Multidisciplinary Optimisation of a Turbine Disc in a Virtual Engine Environment

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Abstract
Increasingly strict requirements for engine designs force engine manufactures to improve the engine characteristics. Multidisciplinary optimisation of a turbine disc demonstrates such improvements. Chaining the various design and analysis tools involved into a virtual environment allows automating the design and analysis procedure, a prerequisite for multidisciplinary optimisation. To solve the multi-objective optimisation problem, a Pareto optimum criterion has been used. Even using a limited set of design variables obtained a 19% turbine disc lifing improvement with respect to the original design without weight penalty. By introducing more design variables and additional objectives even more improvements are expected.

1. Introduction

Increasing air travel and growing environmental concerns support the European vision[1] for sustainable air transport. This translates into more strict requirements for new engine designs. Such requirements relate to reduction of emissions (like 80% reduction in nitrogen oxide and 50% reduction of perceived noise[1]), increase of the fuel economy (e.g. a 50% cut in fuel consumption per passenger kilometre contributing to a 50% reduction of carbon dioxide emission[1], the latter also relevant with respect to the European Union environmental policy[2]) and improvement of the reliability (for instance 99% of the flights on-time, resulting in amongst others more strict lifing requirements[1]). To comply with these requirements it is imperative to improve the engine characteristics. On top of these challenges, world-wide competition necessitates a reduction of the time-to-market for new engine designs. Accommodating these challenges motivates a move towards innovative concepts like the virtual engine. Such a virtual engine comprises the accurate simulation of the engine design to accurately determine its relevant key performance characteristics.

To address the characteristics of a whole engine design, simulation software tools like GSP[3] and PROOSIS[4] are available. Based on such virtual engine designs, the design objectives for its components can be derived. The high pressure turbine disc is a critical component due to the high temperatures and pressures it is subjected to. Affordability requirements and on-time flight requirements imply increasing maintenance intervals which translate into increased lifing of the disc.

The design of a high pressure turbine disc involves multiple disciplines like computational fluid dynamics, thermal, stress, lifing and weight analysis. For an optimal design, a synergistic interaction between the disciplines is needed based on a consistent description of the design for each discipline involved. As such this is a typical example of Multidisciplinary Design Optimisation (MDO) as defined in[5]. For the high pressure turbine disc under consideration, our contribution is the realisation of an advanced integrated multidisciplinary design analysis facility. Existing commercial-off-the-shelf mono-discipline tools are integrated into a single tool chain. The disciplines automatically exchange their data via an integrated design model enabling a consistent design assessment. Such an integrated design model allows easy selection of any available characteristic as an optimisation objective. This paper will illustrate the flexibility of incorporating disciplines into our tool chain as well as flexibility in selecting design objectives. This flexibility is shown, by discussing an example in which the mass is optimised.

The next section describes the various disciplines involved in the design, and how these respective discipline tools are combined in an automated workflow. Subsequently the meta-modelling or response surface approach used is described for the selected objective, which is minimising disc mass. The flexibility of the design tool chain is illustrated by exchanging the lifing constraint and mass optimisation by a mass constraint and an optimised lifing objective. These results lead to the introduction of the Pareto set, which provides the designers information to allow them to exchange mass and lifing objectives within the provided design constraints. The increased knowledge about the design is the outcome of this case study and will lead to the conclusions. In industrial design cases such knowledge would help higher level designers in their decision making processes.

2. Workflow encompassing the multidisciplinary engine disc design tool chain

Figure 1 provides an overview of the disciplines, and their supporting tools, used in the engine disc design case study. The overall engine design objectives, derived from amongst others the vision 2020 objectives[1] and the European Union environmental policies[2], provide the detailed design objectives and constraints for the high pressure turbine compressor. Examples of such component constraints are temperatures and rotational loads of the disc. This paper will not elaborate the aerodynamic design, more information can be found in[6].

