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Assessment of weld manufacturability of alternative jet engine structural components through digital experiments

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1.0 INTRODUCTION

It is expected that aero engine businesses will develop radically new types of propulsion solutions to meet the new sustainability-driven targets [1]–[3]. Consequently, to meet new conditions not previously encountered, both in design and in production, the structural components of the engines will also have to be radically different. For instance, the Open-Rotor engine architectures recently tested in technology development programs [4], will arguably need to mature industrially before being certified and produced. Implications of this are significant for aero engine manufacturers. Production will need to respond accurately and flexibly to provide advanced engine structures to new engine designs. This makes the ability to trade and optimise the balance between functional performance and cost of realising them, critical. Furthermore, the time and accuracy of such investigations is a competitive factor. However, such trade-off studies are extremely challenging, as the range of plausible parameters to vary rapidly increases the size of a typical Design of Experiments (DoE) study beyond what is practical. There is therefore a need to limit the range of variants to explore, which can be done through inclusion of additional constraints in the design space. Such additional constraints could, for instance, be related to downstream processes such as manufacturing or other considerations.

The manufacturability of a component is directly coupled with its design [5]. As a result, the importance of considering manufacturing-related requirements and constraints in the early phases of design of engines and their components is well recognised [6]. However, this is an issue because the information needed to perform manufacturability assessments is typically not available in this phase. In this paper, we present and demonstrate a digital design tool, which is capable of exploring: 1) design variations considering mechanical performance (stiffness and weight of the structure), 2) weld equipment accessibility, and 3) necessary manufacturing considerations which impact geometrical quality.

The method is illustrated using an example of an engine frame. The frame is suggested to be manufactured by assembling parts into a single frame using a robot welding method. Functionality of this design method was first presented and demonstrated at the ICED 2021 conference in Gothenburg, Sweden [7].

2.0 BACKGROUND

Traditionally, approaches such as DFA (Design For Assembly) and DFM (Design For Manufacture) guidelines have been used to assist designers in avoiding problems downstream [8]. However, to evaluate the manufacturability of different design concepts, DFM and DFA are not enough. This need has prompted researchers and practitioners in the industry to employ manufacturing simulations during the design phase, to evaluate the manufacturability of design concepts.

To enable evaluation of the performance and manufacturability of a concept in the early phases of design it is necessary to first define the geometry of the product. However, performing design space exploration often requires large quantities of design configurations to be considered. Creating large sets of geometries manually is not feasible, as it would be highly time-consuming. Thus, a common approach is to generate the models automatically, also known as *generative design* [9]. One of the problems with generating CAD models is the trade-off between flexibility and robustness (discussed briefly in e.g. [10], [11]). Such CAD models utilize constraints to define shapes and features. How these constraints are defined have a significant impact on how flexible the model is with regards to parametric variation. Furthermore, there is also a trade-off between fidelity and flexibility. In the Aerospace industry, it is common to use idealized shell models, which utilize 2D elements to represent 3D geometry [12]. This is done not only to make the analysis faster, but also because it is much easier to vary thicknesses as a thickness in a shell model is merely an attribute of a surface.

Once the geometries have been defined and instantiated it is possible to run simulations on the designs. Once this stage has been reached, yet another trade-off is encountered. High fidelity simulations yield the most accurate results; however, they can be extremely time-consuming. For instance, accurate welding simulations are possible, but are very time-consuming, and can thus only be run on a small sample size. Conversely, low fidelity simulations can be utilized to enable a large sample size, but will not yield the same output accuracy [13], [14]. Thus, it needs to be decided what accuracy is necessary.

