Thesis for The Degree of Licentiate of Engineering

Novel, yet similar: A similarity-assisted product family design approach for structural aero-engine components

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Gothenburg, Sweden, 2023

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Abstract

The aviation industry is in a state of transformation. The climate crisis has amplified the need to innovate, and consequently manufacturers in the aviation industry need to investigate new and more sustainable design concepts. This is challenging, because there is no obvious replacement for kerosene-fueled aero-engines, though there are multiple technologies in development that may potentially take its place. Examples of such technologies include electric or hybrid-electric propulsion, or combustion engines fueled by hydrogen or synthetic sustainable aviation fuels. This increases the challenge for manufacturers, who must deal with high technological uncertainty. At the same time, manufacturers need to assert that the cost of realization is feasible for new aero-engine component designs, while also fulfilling the requirements for safety and performance. There is therefore a need for methods and tools that will assist designers in making fast and efficient design evaluations, to enable the exploration of large design spaces at reduced costs and lead-times.

To make design space exploration more efficient, a similarity-assisted design space exploration method is proposed. This method provides increased trustworthiness in design space exploration results, while also highlighting opportunities for reuse of knowledge and other assets from legacy designs. Additionally, a software tool for automatically generating aero-engine structural components has been developed. This software enriches all generated geometries with information used to facilitate automated manufacturability analysis, as well as evaluation of structural performance. By utilizing the automated geometry generation tool in conjunction with the proposed design space exploration method, designers can quickly and efficiently evaluate the manufacturability and structural performance of novel concepts.

Keywords

Engineering design, design support, design space exploration, similarity metrics, aero-engine structures, aerospace

List of Publications

Appended publications

This thesis is based on the following publications:

[**Paper A**] **Martinsson Bonde J.**, Panarotto M., Kokkolaras M., and Isaksson O., *2021, "Exploring the potential of digital twin-driven design of aero-engine structures"*
Proceedings of the Design Society, Volume 1: ICED21, August 2021, pp. 1521-1528, doi: 10.1017/pds.2021.413).

[**Paper B**] Isaksson O., Kipouros T., **Martinsson Bonde J.**, Panarotto M., Kressin J., Andersson P., and Clarkson J.P., *2021, "Multi-domain design assessment for aerospace components including weld accessibility"*
Proceedings of the Design Society, Volume 1: ICED21, August 2021, pp. 2217-2226, doi: 10.1017/pds.2021.483).

[**Paper C**] **Martinsson Bonde J.**, Brahma A., Panarotto M., Isaksson O., Wärmefjord K., Söderberg R., Kipouros T., Clarkson J.P., Kresin J., and Andersson P., *2022, "Assessment of weld manufacturability of alternative jet engine structural components through digital experiments"*
Proceedings of ISABE22.

[**Paper D**] **Martinsson Bonde J.**, Kokkolaras M., Andersson P., Panarotto M., and Isaksson O., *2023, "A similarity-assisted multi-fidelity approach to conceptual design space exploration of aero engine structures"*
In review for journal publication.

Other publications

The following publications were published during my PhD studies, or are currently in submission/under revision. However, they are not appended to this thesis, due to contents overlapping that of appended publications or contents not related to the thesis.

[**a**] **Martinsson Bonde J.**, Borgue O., Panarotto M., and Isaksson O., *2020, "Automatic geometry alteration when designing for metal additive manufacturing"*
Proceedings of NordDesign 2020, August 2020, doi: 10.35199/NORDDESIGN2020.8.

[**b**] **Martinsson Bonde J.**, Mallalieu A., Panarotto M., Isaksson O., Almefelt L., and Malmqvist J., *2022, "Morpheus: The Development and Evaluation of a Software Tool for Morphological Matrices"*
Proceedings of NordDesign 2022, doi: 10.35199/NORDDESIGN2022.38.

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Paper D - A similarity-assisted multi-fidelity approach to conceptual design space exploration

Acronyms

ACARE Advisory Council for Aviation Research and innovation in Europe

AM Additive Manufacturing

CAD Computer Aided Design

DoE Design of Experiments

DRM Design Research Methodology

DS Descriptive Study

EDR Engineering Design Research

EF-M Enhanced Function-Means

FEA Finite Element Analysis

FEM Finite Element Method

IPS Industrial Path Solutions

KBE Knowledge-based Engineering

MDAC Multidisciplinary Analysis Client

PCP Parallel Coordinates Plot

PS Prescriptive Study

RC Research Clarification

RQ Research Question

SAF Sustainable Aviation Fuel

SBCE Set-based Concurrent Engineering

STL Stereolithography

TRS Turbine Rear Structure

UDF User Defined Feature

Part I

Introductory Chapters

Chapter 1

Introduction

The aerospace industry is facing increasingly stringent sustainability targets (ACARE, 2022), the most prominent of which is to achieve net-zero CO_2 emissions by 2050. Consequently, an array of radically new design alternatives are being considered. This includes novel concepts such as hydrogen fueled turbofans, open rotor engines, electrical propulsion, and hybrid solutions. With all these technologies in development, the future of aviation is unclear.

Due to the uncertainty regarding which technologies will be adopted in the future, manufacturers need to be able to respond quickly and accurately to new technology developments to stay competitive. This involves developing the capacity to investigate large design spaces within short time frames. However, to evaluate a design it is necessary to not only look at performance, but also at manufacturability and economic feasibility. This is important, as complex geometries required for high performance designs can be difficult and costly to manufacture. The challenge is thus to gain sufficient knowledge of alternatives in the design space to make performance and manufacturing cost assessment in a limited time. This poses a problem for the aviation industry, which has primarily conducted derivative engine development since the transition from piston-engines to jet-engines in the middle of the 20th century (Singh et al., 2012). In other words, the utilization of *similarity* to previous products has been a key factor to ensure low-risk development of safe and airworthy aircraft. Such similarities may become harder to identify, but all the more important to secure, for manufacturers within the aviation industry to make confident technological jumps towards more sustainable radically new concepts.

In manufacturing companies that have a clear product platform strategy, or a product family approach, engineers make use of design solutions that have been designed and produced before (Jiao et al., 2007). In design situations, engineers frequently use arguments such as that a proposed design has a reduced risk as it has been ”proven in similar products”. The validity of such similarity arguments are however rarely put to the test. It is an open question as to whether the degree of similarity between a proposed new design and an existing design is sufficient to make firm design decisions.

The research presented in this thesis targets aero-engine component designers with the intent to provide methods and tools to assist in making design decisions. That includes methods to identify similarities to existing designs, and tools that makes the process of exploring this vast design space more efficient.

1.1 The state of the aviation industry

Due to the ongoing climate crisis, the aviation industry is forced to reduce emissions. In 2022 it was estimated that the aviation industry was responsible for about 2% of all human-caused carbon-dioxide emissions (Zhang et al., 2020). Organizations such as the Advisory Council for Aviation Research and innovation in Europe (ACARE) has claimed that their end-goal for the aviation industry is to have net-zero emissions by 2050 (ACARE, 2022). Similar claims have been echoed in the United States (Federal Aviation Administration, 2021), and the United Kingdom (Department of Transport, 2022). It is also stated that "significant advances" has been made over the past two decades. While the fuel consumption per passenger mile has been reduced, the gains made with respect to sustainability are outpaced by the growth by the industry (Zhang et al., 2020), with an exception for the COVID-19 pandemic, which has caused a temporary dip in demand (ACARE, 2022; Grewe et al., 2021).

To reach net-zero emissions, manufacturers are looking into multiple alternatives of engine design for future aircraft. This is often done through the mechanism of demonstrators, such as those conducted within the Clean Aviation research and innovation programme (Brouckaert et al., 2018; Clean Aviation, 2020). Some of the most prominent technological alternatives currently under investigation for use in civil aviation are: *1) combustion of Sustainable Aviation Fuels (SAFs); 2) combustion of hydrogen; 3) hydrogen fuel cells; 4) fully electric; and 5) hybrid-electric aircraft with both combustion engines and electric motors* (Dahal et al., 2021). With this many alternatives being investigated all at once, the future of aviation is highly uncertain. In the meantime, the efficiency of existing kerosene-fueled aero-engines is being pushed to its limit. Between 1968 and 2014 the fuel burn of new aircraft per passenger-kilometer was reduced by an estimate of 45% (Kharina et al., 2015). While this trend sounds promising, there are some issues. First of all, it is a long way to go to reach net-zero. Secondly, the service life of an aircraft is approximately 30 years (Airbus, 2022; Niemeyer et al., 2002). This means that if aircraft manufacturers continue to push out non-sustainable aircraft, then many of those will still be in service in 2050. Consequently, Boeing CEO stated in November of 2022 that potentially no new airliners may be rolled out until the middle of the next decade (2030's), to allow more sustainable technology to catch up (Bogaisky, 2022). This calls for a swift response by aircraft systems manufacturers to deliver solutions that can reduce emissions drastically. For this reason, fast and resource efficient evaluation of new design concepts has the potential to provide a major competitive advantage.

Out of the previously listed prominent alternatives the one that is the most feasible in the short term appears to be to fuel aircraft engines using SAFs.

Burning SAFs does not require radical changes to the engine architecture, which makes them attractive to manufacturers as they thus pose a lower risk than the more radical alternatives. SAFs has already been certified for use (Dahal et al., 2021), and have already been introduced to some degree into the operative phase of existing engines by mixing it with kerosene (Zhang et al., 2020). However, SAFs are not likely to be the final solution to reach net-zero emissions by 2050, as they still have many issues that needs to be solved. Two prominent issues with SAFs are: 1) climate impact due to aviation is not caused exclusively by carbon-dioxide emissions, but also by nitrogen oxides, contrails, etc., and 2) the crops needed for biomass-based synthesis of SAFs require a considerable amount of land, causing it to compete with land otherwise needed for food and natural carbon storage (Searchinger et al., 2022). Consequently, it will be necessary to evaluate more radical concepts.

Migrating to electric propulsion has been proposed for smaller aircraft. Electric aircraft has already been a reality for some time, though not for the purposes of shuttling large quantities of passengers. Electric propulsion can be utilized either through a fully electric aircraft (batteries and an electric drive), or through hybrid solutions that utilize some combination of electric drives and traditional air-breathing engines with or without batteries (Wheeler et al., 2021). One of the main issues with these types of aircraft are that their designs are constrained by battery capacity and weight (Epstein et al., 2019). Indeed, contemporary batteries do not provide enough energy with respect to weight.

Hydrogen has also been considered as a possible source of energy (Khandelwal et al., 2013). However, as with the other radical concepts, hydrogen also has a set of exclusive challenges. Here, I will briefly introduce three of the most prominent challenges. Firstly, the hydrogen needs to somehow be contained. It has been suggested that the hydrogen should be cooled until it reaches liquid form to reduce the space needed to store the otherwise gaseous element (Huete et al., 2021). However, the necessary storage volumes for such cryo-tanks are still much larger than what is needed to contain traditional kerosene, which prompts the need for an entirely new fuselage design. Secondly, it is not entirely clear how to mass-produce hydrogen in a carbon-neutral way (Howarth et al., 2021; Palmer et al., 2021). Thirdly, adopting hydrogen on a large scale would require rethinking flight planning and aviation infrastructure (Clean Hydrogen Joint Undertaking, 2020).

The future of aviation is veiled in uncertainty. Only one thing is abundantly clear: how the business has been conducted as of 2023 can not continue.

1.2 Implications for manufacturers of aero-engine structural components

The uncertainty permeates the entire aviation industry. Ultimately, the choice of engine technology will affect all levels of the industry, from airlines to components manufacturers. This thesis primarily concerns the design of aero-engine structural components.

When a new aero-engine is developed, components manufacturers are asked if they can provide various components. This commences an intensive and heavily time-constrained period during which pre-studies are conducted to evaluate design feasibility. For manufacturers of aero-engine components to commit to a new design, confidence needs to be high. A common strategy to increase confidence in new designs is by utilizing a product family approach (Jiao et al., 2007), which entails that there is a degree of similarity between the products within the family, though each instance has been designed to resolve a unique set of requirements. This strategy is useful, since it enables reuse of knowledge and other resources, thus increasing the confidence in the new design, and reduces the risk of not meeting the requirements. However, now that the technology landscape of aero-engines is on the brink of change, additional methods and tools are needed to assert that new designs can be evaluated rapidly and with high accuracy.

Aero-engine components are, during their operational phase, subject to extreme conditions. Such components needs to be designed to handle critical failures, including if a fan-blade becomes detached, which can have catastrophic consequences if not taken into account. On top of that, these components needs to be lightweight, and aerodynamic, to avoid wasting fuel. This results in advanced geometry optimization, which can result in designs that are hard to manufacture. There is therefore also a need to evaluate, already at an early phase, the manufacturability of a design. Thus, the challenge is to create methods and tools that enables rapid and accurate evaluation of performance and manufacturability in the early phases of design, when designing aero-engine components within a product family.

