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Multidisciplinary design space exploration: An electric fan thruster component design use case

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Abstract

The aerospace industry strives to explore new and, for the commercial aircraft industry, novel technology such as hydrogen, hybrid and fully electrical propulsion systems. Hence there is an increased need for engineering processes that can explore new and novel designs in an efficient way. This paper reports on work accomplished in one of the use cases in a European research project, Design Exploration Framework using AI for Notional Engines (DEFAINE). The project is in its third and final year and result from previous work has been reported in the ICAS conference in Stockholm 2022. A design space exploration process at GKN Aerospace Engines (GKN AE) is described in a generic form with the phases, "Set up study", "create context models", "prepare for analysis", "run analysis" and "evaluate results". Different disciplines operates in the phases performing specific task for that area. The effect of the methods and tools developed in the project are demonstrated on a use case targeting Key Performance Indicators (KPI:s) defined by the industry partners included in the project. Here, the prioritized KPI:s include "design space dimensionality", "Lead-time for design update", "Design point quality" and "Design space sampling quality". The use case describes a novel electric aircraft engine with a ducted fan under development at GKN AE. The Design Space Exploration (DSE) study include objectives and analysis from several disciplines, e.g. computational Fluid dynamical (CFD), acoustics, Strength & Fatigue and producibility that drives cost estimation. The study objective is to investigate the preferred number of vanes or the trade between weight, cost and performance. To improve the KPI "design space dimensionality", a highly parametrized CAD model has been developed with the ability to include configurational changes in a Design Space Exploration study such as different types of vane fitting solutions and hub designs with an optional stiffness wall. Design automation and parametrization is enabled by applying Knowledge Based Engineering techniques targeting the KPI "Lead-time for design update". In order to perform a more relevant DSE study on a component level there is a need to provide appropriate boundary conditions for the component model. This need is satisfied by including a whole engine model. The whole engine model (WEM) is represented in three different contexts; Value Driven Whole Engine Model, Whole Engine Mechanical Model, as well as a CFD Whole Engine model, where attaching geometry of the component of interest is included to better understand the impact of the design variants. As the number of Fan Outlet Guide Vanes are changed, the position of the interfacing flanges moves and the boundary conditions change. Hence the requirement to have a WEM to supply the updated boundary conditions. The increased number of designs studied generates a vast amount of data that are analysed and managed using AI technologies. The paper concludes that the developed methods and tools within the DEFAINE framework has improved our capability to perform DSE and the results are described with reference to defined KPI:s.

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1. Introduction

This paper describes an approach for multidisciplinary set based design within an aerospace research project DEFAINE [1]. DEFAINE is an ITEA [2] project in collaboration between the aerospace manufacturing industry, software providers and academia. The use case at GKN aerospace is run in collaboration with other projects to enable realistic requirements and integrate novel CAE technologies in the Design Space Exploration framework. The Electric Fan Thruster (EleFanT) project studies the aerodynamic design, performance, noise, structural design and manufacturing technology for a ducted fan powered by electricity, either from batteries, hydrogen fuel cells or even more conventional hybrid propulsion solutions [3].

The aim of the Multidisciplinary Design Space Exploration approach is to;

- Reduce the number of iterations conducted in a Product Development project.
- Increase the number of design variants studied.

This is expected to provide more innovative and cost efficient solutions as a larger design space is covered within a shorter time span compared to conventional/traditional PD projects.
The approach is demonstrated by an industrial use case within one of the participating companies and includes a scenario where requirements are represented as a set of ranges instead of discrete numbers. These set of ranges represents a requirement space where every unique instance of requirement can have a number of possible solutions as well as an “optimal” solution.

1.1 Objective

It is evident that in order to perform a more relevant DSE study on a component level there is a need to understand the impact and aspects on an engine level, hence a whole engine model has been included. A whole engine model (WEM) is represented in three different contexts; Model Based System Engineering, Whole Engine Mechanical Model as well as a CFD Whole Engine model where attaching geometry of the component of interest is included to better understand the impact of the design variants.
The objective is to report on work accomplished in one of the use cases in a European research project, DEFAINE.

2. Frame of Reference

This paper focuses on the following engineering disciplines, Set Based and Multidisciplinary Design, Computational fluid dynamics (CFD), Solid Mechanics and Value assessment.

2.1 Set Based and Multidisciplinary Design

Set Based Design (SBD) and Multidisciplinary Design are both important paradigms in the field of engineering design. Set based design emphasize the importance of working with larger number of solutions instead of focus a single point in the design space [4] [5]. Touch et. al. performed a review of Set Based Design in order to discover and analyse the key aspects to consider when developing a model and methodology to transition to Set Based Concurrent Engineering [6]. The review provides a theoretical explanation of Set Based Design in comparison to “point based design”. The authors find that SBD has a relatively low theoretical development, but there is a steady increase in the diversity of contributions. Al Handawi et al. demonstrates a set based approach for managing changing requirements while performing optimisation tasks in the early stages of product development [7]. The work described in this publication provides an example where the SBD approach is applied when designing an aircraft engine component.
Multidisciplinary design involves several different engineering areas, methods and tools working together in a heterogeneous environment. Benaouali et al. describes a fully automated framework dedicated to the high-fidelity multidisciplinary design optimization of aircraft wings [8]. Their design framework integrates a set of popular commercial software, using their programming/scripting capabilities. The framework goes through geometric modelling in SIEMENS NX, aerodynamic meshing in ICEM CFD, flow solution using ANSYS FLUENT, structural finite element modeling in MSC.PATRAN and structural sizing in MSC.NASTRAN. Bussemaker, et al., explains the need for realistic engineering benchmark problems for the development of optimization algorithms to solve black-box, hierarchical, mixed-discrete, multi-objective architectures within Aircraft Jet Engine system domain [9]. The authors present such an aircraft engine domain benchmark problem that is based on the open-source simulation tools pyCycle and OpenMDAO. The benchmark problem is validated by comparing with pyCycle example cases and existing engine performance data. The performance of the benchmark problem is demonstrated using both a simple and a realistic problem formulation, solved using the multi-objective NSGA-II algorithm. The work in DEFAINE aims to contribute to additional example cases and the subsequent evaluation of surrogate models.

