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Similarity-based product family design for aero-engine components

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1.0 INTRODUCTION

The aviation roadmaps to reach a carbon neutral and more sustainable state of air transport necessitates system-level innovation [1]. New architectures, using different energy sources, to propel aircraft implies a radical change for aero-engine manufacturers [2]. The technologies and architectures presently considered differs from contemporary, more conventional, engine architectures. Still, the legacy and experience in the design and manufacturing solutions have brought confidence and experience to the companies over decades. Manufacturing of structural engine components is central to delivering high performance (high thrust, low drag, and with high structural integrity) engines.

Manufacturability has a significant impact on quality and cost. Experience in manufacturing is vital when evaluating new designs, to evaluate manufacturability at an early stage and avoid late design changes. However, as the architectures for next-generation aero-engines are likely to change, it becomes an issue to evaluate how relevant this experience is, for radically novel engine, and consequently component, architectures. The question addressed in the present work is: ***How can new designs benefit from already proven designs in a product family***?

In particular, we want to investigate how the development of structural components for next-generation engines can benefit from the use of similarity metrics, to assist in identifying opportunities to reuse knowledge and other assets from legacy designs. Through leveraging knowledge and assets from previous designs, the development of new, more sustainable, designs can be conducted at a reduced risk and lead-time. A study together with GKN Aerospace Engines on the design of advanced structural aero-engine components has been conducted, where a similarity metric has been applied to facilitate a better-informed design space exploration process.

When conducting design space exploration studies of different architectural variants, it is important to understand the relationship with existing solutions to estimate potential risks and benefits based on previous product experience. Examples of previous designs of a Turbine Rear Structure are, the GEnx powering the 787 Dreamliner from Boeing [3], the family of PW1000 engines from Pratt & Whitney powering a range of aircrafts from Airbus [4], or the CFM56 family from the International Aero Engines [5]. Different variants of designs are represented in these engines where the basic functionality is the same, although different solutions are represented (e.g., the number of vanes, the leaning of the vanes, different support structures in addition to varying manufacturing solutions). Manufacturing alternatives for these types of structural aero-engine components range from casting entire components, to fabricating components from casted sectors, to fully fabricated components composed of sheet metal parts and forgings. Even the welding method varies depending on the material.

First-tier manufacturing companies, such as GKN Aerospace, can gain a competitive advantage by studying earlier designs and understanding their advantages and disadvantages. Through gaining the ability to trade different design concepts with respect to experience from previous models, this knowledge can be used to develop more efficient, reliable, and cost-effective designs in the future.

As new manufacturing alternatives are being developed in combination with an increased need for fuel efficiency, or even new types of fuel systems, there is an increased need for further exploration of novel designs. Although novel solutions may differ substantially from previous designs, they may have a high degree of similarity in specific aspects, such as manufacturing method or even geometrical semblances. This similarity is important to understand, as it provides a link to previous experiences and could potentially reduce the risk in an otherwise novel and uncharted design space.

Together, researchers from GKN and Chalmers University of Technology are developing engineering methods and tools to better conduct advanced design studies. A digital development laboratory environment referred to as the Systems Engineering Design Laboratory, or the "SED Laboratory" has been created, wherein new design support tools are being tested and matured. In the present paper, a tool enabling visual comparison between large sets of design points has been developed and used. The tool has been made open source to enable companies to utilize it, as well as to develop and integrate their own algorithms and features for enhancing design space exploration. The result of this research is information intended to guide conceptual design engineers in evaluating to what extent reference designs can support and guide the early-stage studies of new architectures.

2.0 BACKGROUND

To reduce the risk and cost of developing new products, a common strategy is to utilize a product family approach [6], [7], which seeks to utilize knowledge and other assets from previously developed products. Reusing assets from design has been shown to reduce the lead-time and cost of development [8]. This is commonly referred to as "design reuse" [9]. In the aviation industry maintaining a degree of similarity with already proven-in-flight designs is a common practice, since there is a need to ensure that new designs can *i)* be certified as airworthy, and *ii)* be developed within acceptable timeframes for acceptable costs. This was further highlighted by Schaefer et al., who discussed the issue of remaining within the boundaries of the tested design space to enable "certification by analysis" [10], in which computational tools are used to evaluate compliance with regulatory requirements. Straying too far from the known design space domain entails high levels of uncertainty.

