Thesis for The Degree of Doctor of Philosophy

A computational similarity-assisted multi-domain framework for conceptual engineering design

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Department of Industrial and Materials Science
Chalmers University of Technology
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Abstract

In this thesis, a set of methods is proposed for assisting design engineers in exploring trade-offs among performance, manufacturability, and sustainability, during the early design phase. These methods were developed in close collaboration with a Swedish aerospace company to mitigate the risk of costly redesigns later in development. Among the challenges addressed is how to capture and evaluate the necessary information to consider such trade-offs while there is still enough freedom to make changes to the design.

A computational framework is proposed which serves to elicit the necessary foundation for informed decision-making. This framework entails understanding the similarities among new designs and previous design endeavors through the application of similarity metrics. These metrics provide increased trustworthiness in evaluation results, a means for identifying asset reuse potential, and guides designers into staying within the well-understood regions of the design space. Furthermore, the framework highlights the importance of multi-domain trade-offs, and prescribes methods for how to consider system performance, manufacturability, and sustainability, concurrently. This reduces risk by potentially identifying issues early in development. The framework also provides a means for strategically identifying design configurations that are compatible with future technologies through the application of a new flexibility metric, preventing the risk of early system deprecation. Finally, the methods have been implemented as software tools, enabling them to be flexibly adjusted for different needs, and to be utilized by designers, academics, and students.

For the aviation industry, these contributions serve as proposals for how to explore and integrate new design concepts. This has, in recent times, become increasingly important due to the ongoing climate crisis, which necessitates rapid development of more sustainable propulsion alternatives. Consequently, an improved understanding of how to efficiently integrate new technology is paramount.

Keywords

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

List of Publications

Appended 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, DOI: 10.1017/pds.2021.413).*

[**Paper B**] **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, DOI: 10.5281/zenodo.7973381.*

[**Paper C**] **Martinsson Bonde, J.**, Kokkolaras, M., Andersson, P., Panarotto, M., and Isaksson, O. (2023)., *A similarity-assisted multi-fidelity approach to conceptual design space exploration Computers in Industry, 151, 103957. DOI: 10.1016/j.compind.2023.103957.*

[**Paper D**] **Martinsson Bonde, J.**, Alonso Fernández, I., Kokkolaras, M., Malmqvist, J., Panarotto, M., and Isaksson, O. (2025)., *Managing Combinatorial Design Challenges Using Flexibility and Pathfinding Algorithms Conditionally accepted with minor revisions for AIEDAM.*

[**Paper E**] **Martinsson Bonde, J.**, Isaksson, O., Kipouros, T., Kokkolaras, M., and Andersson, P. (2025)., *Exploring design trade-offs among sustainability, performance, and manufacturability when considering integration of new technologies Accepted for presentation and proceedings publication for ICED 2025, Aug 2025.*

Other publications

The following list includes additional publications from my PhD studies. These papers are not appended to this thesis as they are not necessary to support its claims.

- [**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.
- [**c**] Mallalieu, A., **Martinsson Bonde, J.**, Watz, M., Wallin Nylander, J., Hallstedt, S. I., and Isaksson, O., *(2023). Derive and Intergrate Sustainability Criteria in Design Space Exploration of Additive Manufactured Components.*
  Proceedings of the Design Society, 3, 1197–1206. Cambridge Core.
  DOI: 10.1017/pds.2023.120.
- [**d**] **Martinsson Bonde, J.**, Breimann, R., Malmqvist, J., Kirchner, E., and Isaksson, O., *(2024). The impact of specialized software on concept generation.*
  Proceedings of the Design Society, 4, 663–672. Cambridge Core.
  DOI: 10.1017/pds.2024.69.
- [**e**] Arjomandi Rad, M., Hajali, T., **Martinsson Bonde, J**., Panarotto, M., Wärmefjord, K., Malmqvist, J., and Isaksson, O., *(2024). Datasets in design research: Needs and challenges and the role of AI and GPT in filling the gaps.*
  Proceedings of the Design Society, 4, 1919–1928.
  DOI: 10.1017/pds.2024.194.
- [**f**] **Martinsson Bonde, J.**, Isaksson, O., Panarotto, M., Andersson, P., and Kokkolaras, M. (2024)., *Similarity-based product family design for aero-engine components*
  ISABE24
  DOI: 10.5281/zenodo.14064084.
- [**g**] Arjomandi Rad, M., Panarotto, M., Malmqvist, J., **Martinsson Bonde, J**., Wärmefjord, K., and Isaksson, O., *(2024). Towards Using Functional Decomposition and Ensembles of Surrogate Models for Technology Selection in System Level Design.*
  DS 130: Proceedings of NordDesign 2024, Reykjavik, Iceland, 12th - 14th August 2024, 421–430.
  DOI: 10.35199/NORDDESIGN2024.45.
- [**h**] Arjomandi Rad, M., **Martinsson Bonde, J**., Isaksson, O., Panarotto, M., Wärmefjord, K., and Malmqvist, J., *(2025). Product Dataset Platform: System-Level Design Evaluation Using Feature Engineering and Functional Modeling, A Crashworthiness Case Study*
  Accepted for ASME.

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Contents

Acronyms

AI	artificial intelligence	86
AM	additive manufacturing	52
ARC	areas of relevance and contribution	9
CAD	computer-aided design	16
CPM	change propagation method	15
DFMA	design for manufacture and assembly	12
DFS	design for sustainability	12
DFX	design for X	12
DoE	design of experiments	49
DRM	Design Research Methodology	29
DS	descriptive study	29
DSM	design structure matrix	15
EF-M	enhanced function-means	14
FEA	finite element analysis	16
FEM	finite element method	38
F-M	function-means	14
GUI	graphical user interface	34
IPS	Industrial Path Solutions	37
MBSE	model-based systems engineering	86
MDA	multidisciplinary analysis	23
MDAC	Multidisciplinary Analysis Client	58
MDO	multidisciplinary design optimization	23
MOTAC	multi-objective technology assortment combinatorics	39
PS	prescriptive study	30
RC	research clarification	29
RD&T	Robust Design and Tolerancing	22
RQ	research question	6
MDSE	model-driven design space exploration	19
SAF	sustainable aviation fuel	3
SBCE	set-based concurrent engineering	12
SVG	scalable vector graphics	58
SysML	Systems Modeling Language	86
TRL	technology readiness level	31
TRS	turbine rear structure	5

Chapter 1

Introduction

The ongoing climate crisis demonstrates the urgent need to rethink how aircraft systems are designed and realized. The aviation industry is pressured to rapidly innovate on a system level, and to implement sustainable solutions that are often realized by novel technologies on a subsystem or component level. However, understanding and meeting these needs while at the same time asserting that safety, performance, and cost criteria are met is far from trivial. Nevertheless, manufacturers need to master these complex trade-offs to remain competitive.

The aviation industry is obligated to face these challenges, and the target has been set to achieve net-zero CO_2 emissions by 2050. In addition, drastic reductions of ground-level noise is to be achieved, along with a more ethical sourcing of raw materials, and an overall improved passenger experience (ACARE, 2022; Innovair, 2024). All these targets are to be met despite expectations of a doubled global aircraft fleet size by 2043 (Airbus, 2024). These challenges have prompted the development of novel technologies that need to be matured and integrated. However, the number possible alternative solutions is vast. Multiple radical changes to aircraft and engine systems have been proposed, and each alternative comes with its own conditions for design engineers to master. This has given rise to an uncertainty for all manufacturers in the industry regarding what the future of aviation will look like.

To stay competitive in such an uncertain technological landscape, manufacturers in the aviation industry need to be able to respond rapidly and accurately to new technology developments. Historically, developments within the aviation industry has typically been evolutionary (Singh et al., 2012). Smaller improvements minimize risks during the product life cycle from both a safety and economical perspective. Confidence in engine design has grown steadily over the past 50 years, as each product generation brings with it new improvements, and lessons learned. As a result, modern aircraft systems uphold an exceptional level of safety (ICAO, 2025), which manufacturers are unwilling to compromise when introducing new technologies or concepts.

Utilizing product families is a recurring strategic choice, as it entails a reduced risk through the reapplication of existing assets. A platform of re-

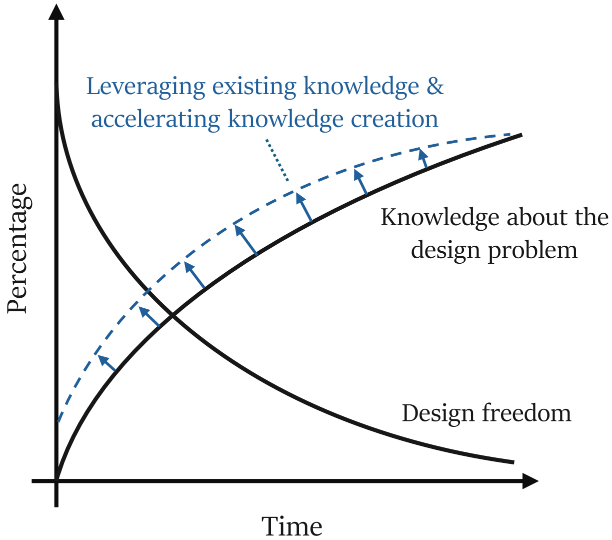

Figure 1.1: The design paradox, based on illustration by Ullman (2009). In addition, the figure visualizes the intended impact of the research presented in this thesis.

sources that are common to all products within the family is developed and leveraged to make development more efficient (Jiao et al., 2007; Simpson, 2004). This common platform, which is strengthened for each new product in the family, enables reuse of resources such as experience, facilities, and equipment. Consequently, the adoption of new technologies in the aviation industry is slow, as larger leaps naturally lead to an augmented risk. With the proposed radical changes to new engine and aircraft architectures, this built up confidence risks loosing its value, as existing resources may no longer be applicable in such radically new contexts. **There is therefore a need for methods and tools that reduce the risk of integrating new technologies into existing product family systems.**

In the early design phase, the opportunity to influence the design, referred to as the design freedom, is high. At the same time, the collection of all possible solutions, the design space, is infinitely vast. And so, designers need to know where in the design space to look for promising solutions. This is generally done by systematically exploring the design space and evaluating different solutions. As development progresses, more is learned about the design space, and decisions are made that increasingly fix the design specification. Each decision that progresses the design specification typically builds upon previous decisions. Thus, if a problem is encountered, changing part of the design becomes increasingly expensive, as previous decisions need to be revisited. Consequently, at the time when designers have gained a thorough understanding of the design, their freedom to act on this knowledge is at its minimum. This phenomenon, as visualized in Figure 1.1, is commonly referred to as the design paradox (Ullman, 2009). That being the case, to reduce the risk of new technology integration, the understanding of the design needs to be increased during the stages where there is still a relatively high design freedom. It is thus critical to improve knowledge creation in the early design phase, such that enough insight into the design space can be gained to avoid problems later in development. **In this thesis, it is thus argued that a multi-domain approach to early design space exploration is necessary. The design space needs to be evaluated with regards to system-level impacts, focusing not only on performance, but also on other critical aspects such as manufacturability, and sustainability. In doing so, more knowledge is gained in the early phase, where there is still enough design freedom to make changes.** By evaluating manufacturability, the risk of high-cost manufacturing and late design changes due to manufacturability issues can be avoided. By evaluating sustainability, it is possible to reduce the risk of the product failing to meet long-term sustainability targets (Hallstedt & Isaksson, 2017), ensuring that the product can remain viable on the market for a longer time. The challenge is to capture criteria related to manufacturability, sustainability, and other key aspects as early as possible, and perform rapid evaluations based on those criteria. Thus, potential issues and opportunities can be identified and acted upon before too much design freedom is lost.

1.1 The industrial need

At the time of writing, the aviation industry is estimated to be responsible for approximately 2% of all man-made greenhouse emissions (Zhang et al., 2020). Further exacerbating the issue, air travel trends indicate a continued market growth that thus far has only temporarily been interrupted during the COVID-19 pandemic (Grewe et al., 2021), indicating that greenhouse emissions caused by commercial aviation are bound to continue increasing. The ongoing growth of civil aviation in already mature economies in Europe and America is outpaced by the emerging economies of primarily India and China. This is resulting in the aforementioned expectation of a doubling of the global commercial aircraft fleet (Airbus, 2024). Achieving net-zero will thus require aircraft systems manufacturers to innovate and implement new technology rapidly, if the 2050 target is to be met. Optimizing aircraft systems to minimize fuel consumption is business as usual to any respectable manufacturer in the aviation industry. However, merely reducing the fuel consumption will not make this problem go away. The energy source itself needs to change, from fossil to renewable. Additionally, it may even be necessary to partially capture the already produced emissions in an attempt to reverse some of the damage.

To meet this challenge of converting to renewable energy, a vast array of new technologies are being considered. Technologies of interest include multiple new propulsion alternatives, the most prominent of which involves turning to biofuels, typically referred to as sustainable aviation fuels (SAFs). In addition, more radical alternatives being explored include different variations of incorporating hydrogen as an energy source, as well as electric propulsion variants, and hybrids. Each alternative has its own challenges, and would require significant changes to aircraft and engine systems. SAFs, of which there are many variants, are the only alternative that has been deployed in commercial aircraft, though merely to a fractional extent. However, SAFs are not expected to solve the emission problems, only ameliorate it. Consequently, other alternatives need to be explored.

This technological uncertainty has not been prevalent historically, as product development within the aviation industry has, for the past 50 years, mostly been evolutionary. Radical changes to aircraft systems have been scarce since the introduction of the tube-and-wing aircraft architecture, and the kerosene-fueled turbofan engine. Since then, manufacturers have aggregated decades of experience with these solutions, rarely straying far conceptually. A solution that has been *proven in flight* is typically considered safe for two reasons: Firstly, it is less likely to run into problems during development and manufacturing, since experience from similar products reduces such risks. It naturally follows that there is a reduced risk of investing in such products. In other words, solutions previously proven in flight are economically safe. Secondly, solutions that have been proven in flight are less likely to result in catastrophic failure during operations, meaning it is also safer for passengers. However, this aggregated experience and confidence falls short when the aviation industry is forced to make large conceptual leaps, such as turning to alternative fuels. Maintaining the same safety standards while simultaneously innovating and keeping costs at an acceptable level is one of the core challenges that the aviation industry is currently facing.

How large the conceptual leap is for aircraft systems depends on which energy source is being considered. SAFs have the benefit of being very similar to their non-renewable counterpart, but even most SAFs have shown to be incompatible with fuel system seals (Hamilton et al., 2024). However, the expected impact of hydrogen-fueled propulsion, electric, or hybrids are far more extensive. For hydrogen-fueled aircraft, containment is one of the most pressing issues. Hydrogen has a significantly lower energy density than kerosene, and has a tendency to degrade alloy structures it comes into contact with (Stefan et al., 2022). Consequently, aircraft concepts that utilize hydrogen need to house large cryogenic tanks that keep the hydrogen in a liquid form, thus ameliorating those issues to some extent. This also means that such concepts tend to either have radically different fuselage shapes, or significantly less available space within the fuselage, relative to contemporary aircraft (Tiwari et al., 2024). The problem with electric aircraft also pertains to storage (Wheeler et al., 2021), as batteries are heavy, require a lot of space, and also have a low energy density compared to kerosene. Consequently, electrification has thus far only realistically has been considered for smaller aircraft, and is often combined into hybrid solutions with gas turbines to extend the range.

Ultimately, the winning technologies in this *race to sustainability* will have a profound impact on all levels of the industry, from airlines to component manufactures. It is therefore important to consider recent experiences within the aviation industry, where late design changes have resulted in expensive consequences (e.g., Garcia, 2024). With this in mind, manufacturers need to have a thorough understanding of the risks involved in the undertaking of new

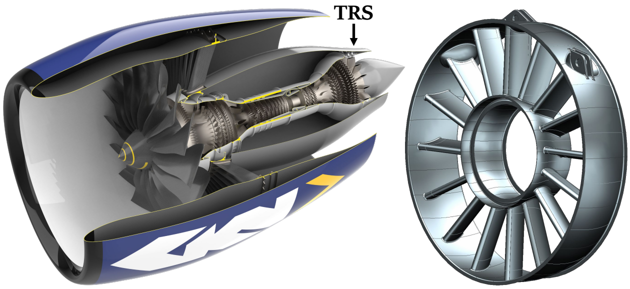

Figure 1.2: Cross-sectional image of an aero-engine, provided courtesy of GKN Aerospace, and a turbine rear structure.

technologies, and how to diminish them. Therefore, to stay competitive, it is critical for manufacturers across the supply chain to understand how their systems will be impacted by the introduction of different technologies. In this thesis, focus will be primarily on manufacturers of structural aero-engine components.

When a new aero-engine is developed, components manufacturers are queried whether they can provide certain components. For manufacturers of aero-engine components to commit to a new design, confidence needs to be high. Thus, such a query initiates an intensive and time-constrained phase during which pre-studies are conducted to evaluate design feasibility. These studies need to conclude that the requirements can be met, and that the component can be manufactured. However, these subsystems are complex, and have multiple conflicting requirements, making such evaluations extremely difficult. For example, consider the turbine rear structure (TRS), depicted in Figure 1.2. It is, among other things, responsible for: i) Deswirling the exhaust gases exiting the turbine stages; ii) Providing mounting points for the engine such that it can be mounted to the aircraft wing pylon; iii) Supporting the housing of a bearing for the central shaft; iv) Absorbing radial loads in case of a fan blade out incident. In other words, these types of components are subject to extreme thermomechanical conditions, but at the same time they need to be as lightweight as possible. The TRS is typically optimized for operational performance, which often results in geometries that are difficult, and very expensive, to manufacture. Over the last decades, efficiency gain has also been achieved through advances in material science, as complex metal alloys are employed to enable the TRS to withstand higher temperatures. While higher temperatures can improve fuel efficiency, these materials come at the cost of other aspects of sustainability, as such alloys are typically composed of critical materials (Hallstedt & Isaksson, 2017).

Now, the manufacturers of these types of structures need to consider the following: i) What will happen if the system which contains this product radically changes? ii) What will happen if the requirements drastically change, such that this solution, in its traditional form, is no longer considered viable? As has been suggested throughout this introduction, both of these scenarios are likely to happen, sooner or later. In this thesis, ideas are proposed for how to reduce the uncertainties such that, when the time comes, the subsystem manufacturers will be ready.

1.2 Research focus

Manufacturers in the aviation industry need to accurately and rapidly respond to emerging technologies to stay competitive. At the same time, committing to radically new designs involves an increased risk of encountering issues during development, which can result in expensive late design changes. It is critical to minimize the risk of late design changes, which are typically expensive and time-consuming. However, there is an insufficient understanding of how to capture, understand, and act on potential lead-time risks in the early design phase. Consequently, the first research question (RQ) concerns the efficiency of implementing new technologies, such that late design changes can be avoided.

RQ1 *What information is necessary to enable efficient integration of new technologies in next-generation designs?*

A common strategy for accelerating the development of new products is to reuse knowledge, and other assets, gained from developing previous designs. This is the foundation of the product family approach. However, exactly what can be reused is not clear, especially when new technologies are being considered for integration into the system of interest. Building an improved understanding of reuse capabilities has the potential to further accelerate development. This is the aim of RQ2.

RQ2 *What assets can be reused between product generations in a product family?*

Finally, RQ3 focuses on the prescriptive aspect: to compile the developed methods into a set of comprehensive tools that can be used in design scenarios. These tools can be used together with industry to demonstrate and test the proposed methods, and as a means of engaging researchers and students. The tools and methods are fitted into a common framework for computational similarity-assisted multi-domain conceptual engineering design, demonstrating how they relate and contribute towards a common goal. The purpose of the tools contained within this framework are not necessarily to be implemented directly into industrial workflows, but primarily to serve as vehicles for the ideas proposed in this thesis.

RQ3 *How can digital modeling support be developed to enable assessment of alternative variants in the early design phase?*

1.3 Scope and delimitations

The research presented in this thesis primarily targets product development activities in *the early design phase*. However, the early design phase is not a well-defined range within the product development process. Thus, to facilitate discussion, the generic product development process (see Section 2.1.1) as described by Ulrich et al. (2020) will be used as a baseline. The early design phase will be considered as the concept development phase, and the system-level design phase. It should be noted that, while this range may seem excessively wide for the *early* design phase, a majority of the research presented in this thesis targets product family design, in which a product platform of core technology already exists. Ulrich et al. (2020) aptly refers to products in these cases as *Platform Products*, as they are not built from scratch, but rather on an existing platform.

Furthermore, much of the research presented in this thesis focuses on the design of products within either the aviation or automotive industry. This limits the possibility to analyze the impact of the research, as development projects within these industries often span longer than a typical PhD project. Instead, impact is typically evaluated by comparing the outcome relative to that of alternative methods, and/or through focused design studies together with experts from the respective industries.

1.4 Thesis outline

Chapter 1 explains the industrial need resulting in this research, and clarifies what the presented research is focused on. Chapter 2 introduces some of the key concepts in the presented research, as well as crediting closely related ideas without which this thesis would not have been possible. Chapter 3 presents the key scientific methods applied in the presented research. Chapter 4 provides condensed overviews of each appended paper, and their highlights. Chapter 5 details the key contributions of the presented research, and how they relate to the research questions. Chapter 6 discusses the research questions, and how the results can be applied to answer them. Furthermore, the framework that ties together the proposed methods and tools is presented. Chapter 7 discusses the validity of the research, and how it may be applicable outside its intended context. Finally, Chapter 8 summarizes the thesis by stating the claims that can be derived from it, and outlines how this area of research can be continued in the future.

Chapter 2

Frame of reference

The purpose of this chapter is to position this thesis against previous research. A visualization of the areas of relevance and contribution (ARC) can be seen in Figure 2.1. This ARC diagram serves as a map of the concepts that are of high relevance to this thesis, and has been used as a basis for what to include in this chapter.

As Figure 2.1 depicts, the key areas to which this thesis contributes are: geometry generation, design space exploration, design trade-off analysis, design reuse, and the toolification of methods. Adjacent to these areas are multiple critical concepts, most of which are explored in this chapter. At the foundation of all these concepts is the product development process itself.

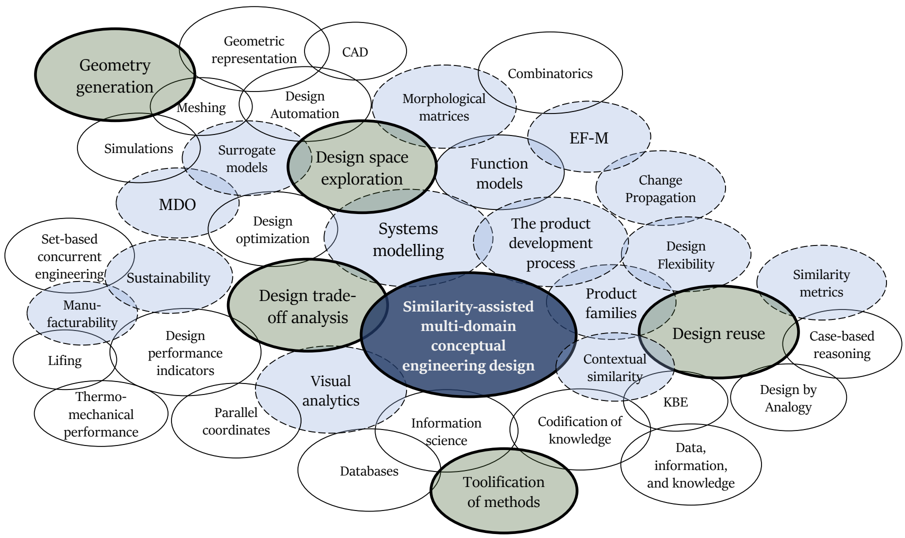

Figure 2.1: An ARC diagram depicting concepts that are important (white) or critical (blue) to the areas which the research presented in this thesis contributes (green).

