<td>Retrofittable Technologies</td>
<td>16.0 - 23.6</td>
<td>3.8 - 6.3</td>
</tr>
<tr>
<td>Retrofittable Technologies (excluding GTF)</td>
<td>6.9 - 9.9</td>
<td>1.8 - 2.9</td>
</tr>
<tr>
<td>In-Design Technologies</td>
<td>26.4 - 35.6</td>
<td>8.5 - 12.4</td>
</tr>
</tbody>
</table>
It was estimated that for retrofittable technologies, that included winglets, geared turbofan engines, drag reducing coatings, WFCS, and a lightweight cabin a potential fuel savings of 16-24% is attainable. This shows that fuel and cost savings can still be made on the existing global fleet through the implementation of these retrofittable technologies, and not require the development of a new aircraft. It was also estimated that for future aircraft designs, including additional to the retrofit case NLF, ALA, and composite structures (both wing and fuselage) a 26-36% fuel savings was achievable. These sort of fuel savings could be reached as early as 2022. However, a maximum fuel savings of around 35%, and thus similar levels in CO\textsubscript{2} emissions, won’t be enough to curve the increasing emissions caused by the ever-increasing amount of air traffic. More radical changes in the aircraft industry is needed, such as implementing radical new technologies and aircraft configurations that improve aerodynamic as well as engine performance. Technologies that improve performance in these areas of aircraft design have shown to be the most promising in reducing fuel consumption and therefore CO\textsubscript{2} emissions. Only by adopting the use of new fuel sources and other radical operational and infrastructure measures will it be potentially possible to reach the FlightPath 2050 CO\textsubscript{2} emission goal in order to combat global warming.

In order to assist in effective communication in collaborative design, the visualisation tool was developed. This tool has been developed to assist in the generation of 2D and 3D plots, therefore aiding in the identification of inter-disciplinary correlations within the IDL. This will ultimately lead to improve transfer of knowledge between involved engineers. The tools functionality has been demonstrated in this report. Along with the results from the technology factor analyses the tool has the ability to assist in the early conceptual design of a technology. Estimates can be made for design goals and knowing whether a certain technology will be beneficial for overall aircraft performance at the conceptual stage of its design. The power of this technology factor analysis combined with this visualisation tool was demonstrated in this study. As shown in this report, this methodology gives an easy way to compare technologies, or combining technologies onto an aircraft and assessing its effect on performance. The system that has been built during this project can be used and built upon as more physics-based analysis tools become available. The visualisation tool can also be applied to other collaborative design projects in order to assist in the effective communication of inter-disciplinary correlations and analysis results.

\section*{8.2 Limitations & Recommendations}

There are a couple of limitations to this study. One of the main ones being that the emphenmage is kept constant throughout the analysis. With changes in masses comes a change in centre of gravity location. This undoubtedly would effect the stability of the aircraft and the size the horizontal and vertical stabilizers, ultimately effecting the MTOM of the aircraft. Another limitation of this study is the use of the NLF technology in the technology portfolio, but the wing planform (except for the area) remained unchanged. With implementation of NLF a drastic change in sweep, airfoil, and HLD will be required in order to achieve laminar flow over the wing \cite{32}. Without making these changes the full effect of this technology on the aerodynamic performance of the aircraft remain uncertain. Another limitation is the analysis procedure itself. The method of artificially adjusting
parameters within the design workflow does have the advantage of giving an insight into
the potential of these technologies and combinations of technologies as well as the in-
teractions between disciplines and their corresponding analysis results. However, further
higher-fidelity simulation of these technologies are required to get a complete overview of
their potential.

Another limitation of this study is that other aspects of the Flightpath 2050 goals are
neglected, such as the tightened restrictions on noise pollution and increased safety and
security. These aspects were not included due to lack of methods to estimate them. How-
ever, this study develops a methodology on which to build upon. The developed workflow
has the ability to have disciplines or higher-fidelity tools (once they become available) added or removed. For example, a tool to estimate noise from a certain technology can be added to analyse its potential in that part of the Flightpath 2050 goals.

