An Engineering Application for Optimisation, Robustness and Reliability Methods Demonstrated on a Gas Turbine Component

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Abstract

Optimisation, robustness and reliability analyses have an increasing importance in aviation industry engineering. Objective of this article is the presentation of the optimisation of a high pressure turbine disc of a fictive gas turbine engine. In order to reduce the numerical effort a simplified axis symmetric 2D-FE-model was used. The conflicting objectives of the analysis are the mass and the life of that disc. A sensitivity study was performed in order to identify the most relevant geometry parameters for a multi-objective optimisation. The optimisation resulted in a Pareto front. It was used to choose a nominal design for a subsequent reliability analysis.

Keywords: Optimisation, multi-objective, reliability, DOE

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1 Introduction

Optimisation, robustness and reliability analyses have an increasing importance in aviation industry engineering. The process of optimisation and subsequent analysis of the influence of varying input parameter is shown in this paper. The application of those methods is demonstrated with a fictive and simplified model of a high pressure gas turbine disc.

1.1 Description of the engineering application

The general engineering object of this article is a fictive gas turbine engine like it is typically used for the propulsion of civil aircraft. The core of such an engine consists of the three main assemblies: compressor, combustor and turbine.
The turbine provides the power to drive the compressor and accessories of the engine. It expands the hot gases released from the combustion system to a lower pressure and temperature in order to produce the driving torque. The turbine may consist of several stages each employing one row of stationary nozzle guide vanes and one row of rotating blades. Those blades are supported by a disc. A disc of the high pressure turbine (HPT) is the object used for the methods described within this document (Figure 1).

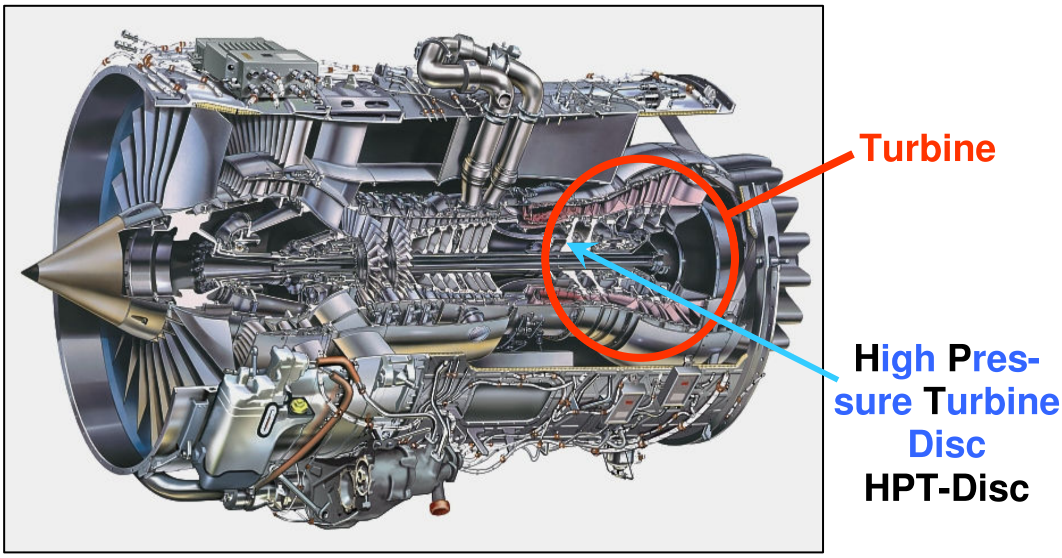


Figure 1: Gas turbine engine

1.2 Description of the analysis model and objectives

The analysed disc is subjected to manifold thermal and mechanical loads. Temperatures and stress distribution for a simplified load case were calculated with the finite element (FE) analysis software ANSYS Workbench.
A full 3D-FE analysis was expected to be too costly for the intended optimisation and probabilistic investigations. Therefore a simplified but fast running FE-model

was used in order to reduce the effort of the numerical analysis. An axis symmetric 2D-model was deemed to be a sufficient compromise for result accuracy and analysis time. The 2D-model neglects the complex 3D-geometry of the disc-blade interface. Therefore, the averaged radial force of the supported blades is applied to the disc. Furthermore, a steady state thermal analysis was performed using temperatures and heat transfer coefficients as boundary conditions (Figure 2).