2.1 The product development process

This section is intended to give an overview of the product development process. How companies has approached the product development process has evolved over the years but, as pointed out by Wheelwright and Clark (1992), in reality the development process varies greatly among companies. Nevertheless, some of the generalized steps covered here are shared by most companies.

Before embarking on the journey through the product development process it is important to note that the nomenclature used in engineering design often differs from what is typically used in systems engineering (INCOSE, 2015). Since this thesis concerns the design of complex systems such as aircraft engines and cars, some readers may expect systems engineering terminology. However, the nomenclature in this thesis is firmly based in engineering design, and thus readers that are coming from a systems engineering perspective may need to stay vigilant. Regardless, the overarching processes described in engineering design literature and systems engineering literature share many similarities, though this is not analyzed here. Curious readers may find the review of design and development process models by Wynn and Clarkson (2018) useful.

2.1.1 The traditional product development process

Ulrich et al. (2020) divides the product development process into six stages, as depicted in Figure 2.2: planning, concept development, system-level design, detail design, testing and refinement, and production ramp-up. These stages are typically performed by three different company functions: marketing, design, and manufacturing, that each have their own set of tasks for every step of the process. The steps, which are performed more or less in sequence, start with the identification of a market opportunity, and ends with the realization and delivery of a product or service that exploits that opportunity.

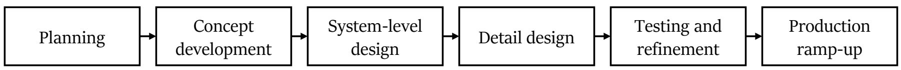

Figure 2.2: The generic product development process, based on illustration by Ulrich et al. (2020).

The market opportunity is identified and defined during the planning phase. It can, for instance, be a problem that has not been resolved by existing technology, or has only partially been solved. After identifying such a gap, the next step is to identify who the potential customers are, and what needs they have with regards to solving the original problem. When discussing aircraft components, there is typically a need to minimize fuel consumption. Needs are typically converted into requirements, which are more precise criteria for 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."* Looking at the example of aircraft components again, a requirement could be to specify the maximum allowed weight to ensure only an acceptable impact on fuel consumption. The requirements thus specify how the final product is expected to perform, and often changes over time as more information is gathered, and knowledge is gained.

Having defined initial requirements, the search for concepts that achieve those requirements can begin. During the concept development phase, designers utilize various creative processes and methods to generate design concepts. A common starting point is to perform a functional decomposition, where the problem is decomposed into the functions necessary to solve the problem. The designers can then focus on achieving the individual functions, rather than trying to solve the entire problem all at once. Then, the individual solutions to each of the functions are combined into a single solution.

Multiple concepts are typically developed, which gain increased levels of detail throughout the concept development, system-level design, and detail design stages. Simultaneously, the concepts are screened for feasibility, and eliminated until only one, or a few, remain. At that point, testing is performed to validate that the design performs as intended, after which manufacturing can commence.

Cooper (1990) observed that companies typically divide this process into stages themselves, and based his stage-gate model on this common approach. According to this model, work is conducted during the stages, which are separated by gates. The gates are used to control the output of each stage, typically by making a *go/kill decision* regarding whether to proceed with the project. These decisions are typically made by a cross-functional team from senior management, and are based on a set of predefined criteria. For instance, a gate positioned immediately after a planning stage 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. Wheelwright and Clark (1992), Pahl et al. (2007), and Ulrich et al. (2020) all offer relatively modern takes on how this process is typically conducted. Historically, the process has been significantly simpler. Design was typically focused on a single point in the design space, which, once finalized, was metaphorically thrown *over the wall* to the manufacturing function (Boothroyd et al., 2010). In other words, the manufacturing and design company functions often worked independently, without a unifying strategy (e.g., Skinner, 1969), towards their own goals, often resulting in problems. While these issues have been considerably ameliorated, modern companies still suffer from variations of these issues even today. Consequently, the research field of improving the efficiency of the product development process, and the creation of new design methods, is still alive and well. In the next section, well-known strategies and methods for improving the efficiency of product development are examined.

2.1.2 Recent considerations for product development

Over time, many different approaches for bridging the gap between design and manufacturing have been proposed and implemented. Among the earliest methods for identifying and mitigating risks of manufacturing problems during design is what is referred to as design for manufacture and assembly (DFMA). The term design for X (DFX) is commonly used to describe techniques, criteria, and guidelines that can be applied during design to achieve a certain goal X (Kuo et al., 2001). DFMA thus encompasses guidelines for designers with the aim of reducing manufacturing and assembly problems (Boothroyd et al., 2010). DFMA includes guidelines such as reducing the need for fasteners, reducing the number of parts, and reusing standard components (e.g., Naiju, 2021). By designing with manufacturing in mind from the start it becomes less likely that manufacturability issues are encountered late in development. This can reduce costs drastically, as late redesigns typically are very expensive. Conversely, there are other sets of guidelines and criteria for additional goals, such as improving the sustainability of the design. Design for sustainability (DFS) (e.g., Ceschin & Gaziulusoy, 2019) can include guidelines for reducing material use, and for ensuring that the artifact can be separated into components for recycling purposes.

DFX techniques and guidelines have historically proven to be highly useful (e.g., Boothroyd et al., 2010), though they do not provide the designer with insight into how different domains trade against each other. For instance, a highly manufacturable design may compromise performance targets, or fail to meet sustainability requirements. In other words, there was a need for an approach which enabled designers to consider *multi-domain* aspects concurrently.

Concurrent engineering is an approach which aims to involve different company functions in the design phase concurrently, enabling, for instance, manufacturing experts to give their input while there is still enough design freedom to act on it. However, as R. P. Smith (1997) once conjectured, *"A functionally separated organization makes it difficult to implement concurrent engineering mechanisms."* Nevertheless, Sobek et al. (1999) observed that Toyota at the time had a successful strategy for avoiding late design issues. Toyota worked with sets of designs, also known as design space regions, which were communicated among design and other functions at the company. Designs are only committed to if deemed feasible by all other organizational functions. Over time, the level of detail of the design concepts within the sets increases as the considered design space region narrows down towards a single point. Through ensuring that any design within the set is manufacturable already at an early stage, the risk of late redesigns is significantly diminished. This approach, referred to as set-based concurrent engineering (SBCE), enables engineering teams from different organizational functions such as manufacturing, design, and marketing, to work concurrently, improving efficiency.

To determine if a design is feasible for a specific organizational function, Sobek et al. (1999) reports that engineers would use documented guidelines (DFX). These guidelines are improved over time as experience is gained with different types of designs. The concept of leveraging experience from previous designs, when developing new and similar designs, is core to product family design.

A product family is, according to Simpson, Maier, et al. (2001), *"a group of related products that share common features, components, and subsystems"*.

What is shared among the products in a product family is referred to as the product platform. This platform is not restricted only to proven design solutions, but also to intangible assets such as knowledge and processes (Robertson & Ulrich, 1998). Through reusing already proven elements from previous projects, the development risk can be reduced (Jiao et al., 2007). A common approach to product family design is the scale-based product family (Simpson, Maier, et al., 2001). In this approach, particular scaling variables are scaled up or down to suite varying customer requirements. For structural aero-engine components, this approach can be used to instantiate products for different engine sizes. This enables the reuse of many important assets, such as models used to evaluate the fitness of scaled designs with regards to emerging requirements.

Another critical asset in modern product development is the data which many products and services generate throughout their life cycles. The availability of life cycle data has led to the advent of data-driven design, where data from existing products is leveraged to inform the decision-making process when developing new designs (Cantamessa et al., 2020). However, repurposing data for new contexts brings with it significant challenges (Woodall, 2017). Key problems include that it is unclear whether the data is relevant in the context for which it is being adopted, and that a lot of background knowledge is necessary to properly utilize collected data (Eckert et al., 2022; Frické, 2015).

At its core, the modern product development process shares many similarities to its traditional counterpart, though its processes have been significantly refined. Product families to maximize resource efficiency is commonplace today. This is especially noticeable when shopping for phones or cars, where the year-to-year differences between product models are often marginal due to the extensive reuse of assets. Such products are too complex to be reinvented every time a new model is developed. Indeed, products and systems are becoming increasingly complex, which is a sentiment that has been repeated over time for at least the past three decades (e.g., Szykman et al., 2000). This amplifies the challenge of creating products that satisfy the requirements of all stakeholders, as designers need to consider multi-domain (e.g., performance, manufacturability, and sustainability) aspects in systems where even small changes can have significant unforeseen consequences. To face the challenges brought on by increased complexity, design researchers and practitioners need to improve their ability to represent systems in the form of models, to better understand their behavior.

2.2 Systems modeling for conceptual engineering design

Throughout the product development process, it is necessary to continuously improve the understanding of the system(s) being developed. In the context of conceptual engineering design, many different concepts need to be evaluated before further resources are committed to developing them. Evaluation using physical testing may, for many reasons, not be possible. Common reasons include that physical testing is resource inefficient or impractical (e.g., Maria, 1997). Nevertheless, in search of the best solutions the design engineers need to somehow evaluate the concepts. To navigate this issue, models and simulations are commonly used (INCOSE, 2015). Models abstract the system of interest into a representation that can be used to facilitate the evaluation process. The concept of simulation, on the other hand, is closely related to modeling. Maria (1997) describes simulations as the operation of models, which can be used to infer the behavior of the system which the model represents. Similarly, INCOSE (2015) describes simulations as *"[...] the implementation of a model (or models) in a specific environment that allows the model's execution (or use) over time."* In short, a model is an abstraction of a system of interest, while a simulation is the use of the model to understand the behavior of the system. Models and simulations are thus critical components of design space exploration, where many different types of models and simulations are used to understand different aspects of the design.

While there exists an abundance of alternative means of modeling systems, this section will only focus on a few different types that are critical to the research presented in this thesis. Function-oriented models are the basis of platform architecture models, which are widely used in product family design. Similarly, design structure matrices are extensively used in product family design to optimize architecture and analyze interactions among system elements. Geometric models are commonly used for various types of physics-based simulations. Finally, surrogate models are briefly covered. While surrogate models are not necessarily models of systems, they are commonly used instead of simulations to approximate system behavior.

2.2.1 Function-oriented models

Function models are typically used in the early design phase to understand the necessary functionality of the system. This is done through functional decomposition, which decomposes the system into the functionality it needs to perform. Models used for functional decomposition typically assume the form of block schematics or function trees (Hubka, 1982). Block schematics visualize the technical process, representing the order of operations conducted to fulfill the main function of the system. Function trees, on the other hand, typically decompose the system by starting from its highest-level functionality, and then iteratively breaking it down into its sub-functions until a useful level of decomposition is reached. The research in this thesis primarily leverages function trees in the form of function-means (F-M) and enhanced function-means (EF-M) trees.

F-M trees Tjalve (1979) expand on the original function tree concept by including the means to achieving each function into the same model, as exemplified in Figure 2.3. With the ability to implement design tools into software, new function model concepts were developed that contained more design information, such as the improved F-M tree proposed by Malmqvist (1997), and later the EF-M tree originally proposed by (Schachinger & Johannesson, 2000). These advancements of the function tree model enabled them to be used not only for initial functional decomposition, but also for design space

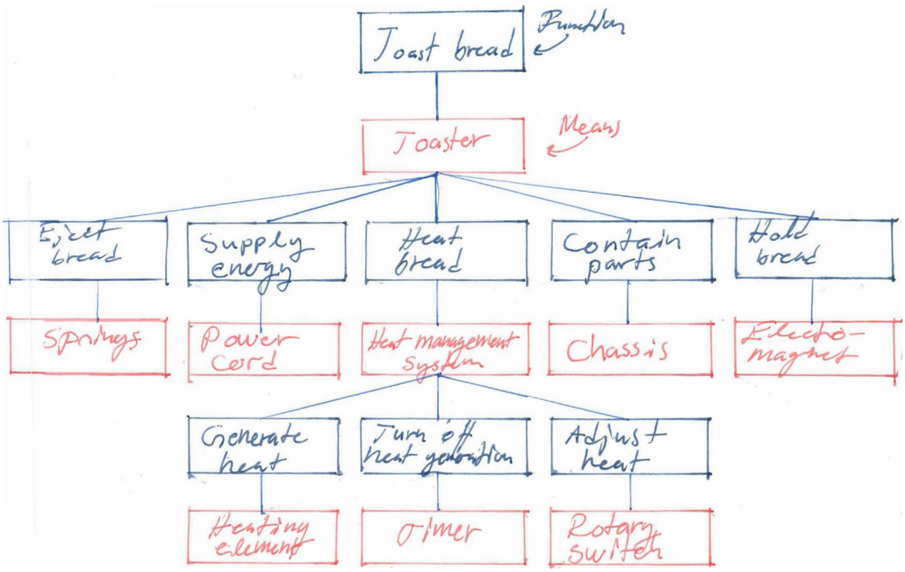

Figure 2.3: Traditional hand-drawn F-M tree with alternating functions and means.

exploration. The EF-M tree can contain non-functional requirements in the form of constraints, and information about interactions among means such as signals or physical interfaces. The mapping of such interactions can also be represented in matrix-form, and it enables analysis of system behavior.

2.2.2 Design Structure Matrices

A common tool for representing dependencies between system elements is the design structure matrix (DSM). DSMs can be used to model product architectures, processes, or even entire organizations, as exemplified by Eppinger and Browning (2012). It is scalable, and simple to read for both humans and computers. As such, it has been used as a basis for various types of algorithms to assist in the design process. For instance, clustering algorithms can be applied to DSMs to identify modularization opportunities (Yu et al., 2003), and the change propagation method (CPM) can be used to identify different types of risk (Clarkson et al., 2004).

CPM utilizes two DSMs as inputs: one DSM that represents the likelihood of change propagating from one system element to another, and one DSM that represents the impact of change propagating between elements. By evaluating the interplay between impact and likelihood, a new DSM can be computed that contains the risk each system element imposes on all other elements. What type of risk is computed depends on what impacts and likelihoods are being measured. Brahma and Wynn (2023) lists multiple examples, such as how much a proposed change to a system might impact the design, product family, or production.

Of significant importance to this thesis is the compatibility between the DSM format, and the interactions mapped using EF-M. These modeling techniques can contain the same information about system element interactions, as was hinted at by Raudberget, Dag et al. (2014), and explicitly demonstrated by Müller et al. (2019). Consequently, EF-M modeling can reap the benefits of analysis enabled by DSM models.

2.2.3 Geometric representations

Detailed modeling of product geometry using computer-aided design (CAD) is generally reserved for the later phases of design (Pahl et al., 2007). At the same time, CAD has been criticized for forcing designers into overcommitting to details too early (Woodbury & Burrow, 2006). Nevertheless, for certain types of development projects, such as when developing a product within a scale-based product family, coarse geometries of concepts can be helpful for early feasibility studies. The CAD geometry itself is useful, as it provides a visual representation of the design which can be used to communicate ideas. But perhaps more importantly for scale-based product families, the CAD format is useful for different types of analysis, and can be meshed for use in finite element analysis (FEA).

In the aerospace industry, it is common to utilize shell-based geometries to represent early designs (e.g., Robinson et al., 2011). An example of such a model can be seen in Figure 2.4. Shell models are composed of surface elements, or *shells*, that lack thickness and are thus of relatively low detail. The thickness of individual walls are instead represented by attributes associated with each individual surface. As a result, shell-based geometries are computationally inexpensive, and can easily have their attributes varied for optimization studies to evaluate alternative thicknesses.

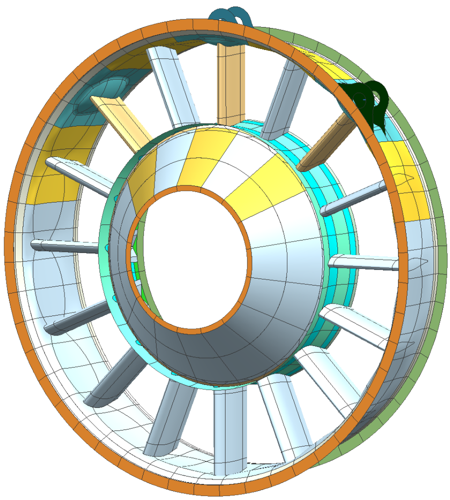

Figure 2.4: A shell model of a Turbine Rear Structure used for early design phase evaluation.

Alternative approaches exists, however, including methods that facilitate the use of solid geometries. Sandberg et al. (2017), for instance, demonstrated the use of CAD journals to automatically generate solid models of the structural components of a turbo-fan engine, which were then used for FEA analysis. Another approach was proposed by Müller et al. (2019), who bridged the gap between function and form by using EF-M modeling as a basis for generating CAD geometries. This particular approach utilized CAD building blocks that were pieced together into different configurations through a special software. This enabled a relatively high modeling flexibility at the cost of complexity in the software that was designed to facilitate this process.

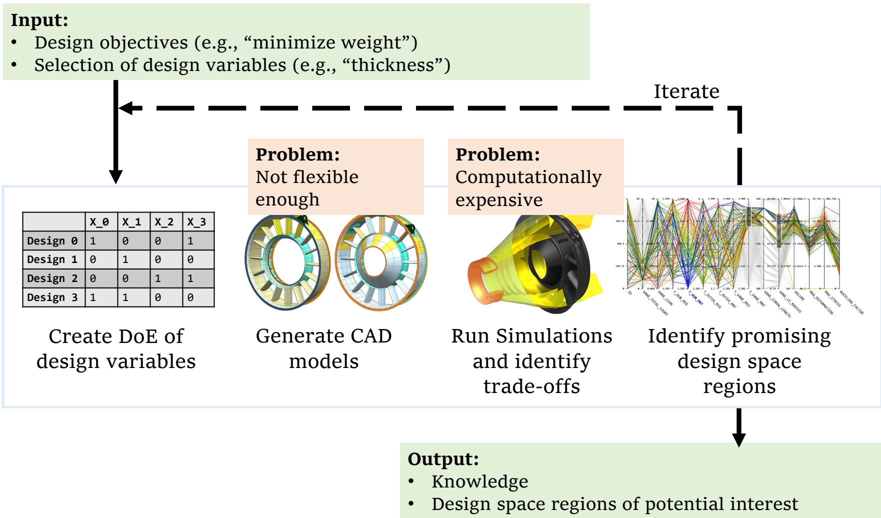

Figure 2.5: Simplified overview of a design space exploration process that highlights the issues with CAD modeling and computationally expensive simulations.

The work of Müller et al. (2019) highlights an important problem with CAD modeling in the conceptual phase in that it is difficult to represent radically different designs. To evaluate novel solutions, it is necessary to be able to represent a wide range of designs (Amadori et al., 2012). The CAD format is limited in its flexibility, but is nevertheless a necessary format for many types of simulations. Parametric variation is possible, but is typically hindered by geometric dependencies in the models which significantly reduces flexibility (Aranburu et al., 2022). The building block approach presents interesting opportunities, but is difficult to implement and maintain. At the same time, the richer the geometry, the more expensive the simulation. This results in a difficult to navigate trade-off during conceptual design, as visualized in Figure 2.5, where engineers need to find an approach that balances these aspects. A common means of reducing computational expenses is to utilize surrogate models.

2.2.4 Surrogate modeling

Simulating system behavior can be computationally expensive. This is especially true for physics-based simulations that utilize FEA. However, when searching for high-performing designs, such as when exploring the design space through optimization studies, it is generally necessary to evaluate large sets of designs. In such scenarios, designers often resort to surrogate models (Papalambros & Wilde, 2017), also known as metamodels (Simpson, Peplinski, et al., 2001). Data-based surrogate models are trained on data produced by higher-fidelity models (or physical tests), such as physics-based simulations. The trained surrogate model can then provide approximations at a significantly reduced computational expense. Examples of data-based surrogate models include polynomials trained using polynomial regression, Gaussian processes, and neural networks. Throughout this thesis the term *surrogate model* is used in short for *data-based surrogate model*.

An important surrogate model property is the dimensionality, which is determined by the number of variables it requires to generate an approximation. A well-known phenomenon is the so-called *curse of dimensionality*, which entails that the higher the dimensionality, the more data is required to train the model for it to yield accurate approximations (e.g., Wang & Shan, 2006). This poses a problem for system behavior approximation, where the number of variables that affect the behavior is often high. Multiple approaches have been proposed to mitigate this issue, including variable screening and reduction (e.g., Viana et al., 2021), and multi-fidelity models (e.g., Giselle Fernández-Godino, 2023). Nevertheless, this presents a challenge for designers, as it is impossible to know with absolute certainty how trustworthy the models are, even though these models ultimately inform critical decisions during the design process.

2.3 Design Space Exploration

Design space exploration is commonly viewed in literature as a computer-oriented exercise where the variables of a system are systematically varied, in search of promising designs. Authors who share this sentiment include Gries (2004) and Woodbury and Burrow (2006). Typically, this exercise is composed of sampling the design space, representing the sampled design points using one or more modeling techniques, and then evaluating the representations based on a set of design objectives. In this thesis a slightly broader definition of design space exploration is used, where sampling and evaluation can also be performed by humans. This broader definition seems to be shared by authors such as (Nelson et al., 2009; Shah et al., 2003), who use the term *exploration* in association with *ideation* and *concept generation*, which traditionally are not computer-exclusive activities. In this section we will look at discrete design space exploration, which is common in the earliest stage of conceptual design, and how designers tackle decision-making by informing themselves of potential trade-offs.

2.3.1 Discrete design space exploration

In the early concept phase, it is common practice to functionally decompose the system of interest and then ideate means of achieving each of the individual functions. Through combining different means of achieving each function, alternative solution candidates can be identified. A similar scenario can also be found in product family design, where multiple alternative means may exist that fit within the product platform architecture, and different instantiations of these means form new design variants (e.g., Siddique & Rosen, 2001). However, a significant difference between these two scenarios is the amount of information available. In the early conceptual phase, little is known about the alternative means. Conversely, in a product family, many of the alternative means may already be well-developed, and thus more information is likely to be available.

The process of identifying and evaluating combinations of means that together form the basis of new designs is referred to in this thesis as *discrete design space exploration*. A traditional method for representing discrete design spaces is the morphological matrix, originally proposed by Zwicky (1967). Morphological matrices list all of the functions which a system is expected to perform, along with alternative means of achieving each of those functions, as depicted in Figure 2.6. Paths can then be traced through the morphological matrix to represent combinations that form design concepts. Alternatively, F-M or EF-M trees can be expanded with alternative means for individual functions, enabling them to contain multiple alternative design concepts. This was exemplified by Müller et al. (2019) who used an EF-M to explore alternative concepts. Müller et al. explored all possible combinations of means within the EF-M by exploiting the richness of EF-M modeling to define parameters, constraints, and interactions among the individual means. This information was then leveraged to generate geometries for each of the alternative concepts.

One of the issues with these types of design spaces is the combinatorial explosion caused by the vast number of possible combinations (Motte & Bjärnemo, 2013). This often makes it infeasible to evaluate all combinations, unless the number of functions and alternative means are kept at a low number. To ameliorate this, a common approach is to map and avoid any incompatible pairings of means (e.g., Pahl et al., 2007), and to avoid considering means that are deemed to be infeasible (Ulrich et al., 2020). Alternatively, a computational approach can be taken where optimization is utilized to identify promising solutions. Alternative computational techniques have been demonstrated by, for instance, Bussemaker et al. (2024), Ma et al. (2017), Ölvander et al. (2009), and Tiwari et al. (2009). It is important to note that, to apply optimization to discrete design space exploration, enough information about each alternative means needs to be available to enable mathematical evaluation. In the traditional morphological matrix, no such information is embedded, but the computational approaches generally enrich the morphological matrices with quantitative properties. Bussemaker et al. (2024), on the other hand, utilizes an entirely different format by representing system architecture alternatives in a tree-based structure, and embedding relatively mature mathematical models.

