A Preliminary Engine Design Process for an Affordable Capability

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Abstract

This paper will examine the military engine preliminary design process used by Rolls-Royce to support 'capability vs. cost' trades conducted at the weapon system level.

The engine is a major sub-system of all air vehicle assets making up a force mix. Changes in the engine capability, e.g. thrust/weight and specific fuel consumption, can be tracked through to air-vehicle performance and ultimately to the force mix capability. In the same manner these changes will impact on the engine and air-vehicle life cycle costs and hence the total system costs.

These trades are vitally important in establishing the optimum affordable system solution early in the design and development cycle thereby preventing the need for expensive changes during full-scale development.

Rolls-Royce has developed a preliminary design process to quickly assess engine capability incurred costs. The process has evolved to enable the rapid definition of an engine including performance attributes and Through Life Costs (TLC's).

1.0 Introduction

Military engine designs are no longer focused solely on achieving performance targets, the cost of achieving that performance must be understood. This cost is incurred on several levels, those being unit, development, in service and disposal costs the summation being referred to as through life costs (TLC's). Modern military equipment procurement policies are now more dedicated to providing affordable capability. It is important that this trend is reflected in the design practices within the industries that support the armed forces. Rolls-Royce has recognised this and has developed preliminary design (PD) tools to enable affordability to be assessed at the concept stage of an engine design. This paper will give a brief description of these tools and will also present an example of a study carried out on the engine options for an unmanned combat aircraft (UCAV).

The Rolls-Royce design process is separated in six distinct groupings that take the engine from its early beginnings to retirement. This process is referred to as the "Create Customer Solutions Cycle" (formally Derwent) and is depicted in figure 1 below.

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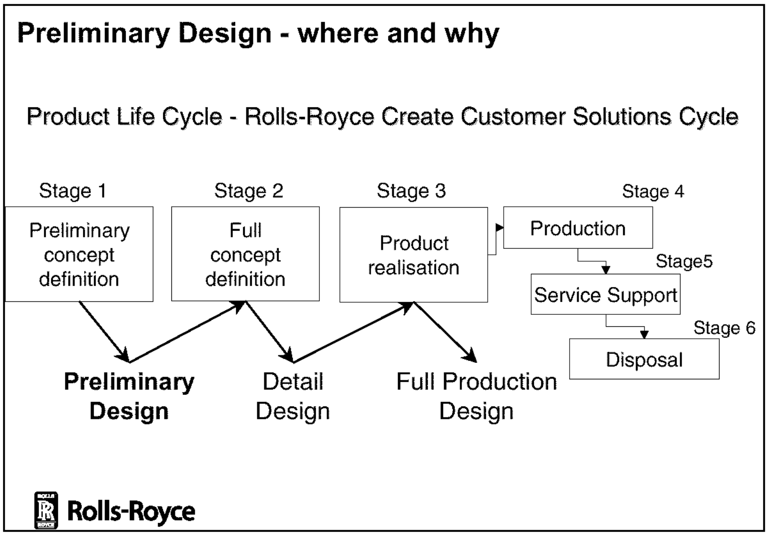


Figure 1. Rolls-Royce development cycle

The preliminary concept definition phase, stage 1, outputs a preliminary design and describes the functional attributes, including cost, that the engine or power system will exhibit.

Preliminary design is a key stage in the design process especially with respect to cost. The basic definition of the engine's thermodynamic cycle defines the fuel burn, the definition of the architecture and hardware defines the weight and so on, all of which have a direct impact on the in service costs.

However, during the preliminary design phase there is a paradox presented: there is little product knowledge but there is a powerful impact on the final design.

The aim therefore of any preliminary design tool set or process is to eliminate as much uncertainty as possible, to increase product knowledge and enable design trades and options to be understood.

The impact of design knowledge vs. determined product cost is depicted in figure 2 which shows that by the end of stage 1, using traditional theory, 70% of the cost is determined but only 5% of the product is defined. The bold line indicates the desire of the Rolls-Royce preliminary design teams, to increase product knowledge in the early stages, to reduce risk for the company and importantly for the customer.