These issues have caught the attention of many researchers. Therefore, assessing the manufacturability of a design before it has reached production has been the topic of many academic papers. A few examples are brought to light here. Runnemalm et al. [15], for instance, highlighted the importance of manufacturing simulations during the design phases. The authors also demonstrated how product geometries and FE-models of an appropriate fidelity can be automatically generated, to enable welding simulations using a knowledge-based engineering system. The automatically generated design geometries were shell models, as described in a separate paper [16]. The purpose of the conducted welding simulations was to ease the search for an optimal welding sequence for a set of designs, thus enabling a degree of manufacturability evaluation in the early phases of design. Sandberg et al. [17] proposed a multidisciplinary approach to aero engine structural design. The authors used a master model approach to conduct performance analytics, as well as a basic manufacturing cost assessment based on weight. Madrid et al. [18] proposed a systematic method for identifying correlations between product geometry parameters and weld quality, further concretising the coupling of manufacturability and design. The authors conducted a design study on a static aero engine structure where weld simulations were utilized to evaluate the designs. Of particular relevance to this paper, Landahl et al. [19] proposed a method which includes generating CAD models from a product platform by leveraging CAD parametrisation. The models are then evaluated and optimised with respect to weld assembly. However, the multidisciplinary aspect of combining design and functional requirements, manufacturability, risk assessment, and decision-making was left for others to investigate.

The authors of this paper argue that there is a research gap in performing accessibility simulations simultaneous to other performance simulations, and at the same time also investigating the interdisciplinary trade-offs. While some design choices can favour manufacturability, it is still important to weigh these against operational performance metrics such as weight and stiffness. Moreover, weld simulations have been performed before by multiple researchers, but typically not in large quantities on solid CAD geometries, especially while also evaluating accessibility and operational performance.

3.0 THE DIAS DIGITAL DESIGN EXPERIMENTS METHODOLOGY

The idea behind the DIAS (Development of Interdisciplinary Assessment for manufacturing and design) digital experiments methodology (see Figure 1) is to extend digital experimentation studies of geometrical and topological variants, with non-geometrical and production process alternatives. In Section 4.0 an example is presented of how the methodology can be applied.

Initially, study objectives are determined. For instance, the study objectives can be to maintain certain performance measures while reducing the weight, of an engine component. An EF-M [20] diagram is then created to model how functional requirements are resolved, and how different components interact with each other. A Design Structure Matrix (DSM) is extracted from the EF-M tree to facilitate analysis on an architectural level. It should be noted here that additional assessment at the architectural level is possible and has been demonstrated in earlier work [7], where quantified risk was evaluated using the DSM together with change propagation simulations [21]. In parallel, what design and process parameters are to be varied in the design study are identified. For instance, these parameters may alter different geometric thicknesses, or impact the manufacturing operation lists. Once the objectives and parameter ranges are established, a DoE is initiated.

To enable flexible automated 3D-model representations of multiple parameter ranges, User Defined Features (UDFs) are used. The usage of UDFs enables modular generation of the CAD model, such that sections of the geometry can be instantiated independently from other sections, thereby increasing the modelling flexibility. The UDFs are thus first modelled manually and are then instantiated into CAD models automatically using a software written in Python, and built using Siemens NX programming interface NXOpen. Once the UDFs are defined, the software is used to generate 3D models of all variants listed in the DoE. The software requires two inputs: the predefined UDFs, and an Excel-spreadsheet containing the DoE with all design parameters that need to be varied. The software outputs two different formats for each 3D model: one *.prt-model* (Siemens proprietary CAD format), and one *.jt-model* which is a format favoured by the IPS software.