Model-driven design space exploration (MDSE) is a different approach to

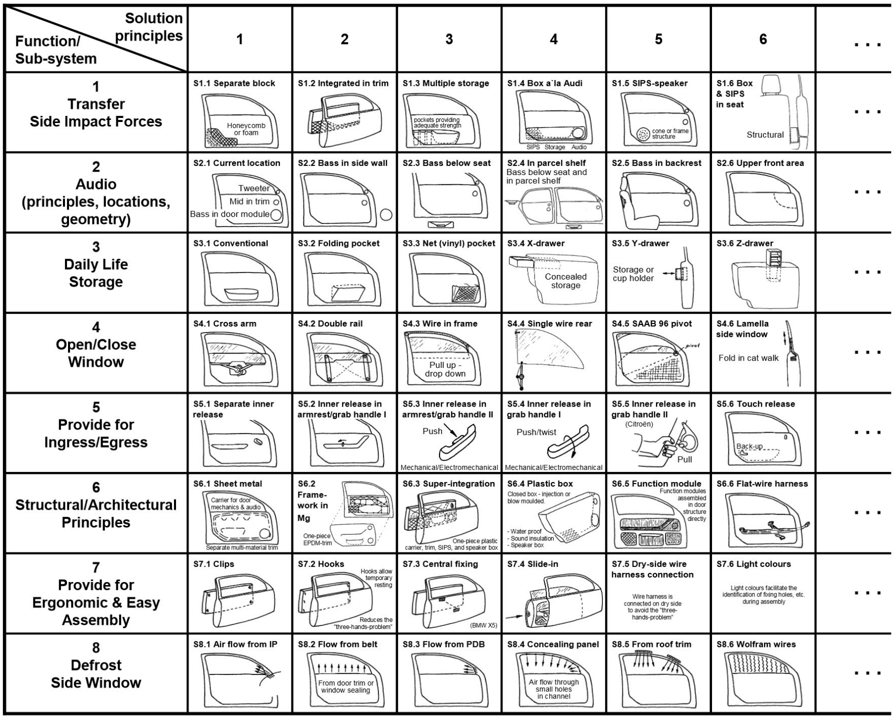

Figure 2.6: Example of a morphological matrix, adopted from Almefelt (2005).

exploring discrete design spaces. It utilizes a system model which is systematically transformed in search of new designs given a set of goals and constraints (e.g., Hegedüs et al., 2015). These transformations are done through a set of pre-determined rules which, when executed, change the system model (e.g., Voss et al., 2023). Since the design space is explored through the application of pre-determined rules which transform the system model in predictable ways, this approach to exploration is discrete. However, as exemplified by Gross and Rudolph (2016), design variables can also be considered in a separate step, thus enabling a combined exploration of the discrete design space and the design variables. Notably, MDSE differentiates from exploration using EF-M or morphological matrices in that the design space is not restricted to a set of possible combinations, as the same system can be transformed using the same rules multiple times. In other words, there is not necessarily an upper bound of possible combinations. Design spaces explored using MDSE are instead limited by the constraints imposed on the system. This may render MDSE less suited for early conceptual design, as defining constraints often require information which is not necessarily available at that stage. On the other hand, it has been shown to be an appropriate approach when the constraints are clear and the assortment of necessary system components is known, but not their required quantities. This is exemplified by the optimization study of a smart building configuration conducted by Abdeen et al. (2014). The system components of this smart building are pre-defined: servers, sensors, devices, and applications. The challenge is to identify resource-efficient combinations which can contain any number of these components.

We can conclude that discrete design spaces provide a particular set of challenges: the combinatorial explosion caused by the vast number of potential pairings of alternative means, and ensuring that all combined means are compatible. Many approaches have been proposed for exploring such spaces computationally, though such methods generally necessitate additional information that can be difficult to elicit during the early stage of conceptual design. Furthermore, discrete design spaces are found not only when creating new products from scratch, but also when searching for novel instantiations within established product families.

2.3.2 Informed decision-making

Decision-making in the design space exploration process involves weighing multiple, often conflicting, design objectives against one another. These trade-offs need to be identified and understood to assist designers in making better-informed decisions, while there is still enough design freedom. This entails not only understanding how the design will perform when in use, but also during the other phases of its life cycle. Of additional emphasis is how aspects of manufacturability and sustainability are affected by design choices. In this thesis, these are referred to as *domains*, and these domains often have conflicting requirements that need to be considered. In addition, the concept of flexibility is introduced, as flexible systems maintain a degree of design freedom throughout their life cycle.

Multi-domain trade-offs

Depending on product complexity and production volumes, manufacturing and maintenance are typically responsible for the majority of the cost in a product life cycle (Fixson, 2004). However, it is generally accepted (though debated to what extent) that a significant portion of the decisions resulting in those costs are made during the design phase (Barton et al., 2001; Pahl et al., 2007; Ulrich & Pearson, 1993). In addition, it is known that the cost of correcting design problems significantly escalates the further into the life cycle the problem is identified (Stecklein et al., 2004). With this in mind, it is clearly important to evaluate manufacturability already in the design phase, to mitigate excessive manufacturing costs. Traditionally, DFMA has been used to assist designers in developing manufacturable designs. However, when evaluating large quantities of alternative designs, applying DFMA guidelines is not feasible. Instead, an automated evaluation approach is necessary, similarly to how FEA can be automated to evaluate performance aspects of designs. Examples of this includes Runnemalm et al. (2009), who demonstrated how GKN Aerospace (referred to as Volvo Aero at the time) had started to use welding simulations to evaluate manufacturability. Stolt et al. (2016) demonstrated how the manufacturability of alternative designs can be evaluated by enriching CAD models with weld information. Another example is Söderberg et al. (2017), who discusses the utilization of the Robust Design and Tolerancing (RD&T) software for evaluating design robustness.

Vallhagen et al. (2013) pointed out that it is not only necessary to evaluate the manufacturability of alternative designs, it is also necessary to understand how manufacturability interacts with performance. Put differently, choices made that affect manufacturability can also affect performance, giving rise to multi-domain trade-offs that need to be considered. Vallhagen et al. (2013) proposed a framework which highlights the importance of manufacturability simulations in design, as well as SBCE and the identification of trade-off curves. However, as Siedlak et al. (2015) noted, performing manufacturability and performance analysis concurrently requires information not typically available in the conceptual design phase. Siedlak et al. (2015) exemplifies how this can be done, enabling designers to consider trade-offs between manufacturability and performance by combining structural models, aero models, manufacturing and assembly cost models, and production flow models. Another example of how this can be achieved was demonstrated by Kim et al. (2022), who utilized optimization to trade manufacturability against mission performance to explore alternative aircraft rib variants.

While a few prominent examples of such research exist, the body of research pertaining to manufacturability and performance trade-offs in the early design phase is noticeably sparse. The same can be said for the body of research concerning sustainability trade-offs in the early design phase. A discernible difference, though, is that the toolbox for exclusively evaluating manufacturability is becoming richer, while there is still a significant lack of tools to evaluate sustainability (Hallstedt et al., 2022; Lovdahl et al., 2024). Recent decision support methods for improved sustainability include material criticality assessment, which enables consideration of alternative materials based on their life cycle sustainability (Hallstedt & Isaksson, 2017); the sustainability fingerprint method (Hallstedt et al., 2023), which enables qualitative assessment of alternative concepts with regards to their life cycle sustainability.

While trade-offs among sustainability and other aspects is largely missing from contemporary research, there are some examples of researchers contributing to filling this gap. Al Handawi et al. (2020), for instance, demonstrated an optimization approach to balancing remanufacturing potential against structural performance. Another recent example is the study conducted by Spinelli and Kipouros (2025), who applied Bayesian networks to assess sustainability and performance concurrently.

It is critical to note that sustainability entails looking at more variables than merely greenhouse emissions. Indeed, for a product to be sustainable it cannot have a negative impact on the environment, but also not on society or the economy (Mebratu, 1998; Ramani et al., 2010). For instance, battery-electric vehicles do not generate greenhouse emissions when driven, though the potential health-risks caused by handling of the associated toxic materials (Lehtimäki et al., 2024) and the sources of the electricity used to charge said batteries (Requia et al., 2018) also need to be considered. Focusing only on single aspects, such as CO_2 emissions, can result in sub-optimization and even the emergence of new problems. How to consider such trade-offs within sustainability, and simultaneously towards the domains of manufacturing and performance, is not well-understood. Indeed, the available scientific literature regarding manufacturability or sustainability trade-offs against performance is sparse. To my knowledge there are no scientific records of attempts to conduct trade-offs among all three of these domains simultaneously. However, to assert cost-efficient products that perform as intended while simultaneously not negatively impacting society or the environment, multi-domain trade-offs need to be considered from as early as possible during the development process.

Optimization in conceptual design

To facilitate the identification and quantification of trade-offs, it is common practice to utilize optimization (e.g., Fleming et al., 2005). Traditionally, design optimization has been viewed as a means of identifying the best design alternative (Papalambros & Wilde, 2017), however, it also enables designers to identify and explore the limits of the design space. Indeed, many of the design space exploration studies referred to above take advantage of optimization to some extent. To exemplify, Ölvander et al. (2009) employed Tabu search to find optimal combinations within morphological matrices; Siedlak et al. (2015) traded manufacturability, aero, and structural performance using an optimization approach. Al Handawi et al. (2020) utilized optimization to trade remanufacturability against structural performance. In short, identification of trade-offs using optimization can facilitate SBCE as it enables designers to focus on a range of the best possible designs given a set of objectives and constraints.

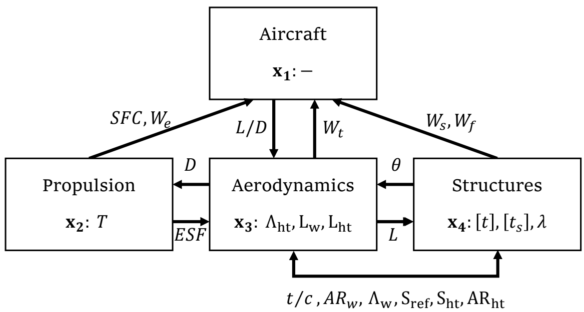

Figure 2.7: Example of an aircraft multidisciplinary analysis (MDA) adopted from Tosserams et al. (2010).

System design often requires accounting for interactions among different disciplines. For example, in aircraft wing design, fuel capacity, wing length, and stiffness are interdependent. Thus, when optimizing such systems it is necessary to account for how these disciplines interact. From this necessity the field of multidisciplinary design optimization (MDO) was conceived. For a review of different MDO formulations, see Martins and Lambe (2013). Accounting for interactions necessitates rigorous mathematical bookkeeping to assert that a common description of the system is consistent in all subsystems, for which multiple approaches have been suggested. One of the most prominent MDO approaches is non-hierarchical analytical target cascading (Tosserams et al., 2010) which, in its compact form (Talgorn & Kokkolaras, 2017), significantly reduces the necessary mathematical bookkeeping.

To evaluate a system using MDO it is first necessary to decompose it and analyze the dependencies among its subsystems. This is referred to as MDA, and it ultimately determines which variables are coupled, shared, or independent. This MDA can be visualized as a flow diagram, as exemplified in Figure 2.7. Then, the problem can be programmed into an MDO solver that conducts the mathematical bookkeeping and potentially outputs a design configuration that satisfies all subsystems without breaking any variable couplings.

Considering flexibility

As a design matures throughout the development process, decisions are made that increasingly constrains the design space. This reduces designers ability to make changes, or take the design in new directions. The ability to change the design, generally known as the design freedom (e.g., Simpson et al., 1998; Ullman, 2009), typically dissipates completely by the end of the design process (Simpson et al., 1998). However, a means of maintaining design freedom beyond the design phase is to design systems such that they can be changed easily. Fricke and Schulz (2005) referred to this as flexibility. A flexible system can thus more easily accommodate emerging customer requirements. Consequently, there is a need to evaluate the flexibility of systems such that they can be designed to be flexible. A well-known method for quantifying flexibility is CPM, which enables calculating how changes propagate throughout a system (Clarkson et al., 2004). Through CPM, the likelihood of changes propagating to other parts of the system and the impact of such propagations are combined to calculate the risk associated with making changes. Other means of measuring flexibility includes Hölttä and Otto (2005), who quantified the effort necessary to redesign a subsystem without significantly impacting other parts of the system. Cormier et al. (2008) proposed flexibility metrics that considered interactions between subsystems, how they interface, and the range between subsystems. Alonso Fernández et al. (2024) developed a flexibility metric that enables designers to consider space allocation for future system changes, taking into account field effects such as heat transfer.

A concept closely related to flexibility is design margins. To facilitate system flexibility, it generally needs to have an excess of capacity beyond the demand of its present requirements. This excess capacity enables the system to absorb uncertainties by providing headroom for future system upgrades (Eckert et al., 2019). However, as (Brahma et al., 2024) points out, this additional capacity comes at a price that must be considered with care to avoid overdesign.

Exploration through visual analytics

To efficiently convey information to decision-makers about the various trade-offs and metrics used to understand the design space, it is often necessary to provide some means of visualization. Furthermore, to facilitate SBCE it is also necessary to enable the identification of promising regions of the design space for further development. To identify such regions, designers often need to explore datasets representing design variants and their performance with respect to design objectives. To that end, visual analytics is a means which allows for visualizing and interacting with data to gain knowledge and insight (Cui, 2019; Wong & Thomas, 2004).

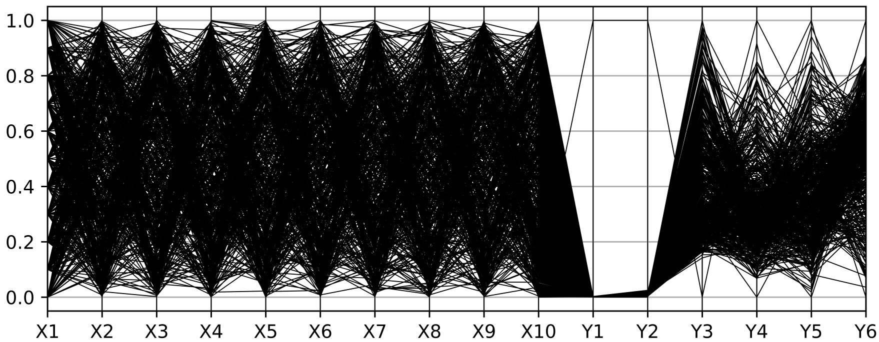

Figure 2.8: Example of a parallel coordinates plot visualizing multiple dimensions divided into system input (X) and output (Y) metrics.

A visual analytics method that is central to this thesis is the parallel coordinates plot (Inselberg & Dimsdale, 1991), an example of which can be seen in Figure 2.8. The parallel coordinates plot is a widely used method for visualizing high-dimensional data. Applications range from exploring trade-offs in aero-engine component design (Kipouros et al., 2013) to analyzing football games (Janetzko et al., 2016). In design space exploration it is commonly used to visualize many design points, represented as lines moving horizontally from axis to axis. This can be used to represent the configuration of each design point, as well as how they perform in different aspects, concurrently.

A critical feature to contemporary implementations of parallel coordinates is the ability to interact with the data, as it enables the user to explore and gain insights as to how different variables interact (Kipouros et al., 2013). A common mode of interaction is to constrain the data shown in the plot based on specific requirements. In doing so, the designer can highlight regions of the design space that achieve the design objectives, thus gaining deeper insight into the design space.

Aside from interactivity, multiple proposals for how the format can be enriched have been proposed. Such developments of the method include clarifying data distribution through, for instance, by clustering the lines (Zhou et al., 2008) or superimposing distribution visualizations directly on the parallel coordinates plot (Janetzko et al., 2016). A recent contribution by Tadeja et al. (2021) evaluated how parallel coordinates can be enhanced through virtual reality, allowing the users to explore the plot in three-dimensional space.

2.4 Reuse and similarity in engineering design

A common means of mitigating uncertainty in design is to rely on existing assets, both tangible and intangible. This is referred to as design reuse (Sivaloganathan & Shahin, 1999). Reusing knowledge is known to reduce the resources necessary to develop new products (Duffy & Ferns, 1998; J. S. Smith & Duffy, 2001). What determines the extent to which knowledge can be reused seems to be determined by how general the knowledge is (J. S. Smith & Duffy, 2001), and how similar the new context is to the context in which the knowledge was originally created (Markus, 2001). The dependency on contextual similarity is demonstrated by approaches to problem solving such as case-based reasoning, and design by analogy. In case-based reasoning, new problems are compared to previously experienced problems in search of reusable solutions (Aamodt & Plaza, 1994; Akmal et al., 2014). Comparably, design by analogy measures the functional similarity between new concepts and existing solutions, thus facilitating the discovery of how other products have achieved similar functionality (McAdams & Wood, 2002). However, reusing existing solutions in new contexts comes with its own uncertainties. Stenholm et al. (2019) comments on this, noting that to facilitate reuse we need to design *for* reuse. In other words, flexibility is an enabler of design reuse.

Both case-based reasoning and design by analogy makes use of similarity metrics (Lin, 1998) to measure contextual similarity. Similarity metrics are commonly used for clustering and classifying data (e.g., Xu & Wunsch, 2005), and there are multiple alternative metrics. Among the most common metrics are Euclidean distance and cosine similarity. Common for these are that they compare quantitative data. However, there are also means of comparing qualitative data. Levenshtein distance (Su et al., 2008) and normalized compression distance (Li et al., 2004) directly compare the content of character-based data, and modern large language models enable measuring the extent to which two texts convey the same meaning (e.g., Y. Feng, 2024).

When describing product platforms Robertson and Ulrich (1998) lists, among other things, mathematical models as a reusable asset. M. Pidd (2002) describes how programmatic models can be reused in a range of different ways. If the context is similar enough, then models can be reused without modification. However, as the context becomes increasingly different it may only be possible to reuse parts of the model, such as functions or snippets of code. This demonstrates that models can be quite flexible, but that they may require modification to serve a new purpose.

Another asset that can potentially be reused is data. An example of this is the digital twin for product development proposed by Tao et al. (2019), in which the data collected throughout the product life cycle is funneled back to the designers, who then leverage it for iterative product development. However, data reuse is challenging, as the relevancy of existing data is unclear when applied in new contexts (Woodall, 2017). Consequently, Eckert et al. (2022) stresses the importance of understanding the original assumptions before attempting to repurpose data.

2.5 Analysis of research opportunity

This chapter introduced the key concepts at the foundation of the research presented in this thesis, along with complimentary research. To conclude, this section is dedicated to briefly connecting the aforementioned concepts to the problem raised in the introduction, and to highlight the research gap which this thesis addresses.

The aviation industry is aiming for net-zero carbon emissions by the year 2050. This entails looking at the introduction of new technologies into existing aircraft systems and subsystems. However, to achieve sustainable aviation, the scope needs to be extended. Focusing exclusively on greenhouse emissions risks resulting in the emergence of new problems. Thus, a systemic view on sustainability is necessary. At the same time, aero-engine components are becoming increasingly difficult to manufacture, and manufacturing issues pose a significant problem. Platform design and product families are used to reduce uncertainties between product iterations, but nevertheless manufacturing problems persist. It can thus be concluded that there is a need for a multi-domain approach that evaluates manufacturability and sustainability alongside performance during the early design phase. A significant challenge is to capture and act on multi-domain aspects while there is still enough design freedom.

The uncertainties associated with the introduction of new technology risk causing significant disruption during the system life cycle. Thus, designers are challenged to capture and reduce uncertainties as early as possible. Change propagation is a well-understood method for quantifying and identifying risk based on probability, which can be used to understand how change due to new technology may affect a system. Additional means of reducing uncertainty include: i) reusing knowledge and other assets from previous projects, and ii) designing for flexibility. Regarding reuse: the aviation industry has decades of experience with proven technology. However, as the context changes due to the introduction of new technology, what can be reused becomes an uncertainty in itself. Designing for flexibility, on the other hand, may facilitate design reuse as it ensures a platform of commonality between projects. However, product families can be configured in many different ways, and even more so when accounting for potential future technology. These configurations span vast discrete design spaces that need to be efficiently navigated to enable the identification of high-performing, flexible, solutions.

Once promising configurations have been identified, geometric representations are needed to facilitate simulations, and surrogate models to facilitate optimization. Here, designers are challenged to assert trustworthiness in their models, as evaluations made at this stage lay the groundwork for detailed design, and the future of the system. In addition, to achieve a multi-domain perspective, a large quantity of variables needs to be considered. A visual analytics approach can potentially provide the appropriate decision-making support to enable designers to consider all necessary aspects of the system.

To conclude, designing flexible product platforms necessitates exploring vast discrete design spaces. There are many established means of exploring discrete design spaces, but none of them consider flexibility. Furthermore, there is a significant research gap in how to conduct multi-domain trade-off analysis in the early design phase. This is necessary to avoid evaluating sustainability, manufacturability, and performance separately, and instead consider how these domains interact. Along with this gap comes the challenge of how to provide suitable decision support to navigate such trade-offs. Finally, the modeling approaches generally used to evaluate performance, manufacturability, and sustainability in the early design phase all entail a significant uncertainty. More research is required in exploring how designers can evaluate the trustworthiness of early design models and simulations.

Chapter 3

Research approach

Engineering design research is a pursuit of both knowledge, and practical application of that knowledge. As Reich (1995) put it: *"In order to sustain credibility, researchers must use and demonstrate that the techniques they develop in design research have some relevance to practice"*. Consequently, in the interest of maintaining scientific rigor, the research presented in this thesis has adopted the research framework proposed by Blessing and Chakrabarti (2009). This framework, referred to as Design Research Methodology (DRM), was chosen since the purpose of the conducted research is to understand existing problems in design, and to develop methods and tools to mitigate those problems. This section will describe how DRM was applied, along with how data was elicited through literature reviews, interviews, and design studies.

3.1 Application of Design Research Methodology

The research presented in this thesis has utilized DRM primarily as a means of organizing the overall approach. It can be argued that, for classification purposes, the conducted research fits what Blessing and Chakrabarti (2009) refers to as a *Type 5 research*: *"Development of Support Based on a Comprehensive Study of the Existing Situation"*. This type of research covers all four stages of DRM (see Figure 3.1), and puts significant emphasis on the first descriptive study (DS), but only initializes DS2. The stages were not conducted sequentially, as previous stages were often revisited when new information was uncovered. Table 3.1 maps the extent to which the appended papers contributed to each individual stage.

The initial research clarification (RC) was mainly conducted through literature reviews, where research gaps were identified. Over time this clarification has been refined, ultimately resulting in the research questions stated in Section 1.2.

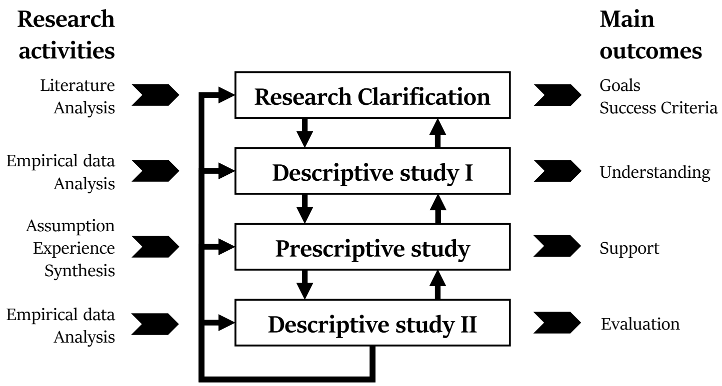

Figure 3.1: The four stages of the DRM framework. Redrawn from Blessing and Chakrabarti, 2009, p 39.

Table 3.1: Map of how each of the appended papers contributed to the DRM process. One dot represents a minor contribution, while three represent a major contribution.

