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# An Integrated Aerospace Requirement Setting and Risk Analysis Tool for Life Cycle Cost Reduction and System Design Improvement

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**Abstract**

In the early conceptual stage of the service orientated model, decisions regarding the design of a new technical product are largely influenced by Service Requirements. Those decisions, therefore, have to merge both technical and business aspects to obtain desired product reliability and reduced Whole Life Cost (WLC). It is, therefore, critical at that phase to define the risk of potential noncompliance of Service Requirements in order to ensure the right design choices; as these decisions have a large impact on the overall product and service development.

This paper presents outcome of research project to investigate different approaches used by companies to analyse Service Requirements to achieve reduced Life Cycle Cost (LCC). Analysis using Weibull distribution and Monte Carlo principle have been proposed here; based on the conducted literature review these are considered as the most widely used techniques in product reliability studies. Based on those techniques, a methodology and its software tool for risk evaluation of failure to deliver a new product against Service Requirements are presented in this paper. This is part of the on-going research project which, apart from analysing the gap between the current Service Requirements achievements and the design targets for a new aircraft engine, it also facilitates an optimisation of those requirements at the minimum risk of nonconformity.


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*Keywords:* Service Requirements, Risk Assessment, Weibull Distribution, Aircraft's Engines, DMTrade

## 1. Introduction

The design of modern aircraft engines is invariably a compromise of conflicting Service Requirements. In the service-orientated business where these products are mostly demanded, new challenges are emerging to deliver customer benefits, improvements in performance and reduction of the overall cost. As a result of these pressures, established industrial companies are pursuing the development of analytical computer processes as an alternative way of evaluating the behaviour of different design concepts considering Service Requirements.

This is the case of Rolls-Royce which was originally set up as a product seller to become now one of the most high value businesses worldwide providing their customers with services. The company is using the Design for Service approach as a procedure to first design the service and then, the product that supports it. With this, there is a strong focus on two main aspects: to minimise the cost of providing the service by the reduction of the LCC and to increase the customer value of the service provided.

Average time between overhaul or Time on Wing (TOW), \$/FH (cost per flying hour) and reliability of an aerospace engine are the three main Service Requirements that the company assesses in the early conceptual phase [1]. The cost requirement is dependent of the TOW by means of an equation that relates both parameters and reliability is represented by Weibull distributions. Therefore, designers have to combine the technical and commercial issues in an effective manner by


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examining different design alternatives and corrective action plans based on those top level Service Requirements.

Currently, Rolls-Royce has developed different techniques in order to analyse and model engines' critical parts reliability and their costs by means of different software tools. Tools such as DMTrade, described in [1], which conducts design and maintenance trade studies involving reliability and maintenance costs. However, existing tools require detailed data, in most cases not available at that stage, hence the assessment of the top level Service Requirements continues to pose a great challenge for the system designers.

It is, therefore, vital to improve the early design practices to help designers make informed decisions, which demand higher degree of vision, versatility and reliability based on Service Requirements. Here is where this research takes relevance; as it aims to present a methodology and its tool in order to foretell the risk of noncompliance of top level Service Requirements for the whole life-cycle of a new engine design and, provide a range of predicted level of Service Requirements to mitigate the WLC avoiding the cost of redesign.

The remainder of this paper is organised as follows: Section 2 presents the two most used approaches followed by industry in order to analyse Service Requirements; explaining the fundamentals of both methods and main equations. Then, Section 3 introduces the modular structure of an aircraft engine and explains the methodology and the risk analysis software tool developed for a new engine design. Discussion and conclusion are given in Section 4.

**Nomenclature**

WLC Whole Life Cost
LCC Life Cycle Cost
PLC Product Life Cycle
CDF Cumulative Distribution Function

## 2. Service Requirements Analysis Methods for Service Provision

Due to the increase in demand and competitiveness of the service driven approach, the necessity of developing and procuring of a service adapted to a series of customer requirements is becoming of great importance.