1.3 Research focus

Due to the high uncertainty of the future of aviation, it is paramount that manufacturers within the industry adapt. That involves improving their ability to quickly and accurately respond to emerging new technologies within this evolving technological landscape. This is necessary to stay competitive, and to be a part of the drive towards a more sustainable aviation industry. In an effort to work towards these goals, the aim of this research is to develop new methods and tools to assist in the evaluation of performance and manufacturability of new structural aero-engine component designs within a product family. The intended outcome of this research is thus an improvement to the speed by which manufacturers evaluates new design concepts. The Research Questions (RQs) which this thesis primarily addresses are the following:

RQ1 *What information is necessary to evaluate cost and performance of alternative design concepts in a product family of aero-engine structural components?*

To stay competitive while also responding to increasingly stringent requirements necessitates a rapid and accurate evaluation of new design concepts. The purpose of RQ1 is to create an understanding of what information is needed to perform such rapid evaluations.

RQ2 *What knowledge and assets can be reused between product generations within a product family?*

To speed up the evaluation, development, and manufacturing lead-times of new designs it is common for knowledge, and other assets such as analysis models to be reused. What can be reused depends on the degree of similarity between the two artifacts. With this RQ the aim is to investigate how to determine what assets and knowledge can be reused, and what obstacles exists that may prevent certain product aspects from being reused.

RQ3 *How can analysis and measurement data from previous designs and products be used in the early phases of design?*

RQ4 *How can an automated modeling and simulation support tool be developed that enables comparative modelling-based assessment of alternative design concepts?*

RQ3 and RQ4 contributes to the prescriptive part of this research. Namely, how can the findings from RQ1 and RQ2 be utilized in practice, by means of tools and methods?

1.4 Scope and delimitations

This research is delimited to focus primarily on the products manufactured by a Swedish aero-engine components manufacturer. Consequently, the generality of the results can be discussed, but not fully claimed. It could be argued that, as this company is a first tier supplier within the aero space industry, it is likely that the results are representative also for other manufacturers of highly integrated engine components within the Aerospace industry.

1.5 Thesis structure

In this chapter of the thesis the problem at the core of this research was briefly described. In Chapter 2 fundamental concepts necessary to understand the research results are explained. In Chapter 3 the research methods used to arrive at the results are explained and motivated. In Chapter 4 the most important results are presented. In Chapter 5 the answers to each research question is discussed. Finally, in Chapter 6 the conclusions are laid out, as well as the foundations for future work.

All references made throughout the thesis are listed after the final chapter. Additionally, all papers from which this thesis draws its results are appended at the end of the thesis.

Chapter 2

Frame of reference

The purpose of this chapter is to position this work of research against other academic work. Foundational to this research is the product development process, described in Section 2.1. Part of product development involves the search for designs that fulfill whatever the customer need may be. This search for design is often referred to as "design space exploration", and is detailed in Section 2.2. Finally, acknowledgement is given to previous work that leverages the notion of similarity in the field of engineering design, in Section 2.3.

2.1 The product development process

The product development process has evolved over the years, and one process certainly does not fit *all* companies. In this section a generalized view of traditional product development will be explained (Section 2.1.1), as well as a more contemporary way of conducting agile product development (Section 2.1.2). Finally, in Section 2.1.3 there will be an introduction to the development of aero-engine structural components.

2.1.1 The traditional product development approach

The product development process has been described in many academic works, two of the most prominent being Pahl et al., 2007 and Ulrich et al., 2020. Typically, the process starts with a market opportunity. This could be a problem that exists in society that has not been resolved by existing technologies. It could also be a problem that has already been resolved by one or more competing products, but the existing products do not fulfill all the needs of a certain group of people. For instance, the existing products on the market may be too expensive for some individuals, or have unpleasing aesthetics. In either case, this leaves a gap in the market that can potentially be filled by a new product.

Once a market gap has been identified, the next step is to identify what the potential customers needs for the original problem to be resolved in a satisfactory manner. When discussing aircraft components, a common need is for the fuel consumption to be minimal. Needs are typically converted into requirements, which are more precise criteria of how the final product needs to perform. As Pahl et al., 2007 puts it: *"Requirements should, if possible, be quantified and, in any case, defined in the clearest possible terms"*. In the case of aero-engine structures, a requirement could be the maximum allowed weight to cater to the need for a low fuel consumption. The requirements list contains not only requirements based on customer needs, but also requirements that are internal (e.g., manufacturing constraints), legal, or from some other third party such as a certification agency. The requirements list defines how the final product is expected to perform, and often changes over time as more information is gathered, and knowledge is gained.

With the knowledge of how the final product needs to perform, the process of searching for solutions can begin. Inspiration for new design concepts can be gathered from existing solutions on the market, patents, or even from nature. A common starting-point is to perform a functional decomposition, by first establishing the main function the new product is intended to solve, and then dividing that into smaller problems (sub-functions). Solutions can then be identified for each sub-function, and be combined into a unified solution concept that solves the main function. Typically, several concepts are defined in this manner, which are then systematically eliminated through a concept screening process. Within this screening process, the concepts are evaluated based on their aptitude with respect to the requirements list. If the process is successful then one, or a few, well-performing concepts move on to become designed in detail and eventually put into manufacturing.

This entire process is often divided into stages according to Cooper's "Stage Gate" approach (Cooper, 1990). Between each stage there is a "gate", in which it is decided whether or not to continue the project. These "go/kill-decisions" are typically made by a multidisciplinary team from senior management, and are based on a set of predefined criteria, working as a sort of quality assurance. For instance, a gate positioned immediately after the planning phase may require a list of customer needs for the project to pass to the next stage.

What has been described above is a condensed explanation of traditional product development. While many of the principles of traditional product development continues, a need has surfaced for a more flexible approach. Set-based Concurrent Engineering (Sobek et al., 1999) and agile product development (De Carvalho et al., 2011) are two examples of approaches that increase the flexibility relative to the traditional product development process. To maintain competitiveness the additional flexibility of these modern approaches has appealed to the aviation industry where it is paramount to stay on top of emerging requirements.

2.1.2 Set-based concurrent engineering and agile product development

Traditional product development, as described in Section 2.1.1, is sequential in how each function in the process is executed. It quickly funnels down the design concepts until there is only one or a few left, and then proceeds to detailed design and manufacturing. Set-based Concurrent Engineering (SBCE), on the other hand, operates under a different array of principles (Sobek et al., 1999). Rather than having the company functions perform their task in sequence, there is an overlap. For instance, the manufacturing function can start working on developing the production system layout before the design is fully completed. The longer the design is developed, the more information becomes available for manufacturing to act on. This also works the other way around: as the more developed the manufacturing system is, the more constrained the design space becomes. This constitutes the "Concurrent Engineering" part of SBCE. To also have a "set-based" approach, design engineers maintain large sets of designs at the same time. These design sets, which can be viewed as regions in the design space, are gradually delimited as knowledge of the problem develops, and new requirements emerge. For instance, as the manufacturing function develops the production process, the available design space will contract as certain processes are only possible for a certain sub-set of designs. Such design-delimiting decisions are made throughout the organization as the development project proceeds. Additionally, new or adjusted requirements can also emerge from the customers, resulting in further design space delimitations. However, by maintaining sets of designs without funneling down on individual solutions too quickly, the development process becomes more resilient to such emerging requirements. Thus, designers who practice set-based engineering maintain large arrays of possible designs for as long as possible, to avoid expensive redesigns due to emerging requirements. Joined together with the aforementioned Concurrent Engineering approach, these principles form what is referred to as SBCE.

Besides rethinking how organizational functions structure their workflow, and how design concepts are selected, the traditional stage-gate approach has also been under siege. It has been criticized for being too rigid, sometimes inhibiting technical innovation (Cooper, 2014). While the idea of stage-gates have not completely been replaced, some companies have also incorporated agile methods as a means to increase flexibility. The agile approach, widely utilized in the software industry, promotes the implementation of small deliverables developed over short periods of time (Stare, 2014). These short periods are referred to as sprints, and are one of the key concepts in the agile approach (De Carvalho et al., 2011). The tasks within a sprint are defined at the end of the previous sprint. Each sprint lasts for a few weeks, and typically end with a meeting where lessons learned from the sprint are discussed, and the next sprint is planned. This means that many activities that were traditionally planned during the planning-phase before development starts are, in the agile approach, instead planned during the development-phase itself (Stare, 2014). This enables engineers to respond more quickly to changing conditions (e.g., changes to customer requirements). Thus, the agile approach can be appropriate in development projects where uncertainty is high.

Arguably, both SBCE and the agile approach are highly relevant for the aviation industry, where the uncertainty is high. To further reduce risk, the notion of "product families" has also been adopted into aero-engine structural components development.

2.1.3 Product family design for aero-engine structural components

A product family is a set of products that are related. This relation can be a common knowledge base, shared components, or other company assets that somehow link each family member together (Jiao et al., 2007). These common assets can be referred to as the product platform (Robertson et al., 1998). The products within a product family are thus similar, in some aspect. The main benefit of developing new products within a product family is reduced risks and lead-times, as already proven practices are reused.

A lot of research has been conducted on the topic of how product family and platform approaches can be used to facilitate reuse of knowledge and assets when developing new products. An interesting example is the work conducted by Landahl et al., 2016, who used product platform assets to evaluate the manufacturability of different variants within a product family. This showcased how powerful product families can be, in that manufacturability evaluations can be performed in the very early stages of product design, using only assets already maintained within the family platform.

Another key example is Johannesson et al., 2017, who developed a cohesive method for the development of product families and product platforms. The method is initiated by a functional decomposition of the entire product using the Enhanced Function-Means (EF-M) modeling method. The EF-M model provides an overview of all functions that the product family solves, as well as the design solutions used to solve those functions. All of these functions and solutions are rendered in a tree-format, enabling a visual overview of the product family. This constitutes a model of the product platform, which grows richer for every new product installment. Through a software, product variant descriptions can be extracted using the information contained in the EF-M tree. This approach was later expanded upon by Müller et al., 2019a, who enriched the process by utilizing the EF-M tree to automatically generate Computer Aided Design (CAD) models. This enables highly flexible design space exploration, as will further be discussed in Section 2.2.

When designing aero-engine structural components, it is common for manufacturers to minimize risk by building new products based on previous experience. To that end, scale-based product families (Simpson et al., 2001a) can be employed. A scale-based product family entails that existing solutions are scaled up or down in dimension to suit new customer requirements. This is typically done by varying what Simpson et al., refers to as "scaling variables", which are key design variables that are common to designs within a product family. In that sense, product development of structural aero-engine components is typically derivative, which Wheelwright et al., 1992 defines as refining and improving existing solutions to better meet the needs of specific market segments. Scaling, in the context of aero-engine components, is often related to engine size (which, in turn, is related to thrust and bypass-ratio). Hence why aero-engine component scaling is often done in the early phases of design, as the engine size is determined based on the required thrust. However, once the scaling variables have been determined the design space exploration process begins, in which large quantities of designs are evaluated using the principles of SBCE.

Product families is a key strategic approach for aero-engine components manufacturers. Having the assets, aggregated over the course of previously conducted products, available at the beginning of the development cycle of a new product can drastically reduce lead-times. However, there is still a lot of untapped potential regarding the facilitation of reuse in this area. There is a need to further develop methods and tools for assisting designers in realizing this potential of reuse.

2.2 Design space exploration

According to Woodbury et al., 2006, design space exploration can be defined as the evaluation of relatively large quantities of design points through the assistance of computers. Before the exploration process can begin, it is thus necessary to decide what needs to be evaluated, as there would otherwise be no way of determining preference between two different designs. What to evaluate is typically dictated by the requirements specification (Pahl et al., 2007).

For instance, when developing an aero-engine structural component, the requirements of the design typically entails a structure that is 1) lightweight, 2) stiff, 3) aerodynamic, and 4) manufacturable at a feasible cost. Such criteria can also be referred to as ”design objectives”, and to evaluate a design point with respect to those objectives entails calculation of the weight, Finite Element Method (FEM) analysis of the stiffness and the aerodynamics, and some manufacturability analysis. This leads to the second point: a design point itself is an abstract construct, and thus needs to be represented by some physical or digital object to enable evaluation.

2.2.1 Design point representation through automatic CAD model generation

A common way of representing design points is by CAD models. This is a useful format, since it can be converted to various context models to facilitate different types of analysis. For instance, a FEM simulation requires a mesh, which can be obtained by converting the CAD geometry. But, as Woodbury et al., 2006 points out, design space exploration *involves representing many designs*. Manually creating CAD model representations of many individual design points is typically not feasible. Instead, such CAD models can be automatically generated.

