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A Systems Engineering Approach to Aero-Engine Life Cycle Costing

UTC for Computational Engineering

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Introduction

Life Cycle Cost (LCC) has been defined to be the total cost associated with the acquisition and ownership of a product or system over its full life. For aero-engine manufacturers, LCC has been identified to be important to their competitiveness. The consideration of LCC has been made even more pressing with the advent of engine leasing arrangements where the manufacturers take on the responsibility and costs of engine maintenance and support. In a leasing arrangement, an aero-engine which is not in use becomes a cost drain to the manufacturer. Thus for aero-engine manufacturers to increase revenue, they must consider the total LCC of their product rather than just acquisition costs. Conventional wisdom tells us that by the time full-scale development has been reached, a large proportion of LCC will already have been committed. Therefore, it is critical that the necessary tools are made available to the designer as early as possible to design for low LCC.

SE Enabled LCC Analysis Process

In general, life cycle cost models are unique to the system/product being analysed and the objectives of the study. There is no single LCC model that has been accepted as a standard model and is in widespread use. There are several factors to why this is the case:

- The diverse nature of the problem;
- The use of different types of equipment, devices or systems;
- The inclination of the user.

Cost modelling is also knowledge intensive and requires skills and knowledge capture from a number of disparate disciplines. A cost model for an aero-engine needs to be able to consider multiple disciplines in order to capture the interactions involved and to facilitate making design tradeoffs.

As the number of systems considered rises, the number interactions between them will rise too. Systems Engineering (SE) methods should hence be used to identify and capture these interactions. Figure 1 shows how SE was incorporated in the LCC process.

Case Study: LCC vs. TET, Cooling Flow Fraction

There has been an initiative for aero-engine manufacturers to reduce fuel consumption of their engines. This trend is motivated by the uncertainty in fuel prices and the competition between the aero-engine manufacturers to provide the most competitive engine in terms of LCC. It is well documented in the gas turbine literature that raising Turbine Entry Temperature (TET) will result in an improvement in specific fuel consumption (SFC) and hence reduce fuel costs. However, raising TET affects a whole host of other factors, one of which is the amount of turbine blade cooling required. With regards to LCC, the amount of cooling flow used can have several effects. Firstly, it influences the thermal efficiency of the turbine which in turn influences fuel consumption. Secondly, the amount of cooling flow changes with the required cooling effectiveness; which is a measure of the achieved temperature gradient between the mainstream gas and blade surface temperatures. Therefore a higher blade surface temperature will reduce the cooling flow requirement but increase maintenance costs due to accelerated deterioration mechanisms. Minimising LCC will hence depend on finding a balance between these competing factors. This case study is an example of how far-reaching decisions made in the design stage can be. It also highlights the need for an approach that can consider the problem from several perspectives.

Objectives and Scope

The main objective of this study is to perform a comparative analysis on how the Turbine Entry Temperature (TET) and the Cooling Flow Fraction of the turbine blades can affect the LCC of an aero -engine. Only the High Pressure (HP) turbine stages will be modelled as these are most directly impacted by changes in TET. Nozzle Guide Vanes (NGV) and turbine discs have not been considered for this case study.

System Model

Figure 2 shows the IDEF0 diagram for this case study. It illustrates the various function and data flows required to relate LCC to the two study inputs; TET and cooling flow fraction.

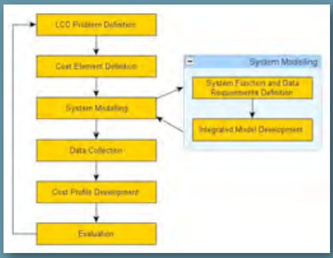

Figure 1: SE in the LCC analysis process.

Model Integration

Figure 3 shows the implementation of the system model, shown in Figure 2, in a commercial software integration package, iSight-FD. Software integration packages provide the capability to link analysis models and define the analysis sequence and process.

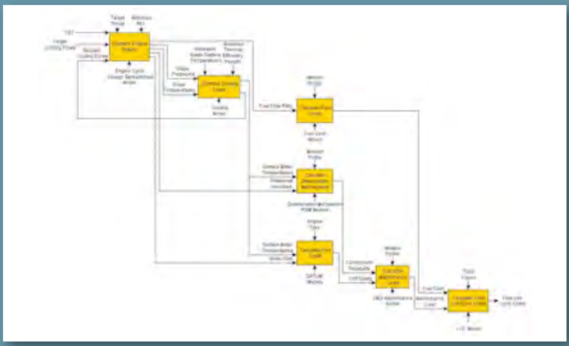

Figure 2: Case study IDEF0 system model.

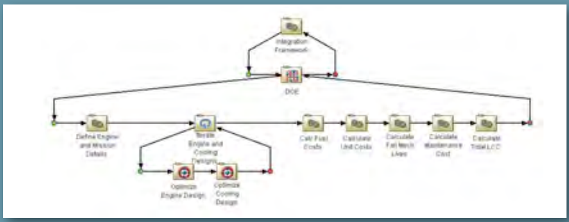

Figure 3: Integration workflow developed in iSight-FD.

Results and Discussion

The range of input values for this case study was 1400 K to 2200 K for TET and 0.05 to 0.3 for the cooling flow fraction. Figures 4 and 5 show the contour plots of fuel costs and maintenance costs respectively against TET and cooling flow fraction. Fuel cost was found to be minimum at maximum TET and minimum cooling flow fraction. This behaviour can be attributed to the improved SFC at higher TETs and reduced thermal efficiency penalties due to cooling. Maintenance cost is lowest at minimum TET and maximum cooling flow fraction because this combination of factors produces the lowest turbine blade metal surface temperatures. As a result, the creep and fatigue lives of the components would be extended.

It is immediately apparent from the above contour plots that the trends of fuel cost and maintenance cost are in direct competition with one another. Performing a LCC analysis gives the cumulative effect of these two competing factors. Figure 6 shows the relationship of LCC against TET and total cooling fraction.

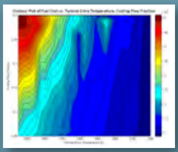

Figure 4: Contour plot of fuel costs against TET and total cooling fraction.

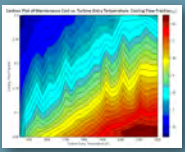

Figure 5: Contour plot of maintenance costs against TET and total cooling fraction.

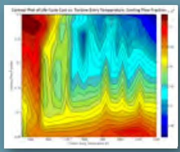

Figure 6: Contour plot of Life Cycle Cost against TET and Cooling Flow Fraction.

Some of the models used in this study are crude approximations of actual tools that should be used for a more accurate study. The behaviour of the models however is consistent with general engineering judgement. The trade-off between fuel and maintenance costs is a genuine consideration in modern aero-engines. Ultimately this initial study presents an approach that integrates models of different disciplines and system levels to allow the system under study to be analysed from different aspects.

Summary

LCC models are difficult to standardize because of the multi-disciplinary, cross system level demands of a LCC analysis. These demands are even greater when the product of interest is as complex as an aero-engine. A complex system will contain many sub-systems and components with various physical and functional interactions. LCC models in the surveyed literature do not consider this aspect. A SE approach to the LCC process was thus proposed. It uses SE methods to identify and capture function and data flows between the different systems involved. This process was applied to a case study which looked at how TET and cooling flow fractions impact the LCC of an aero-engine in operation. The study demonstrates the process of making design trade-offs in the calculation of LCC.

Acknowledgements

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