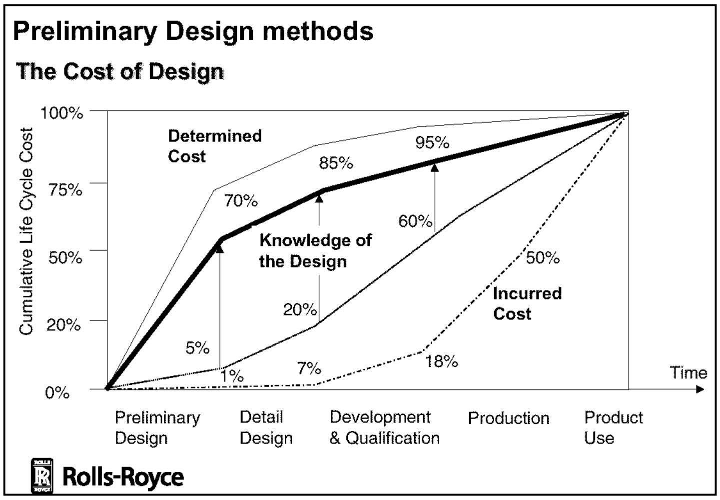


Figure 2. The cost of design vs. knowledge

In order to reliably understand the effects of design decisions in stage 1, it is necessary to have a reliable design tool, one that is also able to produce solutions quickly and enable the whole of the design space to be explored.

Rolls-Royce has developed several design tools to enable this design space exploration to be carried out in stage 1. The tools, which will be described in the first chapter of this paper, cover all the major data groupings:

1. Performance
2. Mechanical design
3. Unit cost
4. Aircraft performance
5. Development cost / inc. production investment
6. In Service and disposal costs

With the outputs from these tools the preliminary design teams within Rolls-Royce are able to assess the affordability vs. the capability of a new or derivative engine. A later chapter in this paper will present an example of a study carried out using these tools.

This paper will conclude by looking at the future of preliminary design within Rolls-Royce. This review will also consider the issues of data integrity and source.

2.0 Preliminary Design methods

The preliminary design process is started with a set of customer requirements that traditionally define the capability requirements of the airframe and power system. A typical requirement will specify the thrust (Fn) and specific fuel consumption (sfc) values around the flight envelope. From this limited data the definition of a possible engine solution can be started. The design iteration loop that is involved is shown in figure 3. This is of course a simplistic representation of the PD process, the iteration often being an order of magnitude more complicated.

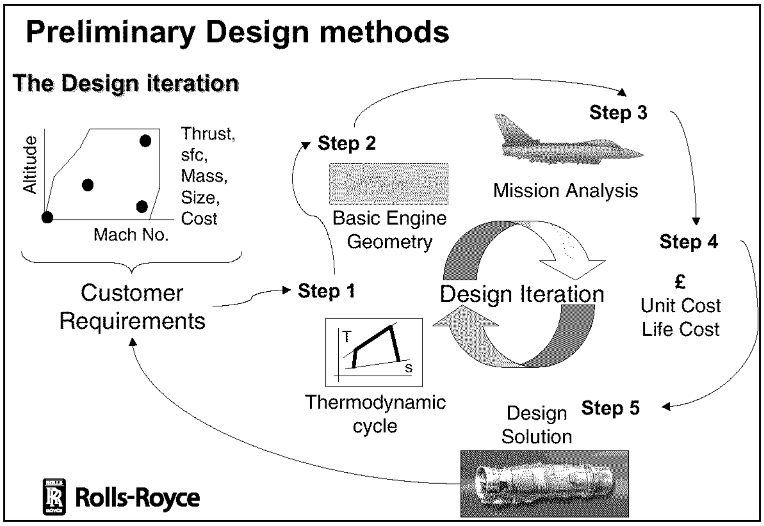


Figure 3. The PD design iteration

2.1 *Thermodynamic cycle creation*

The first step in the process is to create a basic thermodynamic cycle. This is where the first design choices are made, e.g. pressure ratio, bypass ratio, cycle temperatures etc. Using the Rolls-Royce tools, called RRAP (Rolls-Royce Analysis Programme) it is possible to generate station vectors or thermodynamic data at key stations throughout the engine. The programme makes basic assumptions about engine component characteristics.