Paper	*RC*	*DS1*	*PS*	*DS2*
Paper A: *Exploring the Potential of Digital Twin-Driven Design of Aero-Engine Structures*	• •	• • •		
Paper B: *Assessment of Weld Manufacturability of Alternative Jet Engine Structural Components Through Digital Experiments*		•	• •	
Paper C: *A Similarity-Assisted Multi-Fidelity Approach to Conceptual Design Space Exploration*	•	•	• • •	•
Paper D: *Managing Combinatorial Design Challenges Using Flexibility and Pathfinding Algorithms*		•	• • •	•
Paper E: *Exploring Design Trade-Offs among Sustainability, Performance, and Manufacturability when Considering Integration of New Technologies*		• •	• •	•

The purpose of DS1 is to capture the problem in its practical context. This was mainly accomplished through interviews and literature reviews. Two interview studies were conducted together with engineers at GKN Aerospace, one of which was published in **Paper A**. Furthermore, workshops with experts were conducted on multiple occasions, shedding additional light on the industrial perspective of the problem.

Based on the understanding gained from DS1, design support was developed. An iterative approach was taken to design support development in the prescriptive study (PS) phase. Frequent testing and evaluation through workshops, and the opinions of experts, gave further insight, often requiring alterations to the design support to fit the new and improved understanding. At the same time, the frequent tests served as evaluations of the methods and tools. Consequently, the execution of the prescriptive study (PS) was intertwined with both DS1 and DS2, as development of the design support resulted in a more thorough understanding of the problem itself. In this manner, the details of the methods and tools were slowly but steadily refined over time. This process is further detailed in Section 3.2.3.

Due to the long lead-times of product development projects, finalizing DS2 during a PhD project is uncommon. As is the case in this scenario, where DS2 was merely initialized. Multiple design studies were conducted together with experts from GKN Aerospace to evaluate the usefulness of the design support. However, these evaluations could not be performed in an industrial context, and were thus restricted to a lab environment. Most of the methods and tools thus achieved technology readiness level (TRL) 4 (validated in a lab environment), but were unable to advance further. Ideas for how to proceed with validation in pursuit of higher TRLs is outlined in Chapter 7.

3.2 Method utilization

In this section the primary methods utilized for gathering data are presented and motivated.

3.2.1 Literature search

All papers appended to this thesis were initiated by performing thorough literature reviews. These reviews were conducted to identify gaps in existing research, as well as to utilize and build on previously explored ideas. Table 3.2 provides an overview of the focus of the literature reviews conducted for each of the appended papers.

Table 3.2: The focus of the literature reviews of each appended paper.

Paper	***Literature review focus***
Paper A	• Reapplication of manufacturing data in design • Digital twins for use in design
Paper B	• Manufacturability evaluation in design • Automatic CAD model generation
Paper C	• Approaches to multi-disciplinary design space exploration • Surrogate models in engineering design • Similarity in engineering design
Paper D	• Exploration of discrete design spaces • Evaluating and trading flexibility in design
Paper E	• Evaluating sustainability during the early design phase • Managing trade-offs among performance, manufacturability, and sustainability

The approach used to identify relevant literature was typically to, at first, formulate appropriate search queries. If possible, a few sample papers known to be relevant to the subject matter were gathered and used to verify the search queries. The primary databases used were Scopus and Google Scholar. Once relevant literature was identified, further academic works of interest were discovered through backwards and forwards snowballing techniques (Wohlin, 2014).

3.2.2 Interviews

To gather qualitative data, semi-structured interviews (Blessing & Chakrabarti, 2009) were conducted. The interviews for **Paper A** focused on the topic of redesigns due to manufacturability issues, and the prospect of reusing manufacturability data for design purposes. This initial interview study contributed to a thorough understanding of the problems faced in the aviation industry. An additional interview study was conducted for **Paper C**, the purpose of which was to gain an understanding of how knowledge and other assets are being reused in industry. The results of this study were not published, but contributed to achieving the necessary understanding to develop the design support proposed in **Paper C**.

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.

At the time of the interviews the COVID-19 pandemic was still ongoing. Consequently, most of the interviews were conducted using video conferencing software. This put additional emphasis on the importance of verifying the results of each individual interview with the interviewee, as communicating over video can easily lead to misunderstandings. To mitigate this potential risk, all interviews were summarized and sent back to the interviewees for verification. This gave the interviewees the opportunity to retract statements, or to correct mistakes. Based on the feedback from the interviewees, a new summary was created, which once again was sent back to the interviewee. This process was repeated until both parties were satisfied.

3.2.3 Iterative support development through design studies

With the exception of **Paper A**, all appended papers contain a design study. These studies were conducted together with industry experts with the intent of evaluating the design support on realistic cases from industry. In **Paper B, C, and E** those experts were from GKN Aerospace, and in **Paper D** the experts were from Volvo Cars.

Working together with GKN Aerospace, the design studies conducted with them were organized to resemble their process for design space exploration, as depicted in Figure 3.2. Typically, a set of objectives was defined, including objectives such as maximizing stiffness and minimizing weight. Then, the design space was defined by selecting which design variables to vary, and by how much. Typically, a Latin Hypercube (McKay et al., 1979) approach was applied for sampling the design space. Then, those samples were applied to generate context models (e.g., CAD geometry and meshes), which were then used for various types of analysis, including FEA of known load cases. If the results were inadequate at this point, then the process was iterated with refined variable ranges. Otherwise, surrogate models were trained using the analysis data, and used for optimization in search of trade-off curves and promising regions in the design space. This process was used as the baseline, on top of which the proposed methods and tools were applied.

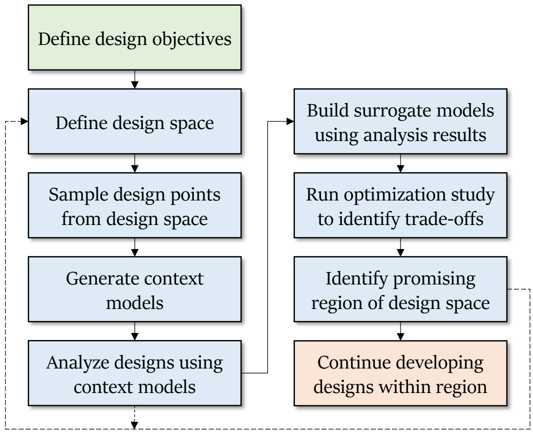

Figure 3.2: Generic design space exploration process inspired by practices used at GKN Aerospace.

When working together with Volvo cars in the design study presented in **Paper D**, the baseline process was instead derived from literature, focusing on how to explore vast discrete design spaces. Initial workshops together with experts from the company were conducted to get a thorough understanding of the system being investigated. Afterwards, the proposed approach was applied and compared against the literature baseline.

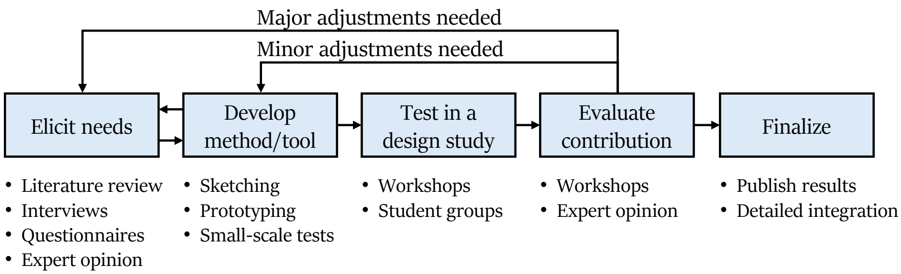

Figure 3.3: Process for developing methods and software tools, and some of the activities commonly performed at each step of the process.

The testing of methods and tools in the design studies was part of a larger iterative development process, as depicted in Figure 3.3. The first step of the process was to understand the needs of the designers. Their needs were generally elicited through interviews, expert opinions, literature reviews, and in some cases from questionnaires (e.g., Martinsson Bonde, Breimann, et al., 2024; Martinsson Bonde et al., 2022). The needs pertaining to the tools were documented and translated into technical requirements. Then, the creative process started, typically by sketching ideas and creating mock-up graphical user interfaces (GUIs), eventually developing them into functional software tools, as exemplified in Figure 3.4. These tools were then used in the design studies, as detailed above. These design studies were typically conducted in workshops together with experts, who gave direct feedback on the results and application of the methods and tools.

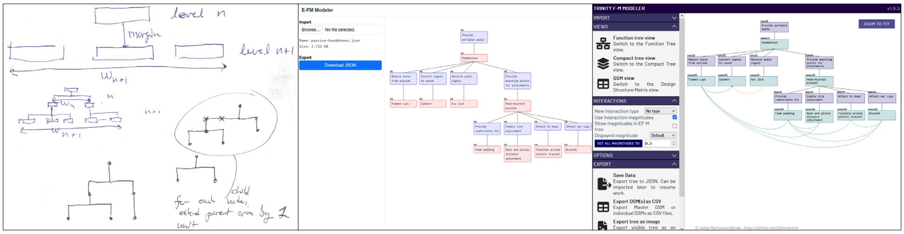

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Figure 3.4: The development of Trinity, one of the software tools, from sketch, to mock-up, to final version.

During the design study workshops, and afterwards, questions were asked to evaluate how the design support contributed to the design study. Typical questions included:

- What new insights can be gained by applying these methods/tools?
- Does operating the model produce results that are in-line with expert expectations?
- How does applying this method/tool/model help in identifying promising designs or design space regions?

The responses to these questions, and the feedback from the experts, typically resulted in the methods and tools being changed. In some cases, only small adjustments were required, such as fixing a bug. Conversely, in many cases new needs were identified which required the methods and/or tools to go through radical changes. If the evaluation of the method and tool concluded that they were useful and that no further changes were necessary, then the final steps towards software integration were taken. This entire process was typically repeated multiple times before the methods/tools were considered complete. By this mechanism, the methods and tools were adjusted and improved to maximize their usefulness.

Chapter 4

Summary of appended papers

4.1 Paper A: Exploring the potential of digital twin-driven design of aero-engine structures

The first appended paper explores the needs of the aero-engine components manufacturing industry through an interview study conducted at GKN Aerospace. It was found that their complex designs often encounter issues downstream, resulting in the need for redesigns (see Figure 4.1).

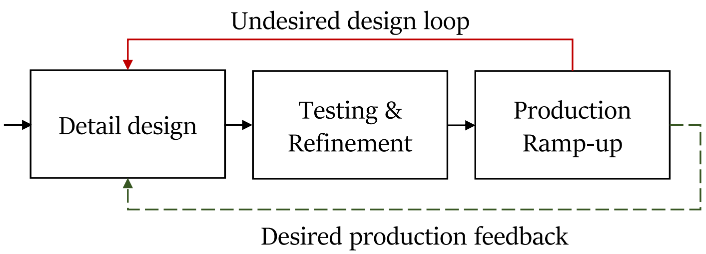

Figure 4.1: Visualization of undesired design iteration loop, and desired manufacturing data feedback loop.

As the design paradox dictates, changes become increasingly difficult to make the later they occur in the development process. Thus, late design changes are significantly more expensive. It can be concluded from the interviews that the decision to redesign is occasionally made as late as during the manufacturing stage. This has led to the need for designers to better understand the risk of their designs already during the early design phase, such that late redesigns can be avoided. An idea is posed that a digital twin could be used to represent manufacturing outcomes of existing products. Extrapolations could then be made from this digital twin to better understand the manufacturability of new designs. The paper highlights that there are multiple obstacles that first need to be overcome, including the fact that data captured in other parts of the product life-cycle are typically not contextualized for design. In other words, since the data has not been captured with design in mind, it is unlikely to be in a format that designers can easily use.

Key takeaways

- Complex aero-engine designs are prone to encounter issues late in development, resulting in costly redesigns.
- Design engineers want to utilize data from existing products to better understand how new designs will fare, before changing them becomes too expensive.
- Of particular interest is to better understand the manufacturability of new designs. In interviews, design engineers propose utilizing manufacturing data from existing designs, to better understand the manufacturability of new designs.

4.2 Paper B: Assessment of weld manufacturability of alternative jet engine structural components through digital experiments

Rather than using manufacturing data to evaluate the manufacturability of new designs, **Paper B** explores an alternative route. If enough is known about the geometry of the design, such as when iterating on an existing concept in a product family, then manufacturing simulations can be used to explore manufacturability during the early design phase. However, such an approach needs to be able to evaluate many design variants, as the exact geometry is still unknown. This means that the geometric representation needs to be of a high enough fidelity to enable adequate manufacturability assessment, while at the same time not too computationally expensive to enable evaluation of many variants. Furthermore, the geometric representation needs to be flexible enough to enable the representation of many different variants without the need for manual CAD modeling.

With these trade-offs in mind, a method for automatically generating such geometric representations was proposed. This method utilizes parametric CAD *building blocks* that can be put together, rearranged, and parametrically varied to create many different variants using only a few models. Unlike current practice, which at the time was to utilize shell models, solid models provide a higher degree of fidelity which is necessary for reliable manufacturability evaluation. In addition, the individual building blocks are tagged with information necessary for both performance and manufacturability analysis. As such, the method produces solid CAD geometries useful as models for analysis of manufacturability and performance, with a relatively large degree of flexibility in terms of design variability. The method was implemented into software, referred to as the TRS generator, and tested in a design study where welding simulations were conducted with the assistance of Industrial Path Solutions (IPS), as well as structural performance simulations. This enabled trading manufacturability against structural performance.

Key takeaways

- A method was proposed for generating solid geometries to facilitate the consideration of manufacturability versus performance trade-offs early in the design phase.
- Through the application of building blocks created with CAD, a software was developed that can generate design variants with a high degree of geometric flexibility.
- The CAD building blocks were enriched with manufacturing-related information, which enabled the geometries to be used in manufacturability simulations without manual intervention.

4.3 Paper C: A similarity-assisted multi-fidelity approach to conceptual design space exploration

In the interview study of **Paper A**, it was found that designers wanted to reuse manufacturing data from existing products to better understand the manufacturability of new designs. While many obstacles preventing this from becoming a reality were identified, an additional problem was encountered after that paper was published: what determines whether data from existing designs are trustworthy in the context of understanding new designs? Extending that question further: how do we know which assets, tangible or intangible, can be reused in new design contexts? In **Paper C**, these questions are examined.

Evolutionary product development is a common means of leveraging knowledge and assets from previous product iterations, while at the same time improving on it. This is core to the product family strategy, as each new system iteration builds upon what came before it. In the aviation industry, this approach to design is heavily utilized, as solutions that have been *proven in flight* are considered to be safer, both from the perspective of financial risk and passenger safety. But, how similar do two solutions need to be for the new solution to be considered proven in flight? And, how can this be measured? In **Paper C**, similarity metrics were used to measure the similarity between two designs. In doing so, the benefits of having already proven solutions can be identified and exploited already in the early phases of design.

Design similarity can be measured between designs that have been evaluated at different levels of fidelity. For instance, the results of a data-based surrogate model can be validated by comparing the design similarity to a design that has been evaluated using finite element method (FEM) simulations. Conversely, simulation results can be validated by comparing against a design that has been tested in a physical rig. An additional benefit is that similarities to problematic designs can be equally interesting to designers. For instance, if an existing product is known to have problems in manufacturing, then similarities to that design should potentially be reconsidered.

Key takeaways

- Similarity to existing products is known to reduce risks.
- Design similarity can be measured and exploited through the application of similarity metrics.
- Similarity metrics can help designers stay within the well-understood regions of design space.
- By quantifying similarity to previous designs during design space exploration, the trustworthiness of results can be increased.
- Identifying similarities to problematic designs, such as designs that encountered issues during manufacturing, can assist designers in avoiding previous problems.

4.4 Paper D: Managing combinatorial design challenges using flexibility and pathfinding algorithms

In product family design it is typically necessary to, over time, respond to emerging stakeholder requirements. This can be done by introducing new functionality, or by finding alternative means of achieving existing functionality. To remain competitive, manufacturers often need to consider future needs long in advance and investigate potential technologies that can satisfy those needs. However, introducing new technologies into existing product family systems can be challenging if the new solutions are incompatible with the existing system, or a subset of its subsystems. Consequently, when developing product family systems, it can be beneficial to design with respect to future compatibility. In other words, system flexibility can improve competitiveness. At the same time, the available alternative means of achieving each system function, together with the considered future technologies, can result in astronomical quantities of possible combinations. This is especially the case in systems with many different functions. These combinations reside in what is referred to here as the discrete design space, where each possible combination is a potential solution candidate.

When dealing with vast discrete design spaces, exploring each possible combination is not feasible. Furthermore, traditional optimization techniques are typically not an option as mathematical models of each alternative means (or indeed each possible combination) are generally not available. In **Paper D**, the problem of exploring such vast discrete design spaces is considered. A method, referred to as multi-objective technology assortment combinatorics (MOTAC), is proposed, which assists designers in identifying promising solutions based on design objectives.

Key takeaways

- To assert competitiveness in a changing technology landscape, systems need to be developed with respect to future technology.
- Large discrete design spaces can be efficiently navigated using pathfinding algorithms.
- Compatibility among contemporary and future technologies can be mapped using DSMs and a morphological matrix. This enables efficient navigation of feasible solutions using pathfinding algorithms.
- Flexibility can be quantified by evaluating how constrained the design space is due to incompatibilities among means.

4.5 Paper E: Exploring design trade-offs among sustainability, performance, and manufacturability when considering integration of new technologies

The ongoing climate crisis has resulted in sustainability regulations and requirements becoming increasingly stringent. Consequently, the viable design space becomes more constrained over time. To stay competitive, manufacturers need to conduct development with the foresight of knowing how their products and services will affect not only their customers, but all interacting systems across the entire product/service life cycle. This includes evaluating how ecosystems are affected by raw material extraction, and asserting fair working conditions throughout the supply chain. This is a major challenge, as the task of considering such a vast scope is seemingly insurmountable with current methods and technology. Matters are further complicated by the tendency of requirements to be in conflict, making it difficult to identify solutions that adequately satisfies the entire set of requirements.

Paper E demonstrates an approach to evaluate how sustainability, manufacturability, and performance will be affected by different subsystem solutions, already in the pre-embodiment phase. This means that the impact of new technologies on existing systems can be better understood at a very early stage. This is done through the application of risk quantification through CPM, and a relative sustainability fingerprint evaluation used to determine the relative improvement to sustainability metrics that span the entire life cycle. Change propagation is applied as a means of approximating how a change in one part of the system risks influencing other parts of the system. If the influenced subsystems are tied to performance and/or manufacturability, then that poses a risk to those domains.

An example study is carried out on a static aero-engine component, for which alternative manufacturing and design solutions are considered. The results from this study are high-dimensional, as they contain information about how each possible design variant affects many different aspects of performance, manufacturability, and sustainability. Through these results it becomes clear that balancing all of these aspects is a significant challenge, even when the information is available.

Key takeaways

- A method, the *relative sustainability fingerprint*, is proposed for evaluating sustainability pre-embodiment.
- An approach for conducting pre-embodiment trade-off studies among sustainability, manufacturability, and performance, is proposed.
- Manufacturability and performance impact is modeled using a combination of EF-M and CPM.
- The difficulty of balancing all important factors from all three domains is highlighted.

Chapter 5

Contributions

In this chapter the individual contributions from the conducted research are summarized. They are presented in order of intended use throughout the product development process. The final section presents the early design software suite which implements some of the key contributions. Each section contains a short summary of how the result relates to the RQs, while a more thorough discussion of the RQs is left for Chapter 6.

5.1 Multi-Objective Technology Assortment Combinatorics

Multi-objective technology assortment combinatorics (MOTAC) is an approach to strategic concept development which builds on EF-M modeling, DSM modeling, and the classical morphological matrix, originally proposed by Zwicky (1967). The intended use is for synthesizing new design concepts, and identifying viable combinations of means/technologies in vast discrete design spaces.

5.1.1 Description of method

MOTAC consists of four steps, as visualized in Figure 5.1. The first step is to create a function model of the system using EF-M. EF-M allows for multiple alternative means for each system function, such that multiple design variants can be extracted by combining different means for each function. Thus, the designer includes alternative means, including means which may not yet be technologically mature.

The second step involves mapping which alternative means are incompatible. This is done using a symmetrical DSM, which is later used to ensure that incompatible means are not combined in the final step.

In the third step, the leaf functions and their alternative means are mapped onto a morphological matrix. However, what differentiates this morphological matrix from the original approach is that the alternative means, and each

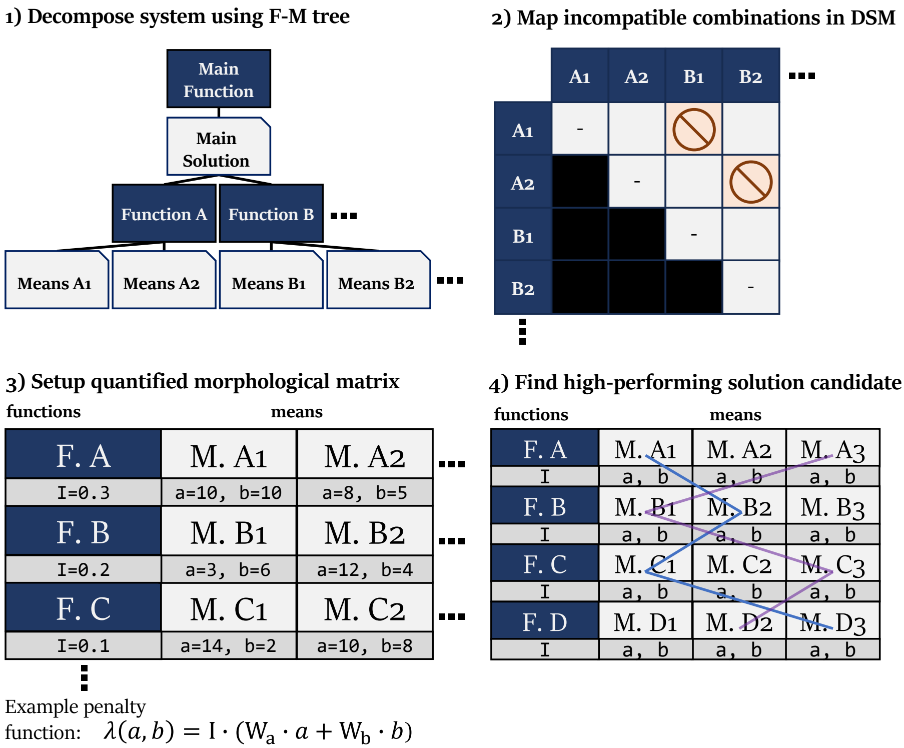

Figure 5.1: Visualization of Multi-Objective Technology Assortment Combinatorics.

function, can contain values that help determine the best possible combinations. The function variable I represents *Importance*, and should indicate how important each function is to the performance of the system. On the other hand, the means can contain any set of variables. Which variables are used depends on the design objectives, which are compounded into a single weighed penalty function λ, which is to be minimized. To give an example, the design objectives might be to minimize cost, and to maximize performance. In that case, the variables of the means can simply be cost and performance. The penalty function could then be formulated, for instance, as in Equation 5.1, where $\mathrm{W_c}$ and $\mathrm{W_p}$ are weight parameters used to determine the relative importance of the cost (c) and the performance (p).

$$\lambda(c,p) = \mathrm{I} \cdot (\mathrm{W_c} \cdot c + \mathrm{W_p} \cdot (1-p)) \tag{5.1}$$

How the variables of the means are populated varies depending on how much information is available to the designers. If little is known, then a simple pair-wise comparison approach is sufficient, comparing the performance of all alternative means of each function, one function at a time. On the other hand, if more information is available then the resolution of the variables can be increased. For instance, the actual cost of each means may be known, in which case the cost could be used directly.