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2.2 Computational Fluid Dynamics

The aerodynamic functionality of the fan outlet guide vanes in an electric fan is the same as for a conventional turbofan engine, that is, to align the flow in the axial direction. The challenge is to ensure that the flow is turned in the axial direction without flow separation for a wide range of operating conditions. For a nominal flight, the electric fan will be operating closest to stall during take-off, and furthest away from stall during the cruise segment. The point where the fan is operating at, along a speedline, for a given flight condition, could be regulated using variable outlet nozzle geometry, but here it is assumed that the outlet nozzle area is fixed for a low weight - low complexity solution.

Aerodynamic performance is predicted using a computational fluid dynamics (CFD) tool, where the level of fidelity can be selected by the engineer. Low fidelity simulations can be used to rapidly evaluate different concepts in an early design phase, while a high fidelity solution is likely needed at a late design phase to verify performance for a wide range of conditions. In an early design phase of a fan system, a single fan blade and fan outlet guide vane are typically modelled, using a periodic boundary condition to account for the complete 360° annulus [10] [11]. At a later design stage, to account for more engine realistic flow conditions, a full annulus simulation can be considered to evaluate the impact of flow distortion [12] on fan performance, something that is computationally expensive but can be done as part of design using theLOOP framework described in Section 3.3.6 of this paper. To enhance CFD capability as part of DEFAINE, ANSYS CFX is integrated as part of theLOOP framework. This gives the aero designer more options in terms of what type of computational models to run, and is also expected to reduce computational time as the ANSYS CFX solver is faster than the existing CFD solver used by the framework.

2.3 Solid Mechanics

The structural response of the fan outlet guide vanes (FOGV) to variation in many parameters including sweep, lean and count are studied. To improve the fidelity of the responses, the Whole Engine Mechanical Model (WEMM) is used to provide appropriate boundary conditions for the FOGV design study. This is in line with one of the KPIs of DEFAINE, namely, “Design space sampling quality”. The structural aspects of all major components (including electric) are captured. Stator components in WEMMs are usually modelled with solid elements or shell elements. Solid elements result in increased model size. Shell elements require mid-surface geometry and book keeping of model thicknesses. Both activities are increased effort. To overcome this difficulty, in the current study, solid-shell elements have been used to mesh thin sheet like regions. The hybrid WEMM model generated with solid-shell and solid elements can be used to run a large number of load cases, for a large number of designs while maintaining good fidelity.

Whole engine mechanical models (WEMM) are built for many purposes and the models built would vary accordingly. E.g. the model could be that of an engine operating normally [13], undergoing a blade out event [14], [15] or experiencing windmilling [16], [17] after failure and shutdown. An important quantity of interest from the solution of these models is component interface loads [13]. These loads are used in the design and sizing of the engine components. Another important quantity is the clearance [18], [19] between rotor and stator at various locations in the engine. The clearance is an indication of the performance efficiency of the engine. In this study clearances are not studied. Of late, due to sustainability reasons, electric power in aviation has started gaining attention. Aircraft could be all-electric [18], [20], [21] or hybrid [22]. The FOGV in this study is part of an all-electric engine. During the conceptual design phase multidisciplinary design optimization (MDO) [23] is commonly used to frontload the design process. MDO studies related to electric engines [24] are different from those of pure combustion engines, since the design parameters are quite different.

2.4 Value modelling

Studies within aerospace [25], space [26] and construction equipment [27] observed how functional requirements (e.g., thrust) often represent the concerns of external stakeholders (such as airlines), who typically have expectations of the product once in use. Internal stakeholders such as company owners and top management have also specific expectations, usually related to cost, risk of development, strategy and production. Internal stakeholder needs are often leading to ‘non-functional requirements’ or ‘ilities’, which are difficult to capture and explicitly expressed (compared to functional requirements and unit cost). As a result, non-functional requirements and ‘ilities’ are often considered in later phases of the project, which leads to technical solutions that are costlier for the manufacturers, as well as prone to scheduling delays [28].

The need to trade functional and non-functional requirements simultaneously has resulted in a number of methodological approaches. Tradespace exploration (TE; [29]) models such characteristics as the utility of a system-aggregated adopting multi-attribute utility theory [30] against lifecycle costs. In TE, design options are assessed in terms of utility and lifecycle costs, which also allow us to compare alternatives in terms of ‘ilities’ (e.g., flexibility,

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changeability and scalability). Value-driven design (VDD), [31] stresses the benefit of aggregating lifecycle costs and utility within the same monetary metric of value, because it provides a practical and convenient means to compare alternatives on targeted business cases. At the same time, VDD recognized the difficulty of computing such a metric since many industry structures are complex, with competing customers, competing manufacturers, and competing lower-tier suppliers. For these reasons, VDD proposed the use of a financial metric-surplus value (SV) [28] to provide a simplified equation to a net present value analysis (NPV) [32], typically used by economists a basis for businesses investment decisions.