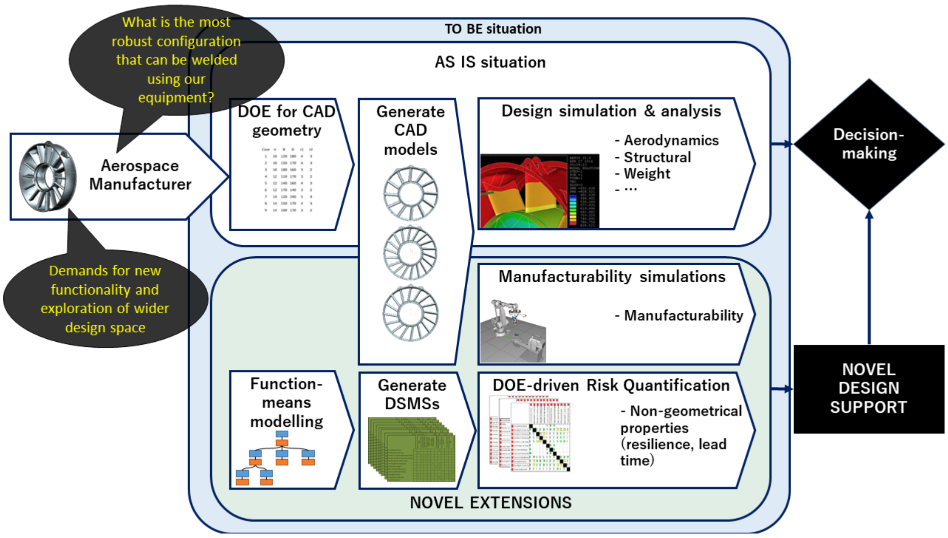

Figure 1 The DIAS digital experiments methodology.

Once all the geometries have been generated, the simulations are initiated. ANSYS Mechanical is used to analyse the structural integrity of the components. At the same time, IPS is used to test weld manufacturability for each component. The results from these studies are stored in a spreadsheet, together with the input parameters.

4.0 DESIGN STUDY: TURBINE REAR STRUCTURE

To test the methodology described in this paper, a design study was conducted for a Turbine Rear Structure (TRS). A TRS (see Figure 2) is an aero engine component with multiple functions. At its core, it houses a turbine bearing. The engine mounts on the top are used to attach the engine to the wings of the aircraft, and the vanes are used to reduce the turbulence of the exhaust gas. It is desirable for the TRS to be of as low weight as possible, but it also needs to be capable of handling the radial forces and torque, which it is subject to. To explore possible design variants, a design study was conducted.

Figure 2 The geometry of a Turbine Rear Structure (TRS).

4.1 Evaluation procedure

As described in Section 3.0 the DIAS digital design experiments methodology considers multiple design parameters, including:

- *vane count*
- *vane lean*
- *vane thickness*
- *vane corda length*
- *weld line positioning*
- *outer case diameter*
- *outer case thickness*
- *hub diameter*
- *hub thickness*

As previously mentioned, for the evaluation, both performance and manufacturability aspects were considered. From a performance perspective, weight and stiffness were analysed. The weight of the structure was extracted using NXOpen after the model was generated, based on the volume of the component and the selected material. The stiffness was analysed by applying a static structural load case to the TRS using ANSYS Mechanical. The load was distributed along the central hub flange, and directed towards the middle engine mount, as depicted in Figure 3.

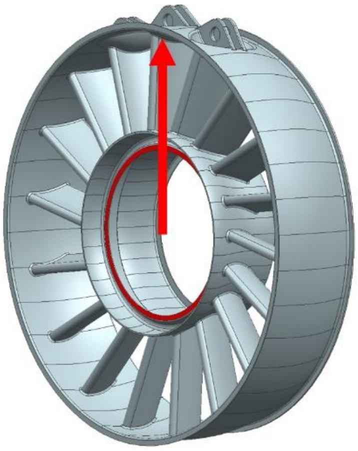

Figure 3 Static structural load case. A force is applied to the hub flange, directed towards the central engine mount.