In the Aerospace industry it is common to utilize shell models in the early phases of design, to represent individual design points (Robinson et al., 2011). Shell models are surface-based representations of 3D-geometry, implying that they lack volume. Figure 2.1 shows a shell model of a Turbine Rear Structure (TRS), which is used for visualizing a design point, but also for stiffness and aero analysis.

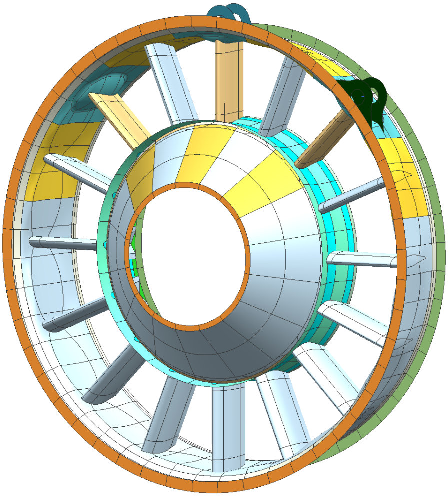


Figure 2.1: A shell model of a Turbine Rear Structure used for early design phase evaluation.

There are many advantages to utilizing shell models for design evaluation. One of the most prominent advantages is that they are computationally inexpensive. When meshing a surface based shell model shell-elements are used, which are significantly faster to run FEM calculations on compared to their three-dimensional counterparts. A second important advantage is how shell models deal with abstracting surface thickness. In short, each surface can be attributed a value that represents the thickness of the surface. This can be done either in the CAD software, or in the analysis software (such as Ansys). This thickness attribute value can then be used by the FEM solver. This simplifies optimization studies, since the model does not need to be regenerated every time the thickness changes. Instead, exploring different design points with varying thicknesses is done by merely changing the surface thickness attributes.

Other approaches exists, however, including methods that facilitate the use of solid models. Sandberg et al., 2017 utilizes CAD journals to automatically generate a solid model of the structural components of a turbo-fan engine. By varying dimensional parameters, different engine variants can be instantiated, from which meshes was extracted for the purposes of Finite Element Analysis (FEA). This work is a clear demonstration of how solid CAD geometries can be automatically generated for the purposes of structural performance evaluation.

Müller et al., 2019a extends the scope of geometry generation by generating solid CAD models based on the functional decomposition of the product. Müller utilizes User Defined Features (UDFs), which can be thought of as "CAD building blocks", which are pieced together based on the characteristics of the functional decomposition. Since this approach utilizes UDFs the flexibility of possible outputs is very high, though it is first necessary to model all of the UDFs. This enables design space exploration beyond the traditional parametric variation, as the geometry can change drastically as different UDFs are applied in various combinations. In doing this, Müller et al., 2019a demonstrates how solid CAD model generation can reach high levels of flexibility, though at the cost of complexity.

The important takeaway here is that automatic solid model generation exists, from the less flexible but more encompassing approach presented by Sandberg et al., 2017, to the highly flexible but more focused approach by Müller et al., 2019b. CAD geometries provides a degree of insight through visualizing the design, and how it all fits together. However, to understand the performance of a design with respect to the design objectives it is often necessary to run simulations, often utilizing the generated geometry.

2.2.2 Design evaluation through simulations and surrogate models

An essential aspect of exploring the design space is to evaluate individual design points. What to evaluate typically depends on a set of design objectives, which are derived from a list of requirements. To evaluate a design is to ensure that the design meets the design objectives as required, and then to compare it against other designs (Pahl et al., 2007). To investigate how well a design fulfills a design objective a common approach is to utilize virtual models and simulations. Simulations enables designers to obtain information regarding a design without committing significant resources (INCOSE, 2015), as performing physical tests is often not cost efficient. However, that does not mean that running simulations is inexpensive. Simulations, especially high-fidelity physics simulations, can be incredibly computationally expensive. For this reason, design engineers often resort to surrogate models.

Surrogate models (also known as metamodels) are, as the name implies, models that are used as surrogates for other models (e.g., simulations) or physical tests. The main reason for using surrogate models are typically that they are significantly less computationally expensive relative to their high-fidelity counterparts (Simpson et al., 2001b). Data-based surrogate models such as response surfaces, neural networks, or Gaussian processes are "trained" using data from another model, such that they can replicate their behaviour at a reduced computational cost. This is particularly useful in optimization studies, where the objective functions are called very frequently. In such a scenario, utilizing a physics simulation (such as a FEA) to evaluate the objective function is often too inefficient. Thus, data-based surrogate models are instead trained using a limited number of inputs and simulation results such that it can predict what the simulation result is (Koziel et al., 2011). Throughout this thesis and its appended papers, the term "surrogate model" is used to refer exclusively to data-based surrogate models.

To maximize the accuracy of a surrogate model it needs to be: a) trained using an appropriate experimental configuration, b) be trained with an appropriate sample size, and c) be an appropriate type of surrogate model. A commonly used Design of Experiments (DoE) configuration is the Latin hypercube (McKay et al., 1979), which is well suited for the purposes of deterministic simulations (Simpson et al., 2001b). The required sample size to produce accurate results is proportional to the dimensionality of the model, a phenomenon often referred to as *the curse of dimensionality* (Keogh et al., 2011). Finally, to select an appropriate surrogate model type requires knowledge of what needs to be predicted (Jin et al., 2001).

2.3 Similarity in engineering design

A common means of mitigating uncertainty in design is to rely on already proven knowledge (Smith et al., 2001). However, for knowledge to be reapplied from one scenario to another there needs to be some degree of similarity between the two. This means that if a new design has similarities to an existing design (for instance, they share common components or a common product platform), then then knowledge can potentially be reused. Naturally, this principle can be exploited by designers by purposefully creating designs that are similar to existing products. This is referred to as design reuse (Sivaloganathan et al., 1999), and can potentially reduce costs and lead-times significantly. This has resulted in methods and tools build around the principle of design reuse, to save time and costs. One such example is Design by Analogy (McAdams et al., 2002), which utilizes similarity metrics to calculate the difference in functionality between two designs. By doing this, designers can be informed of already existing solutions to functions when developing new designs. By utilizing this method designers can avoid having to reinvent the same solution more than once. Another example is Case-Based Reasoning, which also assists in identifying solutions to design problems based on previous design scenarios (Aamodt et al., 1994; Akmal et al., 2014).

Chapter 3

Research approach

Historically, it has been argued that Engineering Design Research (EDR) lacks sufficient scientific foundation (Dixon, 1987), a major issue being the lack of proper hypothesis generation and testing. As (Reich, 1995) puts it: *"In order to sustain credibility, researchers must use and demonstrate that the techniques they develop in design research have some relevance to practice"*.

Engineering design has the purpose of creating or improving some artifact, and thus also incorporates some element of creativity, which is hard to analyze (Antonsson, 1987). Consequently, EDR is not always purely a pursuit of knowledge for the sake of knowledge. However, academics has since committed a substantial effort to bring more structure to design research. Some concrete examples includes how a hypothesis can be formulated to bring EDR into the realm of science (Antonsson, 1987). Furthermore, frameworks such as Design Research Methodology (DRM) (Blessing et al., 2009) has been formulated to provide a standardized way of structuring design research to assert some degree of scientific rigour, if followed.

The research presented in this thesis follows the DRM structure (see section 3.1), to assert a systematic approach to how the research is organized and conducted. Additionally, in response to the criticism voiced by Reich, 1995 regarding the need for design research to have relevance to practice, this research follows the guidelines presented by Isaksson et al., 2020. As discussed in Section 3.2, those guidelines ensures that the research fills an industrial purpose, and that it can be validated.

The aim of this research is not to improve a product, but rather to identify ways of improving the process of developing structural aero-engine components. At no point in this research is an attempt made to find what could be considered "a good design", instead focusing on the methods and tools used to identify "good designs". In this section, the methods and tools used to gather and analyze data is presented, along with the reasoning behind choosing those particular methods and tools.

3.1 Design Research Methodology

DRM consists of four stages (Blessing et al., 2009) (see figure 3.1). The first stage is for the researcher to perform a **Research Clarification** (RC). In this stage, research goals are formulated and the area of contribution is identified. Furthermore, the researcher performs activities to create an understanding and overview of the research problem, such that later research activities can be better planned and tailored for the intended research goals. This often entails extensive literature reviews. The second stage is referred to as **Descriptive Study 1** (DS1). This stage is intended for the researcher to build a better understanding of the current situation, and involves further literature studies and empirical studies where data is collected, for instance through interviews or observations. Once the current situation is understood, and problems identified, the researcher can move on to the **Prescriptive Study** (PS), in which the researcher proposes some type of design support, such as a method or a tool, to improve upon the situation identified in earlier stages. Finally, in **Descriptive Study 2** (DS2), the researcher investigates if the design support described in the PS stage contributes to resolving whatever problem or situation identified in DS1 and RC.

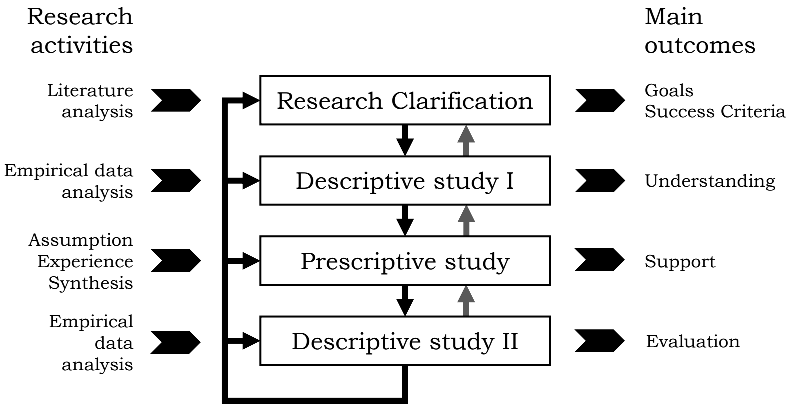


Figure 3.1: The four stages of the DRM framework. Redrawn from Blessing et al., 2009, p 39.

Since one of the aims of the research presented in this thesis is to propose decision support tools and/or methods for use within the design phase in the aviation industry, DRM was deemed a well-suited framework since its structure facilitates that the research gap is identified (RC), and that the needs of the support tools are properly explored (typically in both RC and DS1). Furthermore, DRM highlights the need for verification and validation in its final step, DS2, in which the usefulness of the proposed design support is evaluated. Finally, the stages of DRM allows for iteration (represented by the backwards errors in Figure 3.1), since it is natural that additional questions surfaces as new knowledge is procured.

Table 3.1 demonstrates how the publications appended to this thesis are positioned within the DRM framework, and which research question they attend to. The aim of **Paper A** was to gain a better understanding of the situation at the studied company, and how this research can be positioned relative to the works of others. Hence why **Paper A** contributes both to RC and DS1.

Paper B, C and **D Paper C** all contain prescriptive elements in the sense that design support is proposed. Additionally, all three of these papers contains additional clarification on the current state of the aviation industry, which is why they also contribute to DS1.

DS2 is, for the most part, not covered in this thesis. However, elements of verification are part of **Paper B**, **C**, and **D**. In the form of design studies, the methods and tools proposed in the papers are exemplified, as further described in Section 3.3.3. However, to validate this research its contributions needs to be used in its intended environment, by practicing design engineers. Due to the long lead-times of product development projects in the aviation industry, such a task can only be commenced during a PhD, but likely not completed. The intention, however, is to commence such studies in the near future. In other words, DS2 will be partially addressed in future research.

Table 3.1: How the papers appended to this thesis fit into the DRM framework, and which research questions they address.

Paper	RC	DS1	PS	DS2	RQ1	RQ2	RQ3	RQ4
Paper A	X	X			X	X	X	
Paper B		X	X		X			X
Paper C		X	X		X			X
Paper D		X	X		X	X	X	X

3.2 Journey to validation

In (Isaksson et al., 2020) the importance of focused research claims is discussed. Design research is often conducted in a practical context, and the researcher is expected to make a contribution to both knowledge (for instance, through journal publications) and practice (design support). Isaksson et al., 2020 notes that *"A contribution needs to be novel and to some extent generalizable or transferable. At the same time, it needs to be specific enough to be possible to validate."*. Their paper provides guidelines for how to structure research such that it eventually converges to a claim that can be validated in what they refer to as the *"Journey to validation"* (see figure 3.2).

Research projects are often conducted in collaboration with an industrial partner with a practical problem. However, such problems often span multiple disciplines and are too broad to resolve within the scope of a single research project. Thus it is important to, within this context, identify the research gap and then find a focus within that gap on which to conduct further research. Within this focus a hypothesis can be elicited, and research questions formulated.

The focus helps ensuring that the research is specific enough to be possible to validate. Furthermore, the focus can help ensure that a PhD student have enough time to answer the research questions within the available time-frame.