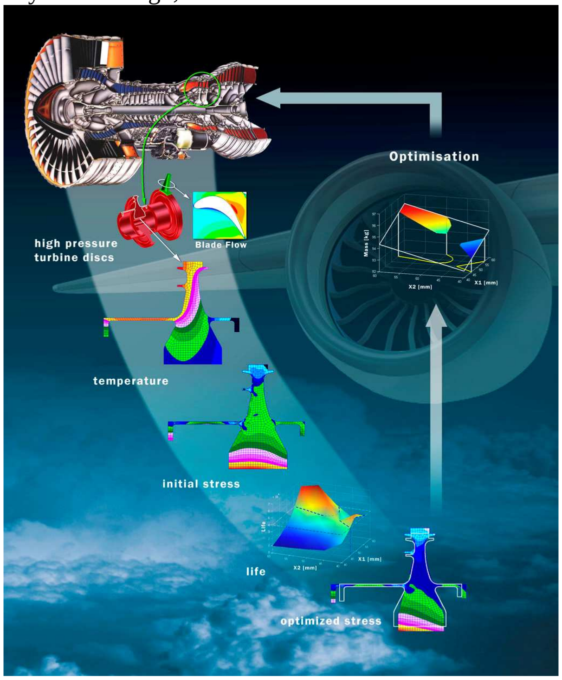

Figure 1: Flexible tool chain to enable synergistic multidisciplinary design of a high pressure turbine disc

At this stage of the design, a detailed simulation of the blade – disc interaction is not needed. Consequently the disc can be considered as axially symmetric, so for the subsequent analysis a 2-Dimensional (2-D) geometry description suffices, allowing reduction of the computational load of the analysis. Figure 2 shows how the axially symmetric 2-D geometry description relates to the 3-Dimensional (3-D) disc geometry.

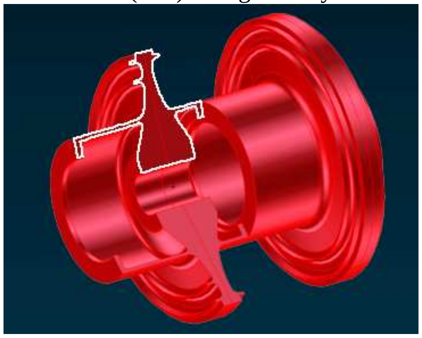

Figure 2: Position of axially symmetric 2-D geometry within the 3-D high pressure turbine disc

As a first step in the automatic design and analysis process the geometry is drawn and parameterised with CATIA V5. Figure 2 shows the full parameterisation of the resulting 2-D geometry description of the disc. Varying all these parameters would result in an unfeasibly large design space, so the two main design parameters used are depicted in the left hand part of figure 3.

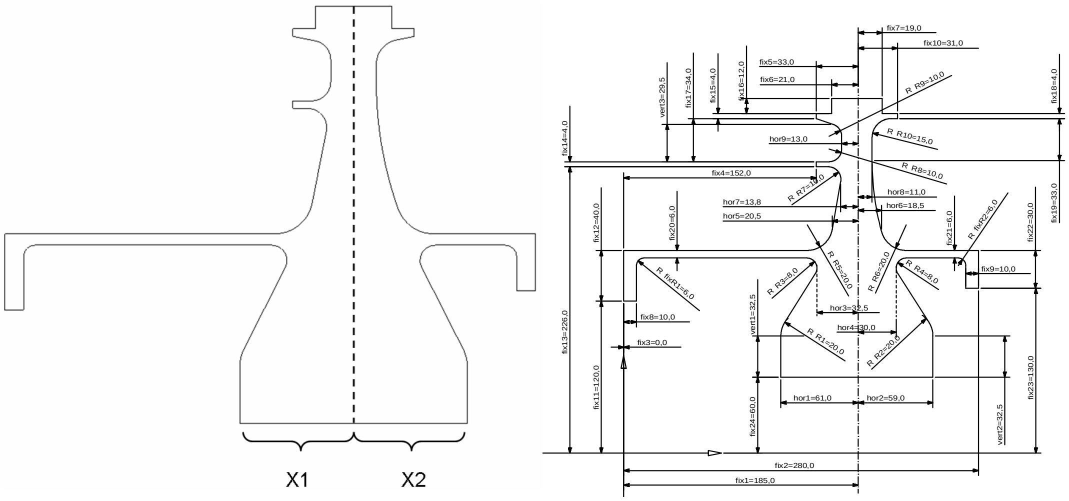

Figure 3: 2-Dimensional shape of disc (left) and full parameterisation of the disc shape (right)

Please note that there are many geometric design constraints including the shaft diameter, disc width and outer diameter which are determined by higher level design steps. Such multi-level design is typical, with different sets of models used for different design levels to allow for feasible computational loads at the earlier design stages. The multi-level approach is not elaborated in this paper but will be included in the next design stages. The geometry is exported to the Initial Graphics Exchange Specification (IGES) format for exchange with a finite element simulation code.