In this section the focus is on the study of two different methods for analysing and aligning the design concepts to the Service Requirements.

### *2.1. Weibull distribution*

Weibull analysis is a very valuable approach for companies where understanding and predicting the failure risk and the reliability of a lifetime data become crucial [2]. It allows managing the life-cycle of a product more accurately, as it provides relevant information to facilitate the right decision-making, especially in the early design stage where design decisions have a large impact in the reduction of the LCC.

#### *2.1.1. Weibull parameters*

The Weibull Distribution used in this research is defined by two parameters. The first parameter, beta (β), is the slope parameter of the Weibull distribution and indicates the class of failure that describes the data. Moreover, this parameter classifies the failure mode and thus, gives a good indication of how the systems / subsystems may fail:

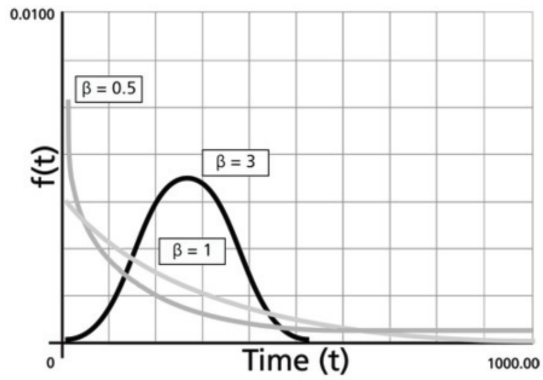



Fig. 1. Weibull Probability Density Function for different β [3].

- β<1 it indicates that the product has a decreasing failure rate;
- β=1 it refers to a constant failure rate;
- β>1 it indicates an increasing failure rate.

The second parameter, eta (η), is the characteristic life parameter which defines the value in time by which 63.2% of the failures will have occurred [4].

#### *2.1.2. Analytical analysis*

The Cumulative Distribution Function (CDF) of the two-parameter Weibull distribution used is expressed as:

$$F(t) = 1 - e^{-\left(\frac{t}{\eta}\right)^{\beta}} \quad (1)$$

Where:
t represents time,
β the slope parameter,
η the characteristic life parameter.

In order to analyse a system and subsystem in-service performance, the probability plotting methodology is considered in this paper. This method is based on the linearity of the CDF or unreliability function of the Weibull distribution.

Equation 1 can be expressed in the linear form as follows [5]:

$$\ln\left(\ln\left(\frac{1}{1-F(t)}\right)\right) = \beta\ln(t) - \beta\ln(\eta) \quad (2)$$

If left side of the Equation 2 is defined as y, and $x = \ln(t)$, the CDF equation can now be rewritten as:

$$y = \beta x - \beta\ln(\eta) \quad (3)$$

This is now a linear equation, with a slope of β and an intercept of βln(η).

In order simplify the evaluation of the Weibull analysis outputs and ensure the right decisions at the preliminary design stage, the visualisation of the CDF and reliability at system level is proposed in this work. Among all the alternative methods to represent Weibull model system the Series Systems model was selected.

In a Series System, the system continues working as long as all its n components are working; this means that the system will fail whenever a component fails. This system model is represented in the Equation 4 [6].

$$Rs(t) = \Pr(X1 > t, X2 > t, \ldots, Xn > t) = \prod_{i=1}^{n} Ri(t) \quad (4)$$

### *2.2. Monte Carlo principle*

Monte Carlo simulation method is a technique used in combination with the Weibull distribution to analyse more accurately the uncertainties in the variables being used when a model is forecasted.

This uncertainty is related to the fact that at the early stage of the new product design detailed reliability data, i.e. Weibull parameters, is difficult to obtain or does not exists yet.. Thus, those parameters are estimated based on historical service data and past experience. However, while this estimate is useful for developing an early model, since it is an estimate of an unknown value, it often contains some inherent uncertainty and risk.

