Institution: City University London

Unit of Assessment: 15 General Engineering

Title of case study: Design for Reliability – shortening the time to market; improving working practices; improving product performance

1. Summary of the impact

Software has been developed by City University London in cooperation with Rolls-Royce that exploits the strengths of Bayesian statistics in improving the design of aircraft engines. The software, '4Cast', allows engineers to elicit design characteristics that in turn allow the design to be modelled relative to reliability targets. The targets are determined by failure rates. This enables better evaluation of design choices and of the risk of faults and failures in engines and supports rapid decisions as to whether a proposed design meets requirements.

By using 4Cast to enumerate reliability, Rolls-Royce has been able to determine confidence in asset management and in project management policies. 4Cast also supports Rolls-Royce's programme to reduce the so-called 'Disruption Index', a measure of the cost of supporting an engine.

The software has had a significant impact on the business performance and consequent economic achievement of Rolls-Royce, a global company supporting civil and defence aerospace, marine and energy markets worldwide.

2. Underpinning research

Survival analysis models the time between failures in equipment and aims to understand the risk of failure, the factors influencing the risk and the prediction of the time of failure. Research in survival analysis and in stochastic operational research began in the 1980s, with the aim of improving the reliability and availability of plant and equipment. The insights gained allow the removal, avoidance, mitigation and management of failures and their causes. At City research in this area has been undertaken by Professor Martin Newby since 1995. The work has been supported through several contracts and cooperative arrangements since 1998, valued at approximately £525,000 (listed in section 3).

The research developed general modelling techniques and software to support design teams. Improvements in reliability, arising out of survival analysis, can have a significant economic impact, allowing for the prediction of future failure. The technical work has been linked to the design process in the capital goods sector where there is strong pressure to shorten the time to market, to ensure high levels of availability and to reduce maintenance and support costs.

Key findings are in the way the techniques of Bayesian statistics can be exploited to provide a link between the needs of the key stakeholders and the statistical and probabilistic modelling that support decision-making. A significant contribution is the improved ability of engineers and designers to build survival models which explicitly incorporate their knowledge and expertise and which learn from empirical and objective data as they become available. In addition the approach facilitates a formal record of the factors influencing design decisions and quantifies their effects.

The three elements of the approach using Bayesian statistics are: elicitation of prior knowledge; using the models to predict product lifetimes; and communicating to the engineers, designers or users of the equipment. The software in 4Cast provides the means of elicitation and presentation in a clear and accessible way through a graphical user interface and records the decisions made as the engineers develop their design. 4Cast takes test and field data and uses prior-posterior analysis to verify and validate the actual design achievement.

3. References to the research

Key publications:

1. Newby M.J., Douglas M., Thomas A. & Tsachouridis V. (2006). *Rolls-Royce – Final report*.
2. Newby M., Houben M. & Sonnemans P. (2010). *Soft Systems and Risk Assessment*, Invited Talk, Royal Statistical Conference RSS2010, Brighton, September 2010
3. Newby M., Barros A. & Grall A. (2012). *Threshold Crossings and Survival Analysis*, Mathematical Methods in Reliability Research, Presentation, London Mathematical Society Meeting, Brunel University, May 2012
4. Sari J.K., Newby M.J., Brombacher A.C. & Tang L.C. (2009). Bivariate Constant Stress Degradation Model: LED Lighting System Reliability Estimation with Two-stage Modelling. *Quality and Reliability International*, 25(8), 1067-1084 10.1002/qre.1022
5. Balasubramanian A., Kevrekidis K., Sonnemans P. & Newby M. (2008). Identifying Factors Influencing Reliability of Professional Systems. In *Annual Reliability and Maintainability Symposium, 2008 Proceedings*, pp. 66-71 10.1109/RAMS.2008.4925771
6. Houben M.J.H.A., Sonnemans P.J.M., Stollman G.M. & Newby M.J. (2009). Reliability Prediction Through Bayesian Inference Based On Product Change. In *Annual Reliability and Maintainability Symposium, 2009 Proceedings*, pp. 293-298 10.1109/RAMS.2009.4914691
7. Newby M. (1994). Perspective On Weibull Proportional-Hazards Models. *IEEE Transactions On Reliability*, 43(2), 217-223.
8. Coolen F.P.A. & Newby M.J. (1994). Bayesian reliability analysis with imprecise prior probabilities. *Reliability Engineering and System Safety*, 43(1), 75-85 10.1016/0951-8320(94)90096-5

The research has been published in highly-regarded journals which undertake rigorous double-blind peer review in the selection of articles. It has also been selected for presentation at top conferences in the field which also have wide reach amongst professionals and companies.