2.5 Surrogate Methods

Design space exploration (DSE) refers to the activity of exploration and investigating design alternatives prior to system implementation. This is used for rapid prototyping, optimization and system integration [33]. In rapid prototyping, DSE helps to generate several prototypes before the system implementation. By simulating these prototypes, engineers can increase the understanding of the impact of design decisions. In optimization, DSE can be used for optimization by eliminating the lower quality designs and selecting a set of design candidates for further analysis. The elimination is done by comparing one design to another using predefined metrics, for instance, design requirements. In system integration, DSE can be used to find legal assembles and configurations that satisfy all global design constraints for the integration of multiple components into a working whole system.
The exploration of design space increases the engineer's understanding of the design problem [34]. The exploration must be done carefully due to a large number of design alternatives. A large system may have millions, if not billions of design alternatives, and it may have infinite alternatives for some design problems [33]. In addition, a larger complex system also has a larger number of design constraints that must be satisfied by every valid design alternative or solution. Furthermore, the analysis of these design alternatives includes higher computational costs. This is where surrogate modelling can play an important role to explore many design alternatives without the need of time computational simulations for analysis.

Table 1 gives a comprehensive overview and lists example publications describing state-of-the-art methods for surrogate model generation including the methods capabilities and limitations.

References	Methods	Capabilities	Limitations or notes to consider.
[35] [36] [37] [38] [39]	Polynomial response surfaces and linear regression.	(1) For problems that are not high-dimensional, display low modality (or unimodality), or where data are relatively inexpensive to compute, the use of polynomial surrogates may be an attractive (and correct) choice. (2) It can only applied to regression tasks. (3) Recommended when the sample size is low.	Polynomial surrogates remain generally not well suited for the nonlinear, multidimensional problems. (2) Multivariate polynomial method is not sensitive to the change of the sample size.
[35] [40] [37] [38] [39] [41]	Kriging (universal Kriging, ordinary Kriging, and simple Kriging)	(1) Widely used methods for building surrogate models due to its better performance. (2) Effectively represent highly nonlinear and multidimensional functions. (3) the use of Kriging method is not trivial to construct surrogate models due to its global optimization process.	Important feature of Kriging is the selection of a suitable covariance function, hence, more knowledge is needed. (2) Kriging method is the can perform well when the sample size is high.
[35] [42] [37] [38] [43]	Radial basis functions	Recommended when the data has high-order non-linearity.	There is no firm conclusion in the literature that show whether RBF are better than the others.
[35] [44] [37]	Support vector regression	It can handle both continuous and categorical data. SVR able to approximate more complex landscapes because of its kernels.	
[35] [45]	Artificial neural networks (multilayer perceptron, multilayer feedforward neural network) neural network	Well known approach for constructing simple and fast approximations of complex computer codes.	Encoding is needed for categorical data. For very complex models. Requires a lot of data. Large amount of trail-and-error associated with the use of this technique.

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[35] [43] [46] [47]	Decision trees and random forests	(1) Can handle all types of data. (2) Shown better for non-linear, high-dimensional and small size of samples. (3) Can provide information (if-then rules) to able to explain model prediction reasoning.	
[38]	Bayesian networks	Can be applied for both continuous and categorical data. Recommended when the noise in data is high.	Determines class based on probability.
[39] [43]	MARS	(1) Shown better for the data with linear relationship, but could also be used for non-linear data as it created splines in design space. (2). The major advantages of using the MARS is to be accuracy and major reduction in computational cost associated with constructing the met model.	Only applied for regression tasks.
[35] [48] [49] [50]	SVD	It can used for solving problems in structural optimization, multiple regression (surrogate modelling/interpolation), and dimensionality reduction	Only applied for regression tasks

Table 1: Methods for surrogate modelling

3. Design Space Exploration of an Fan Outlet Guide Vane assembly

The design of a Fan Outlet Guide Vane (FOGV) assembly serves as a use case for the development of methods in the research project DEFAINE. This chapter presents the design study performed and the results from the benchmark tests with respect to KPI:s.

3.1 Design Space Exploration setup

The methods and tools developed in the project are tested in a "use case". The use case is in line with the EleFanT project with the aim to development of a component in an Electric Fan Thruster, a novel solution for more sustainable aviation [3]. For the FOGV assembly, the design objective is to provide a lightweight, high performance and cost efficient solution. This study builds on the work reported in the ICAS conference in Stockholm 2022 [51].
The first study included the following parameters; Forward Lug Thickness, Aft Mount Lug Thickness, Outer Case Thickness, Hub Thickness. In addition, the number of vanes was varied between 24 to 44 where the vanes are scaled. In the first study, the increased number of vanes provided a lighter component, mainly due to that vanes becomes shorter and thinner so that the combined volume of the vanes is decreased. At the same time stiffness is reduced and it was not possible to compensate decreased stiffness by adding more material with the thickness intervals included in this study.
Hence, this second study include more thickness regions in order to enable a weight neutral design solutions for the different number of vanes included in the study. E.g. Hub Wall thicknesses, Outer Case thicknesses, Vane thickness (Including a core). The scope of the second study also includes several types of materials for the vane.