The second step in the process is the meshing of the disc geometry with the finite element pre-processor MSC/Patran. The IGES file with the geometry is imported and automatically meshed. The mesh density can be controlled over the complete geometry so areas of importance, like those where stress concentrations are expected, can be meshed in finer detail than others.

Material properties are defined with respect to a real turbine disc material. All parameters are kept independent of the temperature to reduce computational burden in the present analyses. Subsequently the external temperature loading and mechanical loading due to blade force and rotational effects are imposed on the disc using MSC/Patran. For the current situation no axial load of the blade due to gas loads nor creep was taken into account.
The internal temperature distribution of the disc, labelled “temperature” in figure 1, is then calculated with MSC/Marc. Based on this information the initial stress due to the combined temperature and mechanical loading is determined using MSC/Marc, labelled “initial stress” in figure 1.

Assuring that the disc will not burst at the applied temperature and external load conditions, a “no burst criteria” was defined and imposed as a constraint in the design and optimisation process. The area weighted mean hoop stress of the disc must be below a specified allowable stress which is dependent on the temperature of the disc.

To be able to calculate the fatigue life a simplified flight cycle is used in the present analyses. It consists of an idle and cruise condition where input parameters such as speed, air temperature and heat transfer coefficients are assumed to be constant over the idle and cruise conditions, i.e. a steady state temperature distribution exists at the end of each flight cycle. The lifing analysis of the disc is based on the temperature and stress distribution in the disc. The lifing is expressed as the number of cycles before failure. The hoop stress is used for the lifing assessment. To keep the process tractable, the hoop stress is only determined for the steady-state reached at the end of the idle and cruise conditions. Such steady state conditions constitute the worst-case situation with respect to cycles where the steady-state is not reached. Based on Nickel Based Alloys with isotropic behaviour, the Basquin-equation is used for the low cycle fatigue:

$$\sigma(T) = c(T)\, N_f^{\,m(T)} \tag{1}$$

$$N_f(\sigma,T) = \left(\frac{1}{c(T)}\cdot\sigma\right)^{1/m(T)} \tag{2}$$

Where T is the temperature, σ(T) is the temperature dependent stress, N_f is the number of life cycles depending on stress and temperature. The temperature dependent coefficients are defined as:

$$c(T) = 0.0062\,T^2 - 5.9094\,T + 3038 \tag{3}$$

$$m(T) = -4\text{x}10^{-7}\;T^2 + 0.0003\,T - 0.1066 \tag{4}$$

Based on these equations for each flight condition a certain life of the disc can be predicted. The results from both analyses (i.e. covering the full flight cycle) are then combined by the Palmgren-Miner-rule:

$$\frac{1}{N_{f\,total}} = \sum \frac{1}{N_{f\,i}} = \frac{1}{N_{f\,idle}} + \frac{1}{N_{f\,cruise}} \tag{5}$$

Where $N_{f\ total}$ is the predicted life in number of cycles. The rule assumes that the total life of the disc may be estimated by adding the life consumed at each flight cycle.

All the tools used in the design and analysis chain are Commercial-off-the-Shelf (COTS) tools. The lifing can be determined based on the above equations or based on a proprietary tool linked to the chain, thereby demonstrating the flexibility of the tool chain. Such mix of COTS and proprietary tools, with some tools often only available on specific computing platforms, is typical for engine multidisciplinary design optimisation. Sometimes due to concerns about intellectual property rights, the tools may not be available at each site, and engineers have to use tools provided at remote computing platforms. This leads to conversion of information from one COTS tool to another and also leads to transfer of significant amounts of information between computers. As many design variations need to be analysed, the set of tools is put into a workflow. The selected workflow engine supports automation of the conversion of information and supports automatic exchange of information, even when some tools are only available on dedicated computing platforms, which might be located at remote partner sites.
Several levels of usability and operability exist ensuring a flexible environment for the design and optimisation process. The workflow is basically based on Unix bash-scripts and Python which give good programming flexibility on a number of different operating platforms. Part of the scripts run on a Windows PC and are used to prepare the input for and execution in CATIA V5. The main part of the script runs on a Linux based PC, serving as an interface between the different analysis modules (MSC/Patran, Marc and the lifing tools). A web based server is implemented which can be operated either through a web interface or an external application client. This enables the execution of the workflow from virtually any location with an internet connection. For more information on the workflow see[7], more information on the distributed tool chain is provided in[8].