To further reduce the risk and cost, simulations are typically used in the early concept design process to evaluate points in the design space with regard to performance, weight, and cost [11]. Additionally, it has been proposed that manufacturability also be evaluated at this early stage [12], [13], to avoid design trajectories that may result in problematic manufacturing scenarios. The results from such simulations are then often used to train surrogate models. However, both simulations and surrogate models are abstractions, whose capability to represent reality can vary significantly. To mitigate, designers often utilize design margins in the form of safety factors [14] to assert safety, despite uncertainty in results. Additionally, it is common to consult experts, and have them provide a measure of face validity [15]. Such expert opinions are typically qualitative in nature, and are based on experience from previous *similar* scenarios. However, in a recent publication it has been proposed that similarities between new and legacy design scenarios can be quantified [16]. This can potentially provide a quantified basis for validation of analysis results. Furthermore, measuring the similarity between new and previous designs opens an array of other possibilities. It may, for instance, be used to help identify opportunities for reuse of knowledge from previous development endeavours. It can also be used to improve the trustworthiness of evaluations conducted in the early design phase by including data from physical tests, or high-fidelity simulations, from legacy designs.

Contemporary research strives to better the capabilities of early design analysis. Multi-physics evaluation of structures has been present in the designer's toolkit for a long time [17], though trading structural performance against manufacturability is relatively novel. However, we argue that there are still gaps in the early design evaluation toolkit that has the potential to assist design engineers in ushering in a new paradigm of engine designs. One such gap is the evaluation of risks that can emerge as consequences of early design decisions. For instance, the risk of reduced aircraft availability. Aircraft availability is a critical need for airlines [18], and is negatively impacted by mechanical fatigue [19] which necessitates inspections and maintenance. We propose a method to approximate necessary service intervals to an engine component, and to trade such properties against other critical attributes such as structural performance and weight. It utilizes similarity metrics to aid the designer in validating the information, and in learning from previous designs.

3.0 SIMILARITY-BASED PRODUCT FAMILY DESIGN

How to measure and identify similarities between new and previous designs can vary depending on the nature of the data. Within a scale-based product family [6], [20], new designs can be conceived by scaling key design variables up and down. Those key design variables can also be used to measure the similarity between designs within the family. For instance, the Euclidean distance within the design space spanned by those variables can be measured, which would essentially yield a metric of the design space proximity of any two designs within that space.

To assist in the quantification and visualization of similarities, a software tool has been developed, referred to as the "Multi-Disciplinary Analysis Client" (MDAC) [21], depicted in **Figure 1**. MDAC can be used to analyse and visualize the similarities between design points of varying evaluation fidelity (e.g., simulation and surrogate model data), based on the method presented in [16]. This is done by providing the design variables that are necessary to perform the similarity calculation (e.g., the scaled variables in a scale-based product family), together with the results data from analysis and physical tests. This data is annotated with its fidelity. For instance, different levels of data fidelity can include surrogate model data, simulation data, and physical test data. Thus, any given design point can be compared to its closest higher-fidelity representation. The software tool informs the user of how similar the input-data is, and what makes them different. This information can then be used together with experts to provide a basis for decision-making.

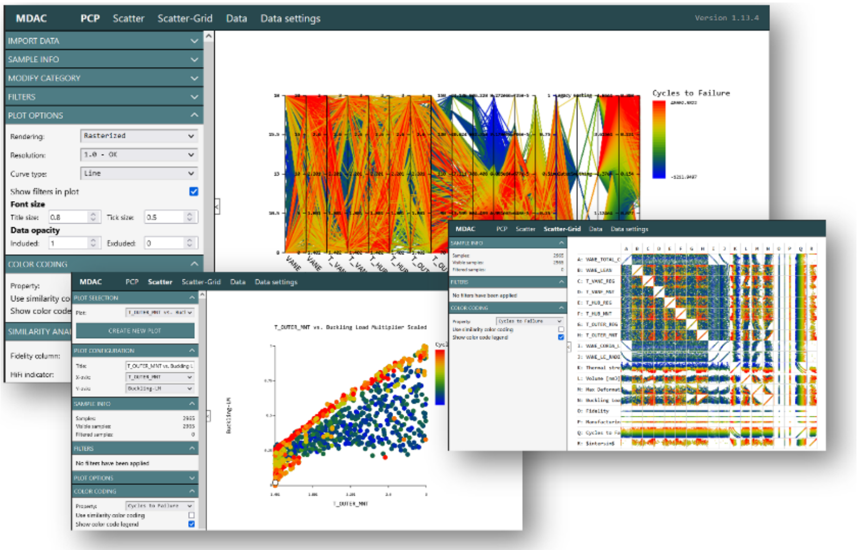

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Figure 1 - Screenshots of the Multi-Disciplinary Analysis Client software MDAC.