A key novelty of the MOTAC approach is its ability to account for **combinatorial flexibility**. In step 1, alternative means of low technological maturity were included. This means that a flexibility metric can be utilized as part of the design objectives to assist in identifying designs that are compatible with future technology. The flexibility is calculated for each alternative means, based on how many possible paths are available through the morphological matrix if that means is selected. As such, combinatorial flexibility is an indication of a means capability of being combined with other means, as visualized in Figure 5.2.

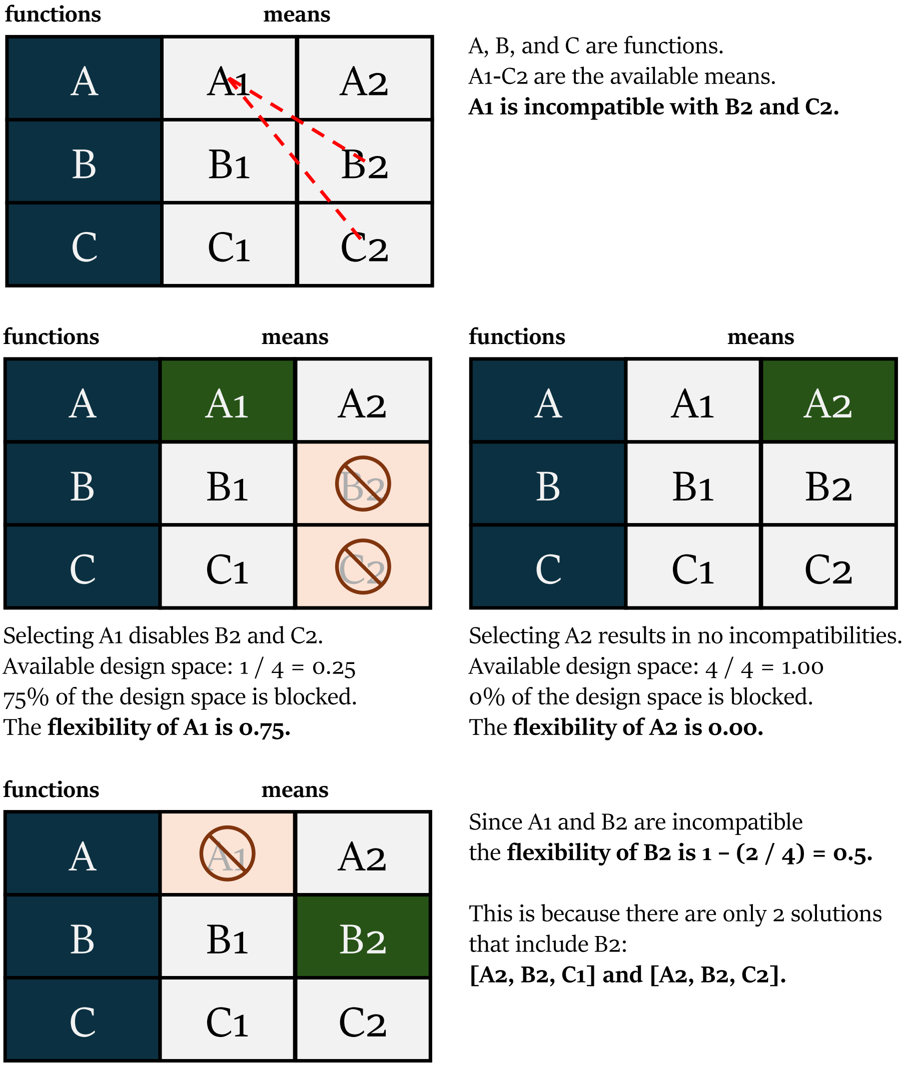

Figure 5.2: Visualization of combinatorial flexibility in a morphological matrix.

Since not all means are compatible, choosing a certain means will result in part of the design space becoming unavailable. In other words, if a means is chosen, then certain alternative (future) technologies may no longer easily be implementable into the system. The metric can be formulated for individual means as in Equation 5.2, where $N_{\text{constrained}}$ is the number of possible combinations with respect to incompatibilities, and $N_{\text{unconstrained}}$ is the number of possible combinations without accounting for incompatibilities.

$$f = 1 - \frac{N_{\text{constrained}}}{N_{\text{unconstrained}}} \tag{5.2}$$

To provide a degree of intuition for this measure, if the calculated combinatorial flexibility f for a given means is 0.20, then the selection of that means screens of 20% of the design space. This metric can be added directly to the penalty function. The previous example, with included flexibility, might look like Equation 5.3, where f is the flexibility (a lower value entails a higher flexibility), and $\mathrm{W_f}$ is the weight of the flexibility term.

$$\lambda(c, p) = \mathrm{I} \cdot (\mathrm{W_c} \cdot c + \mathrm{W_p} \cdot (1 - p) + \mathrm{W_f} \cdot f) \tag{5.3}$$

In the fourth and final step, Dijkstra's algorithm (Dijkstra, 1959) is used to find high-performing solutions. By utilizing the basic mathematical models provided for the design objectives, the variables for each function and means, and the incompatibility DSM, the algorithm identifies sets of compatible means that are high-performing. It is strongly advised that a set of combinations is identified, rather than only looking at a single solution. This is especially true in low-information scenarios where the uncertainty is high.

5.1.2 Contribution to thesis

To efficiently integrate new technologies into existing product family systems, the new technology needs to be compatible with the existing system. In that sense, MOTAC contributes to answering RQ1. Furthermore, leaning into the flexibility of a system enables more of the existing system design to be reused in future iterations, which also relates MOTAC to RQ2. In other words, MOTAC assists in designing for reuse.

5.2 Relative sustainability fingerprint

The **relative sustainability fingerprint** method was designed to enable comparative evaluation of alternative design variants from a sustainability perspective. It serves as an extension of three previously defined concepts: i) The sustainability fingerprint (Hallstedt et al., 2023), which evaluates the sustainability of a design from a system-level perspective. ii) The multi-domain EF-M representation initially introduced by Isaksson et al. (2021), in which manufacturability aspects are introduced into the EF-M model. iii) Pugh's concept selection matrix (Pugh, 1990), which evaluates designs relative to the expected performance of all other design alternatives.

5.2.1 Description of method

Initially, an EF-M model is created for the system, along with alternative means for each system function. The incompatibility feature introduced in MOTAC can be reapplied here to map incompatibilities using a DSM. A table is then defined, as visualized in Figure 5.3, which includes: 1) all alternative means for each system function, and 2) all life cycle phases, and the criteria used to evaluate the sustainability performance in those phases. The life cycle phases suggested by Han et al. (2021) are: material extraction, production, use, and end of life. A criterion for production sustainability can, for instance, be to have a hazard-free work environment. Then, one means is set as the reference for each system function. Finally, for each function, the fulfillment of sustainability criteria for all alternative means are compared relative to the reference means.

		Life-cycle phase:	Material extraction		Production		Use		End of life	
Functions	Means	Criteria:	Criterion A1	Criterion A2	Criterion B1	Criterion B2	Criterion C1	Criterion C2	Criterion D1	Criterion D2
Function 1	Existing means		REF	REF	REF	REF	REF	REF	REF	REF
	Alternative means #1.1		2	1	-1	1	1	0	1	0
	Alternative means #1.2		1	-2	0	0	1	0	2	0
Function 2	Existing means		REF	REF	REF	REF	REF	REF	REF	REF
	Alternative means #2.1		-1	1	0	1	2	1	0	-2
	Alternative means #2.2		-2	2	0	1	1	2	0	0

Figure 5.3: Relative sustainability fingerprint table, where the fulfillment of sustainability criteria for individual means is compared to a reference for each system function.

The resulting table can then be used as a lookup table for any possible combination of means. Thus, the sustainability performance in each life cycle phase, relative to the reference, can be assessed. By representing this table in a format suitable for machine interpretation, such as an Excel-sheet, the relative sustainability evaluation process can easily be automated. A simple script can be created which takes a combination of means as input, and outputs the relative sustainability (S_c) by calculating Equation 5.4 for each criterion (c). M is the number of functions for which there are alternative means, and s_{ci} is the relative sustainability of the means i for the criterion c.

$$S_c = \frac{1}{M} \sum_{i=1}^{M} s_{ci} \tag{5.4}$$

5.2.2 Contribution to thesis

The relative sustainability fingerprint enables designers to consider sustainability aspects already during the pre-embodiment phase, feeding in to the principle of creating as much knowledge as possible while design freedom is still high. This method thus contributes to answering RQ1: To efficiently integrate new technology, critical requirements related to sustainability need to be considered as early as possible. Furthermore, combining this method with the method proposed by Isaksson et al. (2021) enables the consideration of trade-offs among sustainability, manufacturability, and performance, at a very early stage in development.

A script was developed to facilitate the application of this method, enabling designers to consider relative sustainability for many alternative designs. The source code of the script is publicly available, enabling its functionality to be repurposed for other applications. A link to the source code is available at the end of **Paper E**. By implementing this into software that enables assessment of alternative designs, this result also contributes to RQ3.

5.3 Similarity-assisted design space exploration

When evaluating new design concepts it is common to utilize computationally expensive simulations, such as physics-based simulations. This can help designers in assessing whether a design will meet requirements, such as the ability to absorb some physical load, or to maximize aerodynamic performance. However, since such simulations are computationally expensive, the number of simulations that can be performed is limited. To circumvent this issue, design engineers often utilize data-based surrogate models. Such models can be trained using data from simulations, and then used to rapidly evaluate design points outside of the original training dataset. However, this reduction in fidelity comes at the cost of accuracy. Conversely, simulations are a reduction in fidelity relative to physical tests. In either case, it is unclear whether the accuracy of the lower-fidelity approximation is adequate. **Similarity-assisted design space exploration** is an approach that utilizes similarity metrics to inform designers of the similarity between evaluations made at different levels of fidelity. This is intended to give designers insight into the trustworthiness of low-fidelity results.

5.3.1 Description of approach

Assume that a region of the design space has been evaluated at two different levels of fidelity. The set of design points that have been evaluated at a high fidelity is referred to as X_{hf}. Conversely, the set of design points that have been evaluated at a low fidelity is referred to as X_{lf}. The proposed **inter-similarity** metric is calculated by measuring the distance in the design space between a design point in X_{lf} and its closest neighbor in X_{hf}, as visualized in Figure 5.4[1]. In other words, the similarities between a low-fidelity data point $\mathbf{x}_{\mathrm{lf}}$ and all (n) high-fidelity data points $\mathbf{x}$ are calculated using a similarity evaluation function $S(\mathbf{x}_{\mathrm{a}}, \mathbf{x}_{\mathrm{b}})$ (e.g., normalized Euclidean distance). The closest identified similarity is the inter-similarity s_{i}, as expressed in Equation 5.5.

[1]This figure differs from the one presented in **Paper C**. I find this way of visualizing inter-similarity to be clearer, as there are typically more points of low-fidelity data than high-fidelity data. In that sense, this visualization is a better representation of the most common scenario. Additionally, it has been generalized to high- and low-fidelity data to imply that this visualization is representative of other scenarios than surrogate modeling.

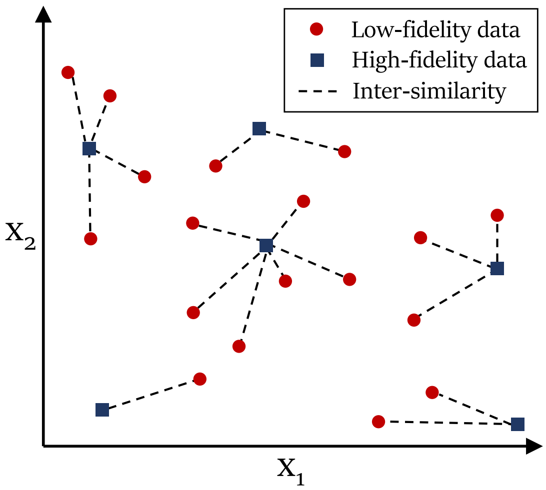

Figure 5.4: Visualization of the inter-similarity metric in a two-dimensional design space. The inter-similarity can be thought of as the distance in the design space between a low-fidelity data point, and its closest high-fidelity neighbor.

$$s_{\mathrm{i}} = \min\Big\{S(\mathbf{x}_{\mathrm{lf}}, \mathbf{x}_1), S(\mathbf{x}_{\mathrm{lf}}, \mathbf{x}_2), ..., S(\mathbf{x}_{\mathrm{lf}}, \mathbf{x}_n)\Big\} \tag{5.5}$$

Inter-similarity can be applied in different ways depending on which levels of fidelity are being compared. In the case of data-based surrogate models, it is typically the case that design points that are close to the training dataset are evaluated at a higher accuracy. This is demonstrated in Figure 5.5, where the inter-similarity was plotted against the mean absolute error using three different modeling techniques to predict the deformation of a TRS under heavy load. A reduced distance in the design space between the data point sampled using the surrogate model and the nearest data point from the high-fidelity training set typically indicated a higher prediction accuracy.

Conversely, it was argued in **Paper C** that this concept can be extended to evaluate the similarity between considered design concepts and previous design endeavors, such as finalized products. To differentiate between the two concepts, this metric was referred to as **legacy similarity**. The presented method focuses primarily on scale-based product families, as they by definition have a set of key design variables which are scaled up or down to generate new concepts. Measuring the similarities of these design variables between a new design and previous design endeavors can give designers various insights into the design space. Examples include:

1. Similar designs should behave in similar ways. Thus, legacy similarity can be used to assist in validating simulation results. If similar previous products exist, then physical test data from such products can be compared against evaluations of the new design. This could help in increasing the trustworthiness of evaluations made in the design phase.

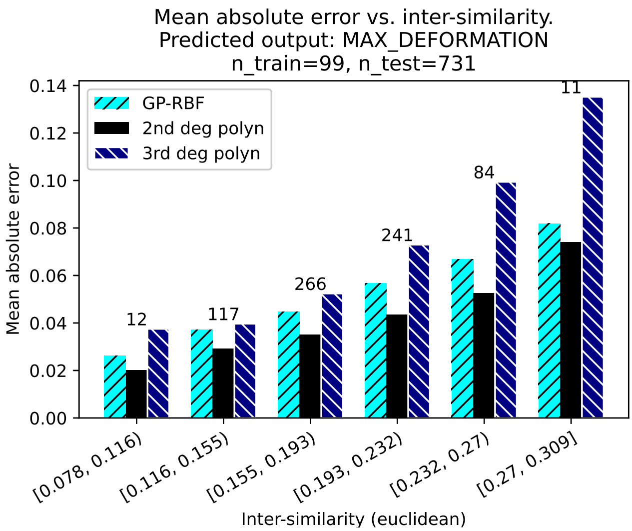

Figure 5.5: Correlation study demonstrating that inter-similarity can be used as an indicator of data-based surrogate model error.

2. The more similar two designs are, the more can be reused. Consequently, if a design is similar to a product that has already been manufactured, resources can be saved and lead-time reduced (Duffy & Ferns, 1998).

3. Similarities to previous designs that encountered issues during development can be identified. In such cases, that region of the design space could be avoided, or the designers could preemptively work towards resolving those issues early in development.

4. Maintaining a level of similarity to previous design endeavors ensures that designs stay within the well-understood regions of the design space. Consequently, less unknown unknowns are likely, resulting in a reduced risk of encountering new issues.

5. Measuring the similarity can provide quantitative evidence for claims that a solution is proven, sometimes phrased as *"this solution has been proven in flight"*. This is important, as such claims necessitates similarities between both the solutions and the intended operational environments.

A proposition for how to systematically utilize inter-similarity and legacy similarity during design studies was developed, as visualized in Figure 5.6. This approach, referred to as **similarity-assisted design space exploration**, utilizes a version of a design space exploration process found at GKN Aerospace as a baseline, and extends it. The process is part of identifying new designs in a scale-based product family, which means that a baseline geometry is already available at the start of this process. The goal is to identify regions in the design space that can fulfill emerging stakeholder requirements, giving the designers a coarse understanding of the geometry needed to meet those requirements.

The baseline process is initiated by defining design objectives, such as *minimize weight*, and *maximize stiffness*. Then, it is decided which design variables should be varied, relative to the baseline geometry. This decision leads to the creation of a design of experiments (DoE), which is used to generate context models. These context models can, for instance, include meshes used for FEA. Simulations are then conducted, the data from which are used to train surrogate models. The surrogate models are then used in optimization studies to identify and explore trade-off curves among the design objectives. Once a promising region in the design space has been identified, the designers can either choose to: i) iterate the process from scratch, but focusing on the identified region(s) of the design space, or ii) if the designers are confident in their findings, they can proceed to more detailed studies and continued development of the concepts.

The similarity-assisted design space exploration method adds two additional steps to this process. The first step involves evaluating the similarity between the surrogate model results, and the simulation results (inter-similarity), and visualizing this information. This assists designers in understanding if the surrogate model results are trustworthy, or if additional simulations are necessary. Legacy similarity is introduced in the final step, where the identified design candidates are compared against previously explored solutions. This can be used to validate data, and help designers stay within the well-understood regions of the design space.

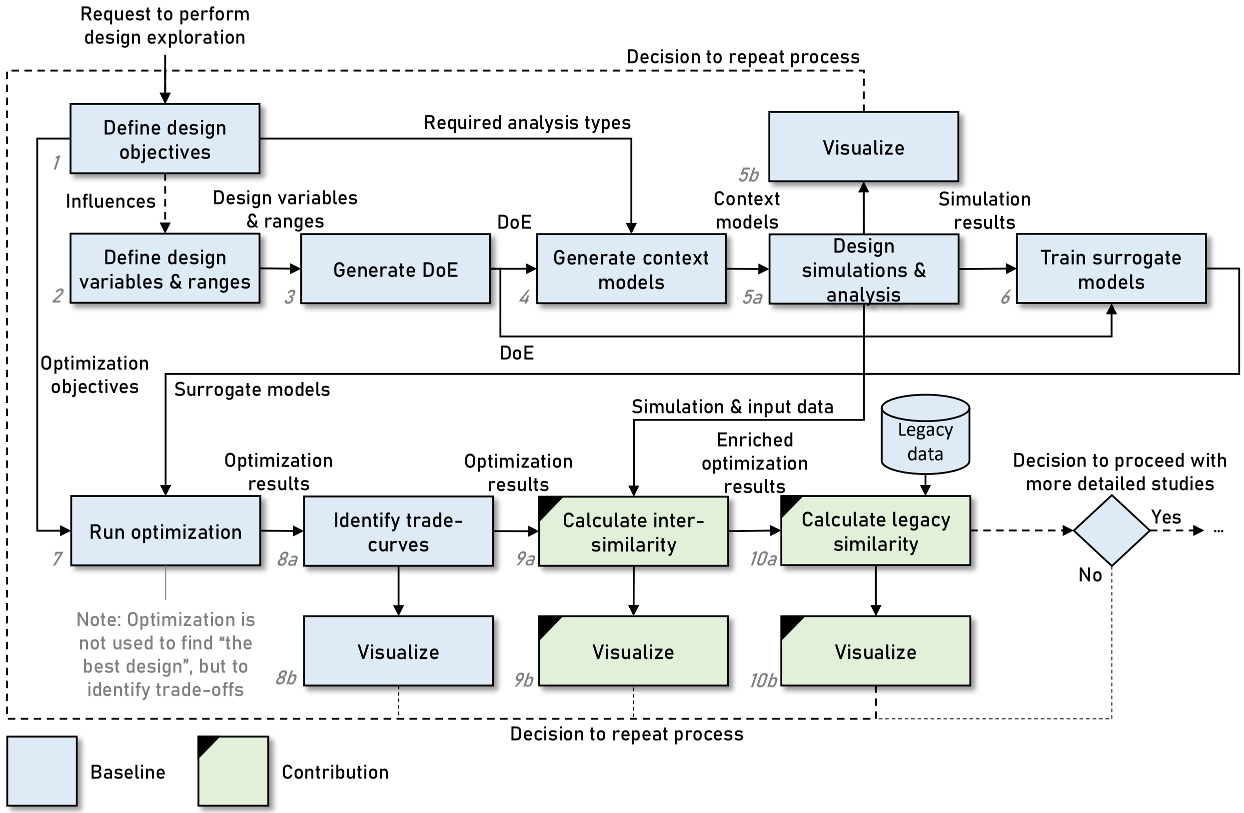

Figure 5.6: Similarity-assisted design space exploration method, designed around a baseline design space exploration process.

5.3.2 Contribution to thesis

The similarity-assisted design space exploration approach mainly contributes to RQ2, as it provides similarity metrics to assist in identifying potential for asset reuse. However, it also contributes to RQ1 by suggesting that information of similarity can make the design process more efficient.

5.4 Enriched geometry generation

To enable multi-domain trade-off studies of a TRS, there was a need to rapidly generate varied solid geometries for use in simulations. A software, referred to as *the TRS generator*, was developed for this purpose.

5.4.1 Development

To design an adequate geometry generation software for early design feasibility studies of scale-based structural aero-engine components, multiple requirements had to be considered. The main purpose of the generation software was to enable concurrent manufacturability and structural performance evaluation. From the manufacturability perspective, the primary concern was accessibility of weld tools, deformations caused by welding, and the welding lead-time. This meant that the traditionally used shell-model approach to model such structures was inadequate, as a higher geometric fidelity was needed to evaluate weld accessibility and deformations caused by welding. Thus, the first requirement was for the TRS generator to output solid geometries, as solid models are better suited for such analysis.

The key reasons for why shell-based models are commonly used, rather than solid models, is because shell-models are fast to create, computationally inexpensive, and highly flexible. A shell-based model can easily be configured to adopt any thickness by merely changing surface attributes in the CAD software. Such attributes can be parameterized and automatically varied using a DoE as input. Furthermore, since shell-models are significantly less complicated than solid geometries, varying attributes such as the number of struts, wall thicknesses, and overall dimensions of the component is relatively simple. Conversely, solid geometries are much more prone to encountering geometric constraints that prevent such flexibility. Nevertheless, the TRS generator needed this level of flexibility to enable the embodiment of the considered design space region. Thus, the second requirement was that the model needed to be flexible enough to vary a set of key variables within certain ranges. These variables included (but were not limited to) the number of vanes, the lean of the vanes, the inner and outer diameters of the structure, and all wall thicknesses. In Figure 5.7, the vanes, vane lean, and inner/outer diameters are mapped to a simple TRS geometry.

Finally, it needed to be possible to evaluate the models using common analysis software such as Ansys Mechanical, for evaluating structural performance; RD&T for weld deformation evaluation; IPS for weld accessibility and

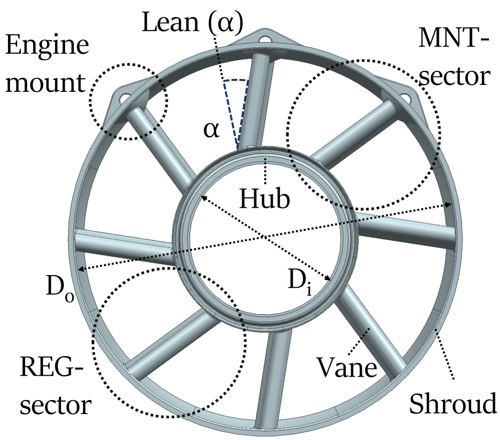

Figure 5.7: Visualization of some of the sub-components and key variables of a TRS.

lead-time analysis; and a separate software for evaluating additive manufacturing (AM) manufacturability. This meant that the software was required to output multiple different formats that could be read by the necessary analysis software. It also meant that the output files were required to contain the necessary information to enable those analyses to be conducted automatically, since too many variants were considered for any manual input to be feasible during the process.