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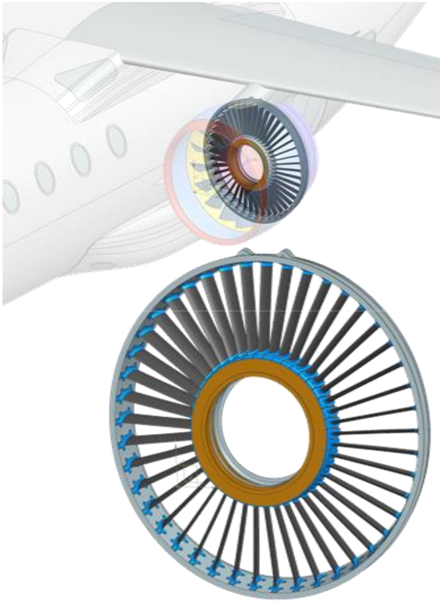
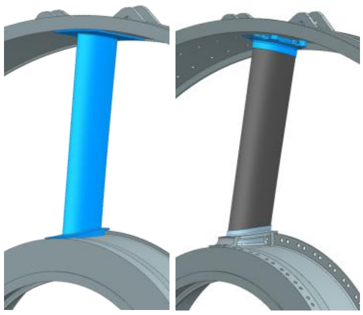
Parameters: Number of FOGV:s

The FOGV assembly described here is located at the rear of the rotating fan. The rotating fan does work on the flow by turning it, and the FOGVs subsequently align the flow in the axial direction. The FOGV assembly also provides a load path from the mount lugs to the core of the engine. The number of vanes is a design variable which can be varied, which has an impact on aerodynamic, aeroacoustic and structural aspects of the fan. To keep the aerodynamic impact low while varying the vane count, a parameter called *solidity* can be kept constant. Solidity is defined as the chord (distance from leading edge to trailing edge) divided by the circumferential distance between two adjacent vanes. If the solidity is increased by increasing the number of blades, while keeping the mass flow and flow turning constant, less mass flow will be turned by each blade - reducing the aerodynamic loading on each individual blade. To keep solidity constant, the chord needs to increase as the number of vanes is decreased. For a 50% reduction in vane count, the blade chord needs to increase by a corresponding 50% to reach the same solidity.



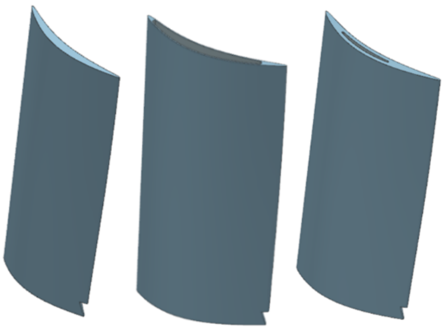
Parameters: Vane Type, Vane Material.

There are two variants of vane configurations. A one piece vane solution with an integrated attachment and a three piece vane configuration where the vane is attached using two fitting features. The one piece vane can be manufactured in metal using Aluminium, Titanium or Steel. The three piece vane can be manufactured using a carbon, aluminium or steel vane together with fittings in Titanium.



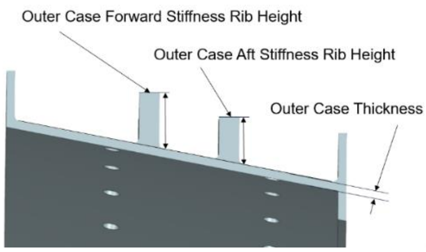
Parameters: Vane max thickness, Vane wall thickness, vane hollowness.

When reducing the number of vanes in the FOGV assembly, the total weight is increased. Mainly due to that vanes become longer and thicker so that the combined volume of the vanes is increased. Hence there is a need to reduce the mass when going for less number of vanes. This can be achieved by making the vane hollow or reduce the vane max thickness. When the vane is hollow the vane wall thickness is a parameter. If the vane configuration is of the three piece type and manufactured of carbon material there is a mid-foam material added.



Parameters: Outer Case Forward and aft Stiffness Rib Height, Outer Case Thickness.

There are three parameters that can be varied independently. By varying the stiffness rib height the structure can be adopted to meet different stiffness and strength requirements.



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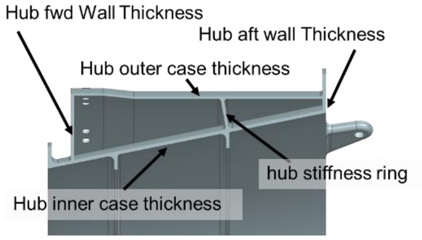
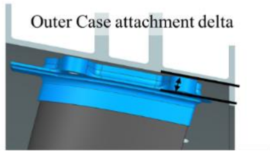
Parameters: Hub fwd Wall Thickness, Hub aft wall Thickness, Hub outer case thickness, Hub inner case thickness, optional hub stiffness ring.

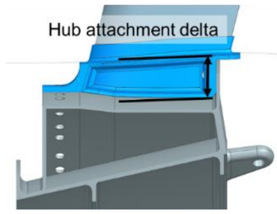
The hub part of the assembly plays an important role of providing a load path from the vane ring and the thrust lugs to the engine core. The hub also provides attachment for the electrical engine and the gearbox.



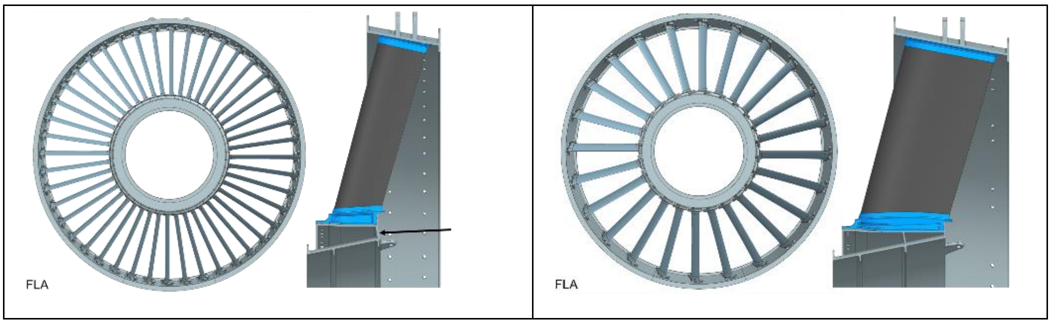
Parameters: HUB attachment delta, Outer Case attachment delta.