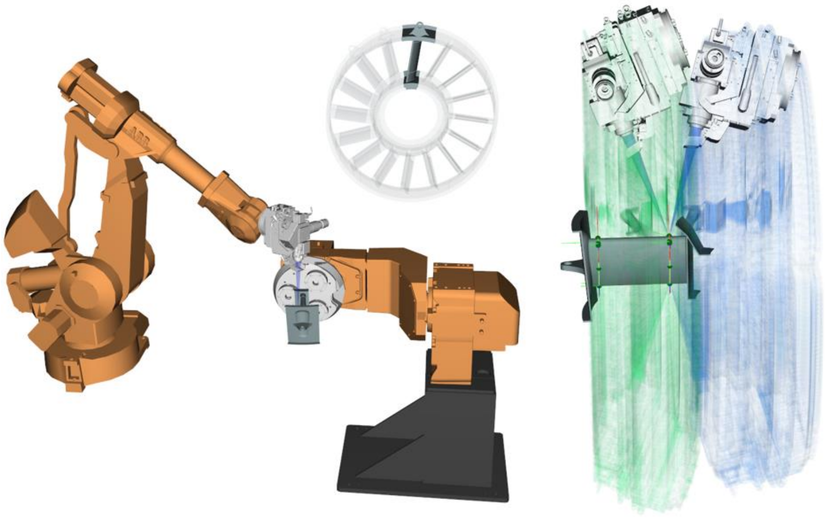

Figure 4 Screenshots from the IPS-software performing a weld simulation.

In the context of manufacturability, weld time and weld tool accessibility were evaluated using the IPS software (see Figure 4). Each design variant was automatically checked for collision-free reachability of the weld tool, and an estimated cycle time was calculated.

Once the simulations had concluded, the results were analysed using parallel coordinates diagrams, in which the design parameters were also plotted out. This enables certain aspects of performance to be linked to specific regions of design space.

4.2 Results

A Latin Hypercube [22] DoE with 108 combinations was executed. The synthetic dataset shown using parallel coordinates [23], [24] in Figure 5, displays how the different design parameters relate to the performance and manufacturing indicators: *maximum deformation*, *volume*, *weld accessibility*, *weld time*, and *total weld time*. In this scenario, “weld time” and “total weld time” differs in that the former is for a single TRS sector, while the latter accounts for all weld lines on the TRS. From the analysis it was identified which combinations of geometric characteristics that generally produce infeasible welds. This means that certain regions of the design space could be eliminated from further and more detailed studies. It was concluded that when a low number of vanes are combined with a high vane lean angle, infeasible welds are produced.

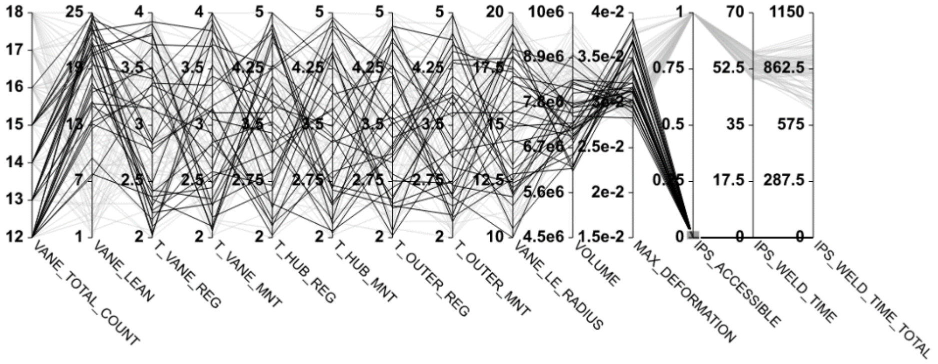

Figure 5 Identification of infeasible weld accessibility. Black lines represent infeasible designs.

To increase the fidelity of the study, and investigate the design space in greater detail, two alterations were made. Firstly, an additional geometric parameter was introduced: corda length (see l_{corda} in Figure 6). This allowed for further investigation of the trade-off between functional performance and the impacting alternatives for welding solutions. Secondly, to maintain the aero blockage area of the TRS (see Figure 7), the vane leading edge radius (see r_{le} in Figure 6) was reconfigured to ensure that the blockage area for all configurations could be set to a determined value. This was done by making the vane leading edge radius proportional to the number of vanes. Thus, all generated TRS designs were configured to have the same aero blockage area. This is important to ensure that the engine performs as intended. However, it also impacts the stiffness of the structure and the geometry of the weld lines.