With these requirements in mind, several prototypes of geometry generation software were designed and tested, two of which can be seen in Figure 5.8. The final iteration worked by combining flexible building blocks of CAD geometry. The building blocks consisted of individual TRS sectors (see Figure 5.7), which were pieced together into a full TRS assembly. The software takes a DoE as input, and outputs multiple different formats depending on what analysis the user wants to perform. The TRS geometry is generated one sector at a time, using the DoE to configure the various dimensions and wall thicknesses of each sector. Once all sector have been generated, they are united into a single

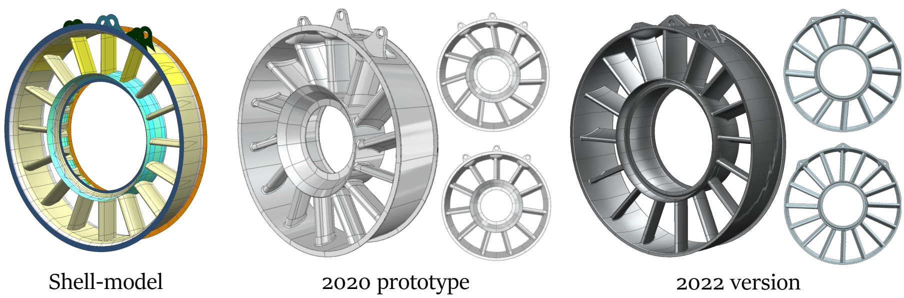

Figure 5.8: Evolution of TRS geometry generation software.

structure. This approach was chosen primarily for two reasons:

1. This approach enables the rearrangement and replacement of individual sectors, resulting in a relatively high flexibility beyond the parameters of the individual building blocks. If a completely new type of design needs to be evaluated, then the designers would only need to create a few new building blocks.

2. Since the geometry of individual sectors is significantly less complex relative to a full TRS geometry, the issue of encountering geometric constraints is less pronounced. This was one of the key lessons learned from the 2020 prototype (see Figure 5.8), which utilized a pattern-based approach rather than building blocks. The decision to use building blocks thus renders the solution more robust than a monolithic geometry approach.

During the generation process, surfaces and edges are tagged by the software with information useful in various types of analysis. For instance: the location of weld lines, and where the FEA software should position different loads. Finally, depending on the location of the weld lines, the software can divide the geometry in different ways to enable simulating multiple manufacturing alternatives, as visualized in Figure 5.9. Thus, the geometry was *enriched* with information necessary to conduct different types of analysis.

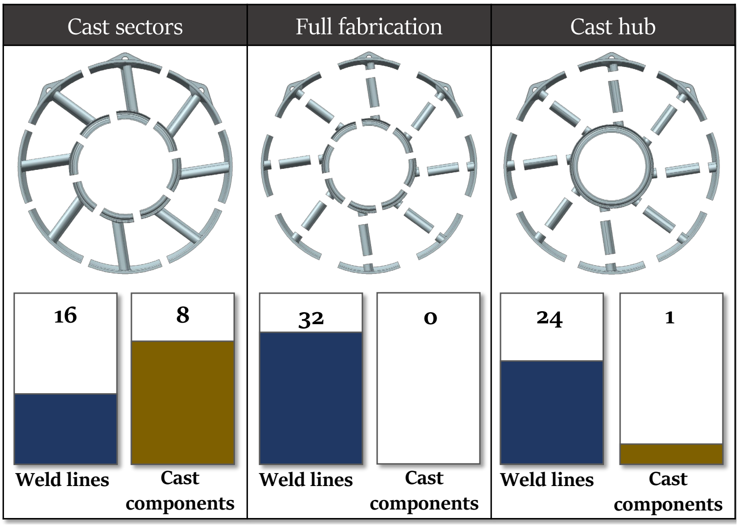

Figure 5.9: Depiction of three different manufacturing variants generated using the same geometric configuration.

5.4.2 Contribution to thesis

This concept demonstrates one possible way of creating some of the information necessary to enable the assessment of alternative variants in the early design phase. As such, it contributes to RQ1 in that solid geometry, more so than shell-based geometry, can be used to gain insight into manufacturability. Furthermore, it demonstrates how geometric representations can rapidly be created to support further computational analysis of design variants, thus contributing to RQ3.

5.5 Early design software suite

To facilitate the design studies presented in the appended papers, it was often necessary to design custom tools to properly test the proposed methods and approaches. While it was sometimes enough to write a small script, or even design a mock-up in PowerPoint or Excel, certain methods required a more thorough approach to testing. The early design software suite is a set of three software applications, complete with GUIs, which all implement one or more aspects of the thesis contributions.

5.5.1 Morpheus

Morpheus is a tool that assists designers in exploring large discrete design spaces. It does so through the use of a morphological matrix, and various assisting features to help designers narrow down the number of possible combinations. One such feature is the implementation of MOTAC, which enables users to find high-performing design candidates by adding quantitative elements to the matrix.

Development

The first prototype of Morpheus was developed with the intent of assisting engineering students with concept generation (Martinsson Bonde et al., 2022). Thus, most of the requirements for the first version of Morpheus were based on student and teacher needs. At the time, students at Chalmers University of Technology typically created their morphological matrices using either pen and paper, or using non-specialized software such as PowerPoint or Excel. This caused three separate issues:

1. Keeping track of large quantities of solutions in the matrix seemed to be difficult for the students.

2. Updating the morphological matrix over time, such as when identifying new functions or means, was difficult.

3. The students were often not systematic in their approach to utilizing the morphological matrix, generating concepts based on arbitrary combinations of means.

The initial prototype thus focused primarily on these three issues. A desktop application with a basic GUI was created to enable the users to create morphological matrices (Figure 5.10). Features included the ability to generate all possible combinations, and to save and revisit all identified combinations.

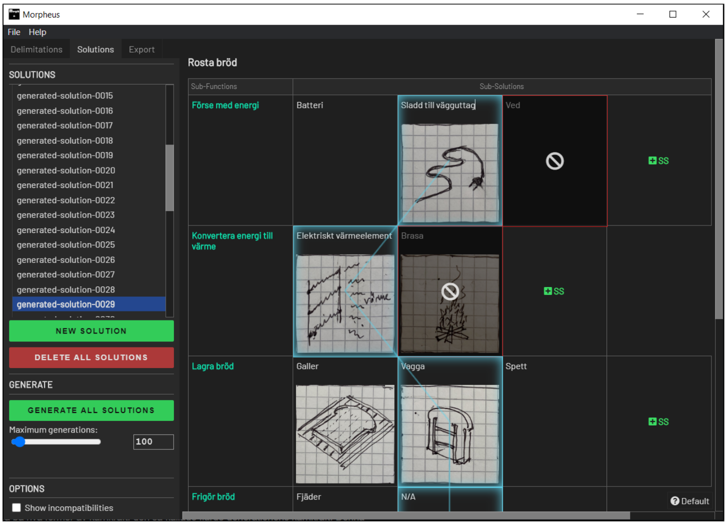

Figure 5.10: Screenshot of an early Morpheus prototype from 2020.

The algorithm used to find all solutions was designed such that the users could mark pairs of means as incompatible. This enables the user to narrow down the feasible design space before starting the solution generation process.

As discussed in Martinsson Bonde et al. (2022) and Martinsson Bonde, Breimann, et al. (2024), there are significant trade-offs to consider when introducing students to these kinds of digital replacements of classical tools. For instance, students who used the tool seemed to focus on quantity over quality when generating new concepts. Nevertheless, the prototype provided a sufficiently solid foundation to warrant further development. The desktop

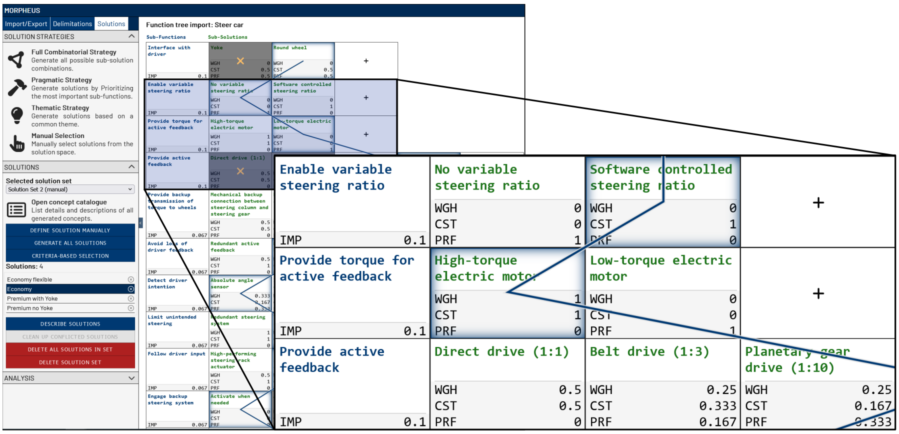

Figure 5.11: 2024 web-based version of Morpheus with integrated MOTAC functionality.

application was dropped in favor of a browser-based version, such that users no longer needed to manually install the software to use it on their computers. This also mitigated the issue of developing an application that had to work on Windows, Mac, and Linux, since browsers provide a more standardized environment for applications to exist in.

With a more mature version of Morpheus in place, work began with implementing MOTAC into the application. A feature allowing users to attach quantitative values to the cells of the morphological matrix was implemented, as can be seen in Figure 5.11. To utilize those values, a separate view was developed which enables the user to define a penalty function to be used by Dijkstra's algorithm (see Figure 5.12). It should be clarified, however, that while an early version of the MOTAC approach had been designed, the details of MOTAC were developed concurrently with the Morpheus implementation. This development was conducted in conjunction with the case presented in **Paper D**, which benefited both the software and the MOTAC approach, as rapid design-build-test cycles could be conducted. Both researchers and experts from industry gave feedback, which improved both the software and the approach.

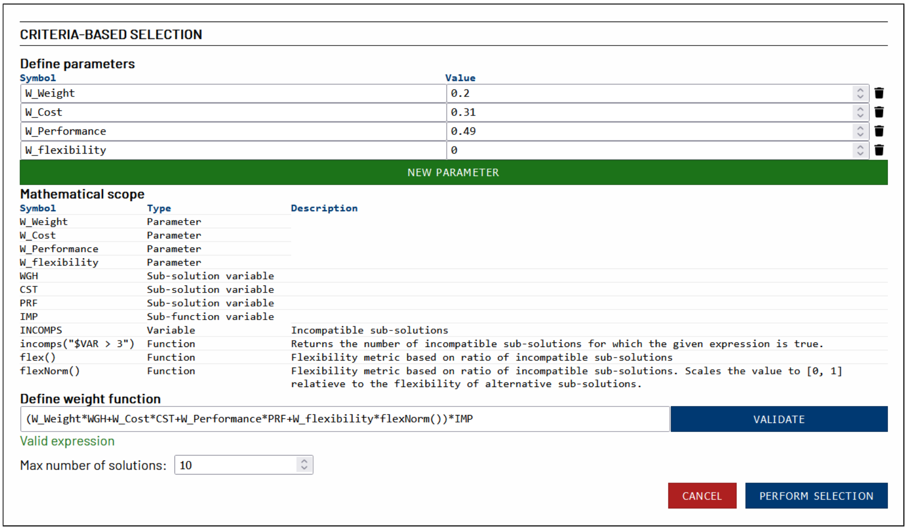

Figure 5.12: View in Morpheus used to define an optimization objective function used by Dijkstra's algorithm to identify promising solution candidates.

If a user of Morpheus creates a morphological matrix, quantifies all elements, and defines a penalty function, then the software can be used to make a *criteria-based selection* of the best possible combinations/solutions. This feature utilizes a modified version of Dijkstra's algorithm to search the matrix using the penalty function and the quantitative matrix values to find a set of optimal combinations.

Finally, combinatorial flexibility (as visualized in Figure 5.2) was implemented as a mathematical function that can be injected into the optimization objective, enabling the identification of flexible combinations. Making this flexibility metric accessible to Dijkstra's algorithm, and modifiable by the user, is one of the key strengths of this approach.

5.5.2 Trinity

Morpheus relies on the user to already have knowledge of all the functions necessary to create and populate the morphological matrix. Trinity was designed as a simple tool to assist designers in performing functional decompositions, which can be imported into Morpheus. However, as Trinity turned out to be more useful than expected, it was extended with additional features, such as DSM creation, CPM analysis, and some EF-M features. In Figure 5.13 an F-M tree can be seen in Trinity, with interactions between means represented as lines beneath the tree, which is a feature adopted from EF-M. In addition, Trinity was extended with some features from MOTAC.

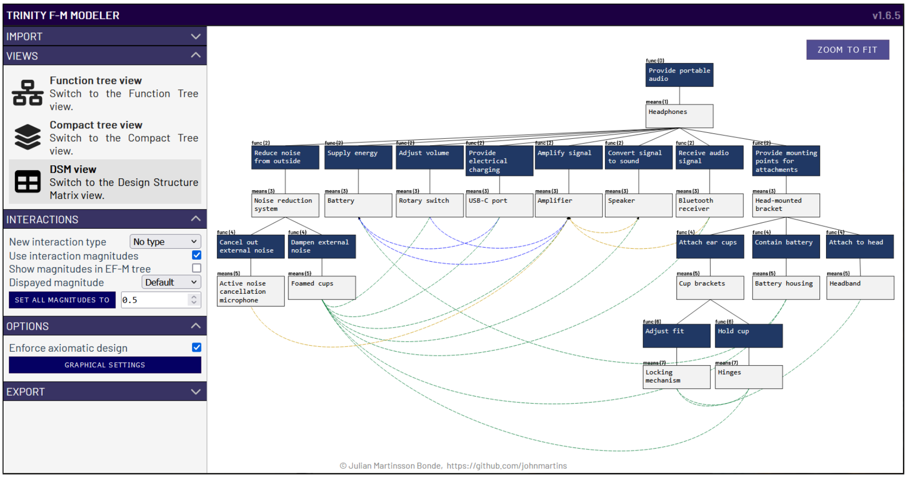

Figure 5.13: EF-M view in Trinity. The model in the screenshot is of a pair of Bluetooth headphones, used in a test together with a group of PhD students.

Development

Since the output of Trinity needed to be interoperable with Morpheus, F-M modeling was selected since this modeling technique can contain the same information as a morphological matrix: functions, and alternative means. While Trinity will enforce having only one means per function by default, the user can turn off this limit to have multiple alternative means for each function.

During the study presented in **Paper D**, a need arose for a simpler way of mapping incompatibilities among multiple functions with alternative solutions. This lead to the development of the *Master DSM view*, as shown in Figure 5.14. This view automatically lists all lowest-level functions and their alternative means in the F-M tree. The user can then click on cells in this matrix to map out incompatibilities. Since DSMs are commonly used to map interactions between subsystems, the Master DSM view was extended to enable mapping interactions as well. As such, any interaction mapped in this view automatically creates an interaction in the function tree. An interaction in the function tree is visualized as a curve that connects the two interacting means, as visualized in Figure 5.13. This feature took Trinity one step closer towards becoming an EF-M modeler, rather than just an F-M modeler.

The ability to map how subsystems interact has been useful in multiple studies. **Paper D** utilized this functionality to map incompatible pairings of subsystems in Trinity. This information could then be imported into Morpheus for use in identifying promising design candidates. In **Paper E** it was used to conduct risk assessments regarding the ability of a product to meet performance and manufacturability targets. For this, the ability to perform CPM analysis was implemented into Trinity. The impact and likelihood values necessary to perform CPM can both be inserted into the master DSM. Then, to perform CPM analysis, Trinity first identifies all possible combinations of means, creates their individual likelihood and impact DSMs, and uses those to create a risk matrix for each design variant.

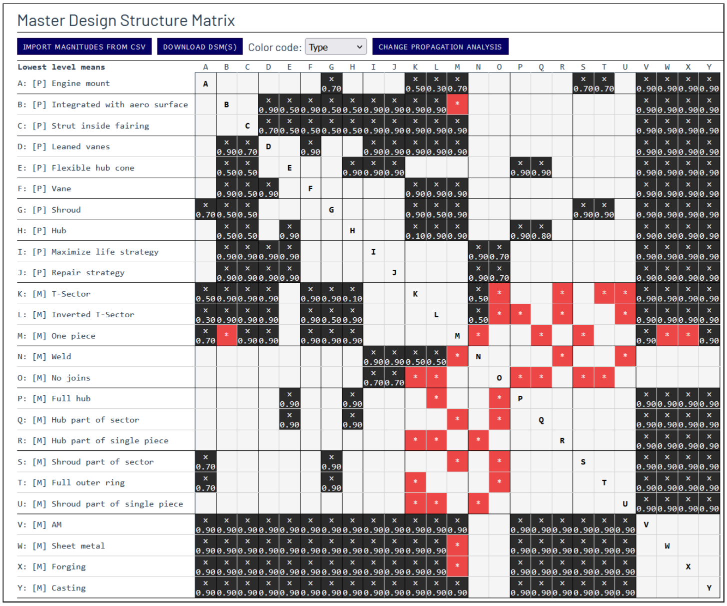

Figure 5.14: Master DSM view in Trinity used here to configure the CPM analysis of all design variants. The red elements in the DSM represent incompatible pairings of means.

5.5.3 Multi-Disciplinary Analysis Client (MDAC)

The Multidisciplinary Analysis Client (MDAC) software was originally designed as an alternative tool for creating and interacting with parallel coordinate plots. It utilized scalable vector graphics (SVG) to render a responsive plot in the browser, which could be interacted with by adding filters. The primary intent was to visualize multiple design points at once, to get an overview of the design space and facilitate trade-off analysis. A design point, in this context, refers to the set of inputs used to represent a design, together with the outputs from whichever evaluations have been conducted (e.g., FEA). Thus, one design points consists of multiple data points, one for each input/output.

Development

During the development of the similarity-assisted design space exploration approach, it became necessary to rapidly calculate and visualize inter-similarity and legacy similarity (see Section 5.3) for large datasets. Such a feature would enable designers to leverage the similarity metrics without the need for any coding, or precise understanding of how the metrics works. After consulting design engineers regarding what would be expected of such a visualization software, a small set of (mostly functional) requirements were elicited:

- It must be able to visualize at least 10,000 design points without a significant performance impact (max 1 second delay for loading and filtering) on a typical work laptop (a Dell Latitude 5340 with a 13th generation i7 was used as a reference).
- It must be possible to screen the data to identify promising designs.
- It must be possible to color-code the data based on the ranges of individual dimensions.
- It must be able to parse and visualize both numerical and categorical data.
- It must be possible to calculate legacy-similarity and inter-similarity for datasets that contain multi-fidelity data.
- It must be possible to interact with the similarity data, such that designs with a high/low similarity can be identified.

Keeping MDAC as a browser-based application meant that it could be developed rapidly, and that it could share common design elements with other software being developed at the time (Morpheus and Trinity). However, it became evident that the SVG rendering used in the prototype version of MDAC was too slow. Thus, the final version of MDAC (see Figure 5.15) utilizes a mixture of SVG-elements and raster graphics to maximize responsiveness even for larger (up to 100,000 design points were tested) datasets, thus meeting the performance requirement. The data parsing and visualization functionality was expanded to also support categorical data. This was a necessary step towards the implementation of similarity analysis, since it needs to be able to differentiate between different levels of data fidelity. By supporting categorical data, users can tag their data with various degrees of fidelity (e.g., simulated data, response surface data, physical test data, etc.). Thus, the similarity between data points of different levels of fidelity can be calculated.

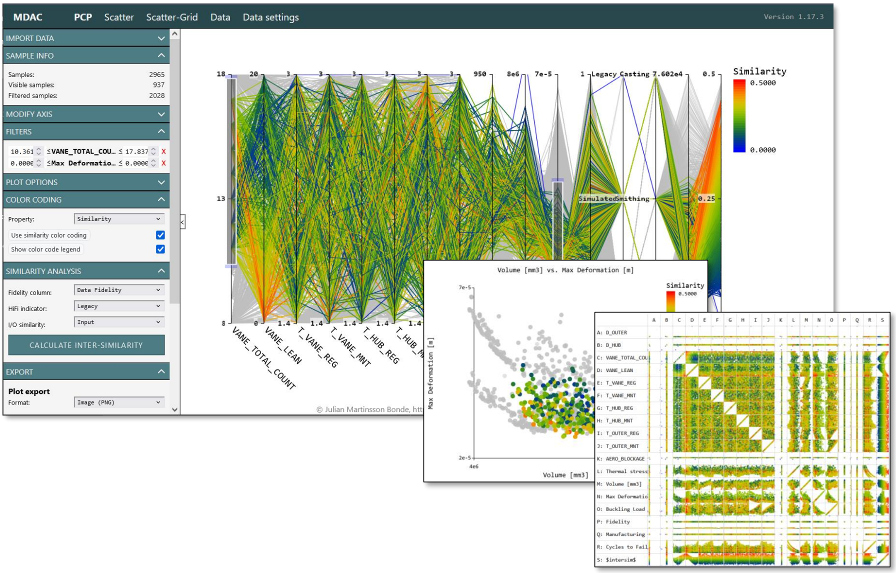

Figure 5.15: Screenshot of MDAC software.

The implementation of similarity analysis works in two steps: First, the user specifies which columns represent inputs, and which represent outputs. Then, the user is asked about the specifics of the similarity analysis in a form, as shown in Figure 5.16. This form asks the user which categorical data column contains information about the level of data fidelity. Then, it asks which value within this column represents a high-fidelity data point. Finally, it asks the user whether to measure input or output similarity. This provides MDAC with all the information it needs to perform the similarity analysis. The results of the analysis are presented in a new column.

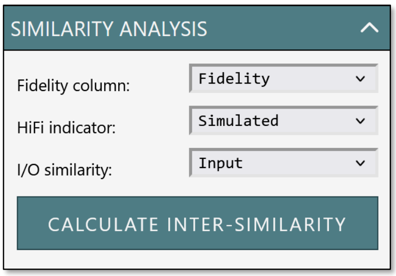

Figure 5.16: Similarity form in MDAC.

The development was conducted with frequent feedback loops together with designers and researchers. Once the initial requirements were fulfilled, additional features were added. Those additional features includes a scatter plot, and a scatter plot matrix to enable visual identification of trade-offs.

Finally, various means of tweaking the layout and details of the plots were implemented.

5.5.4 Contribution of early design software suite to thesis

The early design software suite demonstrates the implementability of MOTAC and similarity-assisted design space exploration, thus contributing to RQ3. In addition, these software make it possible for others to leverage some of the methods and ideas proposed in this thesis, as the software itself was not designed with a specific problem in mind. The generalizability of the software is further discussed in Section 7.4.

Chapter 6

Discussion

In this Chapter the research questions are discussed based on the frame of reference, and the presented results. Finally, the framework which ties together the proposed methods and tools is presented and discussed.

6.1 Research question 1

What information is necessary to enable efficient integration of new technologies in next-generation designs?

Integrating new technology into existing systems, such as a product family platform, involves some amount of risk. To avoid putting passengers at risk, expensive certification processes are necessary to verify the airworthiness of new designs. Consequently, the aviation industry has historically been conservative with regards to introducing new technology, as it can pose a risk both to passenger safety, and to the economic bottom line. Since risk is inevitable, the challenge is to achieve risk-levels that are acceptable, minimizing any uncertainties regarding return on investment. The implementation of new technology into aircraft systems does occur, but slowly and evolutionarily. An example of introducing new technology into aero-engine systems in recent times can be found in Pratt & Whitney's PW1000G engine family. In pursuit of better fuel efficiency, the PW1000G utilizes a planetary gearbox which enables the fan to spin slower than the low-pressure spool. This technological leap resulted in a significantly improved fuel efficiency and noise reduction. However, it also resulted in a troubled market introduction, and later a vast recall of the PW1100G variant (used on the A320neo) due to manufacturing issues which caused crack formation (Singer, 2023).

Nevertheless, ensuring that the performance targets are met is a natural first step towards ensuring return on investment. When designing aero-engine components, care is taken from the very start to ensure that the operational performance of new designs can feasibly fulfill customer requirements. For structural components, this includes looking at load-bearing capabilities, and aerodynamic performance. However, focusing solely on operational performance is not a sound strategy, as there are other factors that influence the success of the design. Of critical importance is whether the design will make sense from a business perspective. In other words, do the gains outweigh the cost? For this reason, manufacturability is paramount, as manufacturing is a major contributor to cost.