The attachment between the vane and outer case or inner hub is realised either with a fitting feature as illustrated in the picture to the right or integrated in the vane as illustrated in the one piece type of vane. Hence the thickness parameter, used here, is a delta parameter that either increase or decrease the thickness in relation to the reference design.





Below are two different vane counts illustrated. 44 Vane Count and 24 vane count.



The 17 parameters are included in a DOE for a Design Space Exploration study. The parameters are a mix of continues real, Nominal discrete and discrete by value, see Table 2. The distribution used is Latin Hypercube and 200 designs.

Name	**Type**	**Kind**	**Range**
Fogv hub aft wall thk	Real	Continuous	1.5:4
Fogv hub attachemnt delta	Real	Continuous	-4:4
Fogv hub fwd wall thk	Real	Continuous	1.5:4
Fogv hub ic thk	Real	Continuous	1.5:4
Fogv hub include stiffner rib	Boolean	Nominal discrete	No;Yes
Fogv hub oc thk	Real	Continuous	1.5:4
Fogv mnt lug ang pos	Real	Continuous	5.0625:10
Fogv oc aft stiff rib height	Real	Continuous	04:29.8
Fogv oc attachemnt delta	Real	Continuous	-4:4
Fogv oc fwd stiff rib height	Real	Continuous	04:29.8
Fogv oc thickness	Real	Continuous	1.5:5
Fogv thrust lug angular pos	Real	Continuous	15.05:34.95
Material	String	Nominal discrete	Alu, Ti64,Steel, Carbon Fibre
Fogv vane t max	Real	Continuous	60:100
Vane thickness	Real	Continuous	1.5:4.99125
Number of fogv	Integer	Discrete by value	24:44

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Use vane core	Boolean	Nominal discrete	No;Yes

Table 2: Parameter data

The models are analysed for aero, acoustic, solid mechanics and manufacturing cost perspectives. By applying an evolutionary optimisation algorithm, new potential designs are identified that meet the requirements with a reduced cost.

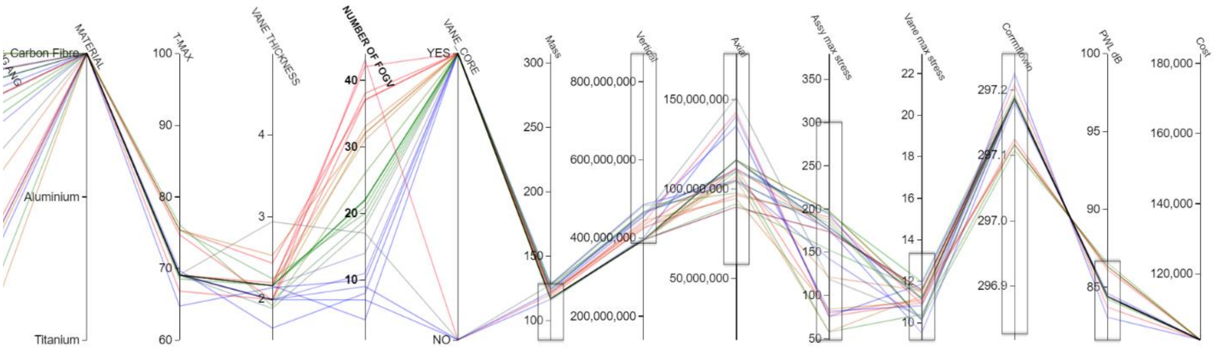

Figure 1: Filtering out new design to include in comming studies.

The new designs are then used in the next design loop to fit/train and verify the results from the surrogate models and act as new reference models where the aim is to further improve the design.

3.2 Benchmark KPI and the process description

The design space exploration process at GKN Aerospace Engines (GKN AE) is described in a generic form with the phases, “prepare design input data”, “create context models”, “prepare for analysis”, “run analysis” and “post processing of the results”.
The baseline process for conducting a DSE on a FOGV is semi-automatic and several steps are executed manually, the process is illustrated in Figure 2.

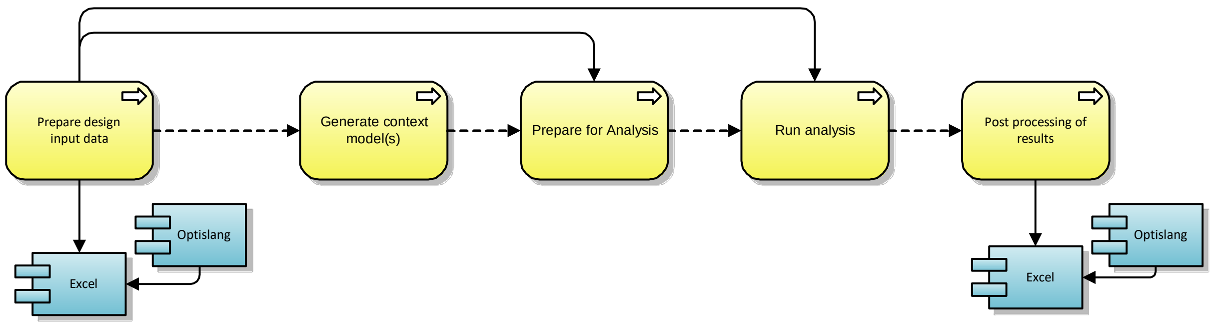

Figure 2: Generic process for a Design Space Exploration Study

Different disciplines operates in the phases performing specific task for that area. The effect of the methods and tools developed in the project are demonstrated on a use case targeting Key Performance Indicators (KPI:s) defined by the industry partners included in the project. Here, the following KPI:s are used to describe improvements; “design space dimensionality”, “Lead-time for design update”, “Design point quality”, “Number of design objectives traded simultaneously” and “Design space sampling quality”.