For future research a few recommendations can be made:

- Implementation of the DACE toolkit within RCE would be useful in automatically
generating a model from DOEs.
- Implementation of the Import function of the visualisation tool within RCE would allow for CPACS data to be automatically saved into the visualisation tool for
communication purposes.
- The visualisation tool could be extended in providing a function that performs the
procedure shown in chapter 7.3 automatically, improving its capabilities in improv-
ing technology assessment.
- In the current study structural health monitoring was not included as a technology
due to the inability to assess its cost saving potential. Analysis into this technologies
benefits on operating cost would be useful in assessing the viability of the Flightpath
2050 goals.
- This methodology of technology factors can be built upon. One such possibility
is to implement an engine cycle analysis tool in order to adjust engine parameters
within the engine cycle itself and observe its effect on performance.
- Implementation of an engine analysis tool that can perform noise analysis would
broaden the knowledge gained on the effect of the technology factors on other Flight-
path 2050 goals.
- A weight and balance analysis is required in order to size the horizontal and ver-
tical stabilizers and have a more accurate perspective of the effects on the mass-
breakdown.
- Analysis on a long range aircraft such as the D250, an A330-like aircraft, would
provide an insight into the differences in performance improvements for an aircraft
with a different mission.
- Workflows to design and analyse radical technological advancements, such as un-
conventional configurations, or open rotor engines will go a long way in assessing
the performance gains to be achieved in future aircraft designs.


Appendix A

Design of Experiment Methods

A number of DOE methods have been developed over the years. These methods include the Central composite design, Monte Carlo Sampling, and Latin Hypercube sampling techniques, which will be discussed in the following sections.

A.1 Central Composite Design

This classical DOE technique \cite{78} is a simple sampling technique with sample points located at the centre and vertices of the design space along with data points outside the design space in order to allow estimation of curvature (see figure A.1). With Central Composite Design (CCD) the number of samples grow with the dimension of the design space, \( n \), according to the formula \( 2^n + 2n + 1 \).

![Figure A.1: A Central Composite Design from classical DOE for design space \([0,1]^2\) and \( n = 2 \) \cite{78}](image)

From figure A.1 several drawbacks with this classical DOE can be observed. The number of sample points increases by \( 2^n \), which for cases with large \( n \) or computationally
expensive function evaluations is unacceptable. Another drawback is that with CCD and other classical DOE methods the interior of the design space is mostly unexplored, with emphasis on or near the design space boundaries. This can be seen in figure A.1 with only one sample point in the interior of the design space.

A.2 Psuedo-Monte Carlo Sampling

Psuedo-Monte Carlo Sampling [78], in many cases know simply as Monte Carlo methods, makes use of a psuedo-random number generation algorithm to mimic a random natural process to pick its sample points. With a design space psuedo-Monte Carlo sampling selects a random number that lies within the design space boundaries. This sampling technique is simple to implement and easily extended to multi-dimensional problems, a two-dimensional problem can be seen in figure A.2.

![Figure A.2: An example of psuedo-Monte Carlo Sampling for design space $[0,1]^2$](image)

One issue with the Monte Carlo method is the selection of a reliable algorithm to generate the random numbers. Another drawback is that, due to the random and independent nature of the sampling sites, large regions of the design space can be left unexplored. A number of modern methods have been developed to counter this problem. One of these are mentioned in the following section.

A.3 Stratified Monte Carlo Sampling

The Stratified Monte Carlo Sampling method [78] was developed to attempt to provide a more uniform sampling of the design space. In this method each of the $n$ intervals are divided into subintervals (so called "bins") of equal probability. Thus for a problem with all design variables having a uniform probability distribution the bins would be of equal dimensions. Then a sample point is randomly selected in each bin. The Stratified Monte Carlo Sampling method is illustrated in figure A.3.