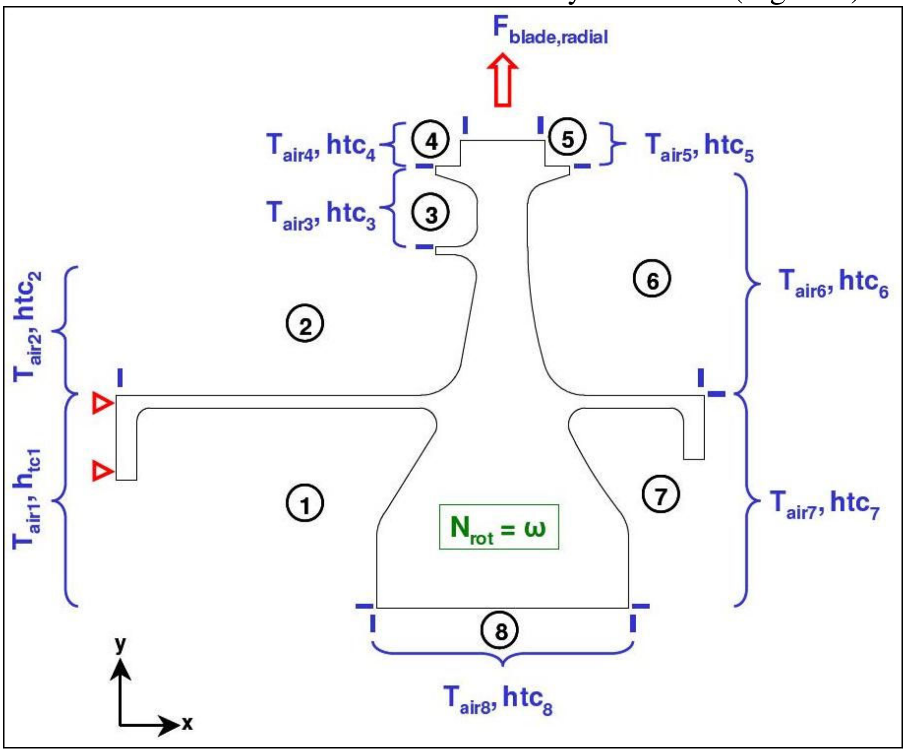


Figure 2: Axis symmetric model with schematic loads and boundary conditions

Two design objectives were considered as customer requirements:

- life cycle number
- mass

The life cycle number was calculated with a simplified lifing curve. Temperature and stress results from the FE analysis were used as input for that easy to use lifing approach. The mass was determined directly from the geometry model.
The software platform OptiSLang was implemented for the analysis process control. It provides a direct interface to ANSYS workbench, hence the analysis process was easy to setup.

2 Sensitivity study

It was aimed to identify the most relevant input parameters in order to reduce the numerical effort for the optimisation algorithm. Therefore, a Design of Experiments (DOE) was setup using distance optimised Latin Hypercube with 513 samples. Only geometry parameters were considered as input variables. All boundary conditions, e.g. temperatures, heat transfer coefficients, were kept constant. It was observed that the minimum life location varies with the actual values of the input variables. Hence the cross section of the disc was partitioned in six regions. Depending on the values of the input variables the location of the calculated minimum life occurs in one of those six regions. Figure 3 shows the arrangement of those regions. The proportion of all DOE-samples to have their minimum life in a certain location is also specified for each region.