3.3 Methods developed

To improve the current framework for Multidisciplinary Design Space Exploration several applications has been developed to support the automation of the process and to include additional disciplines in the range of analysis conducted.

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3.3.1 Parametric FOGV Model

To improve the KPI “design space dimensionality”, a highly parametrized cad model has been developed with the ability to include configurational changes such as different types of vane fitting solutions and hub designs with an optional stiffness wall, see chapter 3.1. Design automation and parametrization is enabled by applying Knowledge Based Engineering techniques. One key feature is the aero profile application that imports aero profile data sets and creates the aero profile and surfaces using Knowledge Fusion, the KBE module in Siemens NX, see Figure 3.

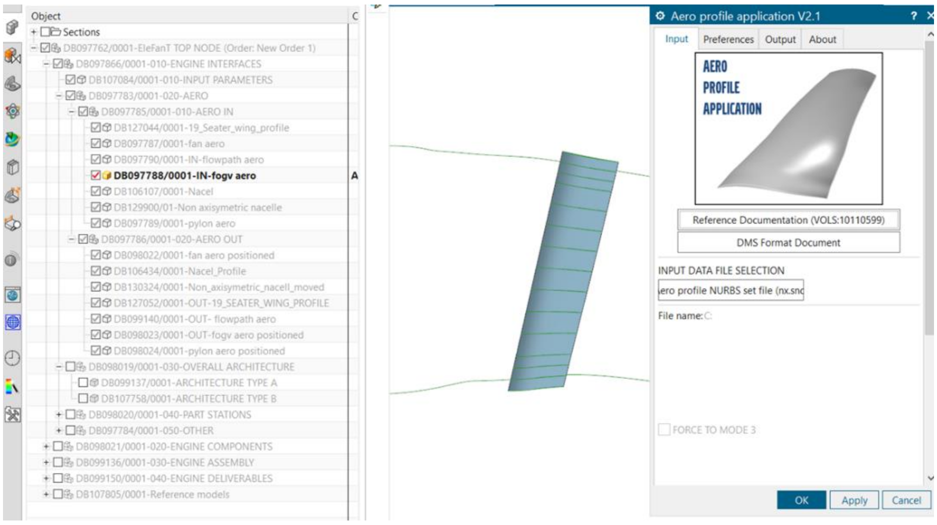

Figure 3: illustrating the aeroprofile application

The aero input is used to create aero surfaces in the CAD assembly and controls key reference points that are used by 2D sketches to build adjacent geometry. E.g. the outer case and the inner hub. The advanced parametrisation support the process of generating new models to be analysed.

The application improves following KPIs;

- *Design space dimensionality*. By increasing the number of parameters and including other types of parameters such as material and configurational variants as one piece vane or three piece vane, and discrete by value such as “Number of FOGV:S”.
- *Lead-time for design update*. The automated advanced parametrisation enables generation of several hundred models in hours instead of days.

3.3.2 Auto tagging application

Metadata is added to the context models to enable and improve functionality for subsequent applications. The process of adding metadata is referred to as “tagging”. Tagging is done by adding “tags” to the geometry. Tags can be added to any part of the geometry, e.g. faces, edges, points, solid bodies, etc.
Each tag consists two coupled variables, one for the name of the tag, and one for the value of the tag. An application to automatically add tags using custom queries has been developed. The queries are used to select specific parts of the geometry based on common properties derived from the geometry. The queries can also access custom attributes in the CAD models making them adaptive rather than constant.

This application improves the following KPIs;

- *Lead-time for design update*. No need to manually add metadata to all models, all the information is stored in the queries. Queries can be re-used between similar geometries.
- *Design point quality*. By tagging the model the mesh can be controlled and refined as needed. This provides higher fidelity on the mesh and analysis results.
- *Design space dimensionality*. The adaptive queries enable us to automate the tagging of larger geometry variations since the query adapts to the attributes in the models.

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3.3.3 CAD autogen application

The “CAD autogen” application is developed to enable automatic generation of CAD model variants. This greatly reduces the time it takes to create a large number of different CAD geometries, making it possible to create more variants in less time compared to the manual process.
Each variant is defined by a number of key design parameters. These key parameters can be anything that alters the geometry in any way, e.g. key dimensions, thicknesses, aero profile and so on. All variants that are to be generated are pre-defined in a DOE, illustrated in Figure 4 where each row is a new variant (design case) and each column is a design parameter.

Name for convenien Type:	DESIGNCASE Number	FOGV_HUB_AFT_WALL_THK Number	FOGV_HUB_ATTACHEMNT_DELTA Number	FOGV_HUB_FWD_WALL_THK Number
Design Case 1	1	4	0	4
Design Case 2	2	2	0	4
Design Case 3	3	3	4	3
Design Case 4	4	4	0	4
Design Case 5	5	1,5	-4	1,5
Design Case 6	6	1,5	-4	1,5

Figure 4. Example DOE for defining geometry variants. Each column represents a design parameter, and each row the values of the parameters for each design.