During the initial interviews presented in **Paper A**, it became clear that design engineers at GKN Aerospace did not possess the information they considered to be necessary to efficiently avoid downstream issues. At the time, manufacturability was of primary concern, and so the design engineers considered it necessary to improve knowledge creation with regards to the manufacturing domain in the early design phase. The main idea which emerged from this inquiry was that more knowledge needed to be extracted from previous design endeavors, such that this knowledge could be leveraged to improve new designs. Developing new designs through the reapplication of existing assets created in previous development projects is part of the product family strategy. However, this initial study indicated that there was a need for improvements in this area. One potential improvement was to utilize manufacturing data to avoid manufacturability issues in new designs. However, extracting manufacturing data for use in design is a challenging (but not insurmountable) prospect. In **Paper C**, it was further discussed that what assets *can* be reused depends on the similarity between new designs, and previously developed designs. Thus, understanding the similarity can assist in efficiently identifying potential for design reuse.

An alternative route to increased knowledge of manufacturability is to utilize manufacturing simulations, but such simulations are typically reserved for later stages in design. In **Paper B**, a means of achieving early design phase manufacturing simulations was proposed for product family design. To achieve such simulations in the early phases there needs to be a geometric representation of an appropriate fidelity, which was achieved through a geometry generation software.

Combining manufacturability evaluation with performance evaluation enables the identification of trade-offs between the two domains. Equipped with the necessary knowledge, designers can identify points in the design space that achieve performance targets, while at the same time making sense from a business perspective, at least in the short term. To understand long-term effects, sustainability also needs to be taken into account.

Insufficiently sustainable systems will also result in downstream issues. In the long term, possibly longer than the life cycle of the system itself, damage done to planetary boundaries can have an adverse effect on the ability to manufacture, maintain, and conduct further business using the system. These effects can seem abstract, and difficult to quantify, but are nevertheless a prominent issue. On the other hand, more concrete effects of not accounting for sustainability can potentially be noticed through increasingly stringent sustainability requirements. It is necessary to minimize the risk of products becoming obsolete before their planned life cycles have concluded. This idea stems from Hallstedt and Isaksson (2017) and Hallstedt (2017), in which it is demonstrated how the design space can be thought of as a tunnel which becomes increasingly narrow as the stringency of sustainability requirements increases over time. In other words, a design which follows contemporary sustainability requirements may no longer do so in 5 years, rendering the design deprecated, or obsolete. Thus, it is also necessary to understand as early in the development process as possible how the design affects key sustainability aspects. This entails looking at societal, environmental, and economical aspects throughout the life cycle of the design. However, methods and tools for conducting this sort of analysis have been lacking. In **Paper E**, an example of how sustainability can be incorporated into the already developed mechanisms for trading manufacturability against performance is demonstrated, thus enabling trade-offs to be made among all three domains.

An important aspect to consider when evaluating these three domains already in the early design phase is that capturing and quantifying key domain indicators, at such an early stage, is a considerable challenge. The earlier these types of evaluations are conducted, the less information is available. Consequently, absolute evaluations of individual design variants are unlikely to be trustworthy. Instead, relative assessment can be conducted, where all designs are compared against each other. Utilizing relative comparisons can assist designers in identifying trends, providing guidance before committing to detailed design. However, even trends can be questionable when charting new design space territory. Once again, the product family approach of building on what is already known becomes important, as experienced designers can assist in verifying identified trends. In **Paper C**, it is demonstrated that similarity metrics can be used to analyze evaluation results. Through measuring the similarity to higher-fidelity data, designers are provided with quantitative proof of similarity, thus complementing expert opinion and improving insight into the trustworthiness of identified trends.

In conclusion, when integrating new technology into a system, performance, manufacturability, and sustainability all need to be considered concurrently, accounting for trade-offs. Failing to do so can result in expensive redesigns, or early system deprecation or obsolescence. With this in mind, how can all three domains be evaluated *efficiently*? The first key to efficiency is to create as much knowledge as possible before committing too many resources to develop and realize the system. This means that evaluation of all three domains needs to be done as early in the design process as possible. The second component to achieve efficiency is to reuse as much as possible of what has been learned in previous design endeavors. But, to understand what can or cannot be reused, the original context of the to-be-reused assets needs to be compared to the new situation, which is addressed by RQ2.

6.2 Research question 2

What assets can be reused between product generations in a product family?

In **Paper A** it was proposed to use manufacturing data from previously produced products to inform the design process and avoid manufacturability issues. In **Paper B**, a software capable of automatically generating geometric representations was developed to enable concurrent evaluation of performance and manufacturability in the early design phase. Both approaches are based on the idea that an asset is reused between development projects. Consequently, these approaches are likely limited to assist in the evaluation of new designs that are similar to previous design endeavors.

Reusing existing data to inform the design process relies on the assumption that the data is still relevant in the new context. Likewise, to reuse a software tool that automatically generates (geometric) models, it too needs to be relevant even in the new context. It must be flexible enough to generate design variant representations within the targeted design space, yet autonomous enough to minimize the need for manual intervention. As such, it will be limited to a finite region of the design space. No fully automated software will be able to generate all possible representations, and no fully flexible software will be autonomous enough to eliminate the need for manual intervention. Thus, to answer RQ2, it is first necessary to understand what determines which assets can be reused between product generations in a product family, to which at least one answer seems to be *contextual similarity*.

In **Paper C** it is argued that reuse of knowledge and other assets, from one design to another, is dependent on the similarity between the two designs. In **Paper C**, the similarity metric is focused on design space proximity, and is measured as the distance between the design variables of two different designs. However, design similarity can be extended to include other aspects of the design context, such as similarity in requirements, or in the intended operational environment. To facilitate this discussion, the possibilities of reuse are divided into three basic categories: the reuse of *data*, *models*, and *knowledge*, as visualized in Figure 6.1.

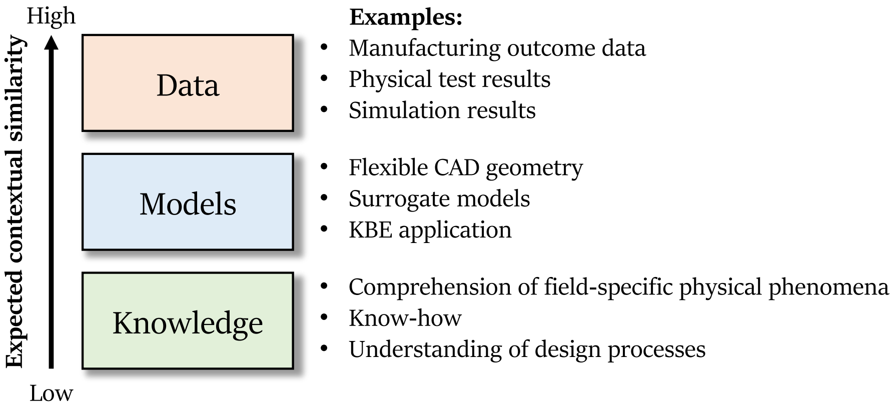

Figure 6.1: Basic model of intangible asset reuse vs similarity.

Arguably, reusing knowledge requires the least amount of similarity. An engineer can potentially benefit from having participated in other product development projects before, as a lot of know-how is not project-exclusive. Nevertheless, the amount of reusable knowledge is at least somewhat proportional to the similarity between the projects. Reusing models, on the other hand, likely requires a higher degree of contextual similarity. Models are designed with a purpose, and are created to capture and represent a concept. Consequently, the farther the new context strays from the original intent, the less likely the model is to be useful. However, as was pointed out by M. Pidd (2002), models can be reused in many different ways. Models can potentially be modified to fit a new context, which can make them somewhat flexible.

I would argue that data is, of the three, the most context-dependent reusable construct. For data to be reusable, the context and purpose of the data need to be a near-perfect match. For instance, when validating a simulation experiment against physical test data, the physical and simulation data need to be descriptions of the same phenomenon. Otherwise, such a comparison makes no sense. However, data can also be reused by training data-based surrogate models. This is what was exemplified in **Paper C**, where data-based surrogate models were created and used to predict simulation results. This increased the flexibility of reusing the data, at the expense of computational resources. It was further demonstrated that the more the new context strayed from the context of the original data, the less accurate the data-based surrogate model predictions became. The idea behind legacy similarity, as discussed in **Paper C** and detailed in Section 5.3, is that this reasoning can be extended to other sets of data of varying degrees of fidelity, including comparing simulation or surrogate model data with data gathered from physical tests or operations. Such a comparison could be useful for validating simulations. It could also be used to ensure that new design candidates are within the well-understood regions of design space, which can potentially reduce risks of encountering unknown unknowns.

This reasoning has led to a new question: if increased similarity leads to reduced uncertainty, should designs be optimized for similarity? This question has ultimately been left for future work, but it warrants further discussion. Needless to say, solely optimizing for similarity serves no purpose, as the final design would merely become a copy of whichever baseline was used for comparison. However, there may be merit in constraining, for instance, performance optimization based on similarity, as designers might then encounter similar designs that perform at a higher level. Even so, setting a fixed threshold on a minimum level of similarity is likely to be difficult, as the metric itself is not absolute, but rather relative to the design space being investigated.

Aside from the reuse of intangible assets, there is naturally the exploitation of existing tangible assets. This includes reusing manufacturing equipment, or common components. This is a thoroughly explored topic, and an established practice when utilizing product platforms. Nevertheless, if the aim is to reuse existing assets, tangible or not, then new products and systems need to be designed to enable such reuse. In **Paper D**, it is explored how systems can be optimized for flexibility. By using the proposed method MOTAC, system configurations can be identified from which future iterations can grow with minimal conflict. Since the original baseline configuration remains much intact over time due to its high flexibility, it also facilitates the reuse of assets, since the context remains similar.

Rounding off the discussion of RQ2, the main take-away of the findings is that measuring the similarity to previous design endeavors can provide insight into the reusability of existing assets. Since reusable assets mean that fewer assets need to be created from scratch, they also entail reduced uncertainty, as fewer unknown unknowns are likely to be encountered. However, consider a scenario where a new design shares similarities with a previous design which encountered issues during development. If those issues were not resolved, then any similarities to such a design should either be avoided or reconsidered. In other words, similarities are not necessarily always beneficial, but knowing about them is generally insightful.

6.3 Research question 3

How can digital modeling support be developed to enable assessment of alternative variants in the early design phase?

A clear characteristic of the early design phase is the overall lack of information. Little is known about the design space, and how the final solution will perform with respect to stakeholder requirements. To mitigate this, product platforms are utilized to enable reapplication of previous knowledge and other assets. Yet, issues still evidently emerge in companies that practice such product platform strategies, as discussed in Section 6.1. This indicates that better methods and tools are needed to assist in the creation of knowledge in the early design phase, and in avoiding downstream issues.

Identifying promising concepts, or design candidates, when little is known about them is challenging. Utilizing simulations or other models to compare absolute performances among concepts is rarely helpful, as absolute values are unlikely to be accurate in the early design phase. A means to circumvent this issue, as exemplified by Pugh's concept selection method (Pugh, 1990), is to perform relative, rather than absolute, comparisons. Following that principle, the software tools presented in this thesis typically encourage investigating large sets of designs, and screening them based on their relative performance against each other.

The tools presented in this thesis are designed to be useful in different parts of the early design phase. Trinity is, at its most basic functionality, useful for functional decomposition, which is a core activity during concept development. Morpheus can then be used to generate, and partially evaluate, large sets of design concepts. As proposed in **Paper D**, designers who utilize Morpheus are encouraged to compare alternative means for each system function. The information uncovered through this comparison is then used to automatically identify a set of design candidates, which should then be further developed and screened in detail. Furthermore, MOTAC (implemented into Morpheus and partially into Trinity) asks of the designer to consider technologies that are not yet mature enough for application, but may be relevant in the future. This information can then be used to identify design candidates that are flexible, and thus more likely to be compatible with future technologies.

When entering the system-level design phase, Trinity once again becomes useful, as it can facilitate the understanding of system interactions. Furthermore, it can be used to map out dependencies among manufacturing options and alternative means of achieving system functions, as conceptualized by Isaksson et al. (2021), and exemplified in **Paper E**. Pre-embodiment evaluation of risk and sustainability can also be conducted using the methods detailed in **Paper E**, and the various design alternatives can be analyzed using MDAC.

The visualization approach implemented into the MDAC software enables designers to compare large sets of design variants, while at the same time constraining the dataset by screening out relatively underperforming concepts. As such, the principles embedded into MDAC furthers the idea of relative selection. In addition, MDAC implements the similarity metrics used for similarity-assisted design space exploration (see Section 5.3), enabling designers to gain insight into the trustworthiness of the visualized data.

Finally, during the system-level design phase, a geometric representation of the design starts to take shape. Here, the TRS generation software can be used to generate large sets of varying TRS geometries. These geometries can then be used for various types of simulations, the data from which can be analyzed and interacted with using the MDAC software.

6.4 A computational framework

The methods and tools presented in this thesis all serve a common goal: to reduce the risk of integrating new technologies into existing product family systems. The computational framework, as visualized in Figure 6.2, serves as an overview of how this thesis contributes towards that goal. The methods in the framework are intended to provide decision-making support for designers, and reduce uncertainties. The methods have been implemented into tools, in the form of software. These software perform the computations necessary to elicit information to support multi-domain decision-making, and to evaluate reuse potential. Two of the software in Figure 6.2 are transparent, indicating that they do not fully implement their associated method.

There are two categories of knowledge to which the methods and tools contribute: i) the understanding of multi-domain trade-offs, and ii) the applicability of existing assets.

To reduce the risk of not meeting performance, manufacturing, or sustainability targets, all three of these domains need to be evaluated. Complicating matters, these domains often have conflicting criteria. Consequently, concurrent evaluation and trade-off exploration is necessary to avoid sub-optimization. Eliciting the necessary metrics to perform multi-domain trade-off analysis during the early design phase is challenging due to the scarcity of information early in development. Nevertheless, this framework provides the following means for pre-embodiment evaluation:

- MOTAC, integrated into Morpheus, enables the consideration of multiple design objectives when searching for concepts, regardless of the domains from which those objectives originate.

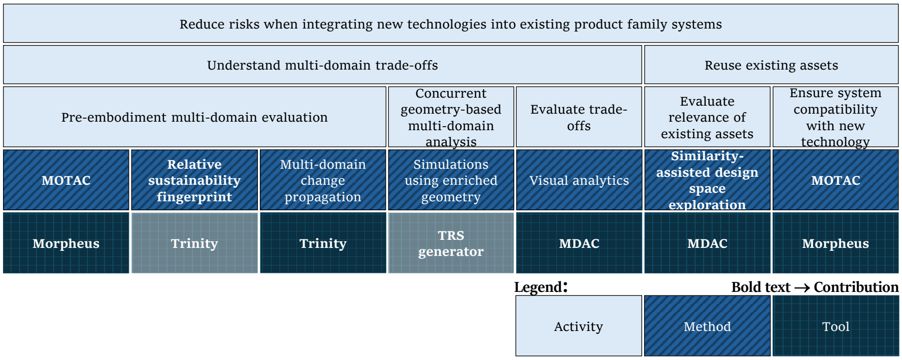

Figure 6.2: Visualization of the proposed computational framework. It demonstrates the connection between the design activities targeted by the presented research, and the proposed methods and tools. Each block in the diagram is directly related to the block above it.

- The relative sustainability fingerprint, which partially makes use of Trinity, facilitates sustainability analysis when evaluating alternative concepts.
- Multi-domain change propagation, fully integrated into Trinity, allows designers to assess how alternative means affects multi-domain aspects of the system.

Depending on the availability of information regarding the geometry of the design, it may also be possible to conduct geometry-based analysis. This includes evaluations such as FEA to evaluate structural performance, or accessibility analysis to evaluate weld manufacturability. When designing products within scale-based product families, geometries can be available early in development as existing solutions are scaled up or down to match emerging needs. For such scenarios, enriching geometries with information necessary to conduct concurrent multi-domain analysis can assist in considering trade-offs. For this purpose, the TRS generator was designed, which rapidly generates the necessary geometry and information to conduct manufacturability and performance evaluations concurrently. However, the TRS generator is naturally limited to generating TRS geometries, and is not generalizable. Practitioners considering this framework should reflect on whether their products are similar enough to warrant the development of a corresponding enriched geometry generation tool. If not, then this component of the framework should be approached with care, and potentially substituted with lower-fidelity evaluations.

To understand trade-offs, it is generally advisable to visualize them to facilitate informed decision-making. To that end, visual analytics provides the methodological foundation, and MDAC implements several techniques to facilitate this process.

The second major component of this framework is the reuse of existing assets, which is a core aspect of product family design. These assets include knowledge, models, and data created during previous development endeavors. However, to reuse assets, it is first necessary to evaluate if they are relevant in the new context, for which similarity-assisted design space exploration was developed, and implemented into MDAC. This enables designers to quantify the similarity to the baseline from which assets are to be reused. That includes comparing new design alternatives to already manufactured designs, and comparing surrogate model inputs to the data on which it was trained. Finally, to strategically facilitate asset reuse over time it is possible to design for commonality in system composition between new and existing solutions. Flexible systems are designed to make change easier, which also reduces how much the systems need to change to achieve emerging requirements. This means that more of the system can stay the same, thus increasing similarity between product instances and, as established, similarity facilitates reuse.

The methods and tools presented in this framework form a comprehensive example of how these activities can be conducted. However, it is naturally possible to substitute individual methods or tools in this framework, and in many cases (as exemplified above with the TRS generator) it is likely necessary.

Chapter 7

Research validation

Validating a design method entails proving that it is useful with respect to a purpose (Pedersen et al., 2000). The method needs to be developed with a certain context in mind, to enable validation within that context. Isaksson et al. (2020) refers to this as the *research focus*. The focus of the research presented in this thesis has remained relatively consistent, targeting early phase design in the aviation industry. More specifically, the context for which most of the presented methods were developed was conceptual design of static aero-engine components.

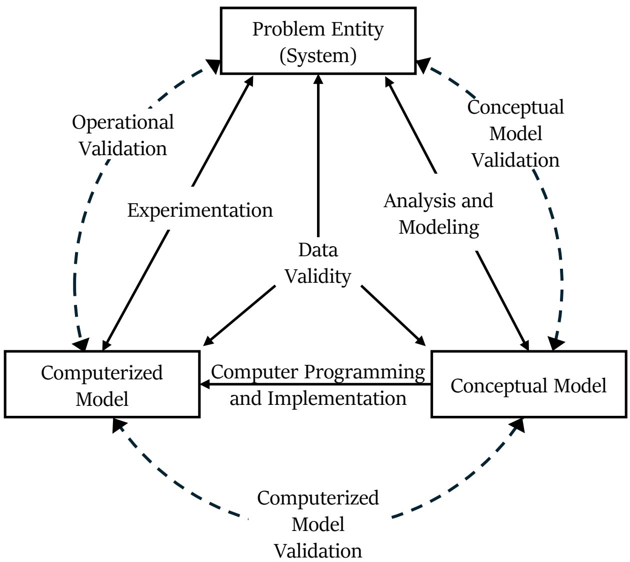

Figure 7.1: Adopted from Sargent (2013).

The validation analysis presented in this chapter uses the simplified validation model proposed by Sargent (2013), as visualized in Figure 7.1. The reason for choosing this particular model is due to its focus on computerized models, which is well-suited for the digitalization approach that permeates much of the research presented in this thesis. With the exception of **Paper A**, all appended publications have some element of digitally representing the problem at hand, and then using the digital representations to gain an enhanced understanding of the problem itself.

Sargent's validation model contains three primary constructs:

- The problem entity, which is the system that is being modeled.
- The conceptual model, which is the abstraction of the problem entity in the form of a model.
- The computerized model, which is the implementation of the conceptual model into a computerized format.

In addition, the validation model describes how these constructs are related, and how they are validated relative to each other. Finally, at the center of the model is the data validity, which interacts with all three constructs as it is used to develop and validate the models. Sargent (2013) notes that data validity is difficult to obtain, and not always considered to be part of model validation. The key purposes of data, in the context of validation, are:

1. To understand the problem entity such that a conceptual model can be constructed.
2. To validate the conceptual model by comparing its resulting behavior to its expected outcome.

Fitting these types of data into the DRM perspective, the first type of data is typically collected during the RC and DS1 phases, where understanding the problem is the key focus. This data has thus primarily been qualitative in the form of interview and workshop results. The second type of data is generally gathered in the DS2 phase, where implementation outcome is validated.

In this chapter, the validity of the proposed models is analyzed using Sargent's simplified validation model. Since DS2 was not finalized, only initiated, this analysis may also serve as the basis for any future work to further validate the models. It should be noted that Sargent's simplified validation model relates all results back to the targeted problem entity, which means that external validity is not covered. Consequently, to argue that some of the core ideas in this thesis are applicable also outside of aviation, Section 7.4 discusses the generalizability of the research results.

7.1 Validation of similarity model

One of the core claims of this thesis is that contextual similarity is a reverse proxy for uncertainty in design. The problem entity being modeled is whether existing assets can be used to better understand new designs. Through consulting both experts and literature, it was found that what can be reused is directly dependent on how similar the new context is to the original context of the reused asset. This similarity is modeled using similarity metrics, that are a construct proven in other fields of engineering, mainly computer science. Through interviews with experts, it was determined that, within scale-based product families, there exist certain driving variables that can help determine the contextual similarity. Thus, the data validity necessary to construct the conceptual model was sound, as both data gathered from interviews and literature are in alignment. Conclusively, the conceptual model is valid based on evidence both in literature and expert opinion.

Due to the abundance of similarity metrics available, implementation of the inter-similarity concept into a computerized format was relatively straightforward. An experiment was conducted in which similarity metrics were used to determine the relevance of surrogate model predictions relative to simulation model predictions. Using the simulation data, this approach could be validated for a set of cases, demonstrating that the computerized model indeed possessed the desired behavior in the tested context.

What could not be tested is the operational validity of the legacy similarity metric. This would require measuring the similarity between a new design, and an existing design, within the industrial context, and then demonstrating that knowledge of this similarity resulted in reduced risk. However, product development processes in the aviation industry are time-consuming, and much of the data is confidential. Thus, the appropriate data necessary for operational validity could not be gathered within the available time frame. However, this obstacle could potentially be avoided. Two alternative ways of evaluating operational validation are:

1. Study how already conducted development projects have been similar to earlier projects. Interview participants from those projects and evaluate whether lower degrees of similarity have historically resulted in more problems during development, and the rest of the product life cycle.

2. Gather a cross-functional team of experts, preferably from both the manufacturing and design domains. Conduct a design study which considers multiple design alternatives of varying degrees of similarity to previously conducted developments. Compare outcomes of the computerized model against expert opinion.

7.2 Validation of discrete design space exploration using flexibility

The development of MOTAC was prompted by the vast discrete design spaces that modern product platforms span. The abundance of alternative technologies, combined with future technologies, creates a difficult-to-navigate landscape, where there are more possible combinations than what can feasibly be evaluated through expert opinion alone. At the same time, manufacturers need to ensure that their systems are compatible with future technological advances, such that they stay competitive even in the face of radical technology developments. This composes the problem entity: the vast discrete design space, and the need to find future-compatible and competitive solutions within that space.

To construct a conceptual model of this problem, the morphological matrix approach was used as a basis, as it is a proven means of representing discrete design spaces. The proposed approach, referred to as MOTAC, modifies the morphological matrix such that it includes expert opinion on multi-domain aspects, such as cost and performance. Additionally, a DSM is used to capture which technologies are incompatible. To evaluate if this is an appropriate representation of the problem, two experts from the automotive industry were consulted. To facilitate the evaluation process, a computerized model was implemented into the Morpheus software.