2.2 Geometry creation

The second step in the process is definition of the basic engine geometry. This can be a more complex step than that taken by RRAP with the number of variables and the complexity of the calculation being much greater.

The software that is used to calculate these parameters is called Genesis. This programme has been developed by Rolls-Royce over the last 30. The programme is able to make basic assumptions about key aerodynamic and mechanical parameters to enable the calculations to be started. An automatic iteration process is then employed to find a solution.

A feature of the programme is the use of correlations based on a database of Rolls-Royce engines. These correlations are used by the programme to allow for real features and correct geometry for Rolls-Royce design practices and rules. This is done because the level of detail is insufficient at this stage in the design to define features such as seals, bolts, drive arms etc. The correlations allow these features to be accounted for in the mass results as appropriate. An example of this process is shown in figure 4 which describes pictorially how the corrections effect the shape of a high pressure turbine (HPT) disc.

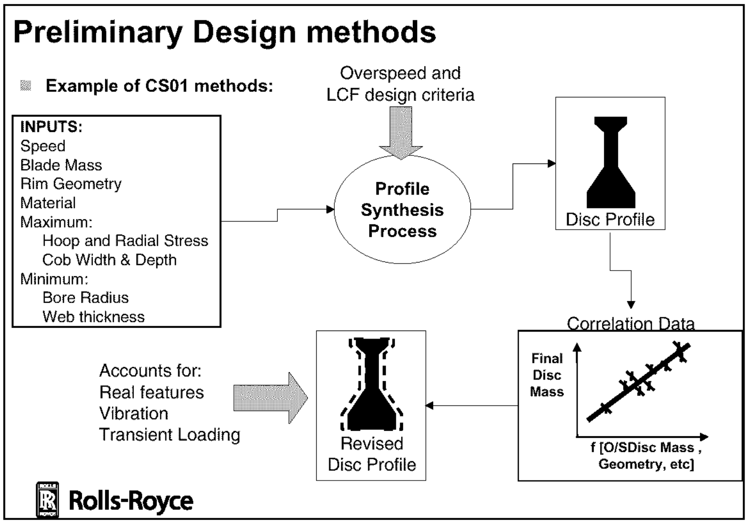


Figure 4. Genesis correlation effect

The main outputs from this element of the Genesis programme are the geometry and mass breakdown. The mass is defined for the whole engine (along with a centre of gravity) and also down to a reasonable level detail e.g. blades and discs.

Once these component attributes have been defined within Genesis this is passed downstream to the aircraft performance and cost analysis phases of the iteration.

2.3 Aircraft performance modelling

Aircraft performance modelling is generally the third step in the iteration problem and Rolls-Royce uses several codes to understand the effect of an engine design on the total weapons system. The most important to this phase in the design process is the scaling capability. This enable the engine to be scaled with the aircraft to understand how the size of the engine improves overall mission capability, e.g. larger engine, larger aircraft, more fuel = longer range. This information is critical to understanding the relationship between the customer requirements and exploring the trade between affordability and capability and its use will be shown later in the UCAV case study.

2.4 Cost calculation methods

The engine unit costing methods are again part of the Genesis package. They rely on geometric and mass data to define simple parameters such as features and numbers, e.g. compressor blades, discs etc. Correlations are applied to once again account for real world features.

The unit costs are calculated using a series of correlations and current cost rate information (manning and material data). The correlations account for scrap rates, casting features (e.g. runners, risers, inserts), machining times and assembly/test times, see figure 5 below.