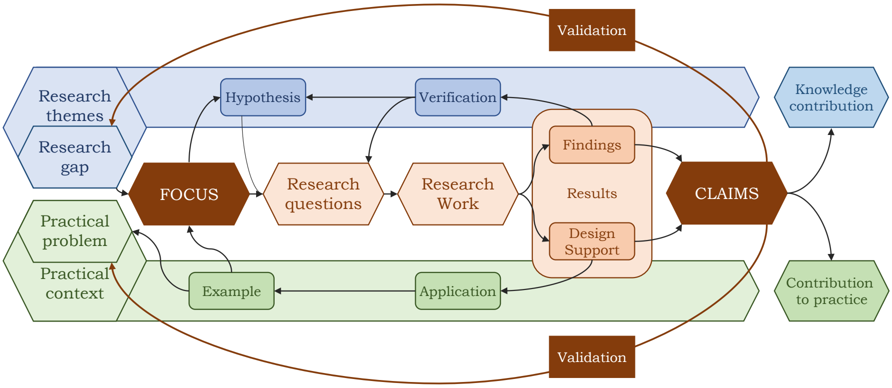


Figure 3.2: The journey to validation. Redrawn from Isaksson et al., 2020.

The research presented in this thesis has been focused to strictly apply to static aero-engine structures. No claims are made that the proposed design support is useful outside of the aviation industry (specifically, aero-engine components design and manufacturing), and thus the claims can be validated through testing within the refined scope. How generalizable the research is, beyond aero-engine structures, can still be discussed. However, the focus remains on this particular slice of the aviation industry.

The industrial context, and the problem which the design support is expected to ameliorate, covers more domains than what can possibly be addressed in this research project, from organizational issues to information science. Consequently, the listed research questions were elicited by focusing on a particular aspect of the original problem which falls within the confines of engineering design. Even with such delimitations in place, plenty of research has been conducted within the remaining scope before. Because of this, extensive literature studies were conducted to identify a research gap within which this research can provide a knowledge contribution, while also contributing to practice through design support.

3.3 Data collection

In this section the different methods utilized for gathering data, for the research in this thesis, is presented and motivated.

3.3.1 Literature search

All academic works appended to this thesis were initiated by performing thorough literature reviews. These reviews were conducted to identify gaps in research, as well as to utilize and build on previously explored ideas. Furthermore, it is paramount that any academic work is positioned relative to other works within the territory to enable the reader to understand the intended context. Table 3.2 provides an overview of the focus of the literature review conducted for each of the appended papers.

Table 3.2: The focus of each literature review for each appended paper.

Paper	***Literature review focus***
Paper A	Manufacturing data and knowledge in design Digital twins in product development
Paper B	Product architecture design Manufacturability simulations
Paper C	Manufacturability in design Automatic CAD model generation
Paper D	Design space exploration Surrogate models in engineering design Similarity in engineering design

The approach used to identify relevant literature was typically to, at first, formulate one or more appropriate search queries. Additionally, a few sample papers known to be relevant to the subject matter were gathered. These sample papers were either already known, or suggested by researchers with appropriate insight. The search queries were then verified by checking if the sample papers showed up as search results. Both SCOPUS and Google Scholar were utilized. Once relevant literature had been identified further academic works of interest were discovered through backwards and forwards snowballing techniques (Wohlin, 2014).

3.3.2 Interviews

To gather qualitative data, semi-structured interviews (Blessing et al., 2009) were employed, primarily for **Paper A** but also throughout the research. The interviews for **Paper A** focused on the topic of utilizing data captured in manufacturing for design purposes. Of particular interest were the reasons for why this is not a common practice, despite the potential value of such data in design. All interview studies conducted after **Paper A** were primarily used to gain an understanding of the industry, and not to produce novel results. These interviews provided insight into the industrial context of the research, and the nomenclature used by practicing engineers. Moreover, the unpublished interviews put a lot of emphasis on the topic of knowledge and asset reuse across product family generations. The results from these interviews assisted in understanding how engineers reuse things such as knowledge and analysis models from previous projects when developing new design concepts. While the results were not published, they helped in understanding the needs for the method proposed in **Paper D**.

Due to the at the time ongoing pandemic, most of the interviews were conducted using video conferencing software. As the research focus is on the design of aero-engine structural components, interviewees were selected from a first-tier manufacturer of engine components. The interviewees were selected based on their competences and roles to provide an even spread of experience from both the perspective of engineering design, but also manufacturing and management. Before the interviews, each interviewee received an interview guide containing a brief introduction to the project, the purpose of the interviews, and the key questions that were to be asked during the interview. The audio from the interviews was recorded. The initial interviews conducted for **Paper A** were transcribed and summarized. The interviews conducted after that were only summarized, but never transcribed. This saved time, allowing for more interviews. However, only summarizing the interview may result in the data becoming skewed to reflect the opinions of the person who created the summary. To avoid this issue, the summaries of the interviews were sent back to the interviewees in an iterative loop, allowing the interviewees to withdraw any statements, or correct any mistakes in the summaries. The corrections were then made, and the interviewees were sent a new version of the summary. This was repeated until the interviewees were content with the summary.

3.3.3 Design studies

In papers **B**, **C** and **D** design studies were conducted to test and demonstrate the proposed methods and tools. The purpose of these design studies were to emulate the stages of early phase design at the studied company. Hence why the design study process was sequenced to mimic that of design studies performed at the studied company. While each paper had its own slight variation on the process, the general steps are depicted, without going into detail, in Figure 3.3.

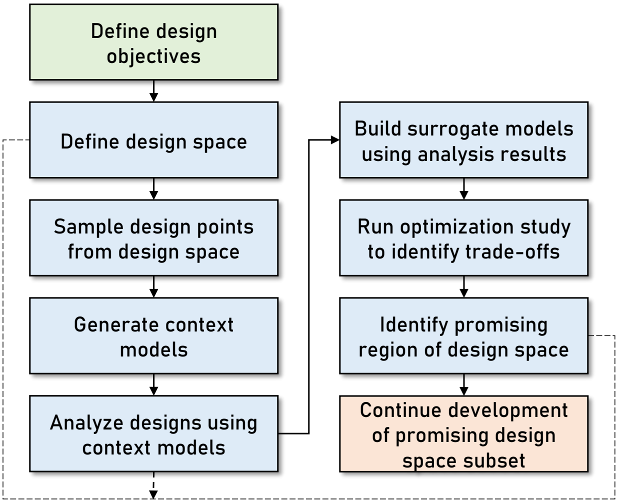


Figure 3.3: Generic design study setup adopted from practices used at the studies company. It starts by defining the design objectives for the study, and concludes with a set of promising designs (or, a design space region) being identified. The continued development was not part of the design space studies. The figure depicts the basic steps performed in each design study, including two "feedback" lines used to represent the event where results are not satisfactory, leading to the design space being redefined.

Essentially, each design study starts with the definition of the design objectives. These objectives typically were to identify lightweight, stiff, and manufacturable aero-engine structures. A design space was defined by identifying which design variables to vary, and then by defining the allowed ranges of those variables. Examples of such variables were structural wall thicknesses and the overall dimension of the studies structures. The design space was then sampled using a hypercube experiment configuration (McKay et al., 1979). This method of sampling was elected due to the deterministic nature of the computational simulations, and limitations in computational resources, for which space covering designs such as hypercubes are well-suited (Giunta et al., 2003). The sampled design points were then used to generate geometries and context models, upon which digital experiments were conducted.

The result of the design studies were typically regions within the design space that looked promising. However, the purpose of the design studies were, as mentioned, to test new methods and tools, and not to identify optimal designs. In **Paper B** and **Paper C** the focus was on how manufacturability can be evaluated in early phase design studies. In **Paper D**, the focus was on how similarity metrics can be used to make the design space exploration process more efficient. All design studies were conducted together with experts from the studied company to assert a degree of realism and face validity.

3.3.4 Geometry sampling

The geometry used in the early phases of design by the studied company is proprietary and thus not appropriate to include in public research. Consequently, no geometries developed by an actual aero-engine components manufacturer could be used in the research presented in this thesis. To mitigate this issue, a 3D model of a TRS was designed using Siemens NX (Siemens, 2019) in collaboration with the studied company. The base-model used throughout this thesis and its appended papers is closely based on a concept TRS design developed and provided by the studied company. To enable analyses on large batches of varied geometries, a geometry generation software was developed to generate varied aero-engine geometries, which is further described in the Results Chapter, as well as in **Paper C**). This software communicates with the Siemens NX API (referred to as NXOpen) to construct geometries on demand using UDFs as building blocks. This geometry generation software was used to generate context models (CAD models and finite element meshes) for digital experiments in both **Paper C**, and **Paper D**.

3.3.5 Simulations and digital experiments

When unable to utilize real data it is sometimes suitable to create data by modeling a virtual representation of the physical scenario (Säfsten et al., 2020). Performing physical tests on large amounts of physical aero-engine structures is not feasible, nor resource efficient. Because of that fact, simulations are extensively used for design studies in the aviation industry, as well as in this research.

In **Paper C** and **Paper D**, as part of design studies, ANSYS Workbench (ANSYS, 2022) was utilized to run stiffness analysis on generated 3D geometries (see section 3.3.4). To evaluate the structural performance of TRSs, a specific load case was employed which is a subset of the load cases utilized by the studied company. The basic setup is depicted in Figure 3.4. A force was applied to the central flange of the TRS, while the outer flange was fixed. This particular load case emulates parts of the conditions that may occur during a fan-blade-out accident, where one of the fan-blades of the turbo-fan engine breaks loose, resulting in a radial force on the central spool. Structural components needs to be designed for such scenarios for safety reasons, which warrants its use as a test for structural performance.

Once the load case was applied the maximum deformation of the structure was measured and used as a proxy for structural stiffness. Additionally, linear buckling was used to estimate buckling resilience. Thus, the process returned two results: the maximum deformation, and the buckling factor.

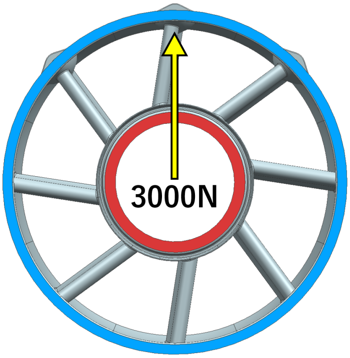


Figure 3.4: Depiction of load case used to test structural performance of a turbine rear structure under fan-blade-out conditions.

As part of evaluating structural performance, the volume, or weight, of the structure was also calculated. This was done as there is a clear need for aero-engine components to be lightweight. However, minimal weight typically trades with maximum stiffness. The volume was derived automatically using Siemens NX. Since the material used for the studies structures are typically the same, then volume was used rather than weight in most cases.

In addition to evaluating structural performance, **Paper B** and **Paper C** also contained a weld accessibility analysis. This was conducted using the software Industrial Path Solutions (IPS) in collaboration with the company Fraunhofer Chalmers. IPS was primarily used to evaluate weld accessibility, which refers to whether or not a weld tool will be able to access all the weld points required to assemble the product. Additionally, IPS returns an approximation of the time needed to conduct the weld. These accessibility simulations require information of where the weld paths are situated on the component, which typically is manually fed to the tool. In **Paper B** and **Paper C** the weld path information was instead fed to IPS automatically.

3.4 Verification and validation

The final evaluation of the proposed method validity is discussed more in the final chapter (see Section 6.3 on ”future work”). However, in **Paper B**, **C**, and **D** design studies were used to demonstrate the usefulness of the proposed methods and tools. Due to the proprietary technology used at the studied company, data from real scenarios could not be used. Instead, hypothetical scenarios were set up to closely resemble the workflow at the studied company. This was done in collaboration with experts from said company. The methods/tools were then applied, and the results were evaluated together with an expert from the studied company. This kind of validation falls under the category of *face validity* (Sargent, 2013). It should be noted that the simulations run in the design studies are of relatively low fidelity. However, the purpose of the design studies were not to identify high-performing aero-engine structure designs, but rather to demonstrate tools and methods for improving the design study process, and the process of exploring the design space. Thus, as long as the simulation results are reasonable, then the results can be used as a driver for further discussion.

Furthermore, the research in this thesis has been focused on aero-engine structural components. This means that, while its generality can be discussed, it has not been validated for general use. This is further discussed in 3.2 the scope of the research in this thesis has been kept focused.

3.5 Ethical considerations

The research project, of which this thesis is a component, was prompted by the need for the aviation industry to change. The aviation industry is facing increasingly stringent sustainability targets, in large parts due to the ongoing climate crisis (ACARE, 2020; European Commission, 2011). This need for change has prompted manufacturers in the aviation industry to consider radically new designs, in search for more sustainable alternatives. Carbon emissions needs to be reduced, but so too does noise levels and the use of socially unsustainable materials. The research presented in this thesis is part of the initiative, to make it easier for aviation industry manufacturers to quickly assess new design concepts such that engineers can make better informed decisions in the early design phase.