The application is fully integrated with other in-house developed KBE applications, allowing for more complex geometry variations. In addition the “CAD autogen” application controls the update sequence of the CAD assembly to ensure the structure is updated in the right order.

This application improves the following KPIs;

- *Lead-time for design update*. The application makes it possible to generate more designs in less time.

3.3.4 Club Design

Club design has been further developed to manage the traceability among high level requirements coming from external stakeholders (e.g., airlines) down to lower-level system suppliers. Also, *Club Design* i developed to balance the (often conflicting) needs between the external stakeholders and the internal stakeholders, usually related to cost, risk of development, strategy, and production. In the first loop of the GKN use case, 5 objectives are traded simultaneously defined in Club Design as “Value Drivers” the right part on the table in Figure 5.

Figure 5. Illustrating the *Club Design* interface

They need to be traded since their increase (or decrease) mutually influences high level needs and expectations of the stakeholders. For example, one obvious need from the airlines is to reduce the fuel consumption. Raja et al [52] demonstrated that the design of static structures have a direct impact on the Specific Fuel Consumption, SFC (Fuel Consumption / Kg). This is since the aerodynamic performance is divided into the function to guide the air flow and the drag induced by the vanes. The volume of the vane translates directly to the weight that directly impact SFC. In *Club Design*, the need to decrease fuel consumption by the TRS design is translated as two value drivers “decrease aero blockage” and “decrease Mass”. Value Drivers (VDs) represent engineering characteristics that engineers can control during the design (and they tend to become requirements after the trade-offs are solved). Aero Blockage is a

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coarse metric used in the first loop, yet more refined metrics can be defined. The SFC can also be improved by increasing the stiffness of the structure, since the mass of the FOGV can be kept lower.
However, the value driver of stiffness also influences another stakeholder need. In fact, increasing stiffness can increase stress concentrations in the structure, undermining the reliability and therefore the increasing the need for maintenance and overhaul. Therefore, the value driver to satisfy this need is formulated as “decrease stiffness”. The last value driver defined is the product cost, which the manufacturer has the interest to be keep low. There could be situations in which improving the aero performances of the structure will force the manufacturer to increase the cost (for example, through tighter tolerances, [53]). Therefore, Club Design supports the trade-off among these conflicting attributes. This is done by applying a Surplus Value simulation [54], not shown in the figure above). In Club Design, more needs and Value Drivers can be added and this will be the focus of the next steps of the GKN use cases. Internal stakeholder needs are often leading to ‘non-functional requirements’ or ‘ilities’, e.g. supplier readiness, which are difficult to capture and explicitly expressed. The same is valid for certain “ilities” concerning the external stakeholders as well.

This application improves the following KPIs;

- *Number of design objectives traded simultaneously*. As the application can handle a large number of objectives, here in the form of requirements.

3.3.5 Surrogate Modelling Application

The Surrogate Modelling Application builds on the “Surrogate Modelling Toolbox (SMT)” [55] [56]. An open source python module and has surrogate modelling methods, sampling methods and benchmarking methods. SMT toolbox is used to explore different data types to build models, and the SMT surrogate methods are: Radial basis functions, Inverse-distance weighting, Regularized minimal energy tensor-product splines (RMTS), Least-squares approximation, Second-order polynomial approximation, Kriging, KPLS (kriging model that uses the partial least squares (PLS) method), KPLSK, GEKPLS (gradient-enhanced kriging with partial least squares approach), GENN (Gradient-Enhanced Neural Networks , Marginal Gaussian Process (MGP).
It is observed that there are some machine learning methods that could be added to this toolbox to explore additional surrogate methods. Hence, Sklearn methods are added to this SMT toolbox for the analysis, and they are Gradient Boosting Regressor, ElasticNet, SGD Regressor, support vector regression (SVR), Bayesian Ridge, CatBoost Regressor, Kernel Ridge, Linear Regression, Random Forest, XGB Regressor, and LGBM Regressor.
The idea by adding all methods to one toolbox is that this enhanced toolbox can now handle any type of data. The type of data that one is expected to encounter in the aero engine component design space are numeric (continuous, non-continues), ordinal, and categorical. Having created this enhanced toolbox one could easily investigate the relative performance of various surrogate modelling methods in one framework.

This application improves the following KPIs;

- *Design space sampling quality*. The aim with the work is to identify the best type of response surface for different types of DSE datasets for design exploration in aerospace application. The reason is due to datasets with small sample availability for response surface modelling since simulations are expensive to conduct, and these datasets has high-dimensionality and non-linear relationships.

3.3.6 Automated CFD Evaluation

theLOOP is an in-house framework used to generate DOEs and to streamline communication between different software’s used for aerodynamic design and optimization. After generating a DOE of design variables, theLOOP can be run to automatically generate geometries, structured computational grids, run CFD simulations on a computational cluster as well as post-process and compile the results. The compiled results from a number of design evaluations can subsequently be used by the designer *e.g.* to build a response surface for variable sensitivity analysis or for surrogate model based optimization. The framework is described in more detail in [10] where it was used to optimize a three-stage low-pressure compressor. The framework has been rewritten as part of work in the DEFAINE project [1], to streamline the code and to include the commercial solver ANSYS CFX as an option for CFD evaluation of geometries. This addition gives more options to the aero designer and is expected to reduce computational time for a design evaluation. A wide range of design variables can be altered using the geometry generation tool that is used by theLOOP, including number of blades, leading- and trailing edge blade angles, camber, sweep, lean, chord length and blade thickness.