With Stratified Monte Carlo sampling the design space is more uniformly explored. In addition flexibility is given to the user in defining how many bins are to be created, allowing for tailoring of the problem to the available computational budget.
A disadvantage to this method is that at best the number of samples increases by $2^n$. Which, similarly to the CCD method, may not be possible for cases where $n$ is large or the function evaluation is computationally expensive.

A.4 Latin Hypercube Sampling

A popular modern DOE, commonly used in aircraft design, the Latin Hypercube Sampling method (LHS) \cite{78} has been found to more accurately approximate the mean value of the function than does Monte Carlo sampling. The LHS method also provides the user more flexibility in the number of sample points to tailor the problem to the available computational budget. This means that the user can decide on any number of sample points regardless of the number of parameters the problem has. This is, unlike many of the classical and modern DOE methods, available where the number of sample points is at best in the order of $2^n$.

For $p$ Latin hypercube samples the range of each parameter is divided into $p$ bins of equal probability. Thus for $n$ design parameters the number of bins is equal to $p^n$. Then $p$ sample points are randomly placed inside a separate bin such that for all one-dimensional projections of the $p$ samples and bins, there will be only one sample in each bin. For a two-dimensional case this means that there will be no more than one sample point in each row and column. The Latin Hypercube sampling method is illustrated in figure A.4.

One disadvantage of the LHS method is that there is more than one possible arrangement of sample points that meet the LHS criteria. One possibility, for the example shown in figure A.4, is that all four sample points are placed in the bins along each diagonal. This does not allow for sufficient coverage of the design space.

There are extensions to the basic LHS method that allow for minimized correlation between the sample points (thus avoiding the issue with LHS mentioned previously) and can even allow the user to define a correlation between the samples.
A.5 Orthogonal Array Sampling

Orthogonal array (OA) sampling \cite{78} produces a set of samples with uniform sampling in any $t$-dimensional projection of an $n$-dimensional design space. OA sampling is very similar to the Latin Hypercube sampling method. LHS is actually a special case of OA sampling where $t = 1$. $t$ here is known as the strength of the OA. An example of the OA sampling method can be seen in figure A.5. In the figure one sample point is randomly placed in the shaded bins, thus for every two dimensional projection of the design space there is one sample in each bin.

A drawback of the OA method is the inability for the user to define the number of samples according to the available computational budget. The number of sample points is defined by the requirement to satisfy orthogonality (see \cite{78}). This means there only certain combinations of OA parameters that satisfy this requirement.
A.6 Quasi-Monte Carlo Sampling

Quasi-Monte Carlo Sampling (QMC) \cite{78} uses a deterministic algorithm that aims to generate samples in the design space that are as close to a uniform sampling as possible. Thus the QMC method seeks to distribute the sample points evenly throughout the design space while not making use of a regular grid or Cartesian lattice. One algorithm that fulfils this task is the Hammersley Sampling Algorithm \cite{78}.

The clear advantage of QMC sampling is that the design space is equally covered, not leaving areas unexplored. This ensures that an adequate analysis of the design space is performed to create accurate response surface models.
Response Surface Modeling techniques

From the design of experiments response data is obtained which should then be interpolated into a so-called response surface model or metamodel. This would allow for a cheap and quick representation of the complete simulation. These models can then be used to gain knowledge on the design space through analysis and optimisation [18]. There are a number of possible methods in order to generate these models which are explained in the subsequent sections.