The multidisciplinary analysis of a single engine disc design is computationally expensive, typically around a quarter of an hour in the presented case study. This study excludes the computational fluids dynamics part which provides a significant additional computational load. As some optimisation algorithms like Genetic Algorithms require numerous design evaluations (typically thousands or more), a meta-modelling or response surface approach is used, which is described in the next section.

3. Computationally efficient meta-modelling

When optimising the objective, i.e. minimising disc mass in our case study, the optimiser needs a multidisciplinary evaluation of the engine disc design at various design points, as determined by the optimisation algorithm. In our example the number of design variables has been limited to two (X1 and X2 in figure 3) in order to visualise and demonstrate the complexity of the design space. In practice, however, the number of design variables is not limited to two and various design variables can be used in the design and optimisation process.

As the analysis tool chain does not provide gradient information, gradient based optimisers need more computationally expensive evaluations. In case the objective has a complicated surface in the design space considered, gradient based algorithms might not be robust and genetic algorithms may need to be referred to. Meta-modelling or response surface methods have been shown to be an effective solution to represent the behaviour of the objective and constraints within the design space considered with high computational efficiency and sufficient accuracy[9, 10 and 11].

A sampling of the design space (X1, X2) is made with the full multidisciplinary analysis capability. Note that as these analyses are independent, they could be performed in parallel. Subsequently a response surface is fitted through the results for the selected objective. Figure 4 shows the results of the accuracy of the fit for various fitting functions. The accuracy is determined by comparing the response surface results with a few additional designs, for which a full analysis is performed. As the best fit turns out to be sufficiently accurate for our optimisation, figure 5 depicts the response surface for the engine disc lifing. The predicted life is expressed in the number of loading cycles. This response surface has been used for the subsequent mass optimisation.

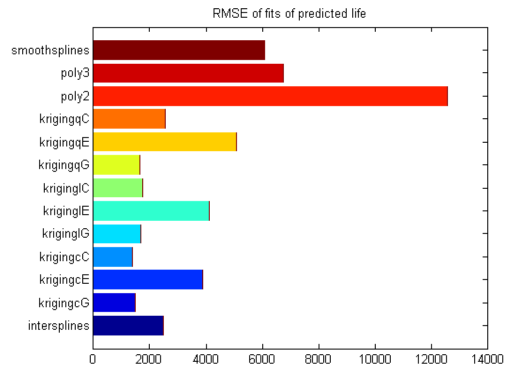

Figure 4: Accuracy of various fit functions of response surface for selected lifing objective. The accuracy is expressed as Root Mean Square Error (RMSE) of the number of cycles

The area of the disc and therefore the weight is minimal if the sizing parameters are minimal. From figure 5 one can see that this value will be reached with a geometry of X2=40 mm and X1 between 45 and 50 mm, satisfying the minimal life constraint of 40.000 cycles. With a numerical approximation of the predicted life data one can find a more precise value for X1 (e.g. 47 mm). This value is then verified by re-running the tool chain for the approximated optimal design parameters. Following this approach the design optimum is found in a more computationally-efficient way than finding it by running the tool chain only. Through the approximation of the design space, explorations of the design space can be made cost effective. Furthermore figure 5 shows that two distinct areas exist where the constraint for minimum life is satisfied. This requires advanced optimisation methods (e.g. genetic algorithms), since not all existing optimisers can handle such a constraint behaviour adequately and robustly.

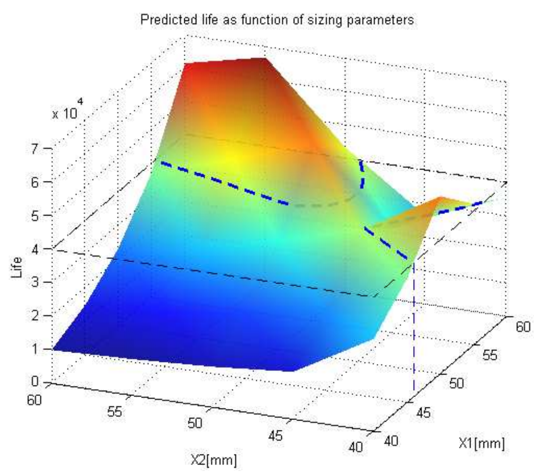

Figure 5: Actual lifing for various engine disc design variants, with part above the waterline complying with the minimum lifing constraint of 40.000 flight cycles