Any technological advancement has the potential to be a double-edged sword. The primary intent of this research is to provide aviation industry manufacturers with methods and tools to make sound decisions in the early phases of design. Such early-phase decisions has the potential of reducing fuel-consumption and cost. However, as costs and fuel-consumption are reduced, it is also possible that flights become cheaper. This can result in an increase in demand, and thus also in aircraft. Consequently, an initial reduction in fuel consumption has the potential of, in the final analysis, increase emissions.

Chapter 4

Results

In this chapter the results from the conducted research are aggregated. The bulk of the research is available in the appended papers, thus Section 4.1 is dedicated to summarizing those papers. The sections that follow will go through individual key results in more detail.

4.1 Summary of appended papers

The aim of the first paper, **Paper A**, was to gain an understanding of what data is captured in manufacturing, and how that data potentially can be used in the design phase. This was done through a literature review and an interview study with employees at a Swedish aero-engine components manufacturer. From the interviews, it became evident that there was a need for designers to better understand the capabilities of manufacturing. Designs would often reach manufacturing, only to be sent back for redesign due to manufacturability issues. To counter this, it was suggested that data captured in manufacturing could be used by design engineers to evaluate the manufacturability of new designs. However, there were two prominent issues with this suggestion: 1) the manufacturing data was difficult to access, and 2) the data was not stored in a format that was easy for designers to understand and use.

It was proposed that a digital twin for design could be established, within which manufacturing data (and other relevant data) is aggregated and used to predict the outcome of new designs. The new designs would need to be *similar* to previous designs/products for this digital twin to be useful. Once in place, it could assist design engineers in decision-making, and potentially improve the manufacturability of new designs. However, this would require major reforms within both the manufacturing and design organizations.

Rather than utilizing data from manufacturing to assist in the manufacturability evaluation of new designs, **Paper B** and **Paper C** explores an alternative, but related, route. By including manufacturability simulations already in the early phases of aero-engine structural component design it is possible to perform trade-off studies where structural performance is traded against manufacturability. In **Paper B** it is demonstrated how weld accessibility can be evaluated in the early phases of design. A set of CAD geometries were generated. These CAD models were then used in weld access simulations. Additionally, structural weight and stiffness were also evaluated. A design space exploration procedure was conducted, in the search for high performing and manufacturable design concepts.

Paper C further improves on the process of evaluating manufacturability and structural performance in parallel by changing how the geometries are automatically generated. Instead of utilizing traditional parametric shell models, the suggested approach in this paper is to utilize CAD "building blocks", referred to in Siemens NX as "User Defined Features" (UDFs). With this approach the variability of the exploration process increases, since it enables more significant changes to the CAD models. This approach, and the software developed to demonstrate it, can be used to quickly generate product family design variants, thus supporting design space exploration within a product family. Furthermore, the process in this paper is automated to a high degree, enabling design generation and simulation to be run without the need for manual intervention.

In **Paper D** a method for design space exploration was developed that utilizes similarity metrics to reduce the need for computationally expensive simulations. When exploring a design space, it is common to generate context models and run simulations using those models. However, this process can be computationally expensive. Because of this, surrogate models are typically "trained" using simulation results. These surrogate models can then be used to predict results without the need to run additional simulations, and at critically reduced expenses. However, the accuracy of the predictions depends heavily on 1) the dimensionality of the input, and 2) the sample size of the dataset used to train the surrogate model. To increase the sample size, supplementary simulations are needed. This gives rise to a trade-off: run many simulations at the cost of time and resources, or run fewer simulations at the cost of surrogate model accuracy. The method proposed in **Paper D** contains a mechanism to assist in mitigating this issue by reducing the need for computationally expensive simulations. This is done through the application of similarity metrics, which are used to assess the trustworthiness of results predicted using low-fidelity surrogate models. This trustworthiness is based on the similarity between the predicted design point, and the closest available simulated design point. Additionally, the method contains a separate mechanism for assisting designers in identifying similarities to legacy products and existing designs. The purpose of this mechanism is to assist engineers in identifying opportunities for reusing knowledge and other assets from previous designs.

4.2 Mechanisms of knowledge reuse when designing aero-engine components

In **Paper A** an interview study was conducted with employees at a Swedish aero-engine components manufacturer. The purpose of the study was to understand how knowledge is carried between product generations within a product family. It was found that the key mechanism was through senior engineers, who provided their expertise gained through experience. Typically, these experienced engineers were consulted during the development of new designs to avoid issues during development and manufacturing. In addition to consulting experts, lessons learned documentation was aggregated after each project, to be used in future projects such that previous mistakes can be avoided.

However, despite these mechanisms, it was found that the company struggled with late redesigns as issues were identified during production ramp-up. A common issue was tolerancing being too narrow, exceeding the capability of the manufacturing equipment. Consequently, it had been suggested by design engineers that data from manufacturing could be reused for the purposes of design, such that the capabilities of the manufacturing organization could be understood already during the design phase. Figure 4.1 demonstrated both the undesired redesign loop, and the desired data feedback loop.

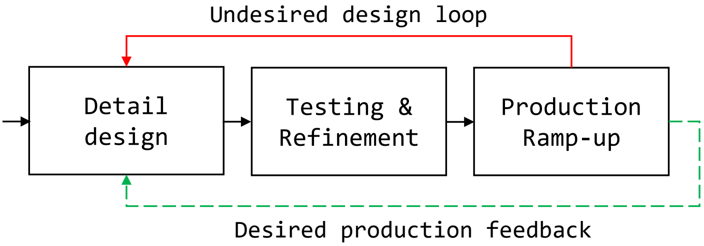


Figure 4.1: Visualization of undesired design iteration loop, and desired manufacturing data feedback loop.

This matter highlighted one potentially fruitful mechanism of reuse that was currently not implemented: the reuse of data from previous product generations. Vast amounts of data are captured and stored during the manufacturing phase, but utilizing it for the purposes of design was, at best, a rare occurrence. The main reasons for this included that: 1) some engineers were unaware of the existence of such data; 2) the data are hard to access; and 3) the data is formatted for use in manufacturing, and is thus not contextualized for use by designers. Consequently, implementing changes into the company that would allow for designers to exploit manufacturing data would require significant changes to how the data is formatted, managed, and stored.

4.3 Generation of enriched geometries

Automatic CAD geometry generation is in and of itself not new, as pointed out in Section 2.2.1. Nevertheless, a means for generating solid CAD models with high flexibility has been absent in industry. The method proposed by Müller et al., 2019b is highly flexible and can also generate solid models.

However, it requires designers to configure EF-M trees which are used as a basis for the design exploration process. The automatic geometry generation software developed for **Paper C**, on the other hand, takes a DoE (in the form of a digital spreadsheet) as an input, and returns the corresponding CAD geometries. Similarly to Müller's work, it too utilizes UDFs, through at a relatively reduced resolution, thus enabling a higher flexibility than traditional parametric variation, but a lower flexibility than the method proposed by Müller et al., 2019b. It should also be noted that, in its current form, the software tool is designed to only generate TRS geometries. In figure 4.2 one such generated TRS geometry is demonstrated.

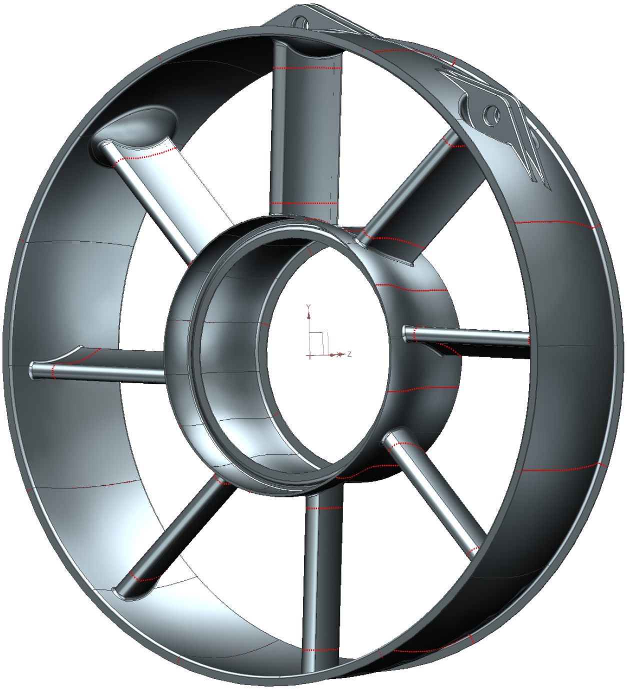


Figure 4.2: Example of an automatically generated Turbine Rear Structure (TRS) geometry. The weld lines are visualized by thin red lines.

The most important feature that differentiates this tool from contemporary alternatives is its ability to enrich the generated CAD models with welding information. This welding information can be used for various types of welding manufacturability analysis, which was demonstrated in **Paper C**. The weld lines can be varied, enabling designers to simulate different manufacturing scenarios. This is useful when comparing the manufacturability of different design configurations, which has a high impact on manufacturing cost. In Figure 4.3 three different manufacturing scenarios have been generated using the same geometric data. In the figure, it is demonstrated how the selection of active weld lines affect which parts are manufactured using casting, and which components are welded together. In other words, different configurations necessitate alternative manufacturing approaches, which may be more or less cost effective.

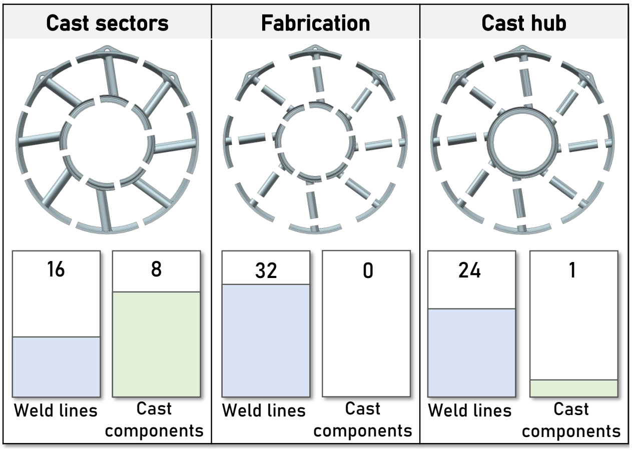


Figure 4.3: Depiction of three different manufacturing variants generated using the same geometric configuration.

The software tool can also be used to generate context models for analysis, such as Stereolithography (STL) models used for Additive Manufacturing (AM) manufacturability analysis, FEM meshes used for load case analysis, and split models used for weld simulations. Thus, this software not only assists designers in generating geometries, but it also assists in preparing models for various types of manufacturability and performance analysis. This enables designers to run trade-off studies where manufacturability is traded against performance. This is important because manufacturability is a key part of cost. This means that this software can assist designers in creating the information that is necessary for designers to balance cost against performance, already during the early phases of design.

4.4 Structural performance vs. manufacturability trade-offs

An approach for conducting trade-off studies for structural performance and manufacturability on structural aero-engine components was sketched out in **Paper B**, and expanded upon in **Paper C**. This approach utilized the automatic geometry generation described in Section 4.3, together with the Industrial Path Solutions (IPS) software. The IPS software was used to run weld accessibility simulations using the weld lines produced by the automatic geometry generation software. Additionally, physics simulations were conducted using Ansys to evaluate the stiffness and buckling resilience of the designs. In combination, these analyses produced results that could then be used to weigh manufacturability against structural performance. To visualize these multidisciplinary results, interactive Parallel Coordinates Plots (PCPs) were used, as these plots enables engineers to get an overview of high-dimensional input/output-data, and interact with it to identify interesting design configurations. The results from the design study conducted in **Paper C** has been visualized in the PCP in Figure 4.4.

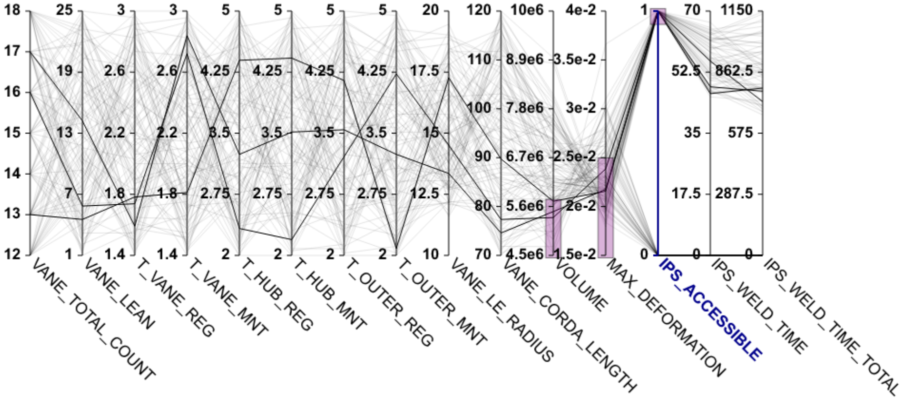


Figure 4.4: PCP used to visualize input data, structural performance analysis results, and manufacturability analysis results from a design study. The rectangular boxes along the axis represent inclusive filters, that can be defined to identify interesting design configurations.