In this paper we explore how similarity metrics can be used to assist design engineers in assessing the impact of design decisions on the choice of manufacturing process, and some of the associated risks. MDAC was used to aid in analysing and visualizing similarities, and in performing trade-off studies.

4.0 DESIGN STUDY: TURBINE REAR STRUCTURE

The turbine rear structure (TRS) is located behind the turbine. Its responsible for housing one of the bearings, providing mounting points for the engine to the wing pylon, and deswirling the exhaust from the turbines, which subjects it to high temperatures. Additionally, the TRS needs to be designed with off-design cases, such as fan-blade-out (FBO) scenarios, in mind. This means that it needs to be capable of absorbing radial loads.

The TRS is commonly divided into sectors, where each sector contains a vane. A sector may also contain an engine mount, and is thus referred to as a “mount sector” (MNT-sector). Sectors without an engine mount are referred to as regular sectors (REG-sectors). **Figure 2** depicts a simplified TRS, and some of its sub-components.

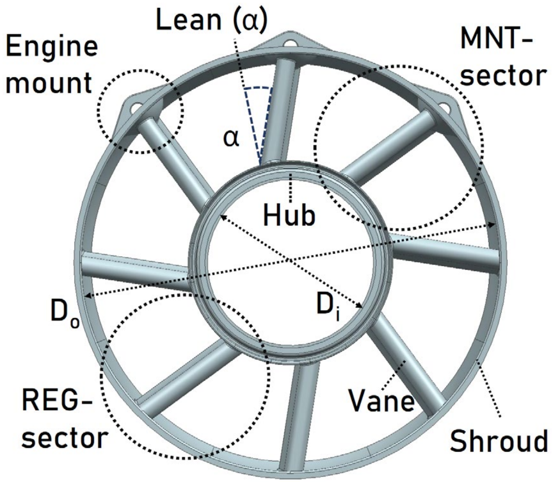

Figure 2 – TRS with some of its sub-components highlighted. Figure repurposed from [16].

The TRS can be considered as a product within a scale-based product family. The outer and inner diameters (D_O and D_i), together with the number of vanes and their lean angle are the key design variables that are varied when initializing the development of a new design. OEM's have established design strategies for alternative engine architectures, for two shaft, three shaft, and geared turbo fan engines. First-tier suppliers have learnt to co-design, optimise, and integrate structural designs and embedded design strategies into the scale-based product family.

4.1 Design study setup

In this scenario, the structural performance of the TRS was evaluated using three separate tests: FBO resilience, lifing, and weight. A total of 500 design variants were generated, out of which 13 failed to mesh, resulting in a sample size of 487 designs. The design variables that were varied in this design study are listed in **Table 1**, which lists 5 different variables. However, the thickness variables were varied such that MNT- and REG-sector wall thicknesses were independent. For instance, the vane wall thickness of the MNT-sectors can be different from the vane wall thickness of the REG-sectors. Thus, the total number of considered variables was 8. Furthermore, the leading edge radius and the chord length of the vanes were adjusted depending on the vane count, to maintain a similar aerodynamic performance for each design variant. In other words, more vanes resulted in a thinner vane cross section and a shorter chord.

Table 1 - Considered design variables

Design variable	**Range**	**Independent mount sector variable**	**Unit**
Vane count	[8, 18]	No	N/A
Vane lean	[0, 20]	No	deg °
Vane wall thickness	[1.5, 4]	Yes	mm
Hub wall thickness	[1.5, 4]	Yes	mm
Shroud wall thickness	[1.5, 4]	Yes	mm

Additionally, for each design variant, three different manufacturing processes were considered: Smithing, casting, and additive manufacturing. Depending on the choice of manufacturing process, the initial crack length was varied to reflect the risk of defects. While such cracks are not necessarily present in all manufactured components, assuming that such a crack exists can be a useful tool in assessing the need for service intervals, which in turn will affect the availability of the aircraft. The assumed initial crack lengths are listed in **Table 2**.