Monte Carlo analysis method consists of a series of computational algorithms that work by repeated sampling of a range of possible values in calculating a series of probability distributions. It uses random numbers to sample from known probability distributions to determine a likely range of the model parameter values. Thus, by taking a random sample from the probability distribution associated with a model inputs, Monte Carlo method enables to obtain a single point estimate, which represents an overall system level output values [7].

## 3. Tool for Rolls-Royce Service Requirements improvement and risk analysis

### *3.1. Modular Engine Structure*

Gas turbine engines are composed of up to 30,000 components and they have to operate reliably in very adverse circumstances where high temperate and pressure are the key aspects of the design. In this work the Rolls-Royce manufactured Trent Engine Family has been used as a case study. The Trent Engine Family consists of the Trent700, Trent500, Trent800 and Trent900 [8]. It is shown in [9] that each of the engine follows a hierarchical system architecture, i.e. it allows breaking down the engine into module level and component level.

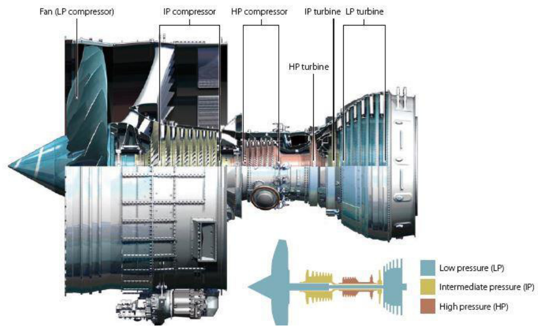



Fig. 2. Three-shaft configuration Trent Family [10]

In this work the modules considered for the risk assessment of the new engine design are based on the previous study described in [11], where the new engine design consists of eight different modules:

- Low Pressure Compressor
- Intermediate Pressure Compressor
- Intermediate Case Intercase
- High Pressure System
- Intermediate Pressure Turbine
- High Speed Gearbox
- Low Pressure Compressor Fan Case
- Low Pressure Turbine

For each component the relevant Weibull parameters are obtained which defines component reliability. The parameters at the component level are then combined to obtain the reliability at the module, and then the engine level using the Equation (4). These data is crucial for the risk assessment as it allows the comparison between predicted and targeted top level Service Requirements.

### *3.2. Introduction to the tool methodology*

The aim of this software tool is to determine the risk of failure to deliver a new engine design against the three top level Service Requirement in the conceptual design stage.

As Ross stated in [12], despite looking for innovative solutions when designing new engines, a high proportion of the design concepts are based on previous designs. The tool described in this paper follows similar approach and takes the historical knowledge from previous engine designs as a baseline for the new engine design.

Two different types of information are provided in the tool; the first is an engine technical specification to allow a quick comparison of similarities in terms of operations with the new engine design, and the second the similarities in terms of design obtained from the Weibull parameters. All these historical data will be used as a reliable reference for the new engine design development.

The DMTrade analysis tool, as has been described in [1], is considered as a very reliable and versatile tool for lifetime reliability and maintenance cost calculations. It is, therefore, integrated into the proposed methodology and it is used as a data processing component.

Following the work described in [13], a three stages risk analysis methodology has been created, as shown in Figure 3.

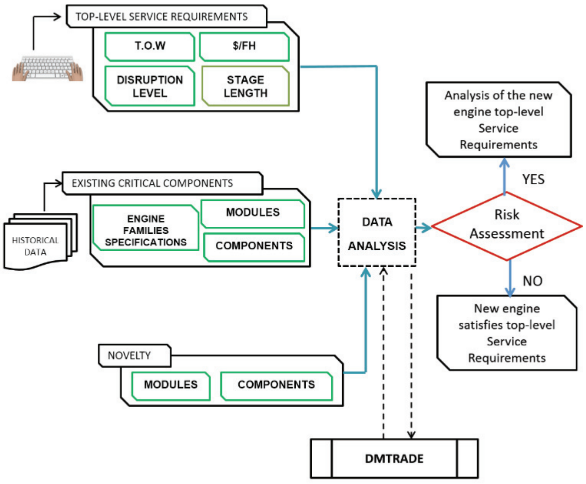



Fig. 3. Methodology for risk analysis of noncompliance of a new engine design with Service Requirements.