In these results, maximum structural deformation (MAX_DEFORMATION) is used as a proxy for evaluating the stiffness of the TRS. The weight was taken into account through the inclusion of volume. But the interesting part here is the inclusion of weld tool accessibility (IPS_ACCESSIBLE) and weld time (IPS_WELD_TIME_TOTAL). By including accessibility into this analysis, any design configuration that inhibits weld tool access to the weld paths can be excluded through filtering the data, while at the same time ensuring that the structure is lightweight, and has an appropriate stiffness.

4.5 Similarity-assisted design space exploration

In **Paper D** a method is proposed to assist design engineers in performing a more efficient design space exploration. This is important, as any method or tool that makes design space exploration more efficient can potentially help designers be more responsive in the face of the fluctuating technology landscape, thus increasing competitiveness. As described in the introduction to this thesis, the future of aviation is uncertain, and manufacturers needs to adapt to become faster and more accurate when assessing new designs to keep up with the competition. To accomplish this increase in efficiency, it is argued in **Paper D** that computational expenses can be reduced by measuring and leveraging the similarity between data captured using simulations, and data generated using surrogate models. In section 4.5.1 the proposed method for accomplishing this is described in further detail.

Additionally, it is also proposed that similarity to legacy products and designs should be measured, as that could potentially help validate simulation results, as well as highlight the potential for asset and knowledge reuse between product generations. This "legacy similarity" measurement is argued to be especially relevant for product families, and is described further in Section 4.5.2. Together, these two measurements can be utilized in what is referred to in **Paper D** as "similarity-assisted design space exploration", further described in Section 4.5.4.

4.5.1 Increasing the trustworthiness of low-fidelity surrogate models using similarity metrics

When performing design space exploration it is common for design engineers to rely on surrogate models to evaluate design points. This is because physics simulations utilizing FEM are typically highly time consuming and computationally expensive. In product development projects, which are often highly time constrained, surrogate models are often seen as an acceptable compromise to evaluation accuracy due to their significantly faster processing time. However, the trustworthiness of such surrogate models depends on the sample size used to train the surrogate model. Since physics simulations are time-consuming and computationally expensive, then surrogate models for such simulations are often trained with a small sample size. Consequently, the predictions produced by such a surrogate model are not necessarily trustworthy. To mitigate this issue, a metric is proposed in **Paper D**, referred to as "inter-similarity". This metric measures the similarity between a design point that has been evaluated with a surrogate model, and the closest available design point that has been evaluated using simulations, as visualized in Figure 4.5.

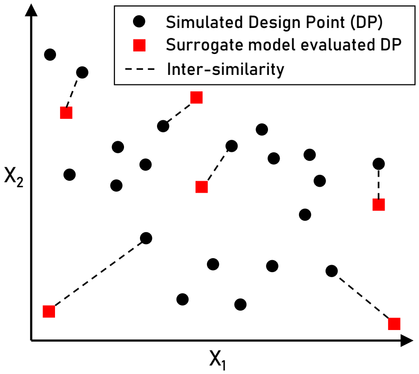


Figure 4.5: Demonstrates the working principle of the inter-similarity metric. Essentially, the distance in the design space is measured between two points: a) a point evaluated using surrogate models, and b) the closest point evaluated using simulations.

To test whether or not inter-similarity can be used as an indicator of surrogate model prediction trustworthiness, a digital experiment was conducted. In this experiment, 99 TRS geometries were generated in a hypercube configuration with eight different design variables. These geometries were then used in physics simulations where their maximum deformation under a specific load was evaluated. The results from the simulations were then used to train a surrogate model, which would then take 8 design variables to predict the maximum deformation of the given design configuration. The surrogate model was then used to make 731 predictions, which were then controlled by running the simulation with the same input data as the surrogate model had been given. The results from this experiment are presented in Figure 4.6. These results show that the more similar the input data was to what had previously been simulated, the lesser the prediction error.

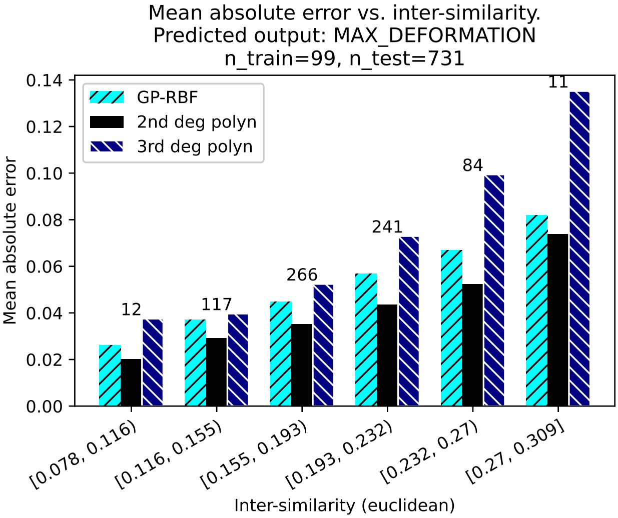


Figure 4.6: Correlation study results demonstrating the correlation between inter-similarity and surrogate model prediction error, for three types of surrogate model. A low inter-similarity score indicates a high similarity between simulation and surrogate model input data. The numbers above the bars represent samples in that range.

These results indicated that inter-similarity can be used as a proxy for trustworthiness. An optimization study was conducted to demonstrate this. A surrogate model was used to generate a trade-off curve between the maximum deformation under a specific load (stiffness) and the volume (weight), which are two conflicting properties of aero-engine structures. Inter-similarity was then used to color-code the surrogate model results in Figure 4.7, to give an indication of the trustworthiness of each individual data point. This can assist design engineers in assessing whether or not more simulations are necessary to provide trustworthiness to a surrogate models predictive capability within a design region. For instance, in 4.7 the green region of predictions is unlikely to change if more simulations are conducted, while the red and orange regions (where the volume is at its lowest) are likely not trustworthy. If the designers are content with the designs in the green region (middle of the trade-off curve), then they can proceed towards more detailed development and analysis. Conversely, if the designers wanted to investigate the low volume design configurations, which are clearly marked as less trustworthy in the plot, then more simulations would likely be required to increase the accuracy of the surrogate model.

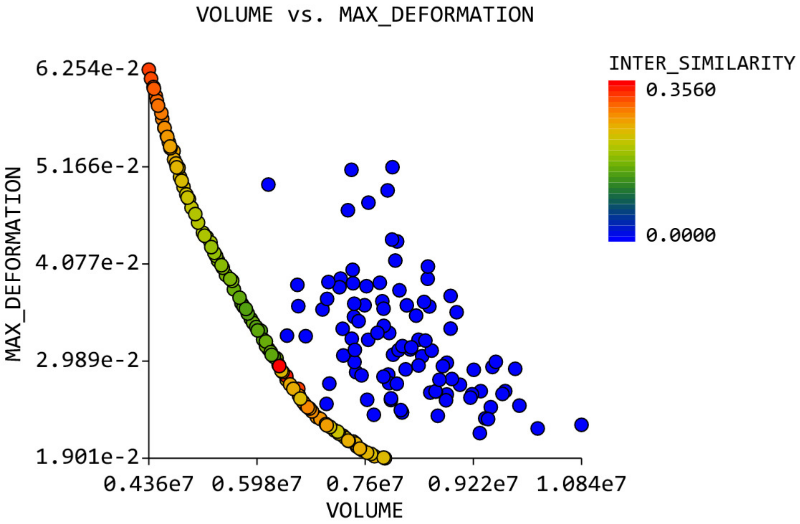


Figure 4.7: Results from an optimization study where inter-similarity is used to indicate the trustworthiness of the surrogate model results (the trade-off curve) through color-coding.

4.5.2 Facilitating knowledge and asset reuse through similarity to legacy designs

A separate metric, referred to as ”legacy similarity” is proposed in **Paper D**. This metric is intended to measure similarities to designs that have been evaluated with a higher fidelity in previous product development projects. These evaluations may be high-fidelity simulations at a more detailed phase of design, or even physical tests. The idea is to use such data to assist in verifying lower-fidelity predictions, as well as to highlight potential for asset and knowledge reuse. In other words, if a particular new design configuration has similarities to a previously manufactured product, then that increases the possibilities of 1) reusing knowledge, 2) reusing analysis models, and 3) reusing data from manufacturing, high-fidelity simulations, or physical tests. All these types of reuse may assist in understanding the new design, and push it through development at a more rapid pace.

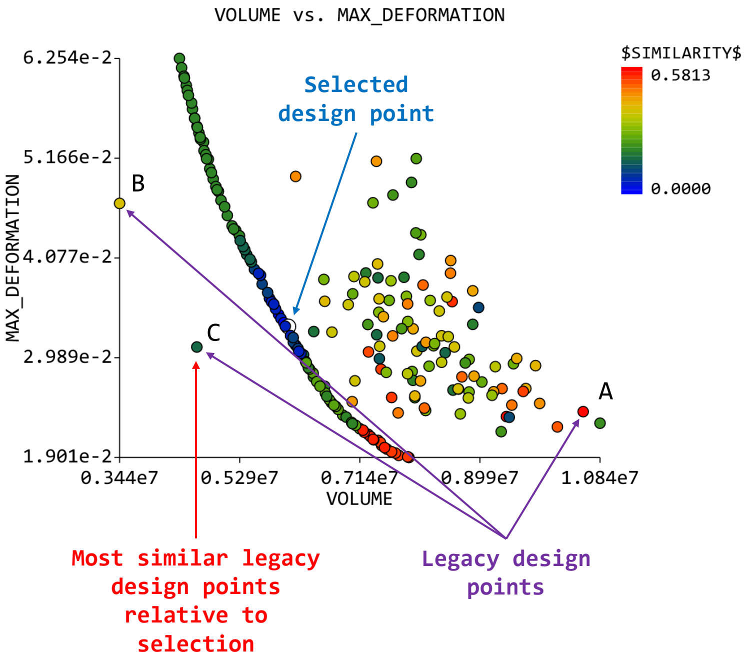


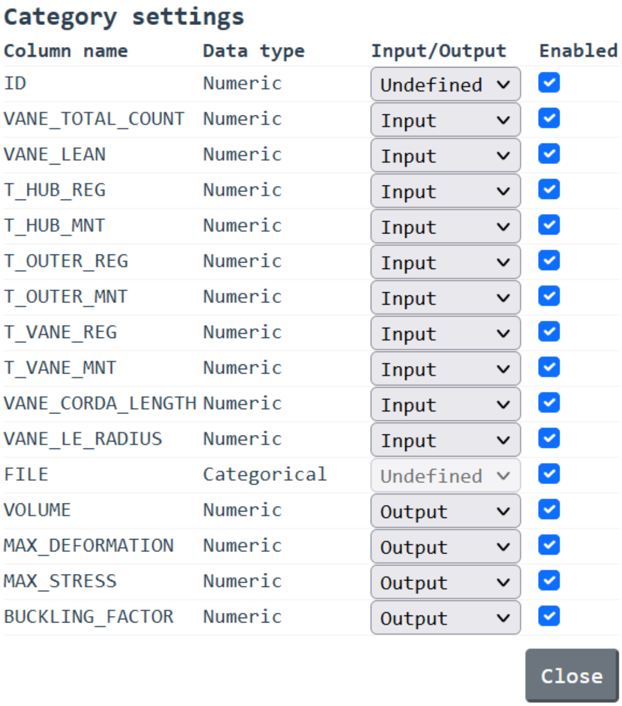
Figure 4.8: Optimization results where data from legacy products has been superimposed on the optimization and simulation data. One of the surrogate model predictions have been selected, which has color-coded all other data based on how similar the input data is for each design point. This reveals that, out of the legacy designs, design C is the most similar.

In Figure 4.8, data from hypothetical TRS legacy designs have been plotted together with the data from the optimization study discussion in Section 4.5.1. Using color-coding based on the legacy similarity metric, design points can be probed in the plot to investigate which legacy design (design A, B, or C in the plot) is the most similar. A highly similar legacy design should also have a similar structural performance, thus assisting in validating the simulation and/or surrogate model results. Conversely, if there is a high similarity to a legacy design, but a major difference in performance, then that should prompt the design engineer to reevaluate the simulations and surrogate models as they may not be trustworthy.