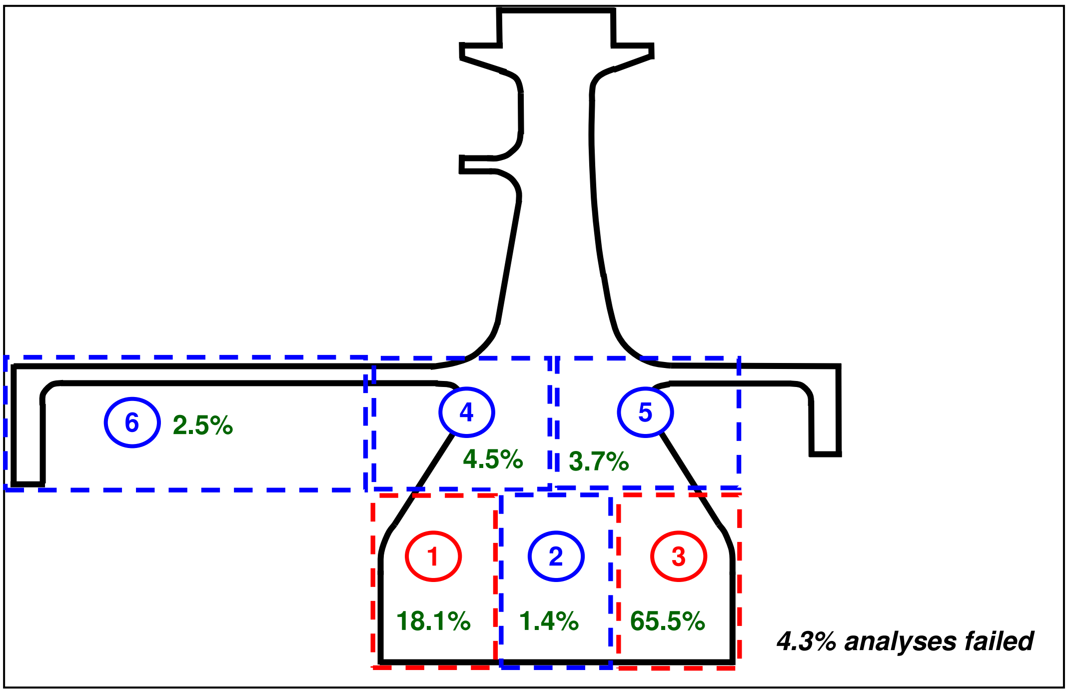


Figure 3: Partitioning of disc cross section to identify location of minimum life. Results of DOE-study: proportion that the calculated minimum life is located in the specified partitions

The relevance of the varied geometry parameters was evaluated using the coefficient of determination:

$$R^2 = \frac{\sum_{k=1}^{N}\left(z^k(x_i) - \mu_{x_j}\right)^2}{\sum_{k=1}^{N}\left(x_j^k - \mu_{x_j}\right)^2} \tag{1}$$

This analysis was performed based on the results of the DOE. In Figure 4 and Figure 5 the outcome for the simple linear case are shown. The influence is illustrated for the four most relevant geometry parameters only.

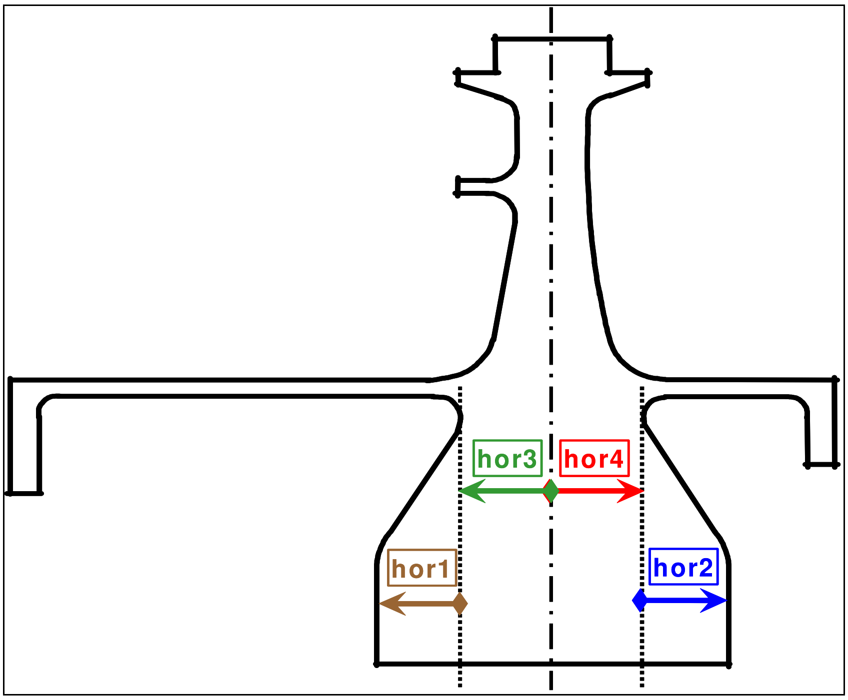
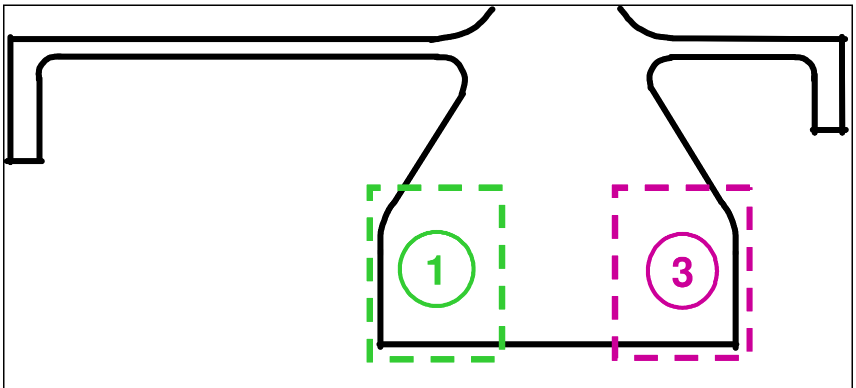