The inputs of the methodology consider three different branches:

- The three top level Service Requirements that the customer is willing to pay for once the engine is working.
- Historical service data – a Parametric Database has been used which stores the Weibull's parameters of the components that failed in the past. This database has been analysed and a parametric data summary has been obtained. This summary contains the critical components that drive a failure for each module of the existing engine families. Moreover, the specifications of the different engine families will be visualised to have a better idea of the similarities in terms of operations, which has been obtained from the meetings in the company.
- This data allows to define and characterise the novelty of the new product design by the modification or removal of the already existing Weibull parameters or the aggregation of new ones.

These three branches are interconnected to analyse the risk of the new product design against the defined top level Service Requirements. The Weibull distribution in a component, module and engine level will be used together with the Monte Carlo simulation performed in DMTrade. Both analysis shall provide as outputs the potential risk of not delivering the new design to the given set of requirements and facilitate the optimisation of them at the minimum risk of nonconformity.

### *3.3. Risk Assessment*

Previous section focused on the methodology followed in order to evaluate the risk of the new design according to Service Requirements. This chapter will explain how this methodology is implemented through a software tool. Figure 4 shows the input screen the user will have to fill to do so.

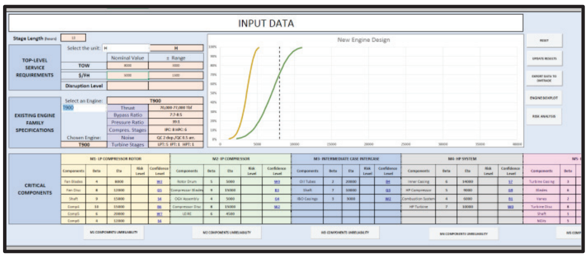
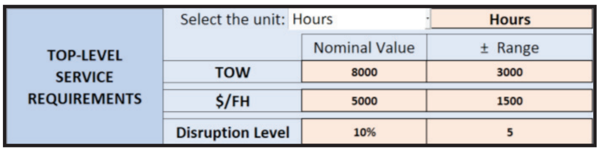



Fig. 4. Input data screen of the software tool.

First, a nominal value and a range for each Service Requirements will be introduced by the user, Figure 5.



| | | | |
|---|---|---|---|
| TOP-LEVEL SERVICE REQUIREMENTS | Select the unit: | Hours | Hours |
| | | Nominal Value | ± Range |
| | TOW | 8000 | 3000 |
| | $/FH | 5000 | 1500 |
| | Disruption Level | 10% | 5 |

Fig. 5. Service Requirements screen.

According to the similarity in terms of operation, the tool provides the option of visualising the specifications of the already existing engine families to match them with the new design concept. This information encompasses for example the level of thrust, bypass ratio and the level of noise in departure and arrival for each existing engine, as shown in Figure 6.

| EXISTING ENGINE FAMILY SPECIFICATIONS | Select an Engine: | EngineType# | |
|---|---|---|---|
| | EngineType# | Thrust | 54,000-56,000 Tbf |
| | | Bypass Ratio | 7:4-7:6 |
| | | Pressure Ratio | 40:7 |
| | | Compres. Stages | IPC: 8 HPC: 6 |
| | | Noise | QC 2 dep./QC 1 arriv. |
| | | Turbine Stages | LPT: 5 IPT: 1 HPT: 1 |

Fig. 6. Engine Family specifications screen (note this is a synthetic data).

Finally, for each of the modules an option of selecting the module out of the four different Trent Families that best fits the new module design is available. This information is stored in the parametric data summary and it aims to help the user to in an easy and quickly manner obtain a baseline for each of the modules of the new engine design, Figure 7.

| CRITICAL COMPONENT | Components | Beta | Eta |
|---|---|---|---|
| | Comp1 | 4 | 8000 |
| | Comp2 | 8 | 12000 |
| | Comp3 | 9 | 15000 |
| | Comp4 | 10 | 15000 |
| | Comp5 | 6 | 20000 |
| | Comp6 | 4 | 12000 |

Fig. 7. Critical components Weibull parameters.