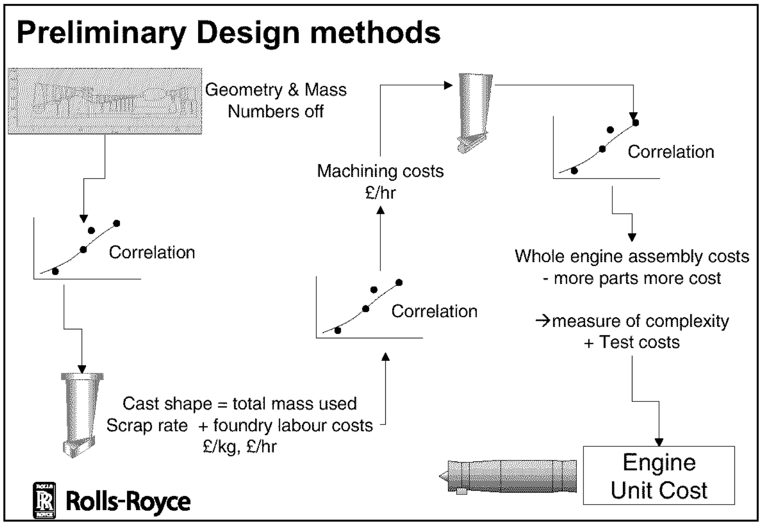


Figure 5. Genesis cost calculation

The development costs are traditionally calculated using correlations based on historical development programme costs. Recently methods have been developed to move away from this arguably pessimistic view. The new methods are risk based and allow the engineer to decide the level of "right-first-time" that will be achieved. This revision has been used to great effect when considering the development costs

The new methods provide the facility to vary the number of assets used during the bench and flight development programmes. Combined with a statistical analysis approach this method will output the least-likely or most-likely non-recurring costs.

The in service costs are calculated using information from the unit cost outputs with the addition of the following:

- Production investment
- Initial support, e.g. support equipment
- Maintenance material, e.g. engine spare parts
- Maintenance labour
- Sustained support, e.g. replacement support equipment
- Fuel and oil

The costs of the above service operations are calculated using a separate programme. This is an engine fleet maintenance simulation model that relies on statistical distributions to predict engine parts failure and rejection. This information is used to calculate investment spares and maintenance labour and material costs. The method takes account of; routine maintenance and inspection, probability of parts rejection due to primary failure, secondary damage or secondary inspection, and probability of repair or replacement.

Fuel and oil costs are approximated by using a mean mission fuel burn per hour, based on an historically derived % of the uninstalled engine max fuel flow. Oil is assumed to be a fixed factor of the fuel usage. The total cost per flying hour is then multiplied by the total fleet flying hours. Alternatively a more rigorous approach can be adopted whereby the engine capability is installed into an aircraft definition and then flown around a defined mission to calculate total mission fuel usage. Codes for this process are available within Rolls-Royce and airframe manufacturers.

The individual cost elements are combined in the 'Engine TLC' routines together with fleet assumptions to calculate the total engine fleet TLC. These routines also calculate Production Investment, Initial Support and Sustained Support costs based on historical data and the fleet assumptions. In addition, the routines take into account other factors such as learner rates associated with large production runs.

3.0 Example of Trade Study

The following is an example of how the tools described in the previous chapter have been used for a recent engine study.

The aim of the study was to examine the options for a new UCAV due to enter service in the latter part of the next decade. The airframe requirements were received from the aircraft manufacturer and the study team chose to consider five different engine types:

A. Off the shelf (available)
B. Off the shelf derivative with additional current technology
C. Off the shelf derivative with additional new technology
D. All new engine at current technology levels
E. All new engine with new technology

The examples of the engine architectures created in Genesis are displayed in the figure 6. The off-the-shelf engine (option A) is representative of a current military turbofan which is then modified (with a fixed core size) to give option B. Option C is derived directly from B with the addition of new LP spool technology. The new engines are D and E. Engine D is all new at current technology levels from and E is derived with the addition of new technology. The study team worked closely with the team from aircraft supplier to derive the scale and size of the engines.