Figure 4: Illustration of the four most relevant geometry parameters as a result of the sensitivity study



Geometry Parameter	global	Region1	Region3
hor1	3%	20%	0%
hor2	20%	2%	27%
hor3	7%	33%	8%
hor4	31%	13%	37%

Figure 5: Results of DOE (linear coefficients of determination) considering different regions for predicted minimum life location life

Case 1 (column “global” in Figure 5) takes all results into account. No care is taken where the minimum life is located. For that case “hor2” and “hor4” are indicated to be the most relevant geometry parameters.
The second case (column “Region1” in Figure 5) considers only the DOE samples that give a minimum life located in Region 1. That case gives the opposite result with parameter “hor1” and “hor3” to be the most influencing.
The last investigated case focuses on DOE samples that have their minimum life in Region 3 (column “Region3” in Figure 5). The outcome is similar compared to the global evaluation of the first case.
Those findings demonstrate how sensitive the results of a DOE might be regarding the range of the input parameters. It shows that care should be taken when concluding which parameter are the most relevant for an optimisation task. Too much limitation on the number of parameters can constrain the improvements obtained by the optimisation. Therefore in this work a higher number of parameters (seven) were considered for the optimisation.

3 Optimisation

The investigation deals with two conflicting objectives: predicted life and mass of the disc. Hence a multi-objective optimisation had to be performed. A multi-objective evolutionary algorithm provided by OptiSLang was employed. Figure 6 shows the calculated Pareto front. This result was achieved after 110 generations have been analysed.