It should be noted that legacy similarity can also be used to actively avoid design configurations that has been historically problematic. Imagine, for instance, that design point C in Figure 4.8 had major manufacturing issues that were never resolved. In such a scenario, any similarity to design point C should alert designers to reevaluate their targeted design space region, and either: 1) attempt to resolve the manufacturing issues encountered by legacy design C, or 2) avoid that region of the design space in an attempt to not repeat past mistakes.

4.5.3 A software tool for visualization of similarity data

To demonstrate how inter-similarity and legacy similarity can be applied in design studies, a software tool was developed. The tool is referred to as the Multidisciplinary Analysis Client (MDAC), and was developed in the JavaScript framework *Vue.js* (You, 2023). This framework was chosen for its responsiveness (which was useful when developing interactive plots), and also for its ability to be packaged in a format that can be viewed in an web browser. This software tool visualizes data in the form of PCPs and scatter plots. What differentiates it from traditional data visualization tools such as those found in e.g., Matlab, Matplotlib, or JMP, is that it can calculate and visualize similarities between data points. When a dataset has been imported into the tool, the user can configure which dimensions of the data should be considered as inputs or outputs through a data-settings panel depicted in Figure 4.9. Using that information, the user can then instruct the tool to color-code the data based on similarities of the input dimensions. In doing so, scatter plots that are color-coded based on similarity can be created, such as the ones seen in Figures 4.7 and 4.8.



Category settings

Column name	Data type	Input/Output	Enabled
ID	Numeric	Undefined	☑
VANE_TOTAL_COUNT	Numeric	Input	☑
VANE_LEAN	Numeric	Input	☑
T_HUB_REG	Numeric	Input	☑
T_HUB_MNT	Numeric	Input	☑
T_OUTER_REG	Numeric	Input	☑
T_OUTER_MNT	Numeric	Input	☑
T_VANE_REG	Numeric	Input	☑
T_VANE_MNT	Numeric	Input	☑
VANE_CORDA_LENGTH	Numeric	Input	☑
VANE_LE_RADIUS	Numeric	Input	☑
FILE	Categorical	Undefined	☑
VOLUME	Numeric	Output	☑
MAX_DEFORMATION	Numeric	Output	☑
MAX_STRESS	Numeric	Output	☑
BUCKLING_FACTOR	Numeric	Output	☑

Figure 4.9: MDAC data configuration prompt used to determine which dimensions/columns should be considered as inputs/outputs. In similarity-assisted design space exploration, similarities between input dimensions are used.

The data can also be interacted with by drawing filters. This is of particular interest in the PCP plot, where certain ranges may be of specific interest to designers. For instance, if only lightweight structures are of concern, then a design engineer can place a filter on the weight/volume in the plot, thus omitting designs that are not light enough. MDAC then allows the designer to jump between the PCP plot, and user-defined scatter plots to visualize the filtered data. Multiple filters can be added, as in Figure 4.4, where both volume, max deformation, and the manufacturability criteria of weld accessibility (IPS_ACCESSIBLE) were filtered, allowing the designer to focus on only those design points that fulfil the design objectives.

The tool has been made available as an open source software, and can be accessed, downloaded, and edited by anyone (Martinsson Bonde, 2023).

4.5.4 Proposed method for similarity-assisted design space exploration

The inter-similarity and legacy similarity metrics were developed to assist design engineers in design space exploration. In Figure 4.10 a proposed design space exploration method has been visualized. In the figure, a baseline process has been marked out. This baseline process is based on design space exploration as it is conducted in the studied company. Additionally, two extra steps are included where inter-similarity and legacy similarity are used to provide an additional layer of information for the designers to use in their decision-making process.

The design space exploration process starts with the definition of a set of design objectives. For an aero-engine structural component this can be to minimize weight, and to maximize the stiffness of the structure. Once the objectives are established, the design space which is to be explored is defined. In a typical parametric study this is done by determining which design variables should be varied, and within which ranges. When investigating stiffness and weight, various thickness parameters can be varied as these typically affect both objectives. A DoE is then instantiated based on the targeted design variables and ranges, where each entry in the DoE represents a unique design configuration. These design configurations are then used to generate context models (e.g., CAD models and finite element meshes) which are used in various types of simulations.

Since high-fidelity physics-based simulations are computationally expensive and time-consuming, the simulation results are typically used to train surrogate models. These surrogate models are then used to evaluate the design objectives throughout the rest of the process. This is especially important in the next step, in which an optimization study is conducted to identify the trade-off curves between the design objectives. In such optimization studies, the objective functions are called to a great extent, therefore it is typically not feasible to evaluate the objective functions using physics-based simulations.

It is at this point where the inter-similarity metric described in Section 4.5.1 can be employed. Since the trade-off curves identified during the optimization step consists of surrogate model prediction results, rather than simulation results, design engineers need to be extra careful in how much trust is put into these results. Inter-similarity can be employed to give an indication of prediction trustworthiness. If the prediction results have a low inter-similarity, then it may be necessary to run additional simulations to increase surrogate model accuracy. Conversely, if the inter-similarity is high, then additional simulations are likely to not provide significant improvements to accuracy. Thus, designers can use the inter-similarity metric to guide their decisions regarding whether or not additional simulations are needed. This can save both time and computational resources in two ways:

1. The engineers will not run additional simulations unless it is necessary to increase accuracy.
2. The engineers are less likely to rely on potentially uncertain information, thus reducing the risk of running into problems downstream.

The next step in the process is to calculate legacy similarity for all results, as described in Section 4.5.2. Legacy similarity calculates the similarity to previously evaluated designs. This can be products that are already in production, or designs that have been evaluated at a higher degree of fidelity (e.g., simulations at a greater degree of fidelity, or even physical tests). Identifying similarities to legacy designs can have multiple potential benefits, such as:

- If there is a high degree of similarity to a legacy design, then the evaluation results of the legacy design can be used to validate the evaluation results of the new design.
- The higher the degree of legacy similarity, the higher the potential of reuse. With this in mind, design engineers can use legacy similarity as an indication of whether or not knowledge, analysis models, or other assets such as data can be reused from the legacy design.
- If a legacy design ran into issues during its life cycle, such as manufacturing quality issues, then any similarities to that design can prompt designers to reconsider or avoid certain design space regions. In doing so, design engineers can navigate around known issues preventing the repetition of past problems.

In the final step of the process, the design engineers has to make a choice. If a design space region has been identified that resolves the design objectives in a satisfactory manner, then the designers can elect to study that region, or set of designs, in further detail. When making this decision, the designers has the opportunity to take into account both inter-similarity and legacy similarity. Should the similarity metrics indicate that there are reasons to doubt the trustworthiness of the results, then additional simulations within the design space region of interest needs to be conducted.

Conversely, if the results of the exploration exercise were inadequate, then the designers can elect to repeat the process. If the process is repeated, then the initial conditions can be changed. This can, for instance, involve changing the design variable ranges, or changing which design variables should be considered in the study.

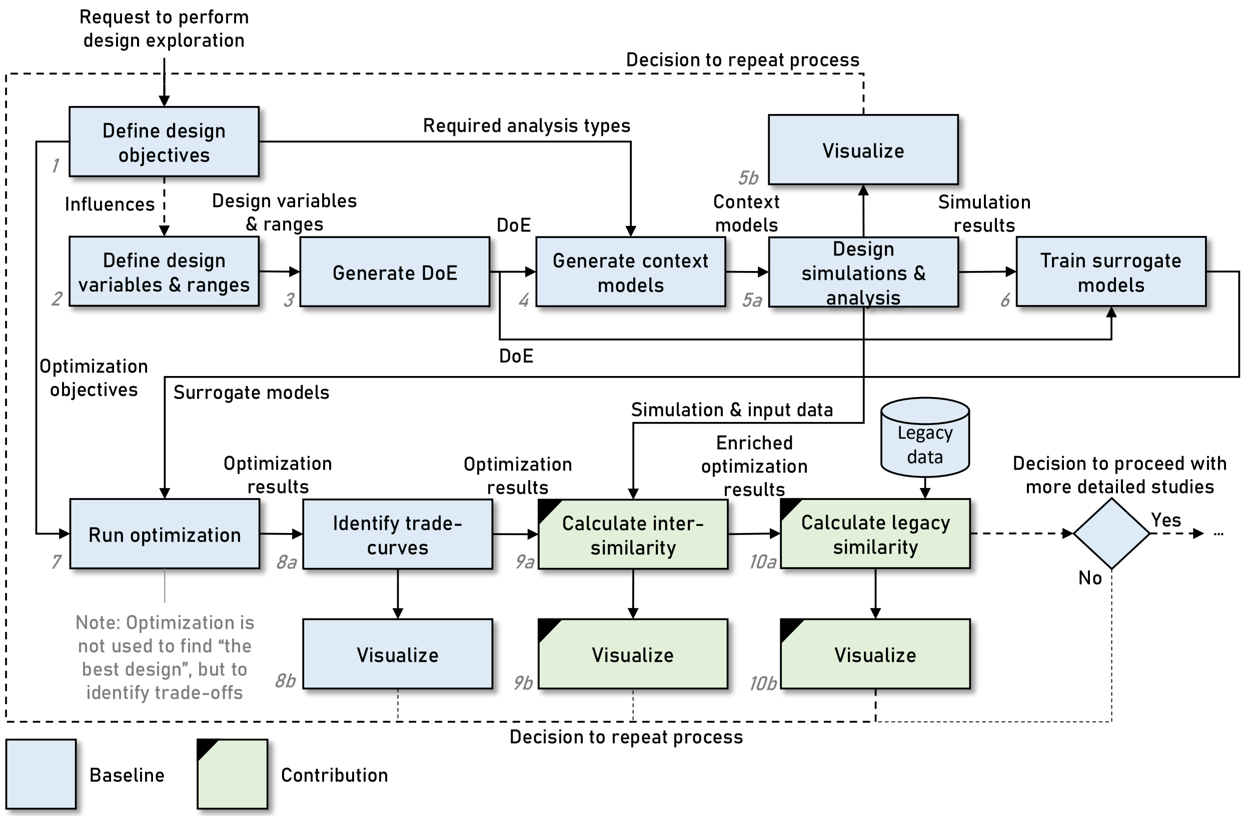


Figure 4.10: Similarity-assisted design space exploration method, designed around a baseline design space exploration process.

Chapter 5

Discussion

5.1 Answers to research questions

In this section the research questions formulated in Section 1.3 will be discussed and answered.

5.1.1 Research question 1

What information is necessary to evaluate cost and performance of alternative concepts in a product family of structural aero-engine components?

During the interview conducted for **Paper A** with employees of a Swedish aero-engine components manufacturer, it became clear that a primary concern was the manufacturability of their family of TRS-products. Despite the consultation from experienced engineers and lessons learned documentation, redesigns were considered too common. The main reasons these redesigns are a problem is because they are very expensive and time consuming. Hence why taking into consideration manufacturability already during the design phase was considered as very important.

A common means of manufacturing structural aero-engine components is through fabrication: welding together a large number of small components into a final shape (Madrid, 2018). In **Paper B** and **C** a significant development effort was directed at creating an understanding for how weld-manufacturability could be operationalized. This was concluded by measuring weld tool accessibility, to ensure that the weld could be accomplished in manufacturing. Additionally, crude weld simulations were proposed as a means to avoid designs with significant residual stresses.

By evaluating the manufacturability of these components already during the early phases of design, issues will be identified at a time when it is still affordable to make adjustments to the design. In doing so, costly redesigns can be avoided. Additionally, by evaluating weld time, designers can get an idea of how long it will take to manufacture a specific component, thus also enabling a relative manufacturing cost evaluation.

This covers the cost (manufacturing) aspect of the evaluation, but there is still the matter of performance. First, it needs to be clarified what is meant by performance in the case of structural aero-engine components. *Structural performance* is considered to be the structure's ability to handle stresses and loads. For an aero-engine structural component this entails maintaining structural integrity over the entire life of the component, and not fail in the event of catastrophic off-design loads. An aero-engine structural component is required to be able to handle ”fan-blade-out” situations, where a fan blade is disconnected, resulting in forces applied to the central axis. Thus, any thorough analysis of a structural aero-engine component needs to also take into consideration such forces, and ensure that the component is sturdy enough for the aircraft to make it safely back home. Additionally, these structural components will have an effect on the engines thrust, and its weight. Thus, performance is also considered to include the components weight, which should be minimal to reduce fuel consumption. Also, while engine thrust is not discussed in any of the papers, it is taken into account by ensuring that the exhaust throughput area (see Figure 5.1) of all the components is kept at a constant value. This is a rough way of establishing that all design configurations has the potential to push through a similar amount of exhaust.