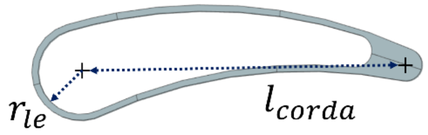

Figure 6 Cross section of a TRS vane. The design parameters *Corda length (l_{corda})* and *Vane leading edge radius (r_{le})* are on display.

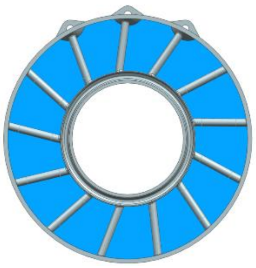

Figure 7 TRS Seen from the front. The blue area shows where exhaust can pass through. The area blocked by the vanes is referred to as the *aero blockage area*. It can be adjusted by altering the vane leading-edge radius.

With the previously mentioned changes in place, a new DoE was initiated with 111 different configurations. The results from the analysis can be seen in Figure 8. To extract potential design candidates, two constraints were imposed: 1) the weld lines needed to be accessible to the weld robot, and 2) a stiffness requirement, which ensured that the maximum deformation was beneath a certain threshold. Design configurations that were unable to meet the required stiffness and accessibility requirements were filtered out. From the remaining designs, the three configurations with the lowest weight were extracted by constraining the allowed design volume. These designs have also been marked in Figure 9, which depicts the trade-off between volume (weight) and total weld time. These three designs appear to perform as required, while also being manufacturable, in this first-order analysis. Thus, all three of them can be considered as candidate designs for further evaluation and development.

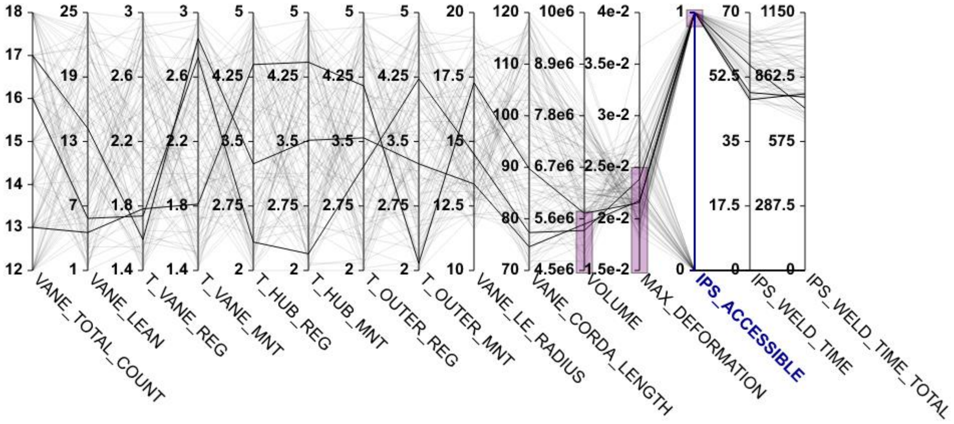

Figure 8 Identification of promising design candidates (dark lines).

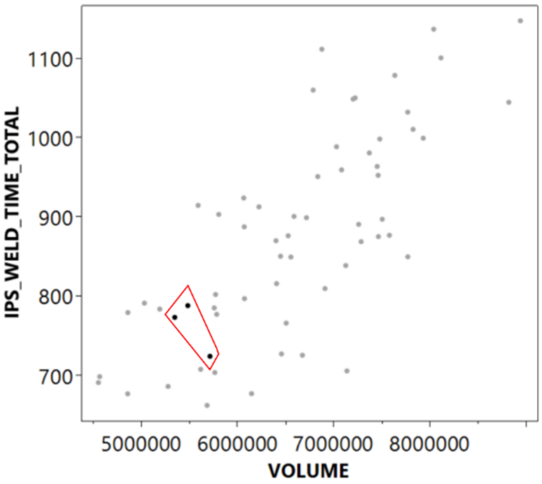

Figure 9 Scatterplot displaying the three selected design concepts in relation to volume and total weld time.