Note that the data in Figures 6 and 7 is fictitious and any resemblance it may bear to any past, present, or future engine is purely coincidental.

After selecting a module of the previous engine families, the user will be able to add the novelty in the new design by adding, changing or removing any of the components' Weibull parameters.

Once all the modules information for the new engine design is populated and modified according to the new design, the analysis begins with a detailed study at a module and component level of the unreliability or prob. of failure. In order to describe the failure distribution of the components, Weibull distributions are produced, based on the Equation (1).

This analysis enables the identification of the critical component of each module which is the first component that drives the engine out of the wing. Figure 8 shows that the orange component is the critical component for the module; as is the one that has more probability to fail at the required TOW specified in Figure 5, 8000 hours. The spotted distribution represents the probability of failure at the module level with is calculated using the Equation (4).

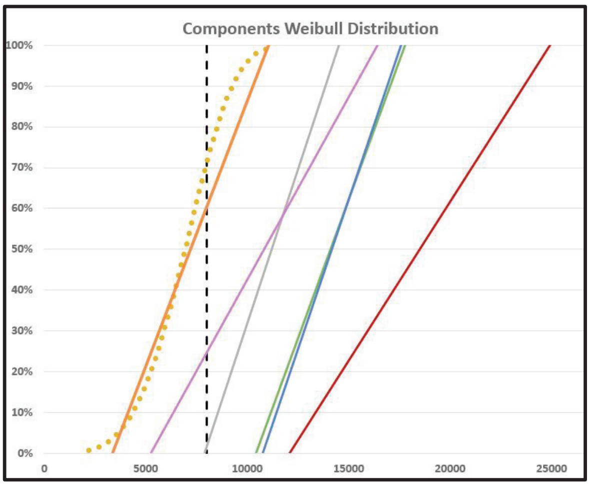



Fig. 8 Critical components Weibull distribution.

This first analysis can be run every time the analyst changes any of the parameters of the components; so multiple modifications can be done until the new design approach is obtained according to the user's expertise and criteria.

The second stage of the risk assessment it performed by populating the Weibull parameters of each of the components in DMTrade and running a Monte Carlo simulation on it. The required information from this tool is related to the shop visit rate and so, this data is extracted and exported again to the software tool. These actions are automatically executed by the tool.

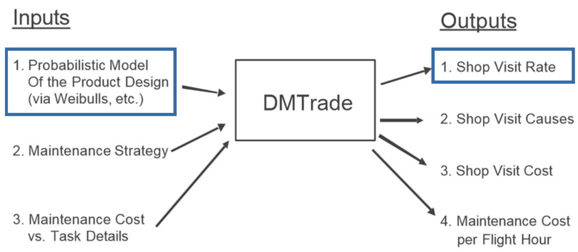



Fig. 9. Inputs and outputs of DMTrade [1].

The information obtained from DMTrade enables the comparison in an analytical and graphical way of the targeted TOW with the one that it is obtained after the Monte Carlo simulation. This data is also used to calculate the $/FH and compare the targeted cost with what the tool predicts in terms of LCC.

## 4. Conclusion and further work

In this paper the work carried out towards the risk analysis of nonconformity of the top level Service Requirements in the complex system design has been described. As the main deliverable for this research a risk analysis methodology and a dedicated analysis tool have been presented. The presented software tool uses Weibull distribution and Monte Carlo simulation for the life data analysis.

The results obtained from the described software tool at a module and component level have been validated using a purpose built Matlab simulation tool and the Rolls-Royce in-house DMTrade simulation tool. The proposed methodology has also been validated by LCC and reliability experts.

The further implementation of the methodology in the software tool is an on-going research work.

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