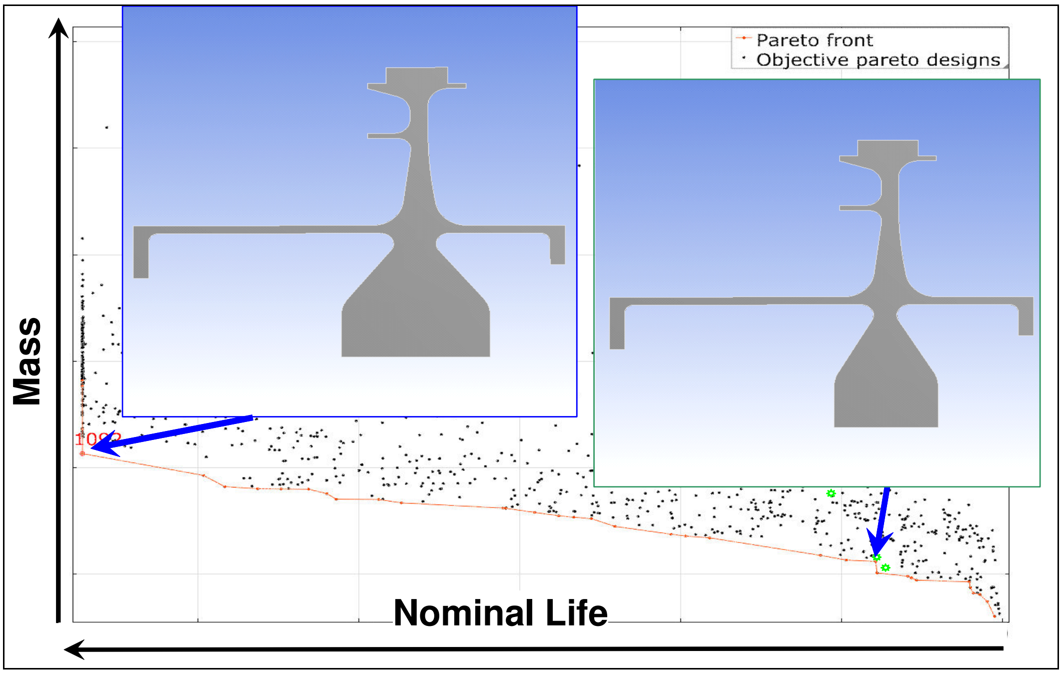


Figure 6: Result of multi-objective optimisation

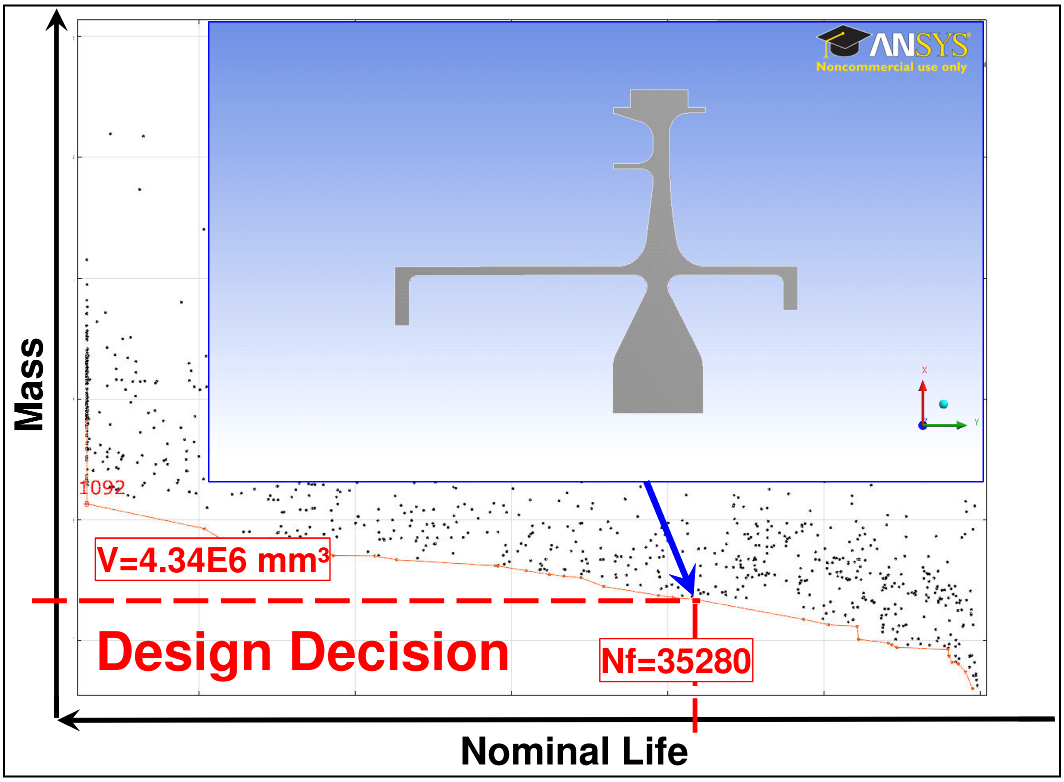


Figure 7: Design decision

A result on that Pareto front had to be identified as the nominal design for the subsequent reliability analysis. This design decision normally is made based on higher-level information, e.g. customer requirements for a certain flight mission. Since no real customer requirements were applicable for this fictive disc, it was intended to have a design with a quite realistic number of life cycles Nf.
Figure 7 illustrates the design decision made. A design with a nominal expected life of 35280 cycles was chosen, which lead to a mass of about 35kg. This nominal design was used for robustness and reliability analyses.

4 Reliability analysis

It was an aim of this work to evaluate the reliability of the investigated component. The new algorithm "Adaptive Sampling on Adaptive Response Surfaces" (ASonARS) implemented in OptiSLang was applied for that purpose. The most relevant geometry parameters (identified in section 2) and the boundary temperature values were varied. Each of those parameters was sampled with an assumed statistical distribution of truncated normal type.
The design chosen in Figure 7 was checked for reliability regarding the expected life. Therefore the predicted life was defined as a fictive requirement. Its probability of failure (POF) was assumed to be less than $1.0\ 10^{-6}$. For a real world

application the question needs to be answered: For which number of lifing cycles that assumed POF will be achieved?

	Analysis 1	Analysis 2
Limit state function (predicted life)	30000 cycles	28000 cycles
Probability of Failure (POF)	3.0 10^{-5}	1.3 10^{-8}

Table 1: Results of reliability analysis

The value for the limit state function of the predicted life was set to 30000 cycles in a first analysis. This limit leads to a POF of 3.0 10^{-5} which not fulfils the set requirement.
A second analysis with a limit state value of 28000 cycles results to a POF of 1.3 10^{-8}. This value exceeds the requirement clearly. Hence, the design decision made in section 3 is not acceptable for the case that it is aimed to have 30000 cycles with a POF less than 1.0 10^{-6}. A new design point with a higher nominal life has to be chosen from the Pareto front and its reliability checked again.
It is clear that the approach of checking the robustness or reliability after the multi-objective optimisation might be very costly (see Figure 8). For each design decision (point on the Pareto front) it is a priori unknown whether it fulfils a given robustness or reliability requirement.