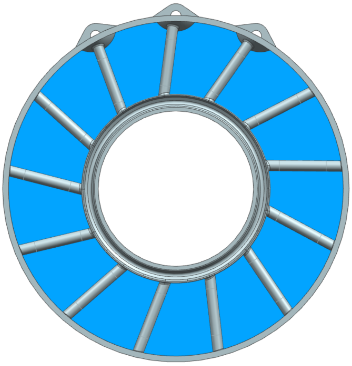


Figure 5.1: Exhaust throughput area (blue regions) of a TRS.

The rapid analyses of these components are made possible as a direct consequence of the evaluated components belonging to a product family. This is because analysis models can be, to a varying degree, reused between product generations due to their inherent similarity. This will be further discussed in RQ2.

5.1.2 Research question 2

What knowledge and assets can be reused between product generations within a product family?

In **Paper D** it is argued that reuse of knowledge and other assets, from one design to another, is dependant on the similarity between the two designs.

Thus, the more similar one design is to another, the more can be reused. To facilitate this discussion the possibilities of reuse will be divided into three basic categories:

1. Reuse of knowledge
2. Reuse of analysis models
3. Reuse of data (e.g., results from physical tests, results from simulations, manufacturing measurements, etc.)

Arguably, to reuse knowledge requires the least amount of similarity. An engineer can potentially benefit from having participated in other product development projects before, regardless if the previous product was completely different. But naturally the amount of reusable knowledge is at least somewhat proportional to the similarity between the products. To reuse analysis models, on the other hand, requires a magnitude higher similarity between the designs.

A paper by Runnemalm et al., 2009 will be used to exemplify the reuse of analysis models. A Knowledge-based Engineering (KBE) application is proposed that assists designers in setting up analysis models for weld simulations. This is possible since the designs for which this tool is used are relatively similar, which enables the same tool to be reused for multiple design variants. In practice, these designs are all part of the same scale-based product family, which consequently leads to them all being relatively similar. The same argument holds true for the previously mentioned paper by Sandberg et al., 2017, who generated analysis models for the structural components of the entire engine.

Finally, even data captured during previous product development endeavours can potentially be reused. Data is a resource that is gathered during the life-cycles of products: during the market analysis phase data can be captured from potential customers when gathering needs; during product development large quantities of data are captured from simulations and potentially even physical tests; during manufacturing measurements are done to assert the quality of each component; during the operational phase data can be collected to understand the "health" of the product (Cantamessa et al., 2020; Pereira Pessoa, 2020). However, continuing the reasoning above, reusing data likely requires a very high similarity between the designs.

Of particular interest is the reuse of manufacturing data in design, as proposed by authors such as Andersson et al., 2008; Madrid et al., 2016. The reason for the interest in manufacturing data is that such data can potentially help designers avoid expensive redesigns, as discussed in 4.2. However, those same authors point out the issue of reusing data initially created for other purposes than design. Typically, the data are formatted in a way that makes it difficult for designers to reuse it, since the original architects of the data did not consider its use for any other purpose than for the organization within which it was created. Furthermore, in the interview study conducted for **Paper A** it was found that relevant data from various sub-organizations may not always be accessible to designers.

5.1.3 Research question 3

How can analysis and measurement data from previous designs and products be used in the early phases of design?

This question was partially answered in **Paper D**, where the use of a similarity metric, referred to in the paper as "legacy similarity" is proposed as an aid to determine whether or not data from previous products is relevant. By measuring the similarity to not only previously manufactured products, but also to previously evaluated designs, then the design space exploration process can be improved. Knowing, for instance, that a new design is similar to a design that has been evaluated with high-fidelity simulations and/or experiments can assist designers in verifying new simulation results. This was exemplified in Figure 4.8, Section 4.5.2, where legacy design data was utilized to assist in evaluating the trustworthiness of simulation and surrogate model results data. Additionally, the legacy similarity was used to assist in identifying potentials for reuse of knowledge, assets, and potentially even data.

5.1.4 Research question 4

How can an automated modeling and simulation support tool be developed that enables comparative modelling-based assessment of alternative concepts?

This question was answered through the development of the enriched automatic geometry generation tool in **Paper C**, as well as the similarity-assisted design space exploration method in **Paper D**. By automatically generating geometries enriched with manufacturing information (weld lines), it was (in **Paper C**) possible to also automate the simulation process. Using the "enriched" geometries, manufacturability simulations as well as structural performance simulations were automated, enabling the provision of design decision support from a manufacturing and performance perspective. Furthermore, the inter-similarity metric proposed in **Paper D** was proposed to assist designers in performing design space exploration at a more rapid pace, by providing an extra layer of information indicating the trustworthiness of the evaluation data.

5.1.5 A way forward

Since the commercial aviation industry embraced the turbo-fan engine architecture back in the 1960's, it has stuck to it. Any new engine is typically an iterative improvement on the last generation. In other words: the utilization of similarity is already an integral part of aircraft engineering, and for good reason. Reinventing the engine would be economically perilous, since such a development program would require major financial commitments, for what might in the end be a product that is not as good as what is already on the market. Moreover, not only is derivative engine development a good idea from an economic standpoint, but it is also an excellent way of keeping passengers safe. Flying with already proven technology ensures that aircraft stay in the air. However, now that humanity is facing the looming threat of a climate catastrophe, it is no longer adequate to merely ensure that flights are cheap and airworthy. *Something* needs to change.

In this thesis, one of the main themes has been of how to reuse knowledge and other assets from existing designs when developing new design concepts. At a glance, this might seem counterproductive to the search for more sustainable engine designs. I would argue that it is not.

In the introduction, SAF-fueled engines were described as a short-term partial solution to sustainable aviation. One reason for the high interest in SAFs is because the engine architecture does not need to change. In other words: new engine architectures can remain highly similar to existing solutions. This reasoning has been extended to include hydrogen-fueled engines, which also can remain highly similar, with a prominent exception being the combustor design (Murthy et al., 2011). In other words, similarity can be of assistance in speeding up the adoption of more sustainable engine technology.

This research is intended to assist in the development of new aero-engine structural components. That includes the development of components for new, more sustainable engines. By enabling manufacturability analysis already in the early phases of design, and trading that against structural performance, designers can make better informed decisions, to save time and cost. Additionally, the similarity-assisted design space exploration method helps in leveraging similarities to existing products through the legacy similarity metric. By ensuring that there is *some* similarity to designs that have previously been proven in flight the similarity-assisted design space exploration method can assist in keeping passengers safe, and financial risk low.

Chapter 6

Conclusions

In this concluding chapter the contributions to knowledge and practice are laid out in Section 6.1 and 6.2, respectively. Additionally, ideas for how to move on from this research are discussed in 6.3

6.1 Contributions to knowledge

Complex aero-engine components that have been subject to advanced geometry optimization risks encountering manufacturing issues. In interviews with employees at a Swedish aero-engine components manufacturer it was discovered that this is indeed a problem, as components often need to be redesigned as manufacturing issues surface. One path for providing designers with the tools to avoid such redesigns is to give designers access and means to utilize data captured in manufacturing. However, due to such data being hard to access, and often in a format that is not useful for designers, such data is not in use today.

Due to the large obstacles encountered with reusing manufacturing data, an alternative approach was investigated: enabling large-scale manufacturability analysis already in the early phases of design. Simulations and design optimization studies are already being conducted thoroughly in the early phases of design. However, such simulations typically utilize shell-models, and primarily focus on physics based simulations aimed at testing performance aspects such as aero-dynamics and structural resilience. To properly perform manufacturability analysis, solid models need to be employed to ensure an appropriate degree of geometric fidelity to facilitate simulation of weld accessibility, ensuring that the weld tools can properly access all welds. Additionally, to evaluate large design spaces in a time-efficient manner, CAD geometries can be enriched with manufacturing information (e.g., weld locations) during automatic geometry generation, which can be used to run automated manufacturability analysis. Results from both manufacturability and performance analyses can then be utilized in trade-off studies. In such trade-off studies designers can evaluate not only the performance of different design configuration, but also their manufacturability, thus potentially reducing the risk of late redesigns due to manufacturing issues.

Generating results data from simulations can be computationally expensive, and highly time consuming. Especially so for physics-based FEM simulations. This is a problem for product development projects where there is a limited computational budget, as well as time constraints. To reduce simulation time, surrogate models are used, which is especially useful for optimization studies. However, it is common for designers to utilize relatively small sample sizes to train the surrogate models, resulting in untrustworthy surrogate model predictions. To avoid this, similarity metrics can be used to measure the similarity between design points used for predictions, and their closest simulated neighbour in the design space. This is referred to as ”inter-similarity”, and gives designers an indication of the trustworthiness of the surrogate model prediction. It was demonstrated in an experiment how inter-similarity can be an indicator of surrogate model prediction trustworthiness.

An additional metric, referred to as ”legacy similarity” was proposed. The purpose of this metric is to measure the similarity of new designs to legacy designs evaluated in previous product development projects with a high degree of fidelity, or even through physical tests. The aim of this metric two-fold: Firstly, it can assist designers in verifying evaluation results. If a new design configuration is highly similar to a legacy design, then it is typically expected that both designs should also perform similarly. Thus, the legacy similarity metric helps designers in identifying comparable design scenarios. Secondly, legacy design can assist designers in highlighting potential for reuse of knowledge or other assets, as similarity is proportional to reuse-potential.

6.2 Contributions to practice

In this research a set of methods and tools were created with the purpose of exemplifying how this research can be applied, and lay down the ground work for potential further developments in the future.

First, to enable rapid evaluations of large design spaces, it is necessary to automate the process of geometry model creation. Once a geometry has been conceived in a CAD format, it can be exported into various types of context models used for different analyses. One of the key contributions of this research is the automatic geometry of solid CAD models enriched with manufacturing information, and simulation interfaces. This approach was packaged into a software, capable of generating flexible TRS geometries with variation beyond merely varying CAD parameters. The generated models contains weld lines used by manufacturability simulations (weld accessibility simulations and weld simulations), and interfaces to enable structural load case analysis in physics simulation software such as Ansys. By enriching the models with this information, the whole process, from geometry generation to physics and manufacturability simulations, can be automated. Thus, large design spaces can be evaluated without manual intervention.

To further improve on the process of evaluation large design spaces, a method for similarity-assisted design space exploration was proposed. This method utilizes similarity metrics to speed up the exploration process by providing design engineers with an additional layer of data that indicates trustworthiness of surrogate model predictions. The method itself provides explanation to how the different steps can be conducted to perform such a design space exploration. In addition, a software tool was developed to assist in the visual aspect of the method. This software tool, referred to as the ”Multidisciplinary Analysis Client” (MDAC). This software tool provides design engineers with a visual interface where data can be plotted and interacted with. What differentiates it from other visualization software is its ability to measure and visualize data similarities. Thus, the program can be instructed to calculate inter-similarity and legacy similarity. This means that the software can be used to assist design engineers in design space exploration, to provide visual feedback on prediction trustworthiness.

Providing methods and tools that leverages similarities to existing ”proven in flight” designs has the potential to give manufacturers within the aviation industry a competitive advantage. The similarity aspect provides a speed-boost, while the enriched automated modelling approach assists in accounting for manufacturability, and thus also cost. Ultimately, the purpose of these methods and tools is to assist in the search for novel, yet similar, concepts.

6.3 Future work

This research has laid down a lot of the groundwork necessary to run performance and manufacturability trade-offs in the early phases of design, as well as identifying potential for data, analysis model and knowledge reuse. The intention is to continue to develop this automated and similarity-assisted approach to design space exploration. At least three major milestones are on the horizon:

1. Implementation of sustainability evaluation to be run in parallel with structural performance and manufacturability evaluations.
2. Reusing existing data through application of the legacy similarity metric
3. Validation of research methods and tools in an industrial environment.

The implementation of sustainability evaluation goes hand in hand with the goal of this research: to provide methods and tools for designers to assist in the search for more sustainable aero-engine technology. A paper has already been submitted to the ICED 2023 conference in which a partial step in this direction has been taken, by approximating the buy-to-fly ratio of aero-engine structures manufactured using AM technology.

The next big milestone is to utilize data (e.g., manufacturing data) from existing designs when developing new design concepts. Through the introduction of the legacy similarity metric discussed in Section 4.5.2, the journey towards data reuse has been commenced. However, as the challenges listed in this thesis forecast, this will be a difficult but worthy endeavour. It is unlikely to be fully developed and validated in the duration of the research projects of which this thesis is a component, though parts of the groundwork can be attempted.

Finally, the tools and methods developed in this research need to be validated in an industrial environment. This is the essence of DS2, which at the time of writing has not yet commenced. True validation in an industrial setting is time consuming, as a consequence of the relatively long lead-times of product development projects in the aviation industry. Thus, full validation is not feasible within the scope of a single PhD research project. However, it is feasible that a demonstrator design study can be conducted at an aviation industry company, to evaluate the methods and tools in the hands of practicing design engineers.

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