This application improves the following KPIs;

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- *Lead-time for design update*. No need to manually add metadata to all models, all the information is stored in the queries. Queries can be re-used between similar geometries.
- *Design space dimensionality*. The integration of the in-house framework has increased the design space dimensionality and will enable broader multidisciplinary design space exploration studies.

3.4 Whole Engine Model

There are several different variants whole engine models. E.g. *System Engineering Model*, *Performance Model, Mechanical engineering Model, Computational Fluiddynamics Model*. All these models has the purpose of providing boundary conditions for the component of interest. In this section we briefly describe the EleFanT Whole Engine Mechanical Model and the Whole Engine CFD Model. By developing whole engine models to support the component design, the *Design space sampling quality* KPI is improved, as it provides more realistic boundary conditions and a better understanding of the system as a whole.

3.4.1 EleFanT Whole Engine Mechanical Model

An electric fan thruster (electric ducted fan) is considered as the use case in DEFAINE. The component of interest is the fan frame. The fan frame consists of an array of OGVs (Outlet Guide Vane), supported by an outer ring and a hub. The front mount lugs are on the outer ring. The thrust lugs are on the rear side of the hub. The rear mount lug is on the motor housing. The mount links and the thrust links are connected to the pylon. During engine design the requirements include structural aspects such as stiffness, out-of-roundness, centerline shift, strength and fatigue. In order to study the satisfaction of these requirements for various candidate designs, the boundary conditions applied to the component of interest need to be of reasonable accuracy. It is to obtain these boundary conditions for the fan frame, that the whole engine mechanical model (WEMM) is considered. Depending on the phase in design cycle, some of the structural requirements may not be considered (e.g. fatigue may not be considered during conceptual phase).
The whole engine model needs to capture the stiffness and inertia distribution across the engine with reasonable accuracy. However, this model need not have a very high fidelity so as to predict correct stresses. The main objective of the WEMM is to obtain resultant (not distributed) interface loads accurately; i.e. the load paths and resultant loads need to be captured correctly. With this objective in mind one needs to generate a whole engine finite element model which has as few degrees of freedom as possible, and be generated in the shortest time possible. Since the WEM is part of the multidisciplinary optimization (MDO) framework, the generation of WEMM must preferably be automated. In the current study, a combination of geometry abstraction, geometry splitting, mixed-dimensional meshing, efficient interface connection strategies are used to achieve the interface loads in a very efficient manner. For thin sheet-like regions a solid-shell element is used as opposed to solid or shell elements. This has the efficiency of shell elements without the necessity to keep track of the thicknesses, offsets, etc. This element can naturally be connected to solid elements. It is ensured that the global element size captures the stiffness's correctly. Some difficulties faced are the geometry topology changes due to the change in the number of vanes and change in the location of mount and thrust lugs. The WEM is built in a modular way such that only the portions with changes need be updated. The entire process is generic, modular and independent of the software used.

3.4.2 EleFanT Whole Engine CFD Model

While some aerodynamic design work can be done considering only the internal flow in terms of a fan duct, a fan blade and a fan outlet guide vane, more details need to be included at a later design stage to account for more realistic flow variations during service. Large variations in the capture area ratio (area of the upstream streamtube ingested by the engine relative to the intake area at the nacelle lip) impact the boundary layer growth on the nacelle end walls, and performance for various levels of flow distortion needs to be evaluated to ensure safe operation.

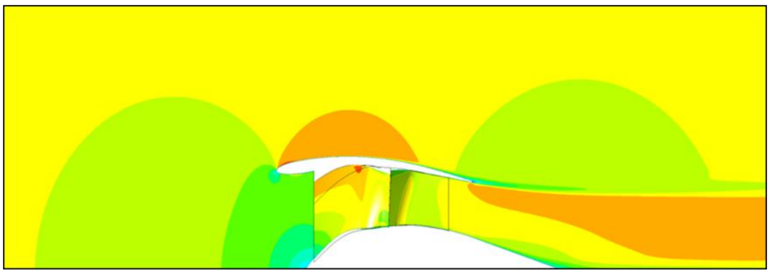

Figure 6: Mach number contours from a CFD simulation of the EleFanT engine

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4. Discussion and conclusion

The paper presents achievements made so far in the DEFAINE project demonstrated in the GKN Aerospace Engines use case, a design space exploration study of an electric fan thruster component. The methods and tools developed are targeting a number of Key Performance Indicators (KPI:s) that are defined by project partners to guide the development and measure progress. The project has entered the final year and more detailed description of achievements and KPI measures are to be reported at the end of the project. The paper include six applications with a brief description of the tool and in what way they improve KPI drivers. For proprietary reasons it is not possible to present resulting designs from the study itself. It is evident that in order to perform a more relevant DSE study on a component level there is a need to understand the impact and aspects on an engine level, hence a whole engine model has been included. Here, the whole engine model (WEM) is represented in different contexts; Value Driven Model, Whole Engine Mechanical Model as well as a CFD Whole Engine model where attaching geometry of the component of interest is included to better understand the impact of the design variants. E.g. as the number of Fan Outlet Guide Vanes are changed, the position of the interfacing flanges moves and the boundary conditions changes. The increased number of designs studied generates a vast amount data that are analysed and managed using AI technologies. Here, a guided approach is needed to choose methods based on response types and the data characteristics to build response surface models for DSE.

The paper conclude that the developed methods and tools within the DEFAINE framework has improved the companies capability to perform DSE and the results is described in reference to defined KPI:s.

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