4. Flexible engine disc design optimisation

For the part of the design space which is feasible with respect to lifing, a second response surface is made with the engine disc mass as design objective. Figure 6 depicts the mass of the high pressure turbine disc as a function of the design variables. The coloured areas comply with the minimum lifing constraint of 40.000 flight cycles. Clearly the two feasible design areas can be seen. The starting design was X1=X2=55 mm and is located in one of the feasible design areas. As a result of the optimisation process using only two design variables, the disc mass was decreased from 95.3 kg to 93.2 kg (2%). The optimum is found in the other feasible design area then where the optimiser started from. Note that gradient based optimisation would have given the wrong optimum and the use of a genetic algorithm is therefore the preferable choice here.

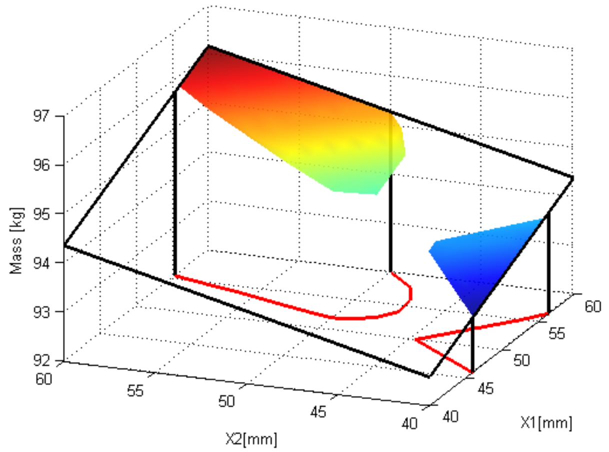

Figure 6: Actual mass of various engine disc design variants, with coloured parts complying with minimum lifing constraint of 40.000 flight cycles.

The number of flight cycles satisfies the minimum lifing constraint in the optimum. Its value was decreased from 44.600 for the original design to 40.000 for the optimal design. Physically, the reduction in mass is achieved by removing most of the material at the design variable X2-side where relatively low temperatures exist.

To illustrate the flexibility of the tool chain and the MDO workflow, the maximisation of the predicted life is considered. Increasing the life of the disc would lead to an increase of mass, so a constraint was placed on the mass of the turbine disc. In figure 7 the response surface approximation of the predicted life with the mass constraint of 95.0 kg is shown. The maximum predicted life is found at X1=55 mm, X2=50 mm where the predicted life is 53.200 flight cycles, a significant 19% increase in lifing at slightly lower weight. Note that the optimum disc design using this objective/constraint combination is close to the starting design of X1=X2=55 mm. The original disc was obviously designed for maximum life, still with the MDO approach a significant lifing improvement can be obtained without incurring a weight penalty. This is consistent with references[12 and 13] where multidisciplinary design optimisation is considered a key technology to improve aircraft performance.

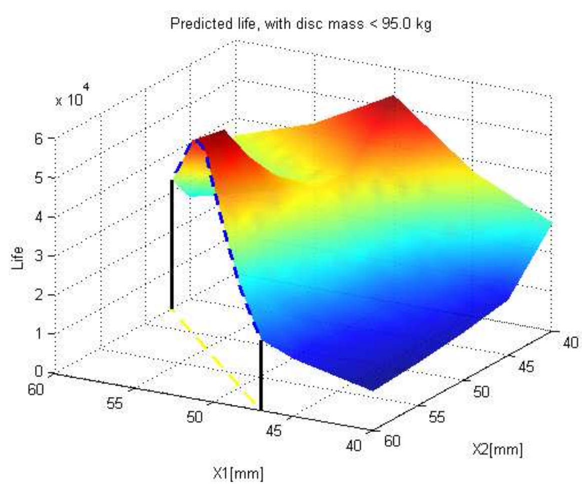

Figure 7: Actual lifing for various engine disc design variants, with feasible part complying with the maximum disc weight constraint.