The computerized model utilized DSMs and quantified morphological matrix together with a well-known pathfinding algorithm to rapidly identify feasible design candidates. Using the tool, the experts were able to represent a realistic problem from the automotive industry. A degree of operational validity was achieved through conducting a design study this problem. The experts were consulted to map out the design space, incompatibilities, and populate the numerical models in the morphological matrix. This demonstrated that the problem could indeed be mapped using the software, and represented by the computerized model. After the study had concluded the experts confirmed the feasibility of the results. As such, data was collected from the workshops with these experts that assisted in validating the conceptual and computational models.

Since the design study was based on a real scenario, and experts were consulted about the setup and results of the study, there is high confidence in data validity. At the same time, certain simplifications or omissions needed to be made due to proprietary and confidential data. Thus, full operational validity could not be achieved, as that would require testing it on data considered to be proprietary. This could potentially be achieved in an internal design study, where data sensitivity is not an issue.

7.3 Validation of sustainability and risk evaluation

Increasingly stringent sustainability requirements are forcing manufacturers into considering sustainability during the early design phase. At the same time, technology intended to improve sustainability, but which has not yet been implemented, can often be of a lower technological maturity. Low maturity entails a higher risk, resulting in a trade-off between risk and sustainability. The validity of these assumptions was supported by the literature review presented in **Paper E**. A proposition for how to model this problem was developed. The relative sustainability fingerprint method deals with measuring sustainability when little is known about the solution, while the risk-aspect is approached using CPM, using TRL as a reverse indicator of the likelihood of encountering unknown unknowns.

The proposed method enabled rapid synthesis of results. Thus, it was possible to iterate on the conceptual model multiple times in search for a configuration that generated expected first-order results. For instance, it was expected that any solution that utilized AM should enable lower-weight structures at the cost of a higher overall risk due to its low maturity within the context of the studied use case. As such, data validity was achieved by having an expert and a team of researchers compare the outcome of the model to the expected outcome. It was found that the computerized and conceptual models were representative of the problem entity, but that it relied heavily on what was used as input, and that some calibration is likely to be necessary in practice.

The question remains, however, whether this means of modeling sustainability and risk in the early phase of design is sufficient to avoid *new* problems. **Paper E** demonstrates how it is indeed possible to identify issues with designs using this method, but a more extensive study would be required to verify that the method can be used to identify problems that engineers are not already aware of. In other words, operational validation is lacking. Ideas for further evaluating the validity of this method includes:

1. Evaluate an already conducted product with a teams of engineers who are unfamiliar with the outcome of that product. Then, compare the results to what actually happened.

2. Have teams of engineering students utilize this method during project courses where they develop product concepts.

7.4 External validation

According to Blessing and Chakrabarti (2009), *"the aim [of external validation] is to determine whether the results are person, setting, and time independent"*. The research scope has remained relatively consistent, focusing primarily on structural aero-engine components. However, in pursuit of external validity, two key actions were taken. Firstly, one of the journal contributions (**Paper D**) was focused on the automotive industry, thus repurposing some of the developed reasoning for another context. Secondly, the majority of the proposed methods have been implemented into software that, with the exception of the TRS generator, is designed to be **application agnostic**. This application-agnostic software has been used in several studies, many of which are outside of the aviation context.

As detailed in Chapter 5, the presented research has resulted in three web-based applications with graphical interfaces, and a handful of libraries used to generate data and run experiments. The first application, MDAC, was originally developed for **Paper C**. However, it has since then been used by several practicing engineers, and other academics for various applications (e.g., Al Handawi et al., 2023; Martinsson Bonde, Isaksson, et al., 2024; Pradas Gómez et al., 2025). This includes use of the similarity metric which, for instance, was utilized by Arjomandi Rad et al. (2025). Multiple features have been added to satisfy needs emerging from various use cases, such as the ability to export basic requirements based on the parallel coordinates filters.

The second software, Morpheus, implements MOTAC. The MOTAC-specific features are not yet publicly available in Morpheus at the time of writing. However, the fundamental features upon which MOTAC was built are available, and has been used in multiple studies in non-aviation contexts (Martinsson Bonde, Breimann, et al., 2024; Martinsson Bonde et al., 2022), and by practitioners outside of the aviation industry. Martinsson Bonde et al. (2022) focuses on the development of the initial version of Morpheus, and some of the challenges with converting traditional methods into a digital format. Two years after that initial Morpheus paper, the software had matured significantly. Additional features were added to further assist the users in conducting systematic design space exploration, and a new study was conducted to evaluate their usefulness (Martinsson Bonde, Breimann, et al., 2024). Some of the lessons learned from this study eventually led to the development of the method presented in **Paper D**. This demonstrates the scalability of the software, as new research results can be utilized to improve and iterate on the software, making it useful in new scenarios.

The third software, Trinity, has also grown through the needs of different design studies. An early version of Trinity was developed for the study conducted by Martinsson Bonde, Breimann, et al. (2024). Similarly to Morpheus, Trinity was drastically improved based on the results of the study, such that it could be utilized in **Paper D**. These studies were radically different, and the study conducted in **Paper D** required the implementation of certain elements of MOTAC (incompatibility avoidance and combinatorics), again demonstrating the scalability of this approach to tool-crafting. It has, in addition, been used in **Paper E** and other thus far unpublished studies, where it has been used to conduct CPM directly on EF-M trees, and also for certain MDO applications discussed more in Section 8.2.

Chapter 8

Conclusions and outlook

This thesis has presented a set of methods intended to improve the design space exploration process such that designers can make better-informed decisions in the early design phase, where the design freedom is still high. In this concluding chapter, the main claims are presented along with the contributions to knowledge and practice. Finally, directions for future research in this field are suggested.

8.1 Claims and contributions

Claim 1

Contextual similarity to previous design endeavors can be measured and exploited in the early design phase

The reuse of knowledge, data, and other assets captured during the development of previous designs is part of the product family approach to product development. However, what can be reused is ultimately dependent on the similarity between the new and previous contexts. The information regarding whether there is a similarity between two contexts can be of high interest already during early design space exploration. In **Paper C**, it was demonstrated that similarity can be considered as a proxy metric for how well a certain design space region is understood. The less that is known about a design space region, the higher the risk of new unknowns, and thus also the risk of encountering new problems during the product life cycle. Whether the new context is similar or not to previous contexts has, traditionally, been determined qualitatively through expert opinion. This has made it difficult to leverage such insights in design space exploration exercises, which typically evaluate too many design variants to enable expert opinion to be granted to each design variant. In Section 5.3, it was proposed that this contextual similarity be quantified. Quantitative assessment of contextual similarity using similarity metrics can yield non-trivial insights during design space exploration. Thus, such metrics can increase the understanding of the design space and enable better-informed decision-making during the early design phase.

Claim 2

Strategically maintaining product family compatibility with future technologies can reduce uncertainty in a changing technology landscape

As shown in **Paper D**, to stay competitive in a changing industry it is critical to enable compatibility with emerging technologies. However, as the number of alternative technologies increases, the number of possible combinations multiplies rapidly. This problem is difficult to tackle, as large numbers of combinations cannot possibly be evaluated at a high resolution. Through the application of MOTAC, as described in Section 5.1, such discrete design spaces can be explored at a greater pace. In combination with conventional pathfinding techniques and a novel combinatorial flexibility metric, it is possible to rapidly converge on a set of design candidates that are compatible with known future technologies. Thus, new systems can be developed with the future in mind, reducing the uncertainties of future technology integrations.

Claim 3

A multi-domain modeling and trade-off approach is a step towards gaining the systematic perspective necessary to achieve sustainable product development

Emerging sustainability requirements necessitate employing a holistic system-perspective of product development. Thus, the impact of new technologies on the entire system life cycle needs to be evaluated as early as possible to avoid costly late design changes. To enable this, potential impact modes need to be modeled such that an early approximation of system-level impact of new technologies can be evaluated. In **Paper E**, an approach to exploring these dimensions concurrently was demonstrated, but it was also highlighted that there is a need for a means of balancing multi-domain criteria. A potential avenue of development is to explore how the already known EF-M, CPM, and MDO constructs can be used in symphony, as is further discussed in Section 8.2.2.

Claim 4

It is possible to implement similarity analysis, MOTAC, and the relative sustainability fingerprint into general purpose tools

The development of MDAC, Trinity, and Morpheus demonstrates that the method contributions in this thesis are implementable, and generalizable. These tools do not assume any particular industrial context, nor do they assume any particular type of artifact. Notably, among the contributions a clear exception to this is the automatic TRS geometry generation tool, which strictly focuses on a particular type of artifact. The remainder of all contributions, including the relative sustainability fingerprint, have all been integrated into application agnostic software that can be repurposed for other products or services.

8.1.1 Contributions to knowledge

When studying the needs of the industry, and the state-of-the-arts, it was found that there are knowledge gaps in the understanding of how systems are impacted by new technologies. One of the findings was that the early design of aero-engine components typically focuses on performance, often leaving out other crucial parts of a system-level evaluation. This often results in geometries that are difficult to manufacture, giving rise to high costs and late design changes. Traditionally, manufacturability has been incorporated into design through the application of DFMA guidelines. However, DFMA does not give any insight into product-specific trade-offs with other domains. Understanding manufacturability trade-offs during the early design phase has, in recent times, attracted research interest. One of the challenges has been how to capture manufacturability aspects already during the early design phase such that it can be used in trade-off studies. To that end, the enriched CAD model generation technique described in Section 5.4 serves as a means. It extends the concept of enriching CAD models originally proposed by Stolt et al. (2016) primarily in two ways. Firstly, it employs solid geometry rather than shell-based geometry. Secondly, it utilizes CAD building blocks instead of varying high-level parameters in a monolithic model. As such, it improves on the common practice of utilizing shell models for early aero-engine component performance analysis, thus increasing geometric fidelity. The building block approach serves to avoid compromising on model flexibility, as these blocks can be rearranged and customized for a high degree of model variety.

Indeed, considering manufacturability during design is critical to avoid late changes and high costs. However, manufacturing is not the only domain in which trouble can manifest during development. Problems can emerge at any stage of a product life cycle, though encountering new problems can, to some extent, be avoided by staying within the well-understood regions of design space. Design reuse, and the benefits of having similarities to already tried-and-tested solutions, are well-understood and thoroughly documented. This thesis contributes by detailing a means of utilizing similarity metrics to compare new design evaluation data against higher-fidelity datasets. This method draws inspiration from design-by-analogy (McAdams & Wood, 2002) and case-based reasoning (e.g., Aamodt & Plaza, 1994; Akmal et al., 2014). However, rather than using similarity metrics to identify functional analogies, it measures the similarity among design representations of differing levels of fidelity. This means that the often-made claim that a solution has been *proven in flight* can be supported with quantitative evidence. Through the application of similarity metrics during the early design phase, designers can be informed whether a concept is farther or closer to designs previously evaluated at a higher fidelity. Straying far from previously explored design space regions involves higher risk, while staying closer to them increases design confidence.

Another risk addressed in this thesis is of systems not being compatible with future technologies. A product family typically has a platform architecture that is varied and updated for each new product variant that emerges from it. These platform architectures can be considered as systems. To stay competitive, it is critical that the development direction of such systems is aligned with future technologies, and that the impact of future technologies on such systems is well-understood. If future technologies are incompatible with existing systems, then larger leaps within the design space will be necessary to accommodate them. This, as previously mentioned, comes at a high risk. Thus, MOTAC was developed, which focuses on evaluating the design space with regards to flexibility, such that product families can strategically develop in a direction that will result in a minimal impact of future technologies. MOTAC unites the concept of flexibility with quantified morphological matrices. It extends the quantified morphological matrix concept previously explored by Ölvander et al. (2009) and Tiwari et al. (2009) by also considering functional importance, applying Dijkstra's algorithm, and introducing flexibility metrics. Furthermore, it extends the concept of flexibility (Fricke & Schulz, 2005) to also be quantifiable in a constrained discrete design space.

The final risk addressed in this thesis is that of system deprecation or obsolescence due to failure to meet long-term sustainability targets. Hallstedt and Isaksson (2017) illustrate the design space as a cone that narrows over time as sustainability requirements become increasingly stringent. Indeed, for a system to stay competitive within its intended life cycle, its position within the design space must not intersect with the walls of this cone, as illustrated in Figure 8.1. However, as established by authors such as Hallstedt et al. (2022) and Lovdahl et al. (2024), there is a lack of tools available to designers to avoid this problem, especially in the early design phase where information is scarce. The sustainability fingerprint, detailed in Section 5.2, takes the sustainability fingerprint method created by Hallstedt et al. (2023) and modifies it to suit early concept development. This is done by relying on relative comparisons among known alternative means, rather than providing absolute metrics. As such, designers can start to steer away from the boundaries of this narrowing design space already in the early design phase, thus reducing risk of deprecation.

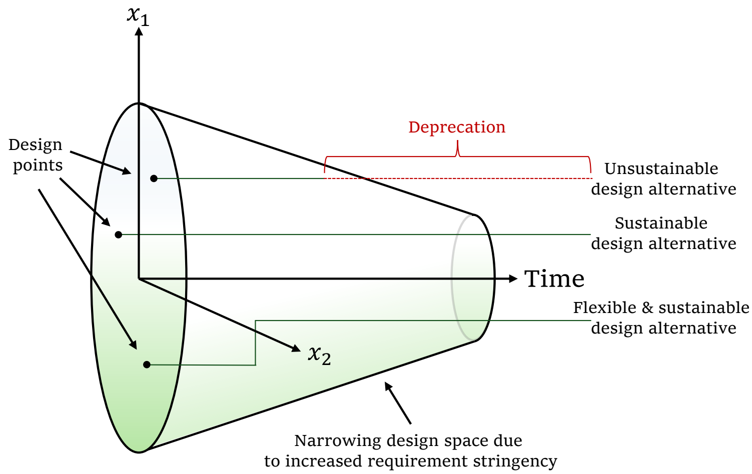

Figure 8.1: Visualization of how the design space narrows as sustainability requirements become increasingly stringent. Design points that intersect with the boundaries of the cone become deprecated.

Implementing new technologies will always involve some degree of uncertainty and risk. However, through a thorough understanding of multi-domain trade-offs, system flexibility, and potential for asset reuse, the uncertainty can be significantly reduced. A framework was proposed for how these factors are related, and how they contribute towards a common goal. It lists and connects methods and tools that can assist in creating the necessary understanding in the early design phase.

8.1.2 Contributions to practice

From the perspective of industry, there are multiple notable insights from the research presented in this thesis. Firstly, flexible solid geometry generation can be achieved using a modular approach. Such an approach has multiple benefits, including high variability, but also the possibility of enriching the models with information that can be used for later stages of analysis, such as manufacturability evaluation. **Thus, this approach ameliorates the problem of traditional geometry generation not being flexible enough to evaluate designs that vary greatly in shape and form.**

Furthermore, the difference between known designs and new designs can be measured using similarity metrics. These metrics can be exploited and used for design space exploration, assisting designers in staying within the well-understood regions of design space, or potentially avoiding design configurations that have previously proven to be problematic. **This partially mitigates the problem of expensive late redesigns, as problems can be avoided by staying within the well-understood regions of the design space.**

The transport industry as a whole faces increasingly stringent sustainability requirements, forcing manufacturers to consider multiple new technologies for integration. The number of potential combinations with known and future technologies are vast, creating a discrete design space that is difficult to navigate. Through the application of flexibility-informed pathfinding algorithms, it is possible to rapidly converge on design candidates that are compatible with future technologies. **This solves the problem of finding multiple design candidates in otherwise too vast discrete design spaces. Additionally, it ameliorates the problem of strategizing such that contemporary systems are developed with minimal hindrance of future technology incompatibilities.**

Finally, the industry needs to understand the impact of new technologies on a holistic level. This entails modeling and evaluating large complex systems with high degrees of coupling and interactions. Through the combination of EF-M and CPM, together with a comparative sustainability evaluation, it is possible to evaluate the impact of system changes on sustainability, manufacturability, and performance, in the early phases of design. **This contributes towards understanding how multi-domain aspects can be elicited in the early design phase, and how their trade-offs can be considered.**

8.2 Future work

This section is dedicated to opportunities for future research aligning with the research presented in this thesis. First, the potential to leverage similarity metrics during optimization is discussed. Then, the idea of combining MDO and EF-M is outlined, as such a unification has the potential to strengthen multi-domain evaluation in the early design phase. Finally, a more general direction of future research is discussed.

8.2.1 Similarity-assisted design optimization

One potential avenue for future research is to explore how the similarity metrics proposed in this thesis can be applied for design optimization. Specifically, similarity metrics could be used to formulate inequality constraints that keep the optimization algorithm within the well-understood regions of design space. Inter-similarity, as defined in 5.3.1, could be applied as expressed in Equation 8.1, where f is a design objective, i is the number of design objectives, and $\mathrm{T_s}$ is the minimum similarity threshold. Note that the similarity function S is assumed to produce a value in the range $[0, 1]$, where 0 represents the closest possible similarity.

$$\begin{aligned} \min \quad & f_1(x), f_2(x), ..., f_i(x) \\ \text{s.t.} \quad & g_{\text{sim}}(x) \leq 0 \\ \text{where} \quad & g_{\text{sim}}(x) = \min\{S(\mathbf{x}_{\text{lf}}, \mathbf{x}_1), S(\mathbf{x}_{\text{lf}}, \mathbf{x}_2), ..., S(\mathbf{x}_{\text{lf}}, \mathbf{x}_n)\} - \mathrm{T_s} \end{aligned} \tag{8.1}$$

Since the similarity metrics proposed in this thesis are not absolute, the exact threshold for when a design is *similar enough* is unknown. To circumvent this, a parametric approach is proposed where the similarity inequality constraint g_{sim} is gradually relaxed by increasing the threshold $\mathrm{T_s}$. This will enable the search for designs that are as similar as possible to the baseline designs, while at the same time maximizing design objective performance.

This approach has the potential to integrate similarity analysis to a larger extent into design space exploration through optimization. It would also reduce the need for external tools, such as MDAC, to perform the similarity analysis. However, the details of how to efficiently utilize similarity metrics in design optimization is yet to be explored and tested. A first step could potentially be to attempt to replicate the results from **Paper C** with the approach proposed above.

8.2.2 Uniting multidisciplinary analysis and enhanced function-means

In **Paper E**, one of the problems identified was the difficulty in balancing triple-domain trade-offs (performance, manufacturability, sustainability). An idea that emerged from this was to evaluate how MDO could be leveraged to identify balanced design concepts. When performing MDO studies, it is common to initiate the process by conducting an MDA to chart how each individual subsystem interacts with all other subsystems, as described in Section 2.3.2. This process could potentially be facilitated using an EF-M which, in addition, is able to represent multiple system variants. Furthermore, as demonstrated in e.g., **Paper E**, it is possible to utilize the richness of EF-M modeling to conduct risk analysis through CPM. In other words, a unification of MDO, EF-M, and CPM could enable the identification of high-performing configurations for alternative system variants, while simultaneously approximating the risks such configurations might entail.

An initial idea for how to map EF-M information to MDA has been conceptualized. Essentially, the EF-M interactions can be used to infer which optimization variables are coupled, shared, or independent. Thus, much of the information utilized in the compact implementation of non-hierarchical target cascading (Talgorn & Kokkolaras, 2017) can be extracted from the EF-M interactions. Aside from variable dependencies, their ranges and how they are constrained also need to be known. How this information can fit in an EF-M was demonstrated by Müller et al. (2019). The rest of the bookkeeping information necessary to conduct non-hierarchical analytical target cascading (e.g., subsystem and variable indices) can be automatically collected by the software used to control the EF-M, such as Trinity.

8.2.3 Directions of future research

In this thesis, recurring themes have been the reuse of data in design, systems modeling, and design space exploration. This final section is dedicated towards a few challenges in these fields that were encountered during the research conducted for this thesis. Perhaps these challenges can provide direction for future research within the field of conceptual engineering design.

Data-driven design

The research presented in this thesis was initially conceived out of the desire to reuse data from previous designs when developing new products. Indeed, the first appended paper from 2021 (**Paper A**) discusses the potential of *digital twin-driven design*. Along the way, interesting questions, uncertainties, and obstacles were encountered. Five years later, that original desire remains unsated, but not for lack of trying. The first major obstacles encountered, discussed briefly in **Paper A**, were:

1. Data must be contextualized for its intended use. To enable the application of life cycle data in design, the data themselves need to be designed to be used in design.

2. Large companies comprising multiple sub-organizations must organize their data such that they can be readily accessed and utilized by individuals other than those responsible for collecting them.

If these issues remain unresolved, any ambitious data-driven design approach that siphons data from the entire product life cycle is unlikely to be practical.

Many companies already utilize some amount of life cycle data from existing products during the design phase, demonstrating that perhaps these obstacles can be overcome. Be that as it may, another important question is how much of all the captured data within organizations *should* be made available. Storing data is expensive, as it requires computer infrastructure. Making the data accessible throughout a company is a significant step up in complexity, as it requires additional infrastructure for networking and security. So, deciding to store and make data available for a longer period of time is often likely to be a costly decision. As Frické (2015) pointed out, we should be mindful of what data we choose to collect. To conclude, there are significant opportunities for exploring *how much* and *what* data need to be captured and stored, and what structure product life cycle data needs to assume to satisfy all stakeholders who are interested in consuming them.

Bridging conceptual design with model-based system engineering

Product are becoming increasingly complex, making manufacturers turn to model-based systems engineering (MBSE) to represent their systems. The idea is to have a *single source of truth* (e.g., Madni & Sievers, 2018) provided by a monolithic representation of the system. As such, engineers from all disciplines can have a shared representation of the system, reducing the risk of miscommunication. However, these models seem to obstruct conceptual design (Morris et al., 2016), as the need for consistency in these large and complex models constrains the designers. Due to the need for all perspectives of the system to be consistent, designers struggle with representing design variety beyond the parametrical. Thus, promising solutions risk being overlooked due to limitations of the modeling paradigm. An answer to this may be to bridge MBSE and traditional design (Shoshany-Tavory et al., 2023). This interface presents major opportunities for research. One potential path towards unification is through the toolification of traditional design methods, as discussed in this thesis. The digital format of design methods could potentially enable conversions between traditional formats, and formats better suited for MBSE. For instance, the EF-M tree from Trinity, once a promising concept has been identified, could perhaps be exported to Systems Modeling Language (SysML).

Generative artificial intelligence and design software

At the time of writing, the past three years have witnessed rapid and transformative advancements in artificial intelligence (AI) technology. Large language models can understand user input and generate cohesive responses; images and videos can be produced with similar ease; and AI agents can be deployed for specialized tasks, such as performing calculations. Notably, AI has quickly been found to be of additional use when integrated into other software, sometimes referred to as *AI co-pilots*. During the early development of Morpheus and Trinity, attempts were made to implement an AI co-pilot to assist in the generation of alternative means and functions, and to generate sketches for alternative means. In short, a generative AI interface was integrated into the software to assist in design space exploration. However, this was in the early days of the so-called *Chatbots*, and the results were erratic. Today, almost three years later, this seems to be significantly more feasible. AI could potentially be used to assist in brainstorming alternative means in morphological matrices, generate sketches, or assist in imagining how particular combinations of means might look and behave in symphony. The introduction of co-pilots in design software could have major implications for designer workflows, similarly to how it has changed the workflow of software developers (Vaithilingam et al., 2022).

The race towards finding how AI can be fitted into existing design methodology has begun, and there are already promising results. However, while there are reasons to be excited, there are also reasons to be cautious. Perhaps co-pilots can assist designers in brainstorming, or by providing useful starting points for problem solving. What we know for sure, however, is that it can outright make things up (*hallucinate*), and commit copyright infringement without user knowledge or consent.

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