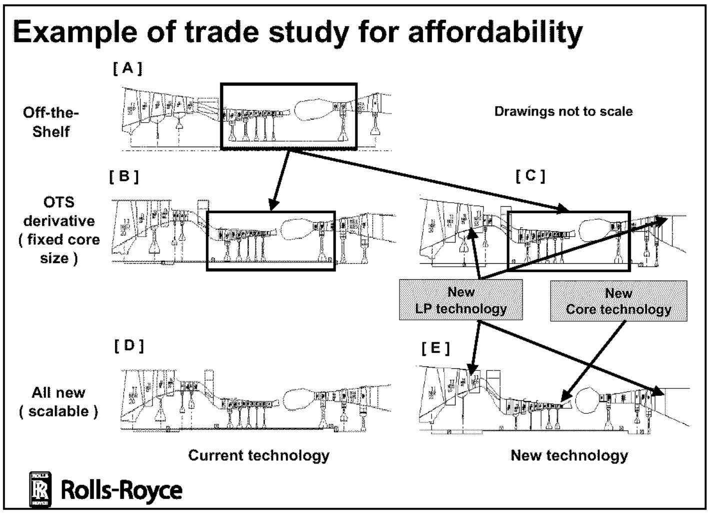


Figure 6. Engine architectures for trade study

The team took all of the engine options and created a series of cost models. The costs (unit, development and ultimately TLC) were calculated to permit a trade of capability vs. affordability.

The results of this study are plotted in figure 7. The engines are plotted against a datum requirement with the y-axis describing the relative TLC, the x-axis radius of action (a measure of capability), both as a % of a datum.

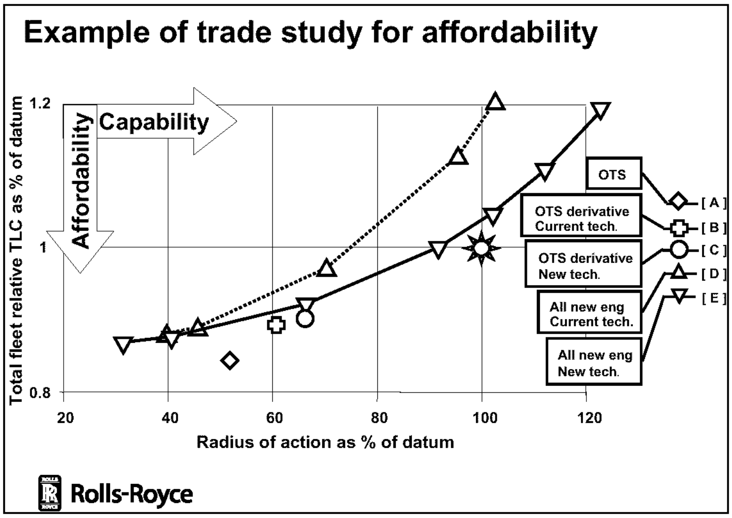


Figure 7. Capability vs. Affordability

The off-the-shelf engines are plotted as single points as they are of a fixed size whereas the all new engine have been scaled to permit a range of sizes. All engines have been modelled in a UCAV with a constant payload and in-flight performance.

From figure 9 it can be seen that the OTS engine achieves approximately 50% of the datum radius-of-action but for 16% lower TLC. A derivative engine, with current technology, will increase the radius-of-action to 60% of datum for an 11% saving in TLC relative to the datum. This is due to the better SFC of this engine and the higher thrust enabling a larger fuel fraction. Technology insertion into the LP system of the derivative engine increases the radius-of-action by a further 6%, relative to the datum, for virtually no increase in TLC. This TLC is approximately 6% less than an equivalent current technology all-new engine. For increases in range greater than this it is necessary to use an all-new engine where the scale of the engine can be increased to match the increase in vehicle size. There is a steady increase in LCC with radius-of-action as vehicle and engine size increases. At all but the lowest levels of radius-of-action the new technology all-new engine achieves a given radius-of-action for a lower LCC. This is due to the better SFC and the higher Thrust/weight ratios, both of which enable smaller and lower cost air-vehicles.