B.1 Polynomial Response Surfaces

Polynomial response surface models [20] have been widely used for generating approximations for many applications. The form of a second order polynomial response surface can be observed from equation (B.1)

\[
\hat{y} = \beta_0 + \sum_{i=1}^{k} \beta_i x_i + \sum_{i=1}^{k} \beta_{ii} x_i^2 + \sum_{i} \sum_{j} \beta_{ij} x_i x_j
\]  

(B.1)

The coefficients \( \beta \) are determined through least square regression to minimise the sum of the deviations of the polynomial approximation from the previously determined response data. This is done using the following equation:

\[
\beta = [X'X]^{-1} X'y
\]  

(B.2)

where \( X \) is the design matrix of sample data points and \( y \) is a column vector that contains the values of the response data. Polynomial response surface models have the benefit of easy construction and is advantageous when it comes to smoothing out noisy data; however, the disadvantages of this method appear when highly nonlinear or irregular behaviour is modelled [20].
B.2 Kriging

Originally developed to produce maps of underground geologic deposits based on widely spread samples the Kriging interpolation method has found wide utility in a variety of applications. This is due to the methods benefit of being able to model irregularly spaced data and being able to model surfaces with irregular behaviour [21].

The notion of Kriging is that the sample response data exhibit spatial correlation, with response values modelled via a Gaussian process around each sample location [21]. These Kriging models exhibit the following form [18]:

$$\hat{y} = \sum_{j=1}^{k} \beta_j f_j(x) + Z(x)$$  \hspace{1cm} (B.3)

where the first term is the polynomial approximation of the system and $Z(x)$ is a realization of a stochastic process with mean zero, variance $\sigma^2$, and nonzero covariance. The polynomial approximation provides a Global approximation of the design space while $Z(x)$ applies local deviations such that the model interpolates the sample points [29]. $Z(x)$ is given by [18]:

$$\text{Cov}[Z(x_i), Z(x_j)] = \sigma^2 R(x_i, x_j)$$  \hspace{1cm} (B.4)

where $R$ is the correlation. The basic kriging technique uses only the function value of the sample data. However, the faculty of Aerospace Engineering has developed an extension to this method; a kriging method that makes use of gradient information [80]. This method is called Gradient-Enhanced Kriging (GEK) and has been proven to provide more accurate approximation of a design space with a small amount of addition computational effort required.

Thus kriging is an advantageous interpolation method when sparse sample points are modelled; however if the sample points are too close together the matrix $R$ becomes ill-conditioned, leading to the method becoming unstable [21]. Thus an appropriate DOE to maximize the distance between sample points, such as the LHS method, is required.

B.3 Radial Basis Functions

The Radial basis functions [20] makes use of linear combinations of a radially symmetric function to construct approximation models. A simple radial basis function has the form [20]:

$$\hat{y} = \sum_{i} \beta_i \|x - x_i\|$$  \hspace{1cm} (B.5)

where $\| \cdot \|$ represents the Euclidean norm, and the sum is taken over an observed set of system responses. The coefficients $\beta_i$ are determined by substituting $\hat{y}$ and solving the linear system.
B.4 Multivariate Adaptive Regression Splines

Multivariate Adaptive Regression Splines (MARS) \cite{20,81} approximates the design space by making use of truncated power spline basis functions. The MARS model can be written as:

$$\hat{y} = \sum_{m=1}^{M} a_m B_m(x)$$  \hspace{1cm} (B.6)

where $B_m$ are the basis functions and $a_m$ the coefficients of the basis functions. The basis functions used in the model can be chosen by the user to be either linear or cubic spline basis functions. The MARS algorithm employs a forward/backward stepping process to add/remove spline basis functions from the model. MARS, like polynomial regression, does not exactly interpolate the response data but has the ability to smooth noisy data. A benefit of MARS over the Kriging method is that the approximation process can handle large number of samples that are close together.
Response Surface Modeling techniques
The workflow discussed in chapter 4 was constructed in the integration tool RCE, introduced in section 2.2.2. The various tools and components involved are connected by the CPACS central data exchange format (see section 2.2.1). There are several tools and components involved for not only analyses but data handling and storage as well. The analysis workflow as was implemented in RCE can be seen in figure C.1.
C.1 Initialisation

The first stage in the analysis workflow is the initialisation of the aircraft configuration. This segment of the workflow is shown in figure C.2. During this stage the CPACS input file is provided by the input provider tool. Within this tool all top-level requirements and design parameters are provided in the format VAMPzero and FuCD requires. VAMPzero begins the initialisation of the aircraft configuration by performing conceptual analysis using the requirements and parameters provided. FuCD provides an improved estimation of the fuselage mass and dimensions from the mission and payload requirements. Integration of these tools in RCE is simple since these tools have been developed to be run in RCE. Simply providing the input CPACS file with the input provided in the required format is all that is needed for integration of these tools. The final tool is a simple Component Mass Updater (CMU), which simply updates the OEM given as output by VAMPzero with the updated masses from FuCD.