Table 2 – Assumed initial crack lengths for each considered manufacturing process

Manufacturing process	Initial crack length
Additive manufacturing	2.0 mm
Casting	1.5 mm
Smithing	1.0 mm

The FBO resilience was evaluated through applying a load case in ANSYS Mechanical, where each design variant was subjected to a load of 3000 N on the central hub flange, directed towards the engine mounts. Then, the TRS was evaluated with regards to deformation, and buckling.

The lifing was also approximated using a load case in ANSYS Mechanical. A typical high-stress scenario was replicated, heating the vane surfaces up to a degree of 650 °C, while maintaining a temperature of 450 °C in the central hub, and 300 °C in the outer shroud. This causes high thermal stresses to occur, in particular around the edges of the leading edge of the vanes. These stresses were used to calculate the number of flight cycles before a critical crack length is reached. For each design, the three different manufacturing processes were considered, resulting in the evaluation of 1500 different scenarios.

Finally, the weight was approximated by polling the CAD software. This resulted in the following outputs: Weight, deformation due to FBO, FBO buckling margin, expected cycles until failure.

4.2 Design study results

The design space was screened for design points that are of low weight, with a high buckling resilience, and an expected life that exceeds the inspection interval. In this scenario, since it is assumed that a crack exists in each design, the service interval is set to 12,500 cycles before inspection is required. Thus, all design points that were expected to fail before inspection were filtered out. This screening was conducted using the MDAC software, which represented the design space in the form of a parallel coordinates diagram, as shown in **Figure 3**. This allowed filters to be applied to the design space, thus identifying regions in the design space that may be of interest for further development.

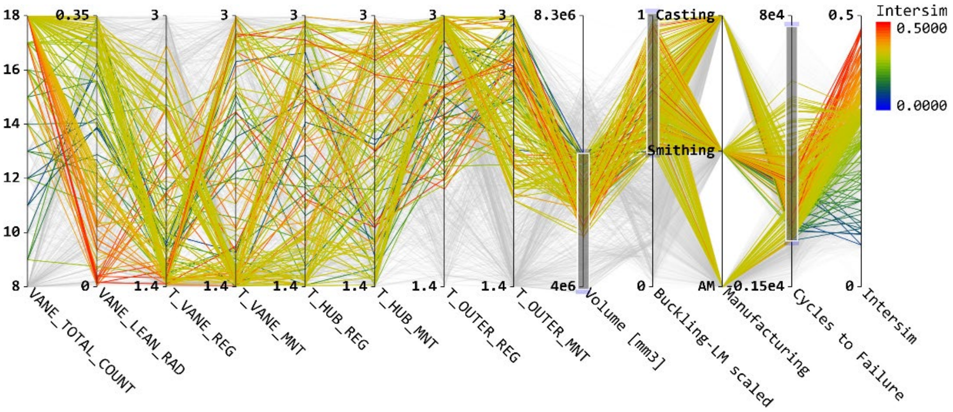

Figure 3 - Screening of design space with respect to similarity ("Intersim") to existing designs. The colour of the lines indicates the degree of similarity to existing designs.

The buckling resilience favours designs with higher vane counts and thicker walls, which is in direct contradiction to the needs of reducing the weight/volume of the structure. The relationship between "cycles to failure" and the design variables is less clear, though the designs which performed best in this regard tended slightly towards having a higher vane lean angle.

Furthermore, a similarity analysis was undertaken. This compared the outer diameter, hub diameter, vane count, and vane lean of each design point to existing designs. A closer resemblance results in a lower inter-similarity (intersim) value. By focusing on the designs that are more similar to existing designs, as seen in **Figure 4**, it was possible to narrow down the viable design space further. This slice of the design space is not only well-performing, but it is also a region that is familiar, and thus potentially of a reduced risk with regards to development lead-times. Furthermore, the design space contains all three manufacturing method alternatives: AM, casting, and smithing. Thus, a choice can be made regarding potentially reduced manufacturing costs, but at the expense of increased inspection intervals.