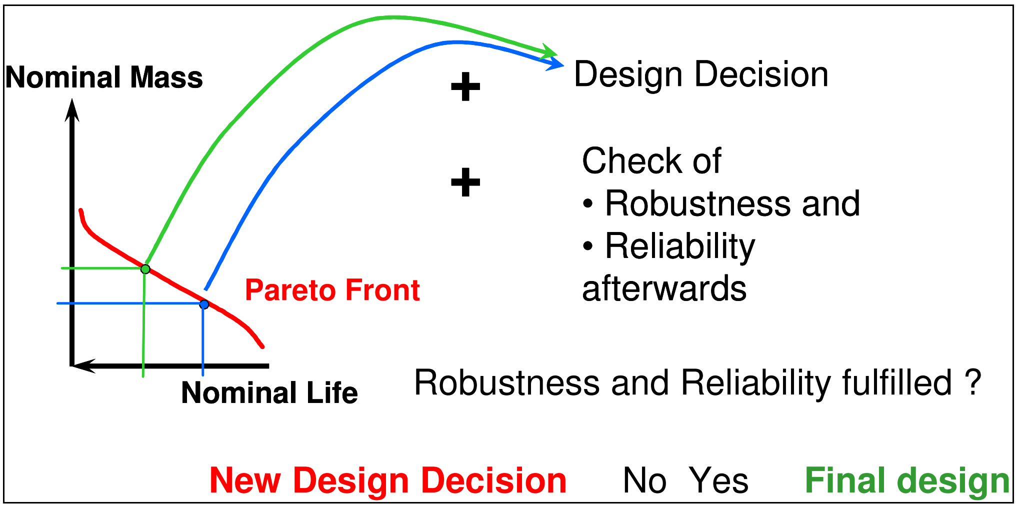


Figure 8: Today's approach to find design with required reliability

Hence it seems worth to include the reliability information within the multi-objective optimisation, i.e. to perform a reliability optimisation (see Figure 9).

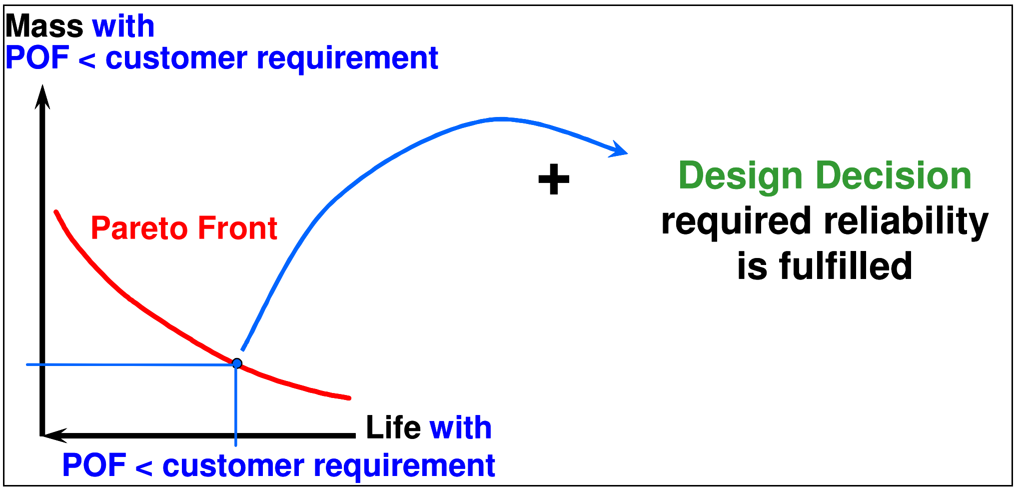


Figure 9: Future approach to find design with required reliability

5 Summary/Outlook

A simplified turbine disc model was investigated with mass and predicted life as subjects of interest. A sensitivity study was performed in order to identify the most relevant geometry parameters for a multi-objective optimisation. It was shown that a simple DOE can mislead that identification if the location of the minimum life is not considered. The multi-objective optimisation resulted in a Pareto front, which was used to achieve a design decision. For that design a reliability analysis was executed. The iterative process to find a design that fulfils the reliability requirements can be long winded. Hence, it is desirable to integrate the probability of failure during the optimisation process. This enables a direct design decision considering all requirements.

6 Acknowledgement

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