This study is an example of how affordability can be traded against capability and the next chapter will go on to discuss the future of the tools used to calculate this type of data.

4.0 Improving the solution

The dilemma faced by any preliminary design team is the need for accurate and comprehensive data and the obvious lack of any data at all. The following chapter will look at the relative accuracy of the Rolls-Royce PD tools and also review studies for future improvements.

4.1 Accuracy of the solution

The Genesis tools described in the previous chapters use a set of basic correlations against existing engine designs to provide the start point and enable the calculated data to be corrected for the real World. The accuracy of this method is relatively good as depicted in figure 8 below. The accuracy of the solution depends on the nature of the engine, e.g. mixed turbofans are generally very well modelled in Genesis, however, significantly different architectures are less well modelled.

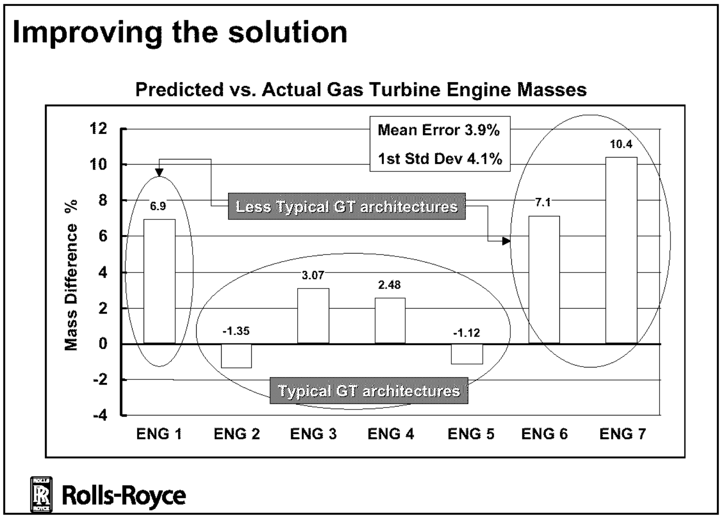


Figure 8. **Accuracy of Genesis models**

The differing levels of accuracy are due to the database being more populated with data from some types of powerplant, an obvious drawback with the correlation based methods employed. However, the mean error is only in the order of 4%, an accuracy level that is acceptable for this type of stage 1 tool

4.2 The design space

The example study that was carried out and described in the previous chapter highlighted the need for a comprehensive survey of the available design options. By completing a full survey, the proper choice between a new or derivative engine can be made and the proper compromise between capability and affordability chosen.

The next question asked of the preliminary design tools and methods is how to improve the coverage of the design space especially where a solution is more likely to develop. This improvement can be achieved through reduced computation times or use of computer driven intelligent optimisation techniques.

The computation time varies depending on the tool that is being employed. The definition of computation time can be simply defined as the time taken for the computer to execute a series of commands and achieve an answer. With today's computer systems this is less of an issue, the computation time for these relatively simple codes is small. The definition of computation time must therefore be broadened to include the time taken to first generate and subsequently modify the model.

The computation time for a full Genesis geometry model, using the above definition, is in the order of 25 hours for a new model, falling to approximately 10 minutes for a derivative model. This can be compared to the time taken to produce a full TLC model, a more complex and more stage 3-biased tool. On average a new TLC model can take over 80hrs falling to 25 hrs for a derivative model.

It is clear from the above comparison of computation time that a bottleneck downstream of the basic product data creation occurs. Methods development should be directed into this field especially if affordability is to be better understood and for it to emerge as a primary design driver.