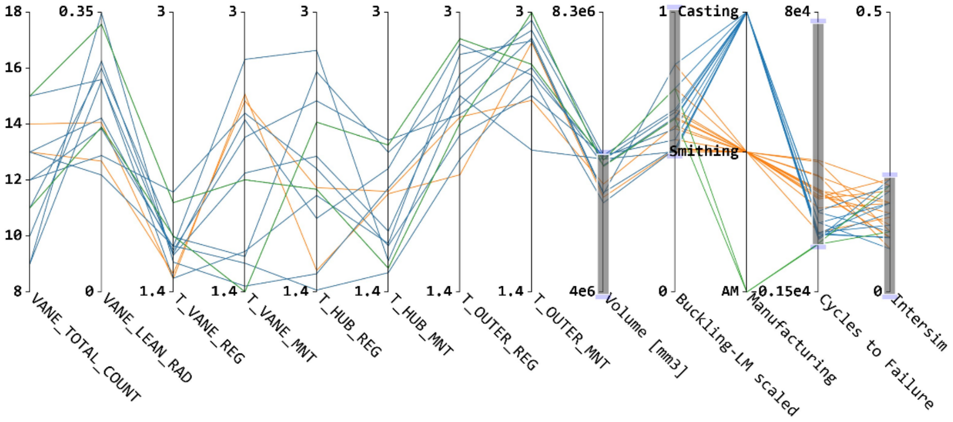

Figure 4 – Design space focused on designs that are similar to already existing designs. The colour of the lines indicates the assumed manufacturing method.

5.0 DISCUSSION

In this study, tool support (MDAC) developed in the SED Laboratory at Chalmers University of Technology, has been used to study alternative engine frame design variants. The novel similarity metric was included together with uncertainty parameters: the risk of needing excessive inspections and maintenance due to the choice of manufacturing procedure, and the structural performance in off-design scenarios such as a fan-blade-out event.

The inclusion of a metric that measures the similarity to existing designs can assist in providing evidence to the often-made claim that a design solution has been "proven in flight", and is thus less of a risk to pursue. Measuring the similarities provides numerical evidence of the potential to leverage existing assets and knowledge. This can be helpful in reducing the risk of introducing novel sustainable technologies and architectural solutions, as will be necessary to achieve the sustainability targets set in contemporary aviation roadmaps.

It should be noted that any analysis made at such an early stage of design will require significant simplifications. The simplifications and idealisations made to enable the evaluation of design variants in the early phases of design makes accurate predictions of, for instance, structural life unreliable for any single analysis. However, for the purpose of comparative and early-phase conceptual design exploration it is sufficient to discover non-trivial correlations, and drive the detailing of concepts. Such insights are valuable to develop robust design strategies.

In future work we intend to validate this method by applying it to novel aero-engine component concepts in an industrial setting. However, the less similar the novel concepts are to existing designs, the more difficult it is to quantify and measure the similarity. It is therefore of interest to involve other aspects of the design in the similarity metric. In this paper, key design variables in a scale-based product family were used to measure the distance in the design space between a new and an existing design. However, there are other aspects that can be considered. Qualitative aspects such as the selection of manufacturing process, the material composition, or even the choice of suppliers, can be included into the similarity analysis. Other quantitative aspects can also be considered, such as the intended operating temperature, or thrust.

6.0 CONCLUSION

The more that can be learned about a design at an early stage, the lower the risk of expensive late changes to the design. This may be more critical now than ever, due to the advent of novel aero-engine concepts, of which experience is very limited. Thus, the development of methods and tools that assists engineers in learning about their designs, and in making informed decisions, is paramount. Additionally, identifying similarities between novel and previous designs can potentially aid in reducing the uncertainties. We have demonstrated how to include a similarity metric in a multidisciplinary design study, and demonstrated how non-trivial insights can contribute to designers understanding of the design space.

A design study was conducted to demonstrate how similarity-based product family design can be used to evaluate the need for service intervals and inspections during a components operational phase. This was done by comparing key design variables of new designs with those of existing designs, and then identifying new designs that were similar, yet high-performing. The similarity metric was thus used in guiding the decision-making process regarding which regions of the design space that could potentially be suitable for further investigation. In addition, it is expected that new designs that are similar to existing designs should have a comparable performance. Thus, the similarity metric can be used to assist in validating analysis results in the early phases, but also in following stages of detailed development. This can assist designers in reducing risks when developing sub-components for novel engine designs.

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