In order to access whether the results provided by VAMPzero and FuCD are accurate enough a validation of each tool was performed.

C.1.1 VAMPzero

VAMPzero has been utilised in numerous studies and thus has been validated many times in the past. However, the tool is constantly being updated and bugs in the code being fixed, thus in order to access whether the results it provides remain sufficiently accurate an additional validation of the tool was performed during this study. Two aircraft were used in order to validate the tool: the Fokker 100, and A320-200. The requirements and design parameters of these aircraft are provided in table C.1.

By providing these parameters as input into VAMPzero the mass-breakdowns for both aircraft were generated and are compared to the actual masses, which were obtained from [64]. The results are shown in figure C.3.

From the results shown it can be seen that VAMPzero in general provides adequate results for the initialisation of the aircraft configuration. One result deviates from the actual results by more than 10%, which is the wing mass of the F100. These deviations are relatively large but still acceptable for the initialisation of the mass-breakdown. Higher fidelity tools, such as AAE, might be able to reduce this discrepancy.
Table C.1: Overview of requirements and design parameters for test case aircraft

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Fokker 100</th>
<th>A320-200</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Design Range</td>
<td>2390</td>
<td>3704</td>
<td>km</td>
</tr>
<tr>
<td>Cruise altitude</td>
<td>10500</td>
<td>12000</td>
<td>m</td>
</tr>
<tr>
<td>Cruise Mach number</td>
<td>0.77</td>
<td>0.78</td>
<td>-</td>
</tr>
<tr>
<td>Wing area</td>
<td>93.5</td>
<td>122.4</td>
<td>m²</td>
</tr>
<tr>
<td>Aspect ratio</td>
<td>8.43</td>
<td>9.396</td>
<td>-</td>
</tr>
<tr>
<td>Taper ratio</td>
<td>0.24</td>
<td>0.24</td>
<td>-</td>
</tr>
<tr>
<td>Sweep angle</td>
<td>17.45</td>
<td>25</td>
<td>deg</td>
</tr>
<tr>
<td>Nr. of engines</td>
<td>2</td>
<td>2</td>
<td>-</td>
</tr>
<tr>
<td>Nr. of pax (2 class)</td>
<td>97</td>
<td>150</td>
<td>-</td>
</tr>
<tr>
<td>Cargo mass</td>
<td>1000</td>
<td>5000</td>
<td>kg</td>
</tr>
</tbody>
</table>

C.1.2 FuCD

For the same two aircraft the fuselage weight, dimensions, and furnishings weights were computed using FuCD and compared to actual values. The results can be see in figure C.4.

As shown by the results the FuCD tool generally provides results relatively close to the actual values. The discrepancy from the actual values increases slightly for the lower passenger F100, especially for the fuselage mass, with a discrepancy of 11.82%. Perhaps the tool provides better results for higher passenger aircraft. However, the results provided by the tool seem to be sufficiently accurate its role in the workflow.

C.2 Multi-fidelity Analysis

The second segment in the analysis workflow is the multi-fidelity segment. Within this segment the largest amount of tools, mostly physics-based, are incorporated. The first stage is an adjustment module in which the fuselage, engine, and systems masses are adjusted by simple multiplication of the masses by the specified technology factors. The masses are thus extracted from the mass-breakdown that has been updated by the previous CMU, multiplied by the technology factor and then the mass-breakdown updated with these new masses. This adjustment module is placed prior to the converger so that after the updated mass-breakdown from the synthesis segment is provided after one iteration of the fixed-point iteration the technology factors are applied to these masses before checking for convergence. This way the technology factors will be applied before passing on the final design to the cost analysis tool in the case that convergence is reached.