Intelligent optimisation is the next step, providing that the time taken for each leg of the calculation is reduced to a more realistic time frame. There are many software codes available in the marketplace that are capable of multi-attribute optimisation (MAO). However, the real difficulty lies in defining how to move the gas turbine engine in a computer based optimisation environment and still use existing "tried-and-tested" modelling codes.

The intelligence in today's optimisation activities are driven by engineers with experience and a great understanding of the nature, form and being of a gas turbine engine. For true MAO to occur using this human interface will be extremely time consuming even if computation times are reduced. The computer offers the better solution but in order to achieve this transition, the computer will have to learn how the gas turbine works, learn how the armed forces operate engines and learn boundaries and limits to the mechanical machine. Research is underway in one of Rolls-Royce's groups within the USA in partnership with a technology University but the results are unfortunately not yet available.

A feature of computer driven optimisation is the need for the limits of design and the range of customer requirements to be defined simply and in such a way as to be understood by an computer. The next few paragraphs will describe one possible method of improving the understanding of customer requirements.

4.3 Understanding the Customers Requirements

The design limits are relatively easy to define, and indeed they can be bracketed to allow for new technology to be input into the process. However, customer requirements are not as easily understood or refined.

The solution to this is still being debated, however, a possible remedy has been developed and reviewed by the preliminary design team in Rolls-Royce. The solution is based on an analysis method developed by Japanese industry in the post-war period called Quality Function Deployment (QFD). QFD enables the engineering teams to take a set of customer requirements, weight them and turn them into a set of engineering attributes. An example of the customer requirements being used in current QFD analysis is shown in figure 9 below.

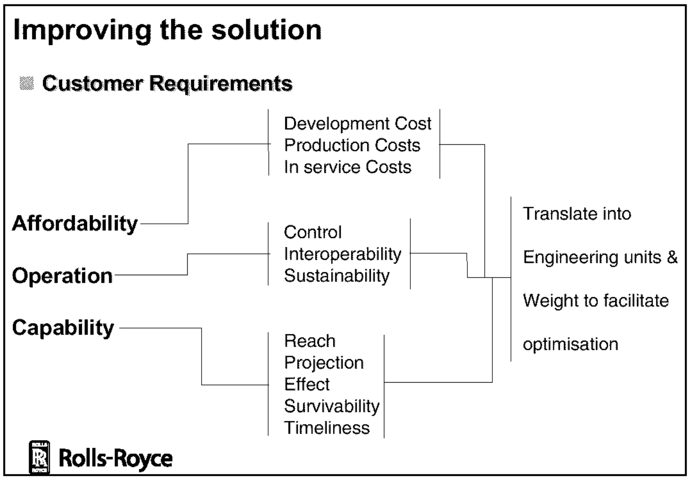
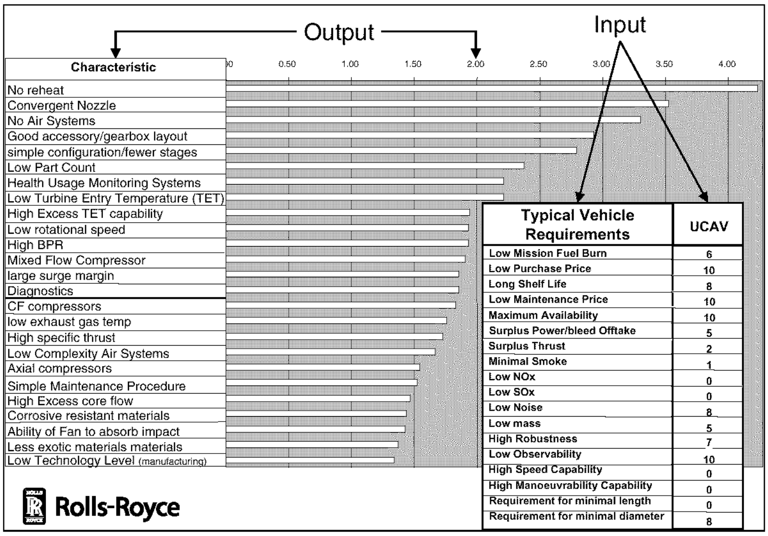


Figure 9. QFD customer requirements input

QFD enables the customer requirements, or WHATS, to be scored against the design criteria or HOWS. An example of the type of output being generated by the Rolls-Royce process is displayed in figure 10 below.