In practice, the optimal design will usually be a trade-off between various objectives and constraints and involves the simultaneous optimisation of more than one objective function. As seen before, it is unlikely that the different objectives would be optimised by the same alternative design variable choices. One of the multi-criteria optimisation methods that can be applied is the so-called Pareto optimisation. Using Pareto optimisation leads to an entire curve or surface of points whose shape indicates the behaviour of the trade-off between different objectives. In figure 8 the Pareto optimal front of the disc mass and lifing parameters is shown. It is interesting to note that disc designs with a mass between 93.5 and 95.0 kg do not comply with the minimum lifing constraint of 40.000 flight cycles resulting in a discontinuous Pareto front. Following the Pareto front by increasing the mass leads to an increase of the predicted life. The designer can select from this a suitable combination of predicted disc life and corresponding mass.

The above described optimisation process is not limited to the design variables or objectives and constraints currently used. For example, a tool for calculating manufacturing costs can be included in the analysis chain which adds in an additional objective function or constraint. Typically, due to commercial sensitivity, such a costing tool can not be provided to other partners, but within the frame of a specific collaboration these partners can be allowed access to the module provided it remains at the owner's site and under the owner's full control.

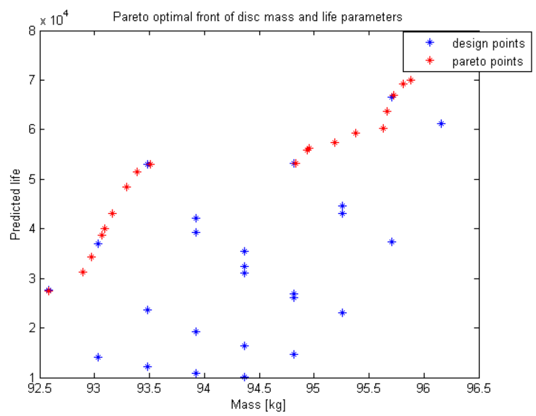

Figure 8: Pareto front (red points) of lifing and weight objectives. Note that disc designs with mass between 93.5 and 95 kg do not comply with the minimum lifing constraint of 40.000 flight cycles causing a discontinuous Pareto front.

It is envisaged that in the continuation of the case study the design and optimisation of the turbine disc the process will be extended to the assembly of two discs. Of course, the information on the relative position of the two discs is then important. A full three dimensional (3-D) analysis of the assembly will be carried out which takes into account a more complex flight cycle including temperature dependent material behaviour.

5. Conclusions

The multidisciplinary optimisation of a high pressure turbine disc of a gas turbine engine is demonstrated based on a parameterised geometry and including thermal, stress, lifing and weight analysis. Chaining the various design and analysis tools involved into a virtual environment allows automation of the design and analysis procedure, a pre-requisite for multidisciplinary optimisation. The tool chain allows for exchanging analysis modules so for example COTS tools and in-house tools can be included.

Full analyses are computationally costly, so a response surface approach is used to allow using various optimisation algorithms. In the case studied, the non-contiguous design space demonstrates the usability of genetic algorithms. These algorithms, by their nature, require numerous design variant evaluations thereby justifying the response surface approach. The optimisation process allows for the selection of multiple objectives and constraints which give the designer increased flexibility in studying the effect of different design goals.

To solve the multi-objective optimisation problem, a Pareto optimum criterion was used. Even using a limited set of design variables obtained a 19% turbine disc lifing improvement with respect to the original design without weight penalty. Introducing more design variables and additional objectives even more improvements are expected.

The innovation of our work is the combination of :

- A flexible analysis tool chain based on a parameterised design ;
- An *a posteriori* meta-modelling method for any objective provided by any of the analysis tools involved. For the resulting response surface any of the supplied approximation functions can be chosen without significant computational penalty ;

- Computationally efficient optimisation with a choice of optimisation algorithms ;
- Providing single-discipline experts with insight into the design space for the selected objectives without the need to consult the other discipline experts involved.

Each of the items mentioned above has been used before. Their combination for engine design is innovative and results in a virtual engine environment supporting multidisciplinary turbine disc optimisation.

Acronyms

2-D	two dimensional
3-D	three dimensional
COTS	Commercial-off-the-Shelf
IGES	Initial Graphics Exchange Specification
MDO	Multidisciplinary Design Optimisation
RMSE	Root Mean Square Error
VIVACE	Value Improvement through a Virtual Aeronautical Collaborative Enterprise

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