The converger module of the workflow consists of the convergence checker and three python scripts that perform different functions, as shown in figure C.6. One provides the required masses to the convergence checker, another checks whether the convergence checker had provided a true boolean (i.e. stating convergence within 1% had been met) for convergence in both MTOM and OEM. This second script, along with the third
Figure C.3: Comparison of VAMPzero results to actual values

script, then passes the CPACS file onto the cost analysis tool or load case generation tool, depending on the outcome of the convergence check. The third script also updates the counter for the fixed-point iteration, which is used in one of the adjustment modules to determine if the fuselage mass technology factor must be applied (seen as it is only applied on the first iteration).

Within the LCGplus tool the current masses passed on from the converger are used in order to update the load case definition for the aerodynamic analysis. The MTOM weight is updated in the definition along with the required lift coefficient for the maneuver for the load case in question. This coefficient is computed using equation (C.1) where $S$ denotes the wing reference area, and $n$ and $V$ denote the load factor and speed of the specified load case respectively.

\[
C_l = \frac{MTOM \cdot g \cdot n}{\frac{1}{2} \rho \cdot V^2 \cdot S} \tag{C.1}
\]
The updated load case definition and lifting surfaces geometry are then passed onto the Tornado tool for the aerodynamic analysis.

C.2.1 Tornado + VRAero

In this tool the aerodynamic performance maps along with the load distribution of the wing is provided. With this tool, along with the VRAero tool, all aerodynamic loads for the aerodynamic performance maps are estimated. The integration of the external tool Tornado has already been done with the help of a tool wrapper in a previous DLR project, which extracts the wing geometry and load case definition and provides it in the required format for the external tool. The VRAero tool was developed for use within RCE and thus with the help of the TIXI and TIGL libraries extracts its own inputs for estimation of the viscous drag. A comparison of the results from the aerodynamic analysis within this workflow with actual test results for the A320 aircraft (obtained from [75]) was made in order to access its accuracy. The results can be seen in figure C.7.

**Figure C.4:** Comparison of FuCD results to actual values
As can be seen the aerodynamic analysis results are close to the actual results of the A320. The zero-lift drag coefficient estimation from VRAero can be seen to be sufficiently accurate for this study shown by the close proximity of the curves at the lower lift coefficients. The slopes of the curves are slightly different, thus indicating that Tornado slightly underestimates the span-efficiency factor, or Oswald factor, of the wing. However, the differences between the curves are sufficiently small for the scope of this study.

The aerodynamic analysis of Tornado and VRAero ends with the aerodynamic adjustment module that makes use of the process outlined in section 5.8.

C.2.2 AAE + PESTsewi

From the Tornado aerodynamic analysis the workflow splits into three parallel computations, two contain the AAE and PESTsewi analysis. For the AAE tool the lift distribution determined by Tornado is provided for the specified load case. From analysing the the D150 model that has already been passed through the Tornado tool the initial wing weight
estimation from the AAE + PESTsewi combination was computed to be 6336.9kg. This is approximately 28% lower than the actual wing weight of an A320. This considerable underestimation of the wing weight can be due to one main reason. This reason is that in order to obtain this value one critical load case was used. It was shown in previous work with the AAE tool at DLR that for a one load case analysis the estimated wing weight was about 20-25% lower than the expected value [73]. This discrepancy is reduced as the number of load cases included in the analysis is increased. Convergence in the estimated weight was found to occur when 10 load cases were analysed. However, due to the AAE version that was made available during this study, analysis with more than one load case was not possible. Allowing for the analysis of multiple load cases would have been time consuming and would have required longer computation times for one sample point. It was therefore decided that the wing weight analysis with multiple load cases was unnecessary for the scope of this thesis. However, by using the underestimated wing weight in the analysis MTOM was found to be too far from actual values for an A320. In order to obtain a valid reference point for the analysis a correction factor of 1.4 was applied to the wing weight. This provided a wing weight estimation of 8871.7kg, considerably closer to the actual wing weight of 8801kg.