Typical Vehicle Requirements	UCAV
Low Mission Fuel Burn	6
Low Purchase Price	10
Long Shelf Life	8
Low Maintenance Price	10
Maximum Availability	10
Surplus Power/bleed Offtake	5
Surplus Thrust	2
Minimal Smoke	1
Low NOx	0
Low SOx	0
Low Noise	8
Low mass	5
High Robustness	7
Low Observability	10
High Speed Capability	0
High Manoeuvrability Capability	0
Requirement for minimal length	0
Requirement for minimal diameter	8

Figure 10. QFD example outputs

In the example above, the customer requirements are predominately focused on low cost and as a consequence the outputs focus on items like no re-heat, low parts count and simple configuration. Using data of the type produced by this example would eliminate some of the options available in the process, e.g. re-heat, and using the basic high level scoring of the customer requirements the optimisation could goal seek more effectively.

5.0 Learning from the past

Looking across the CCS life-cycle there is engine data available in all stages, the accuracy of the data improving as full maturity is reached. Returning to figure 3, the opportunity to increase the design knowledge and therefore reduce risk in stage 1 for derivative or growth engines is great.

A good example of where this opportunity will have greatest effect on affordability is reliability data. The reliability of engine hardware in service is extremely difficult to calculate let alone predict. However, it has a significant effect on maintenance requirements hence LCC and affordability. Therefore, if stage 4 data from fleet engines is imported into models used in stage 1 the accuracy of the solution will only be enhanced.

This future desire for data compatibility throughout the whole life-cycle of the gas turbine engine is currently being designed and worked by teams within Rolls-Royce. The systems design challenges are significant, however, they are perhaps less significant than those of getting the data from in service engines. Co-operation between manufacturers, suppliers and operators will be essential to achievement of this vision through the use of e-enabled environments.

The benefits to the Customer and manufacturers will be reduced risk, the opportunity for more right-first-time programmes and the reduction of overall TLC's. Of course, having more accurate stage 1 data does not lead automatically to this conclusion and it must be complemented by continued capability acquisition through rig or engine test data. However, it will mean that cost will be determined on the basis of robust data early in the design process where the level of design freedom is highest.

6.0 Summary

Rolls-Royce has developed a series of tools that enable is to quickly and reliably define gas turbine engines for the purposes of preliminary design. These tools define cycle data, geometry, mass, unit cost, development cost and finally through life costs. They have been developed to bridge the gap between the knowledge of a design and the determined cost of that design, the aim being to better predict the total impact of design decision as early as possible in the process.

The majority of the tools are at a level of maturity that would make further development a classic case of diminishing returns. However, some of the tools, especially those that have a significant impact on the ability to fully explore affordability aspects of a design are in need of development.

This paper has presented an example of the output from these tools and demonstrated an ability to assess the trade between capability and affordability. The intention behind this is to enable the customers of the future to define the acquisition in terms of capability but also in terms of affordability. To aid this process, Rolls-Royce is developing processes and tools that will enable customer requirements, specified in general terms, to be turned into engineering specifications and weighted to account for their relative importance.

The future of preliminary design tools described in this paper may be somewhat more complex. There is work ongoing within Rolls-Royce to enable more comprehensive surveys of the design space, to further bridge the gap between determined cost and knowledge. This future may include more automated optimisation and more sharing of data across the engine life-cycle. However, the challenges that these futures present are not to be underestimated and will require a great deal of co-operation between all levels of the manufacturing chain and the customer alike.

7.0 Acknowledgements

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It should be recognised that the views expressed in this paper are those of the authors and do not necessarily represent the policy of Rolls-Royce plc.