The results show the ability to perform trade-off analysis with manufacturability, design, and performance. However, the influence of weld time is most likely underestimated, as a constant weld speed is assumed, and the impact of weld behaviour is not considered. Consequently, it is clear that these aspects of the method need to be improved to increase the reliability of the results.

5.0 TOWARDS INTEGRATING WELD PROCESS PERFORMANCE

All welding is expected to distort the welded assembly, the magnitude of which depends on the design concepts. As previously mentioned, to evaluate a given concept with respect to distortion, welding simulations need to be set up. However, transient simulations of the complete thermal-, microstructural-, and structural history are computationally heavy and usually take several hours to perform. Therefore, a sequential process is suggested:

1. All design concepts from the DoE are evaluated using the fast Steady state-Convex hull-Volumetric shrinkage-method (SCV method) [13]. The SCV method is an approximation of a transient simulation and may not be as accurate as a transient simulation.
2. The most interesting concepts from Step 1 are evaluated using a full transient simulation to secure accuracy.

The heat applied during welding leads to grain growth and geometric deformations in the case of metallic materials. To capture all these physical phenomena, transient simulations of the complete thermal-, microstructural-, and structural history are performed. However, the thermal-, microstructural-, and structural dynamics are typically assumed to be weakly coupled. Therefore, within one time-step, the thermal field is first updated, and based on this update, the microstructure is updated. Lastly, based on the previous steps, the structural state is updated. Those calculations are done for several time steps along the weld path. This procedure is simplified in the SCV method, which consists of three main steps:

Step 1 - Steady-state simulation: In this step, the steady-state temperature distribution around the weld path during welding is obtained. This approximation is valid for straight weld paths with constant surrounding geometry. If those assumptions are not fulfilled, a transient heat simulation should be conducted.

Step 2 – Convex hull calculation: In this step, multiple cross-sections along the weld path are defined. Each cross-section plane has the weld path as normal. Nodes close to the weld path are projected to the closest cross-section, and the position in relation to the weld path is recorded for all nodes above the melt temperature. Based on these coordinates the smallest convex hull enclosing all projected coordinates of the melted nodes is constructed (several convex hull approximations can be used to increase accuracy).

Step 3 – Volumetric shrinkage: Here, the convex hull defining the melted zone in Step 2 is applied along the weld path. For all nodes inside the melted zone, a temperature is applied corresponding to the melting and when the weld cools down, the resulting thermal shrinkage approximates the weld-induced deformation.

The SCV method approximates the weld deformation in a fraction of the computation time required for a full transient simulation.

6.0 DISCUSSION AND CONCLUSION

There is a need for assessing manufacturability in the early phases of aero engine structure design. In this paper, a method was proposed for evaluating the design space with regards to manufacturability. In an example design study, solid CAD geometries were generated based on a DoE, and were then used in both performance indicating and manufacturability simulations. This enabled trade-offs between manufacturability and performance to be identified and evaluated. It was shown that manufacturability and performance can be assessed, even during the early phases of design. However, it is evident that there is also a need to run welding simulations to assert that the assembly is feasible. Thus, in future works, the authors of this paper aim to include two stages of welding simulations: one low-fidelity simulation that is run on all concepts, and one high-fidelity simulation that is run on the most promising candidates.

It is recognized by the authors that running full analysis on all generated designs within the design space is too resource intensive. Therefore, the authors propose strategically eliminating regions of the design space sequentially as knowledge is gained. Multiple designs can be eliminated already after the first weight calculation. Further design configurations can then be eliminated both after analysing stiffness and weld accessibility. The progress would, as a result, take on a set-based concurrent engineering approach, where the design space is narrowed down based on the requirements voiced by the various stakeholders and disciplines.

Furthermore, in future works, the utilisation of machine learning algorithms will be investigated. Machine learning provides an opportunity to not only accelerate the process, but also enhance the gained knowledge, and more accurately identify the regions of the design-space that require higher fidelity analysis. The next step is thus to investigate support for efficient weld assessment using welding simulations and machine learning [25], [26].

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