The wing weight then passes onto the wing weight adjustment module which applies a multiplication of the technology factor to the weight.

C.2.3 FSMS

The final component in this segment of the workflow is the FSMS tool. Again this tool has been developed within RCE, thus can be easily added into a workflow in RCE without any wrapper needed. During this analysis certain analysis results will be artificially adjusted at different stages in the workflow, including aerodynamic parameters, OEM components, and SFC. This tool, along with the cost module, will provide the measures of performance for this analysis. Thus it was of interest to check whether the calculated
fuel mass changes as expected when parameter changes in the workflow are implemented. Thus a quick sensitivity analysis was performed, the results of which can be seen in figure C.8.

![Sensitivity analysis of FSMS tool](image)

**Figure C.8:** Sensitivity analysis of FSMS tool

As seen in the plots the FSMS tool provides changes in the fuel mass that are to be expected by the respective changes in the specified parameters. Thus the tool seems to capture the artificial adjustments that will be made during this project correctly.

### C.3 Multi-fidelity Synthesis

The last segment of the analysis workflow is the Multi-Fidelity Synthesis segment (see figure C.9). In this segment the mass-breakdown is re-calculated by VAMPzero while adopting the new higher-fidelity analysis results. In the *NewMasses* tool, the wing and
fuel masses are set in the CPACS file in order for VAMPzero to take these values as constants. The tool also adapts the wing reference area for VAMPzero to use in its analysis by using equation (C.2).

\[ S = \left(\frac{W}{S}\right)_{ref} \cdot MTOM \cdot g \]  \hspace{1cm} (C.2)

Where the first term on the right-hand side of the equation is the wing loading of the reference area. The mass-breakdown is then computed using VAMPzero. Once convergence of 1% was reached by the converger the CPACS file is passed onto the cost analysis module of the initiator.

C.3.1 Cost Analysis

For this tool a \textit{wrapper} was required since only an older version of the initiator had been implemented into RCE to date. For the cost analysis module of the initiator a number of inputs were required in a specific format in an xml file. The inputs included:

- Mass-breakdown (including breakdown of total systems mass)
- Fuselage, wing, engine and emphennage geometries
- Cruise L/D and \( C_{D_0} \)
- Certain performance top-level requirements
All these inputs are provided by the analysis up until this point in the workflow, except for the breakdown of the total systems mass into its sub-components. VAMPzero only provides a total systems mass. Therefore a preliminary run of the *Class2WeightEstimation* module of the initiator was performed in order to obtain a breakdown of the systems masses. The masses are then calibrated to the systems mass determined by the multi-fidelity analysis and adjustment modules. This is an assumption made with this tool, that the ratios of the systems mass components obtained from the initiator are equal to those of the different total systems mass determined by VAMPzero. The required inputs are then extracted from the CPACS file, and along with this calculated systems mass breakdown, is then passed onto the initiator in the required XML file format.

The tool provides a number of outputs, including:

- Operating Cost (both DOC and IOC)
- Non-Recurring Cost
- Recurring Cost
- Unit cost
- List Price
- Quantity of aircraft for break-even

For this study seen as a number of parameters are being artificially adjusted the only outputs that are used for analysis of performance are the operating costs. The other estimations for costs and prices cannot be trusted to provide sufficiently accurate results for this study. For the validation of this tool the reader is referred to [76].
Appendix D

IDL Visualisation Tool User Guide

As the last objective of this thesis a tool to improve effective collaboration between involved engineers from different disciplinary specialisms was needed. This tool would be used in the Integrated Design Lab (IDL) (see figure 2.4) and aimed to provide disciplinary specific output through visualisations and messages understandable for a widely oriented public. This would help convey inter-disciplinary correlations, such as those shown in this study. In this section a user guide for the tool is given. The tool was developed in Matlab 2007b, and has been tested in Matlab 2015a. Thus the tool can be used in any Matlab version in between these two.

D.1 Importing

In order to use the tool some data from analyses is required. In order to extract this data from a large number of CPACS files the import tool was developed. This tool is shown in figure D.1.

In the xml files directory box the folder directory in which the CPACS files to extract the data from are located can be given. The location of the folder can be manually typed in or selected by using the Browse button. Once the user has navigated to the folder the user must select one of the files for the location to be correctly selected. Below the data folder location box are the Inputs and Outputs definitions. The user can add an input or output to extract from the CPACS files by giving a name (of at least four characters) and the xpath of the value. An input/output definition can be modified by selecting the definition, pressing the Edit button, modifying the definition and pressing the Add button. The old unmodified definition can then be removed by making use of the Remove button. Definitions can also be imported from the parameterList.m file by using the Import from m file button. The user must observe the example file in order to determine the required format for the file. The definitions defined in the tool can also be exported to the parameterList.m by pressing the Export to m file. The user must then define the name for the dataset (a default name will be used when no name is specified) and can
select a reference file that must be located in the CPACS files folder defined previously. An option to create an excel sheet containing the data is also available. Thus by using the Import or Import using file definition button the tool will import the defined data. The user can then switch to the visualisation tool by pressing the close button.

D.2 Main Tool

The main visualisation tool interface is shown in figure D.2. With this interface an unlimited amount of 3D and 2D plots can be easily generated. In the Dataset options box the dataset can be chosen from those already imported using the importing tool. The importing tool can be opened by pressing the Import Data button. The user must always press the Refresh button in order to have recently imported datasets visible in the drop-down menu.

For any of the plots the RSM technique can be chosen to be either a polynomial model or Kriging model. The RSM technique can be chosen in the RSM method box. The order of the model for the polynomial model along with the initial guess for Theta and the order of the regression model for the kriging model can be defined. In the Parameters box the
values of the input variables can be defined either by inputing the value manually in the
dialogue box or using the provided sliders. The values are set at the reference values by
default. As seen in the tool interface the number of possible input variables is limited to
ten due to the limitations of the current version of the tool.

In the Results box the values for the selected output variables (selected from the drop-
down menus) can be computed by pressing the Compute results button. The results can
be shown as the absolute value or a ratio of the reference value by selecting the reference
checkbox.

2D plots can be generated by using the 2D plots button. A plot with all the selected input
variables (selected in the Inputs selection menu, multi-selection is possible here) will be
generated. In the plots the output variable can be selected, along with the option to place
a 2nd output in each plot and/or a reference line with the respective checkboxes. One
limitation to the function is that the total number of input and output variables cannot
equal more than eight. For example, if a 2D plot with two outputs is to be produced the
number of inputs is limited to six. This is due to the algorithm used to define the plot
handles in the current version of the tool.

3D plots are generated through the 3D plots button. Each time the button is pressed
two 3D plots will be generated side-by-side with the inputs and outputs selected in the
3D Plot options box. By selecting the plot DOE points checkboxes the data points of the
entire data set will be plotted on the generated 3D plot.

The Update plots button updates all the generated plots with the values defined in the
Parameters box. The auto update checkbox allows this updating of the plots to happen
automatically every time an input parameter value is defined in the Parameters box.

The Position Figures button opens up an interface that allows for easy positioning of
figures on a display. This interface is shown in figure D.3. The display is divided into a 3×6 grid. By selecting the desired location of the top-left and bottom-right corners of the last plot that was selected as the current figure (including the tool’s main interface) and pressing the Position button the plot will be positioned in that location. This tool allows the user to easily position plots on a large display, such as the screen in the IDL.

![Figure D.3: Plot positioning interface](image-url)