Grants in support of the research:

1. *Design for Reliability,* supported by the Department of Trade and Industry's major initiative on Defence and Aerospace Research Partnerships (DARP) launched in 1998 and Rolls-Royce Commercial Engines. Led to the development of 4Cast
2. *Reliability Modelling and Diagnostics,* supported by Rolls-Royce
3. *Ultra-Reliable Aircraft Project*: *Design For Reliability Software Tools* jointly with Warwick Manufacturing Systems, supported by DARP
4. Interdisciplinary Research Collaboration in *Dependability of Computer-Based Systems: Complex System Reliability*
5. *Stochastic Models for Maintenance,* Dr E Boguslavskaya, post-doctoral researcher (employed at City 2005 to 2008)
6. *Maintenance Planning and Optimisation,* two completed PhDs.

4. Details of the impact

The viability of the business case for an engine rests, among other things, on whether it meets reliability requirements. By improving and automating the ease of use and communication of results, 4Cast allows engineers and designers to do many more analyses. The Weibull continuous probability distribution is used as a standard to characterise reliability in the aerospace and defence sectors: 4Cast provides a simple and efficient means of performing Weibull analysis. 4Cast graphics show the prior lifetime distributions and the predicted lifetime distributions and provide a visual comparison of the achieved reliability and required Reliability Target Line (RTL). The collaboration with Rolls-Royce extended across several global sectors of the business, originating with the Rolls-Royce Safety and Reliability group and extending to both the Aerospace and Energy sectors of the company.

Improved working practices

The design process at Rolls-Royce Aerospace is highly detailed and requires designers and engineers to make reliability assessments for many systems, subsystems and components at each

milestone in a project. Typically a design is broken down into subsystems and components: for example, an engine contains several compressor discs and a compressor disc consists of several blades anchored in a disc.

4cast allows the behaviour of each component and subsystem to be modelled, taking into account design decisions and expected operating conditions. Outputs are combined to model the failure behaviour of the whole engine. 4Cast is embedded within the Rolls-Royce 'Airlines Local Procedure' (ALP C.2.6/13) *Reliability Target Lines,* issued in July 2009. The Reliability Target Lines (RTL) is determined as a minimum reliability that still gives a profitable business case. In the RTL procedure the overall reliability is shared across the components based on service experience with other engines. The procedure compares the predicted or achieved reliability with the target component by component, allowing the design to be accepted without change, managed or rejected depending on whether it meets the requirements of the business case. The Trent XWB (the engine for Airbus 350) project was the first to adopt this approach in 2008 and uses 4Cast extensively. An example is given in the *Reliability Target Lines for the Trent XWB LP Turbine*.[1]

Assessing reliability requires as much data from users' experiences as objective data. 4Cast allows users to input all kinds of relevant data. Through instant feedback and the ability to explore scenarios designers are able to experiment with alternatives. As objective data become available in later stages, so the prediction of reliability improves and certainty increases. The modelling and software make explicit the assumptions, the quality of data and the level of uncertainty to support the designer. Analyses of historical data carried out using 4Cast have also identified formerly unrecognised risk factors in engine failures. Scenarios based on design choices then feed into the modelling of lifecycle costs and maintenance planning which in turn are the basis for contract pricing used in the "Power by the hour" approach, Rolls-Royce's pioneering approach to engine maintenance management, which forms the basis of the company's market-leading CorporateCare® service.[2, 3, 5]

4Cast uses formal design methodologies and problem structuring techniques supplemented by generic and company databases of component data and engineering parameters. The explicit incorporation of these formal methodologies force design teams to record accurately the basis of their models and the roles of those involved in the design choices. This formality improves the traceability of design changes and provides version control to avoid errors, for example a choice of incompatible materials or components.

The simplicity of use also puts the control of modelling and analysis in the ownership of the project team and so improves teamwork. Previously teams were dependent on specialist skill and resource owners to carry out the modelling.

4Cast software has been used throughout the Rolls-Royce group since 2006. The software has been deployed to model and improve the performance of combustion chambers in Rolls-Royce's family of Trent engines, used in electricity generation[4]. In response to the analysis, the design of the combustion chambers was adapted to reduce the effects of thermal fatigue and extend the working life. The software has also provided graphics and illustrations to communicate the results to designers and clients.

Economic Impact

The capital goods industry has changed from one in which the product is sold (often below cost) and profit is generated by after-sales service and support, to a service model in which all after-sales support is included in an initial price and contract. This change requires risk assessment and life cycle costs to be estimated from the outset of a project in order to sustain returns to the company. The determinant of economic success is the availability of the system: the proportion of time that the system can earn revenue. Interruptions to service reduce earnings and incur costs for maintenance and compensation. Rolls-Royce measures loss of engine availability and its consequences in a Disruption Index. The 4Cast software is used as part of a programme to reduce the Disruption Index[2] to 20% of its current value with a potential saving of around $8M per month.

The software has had a significant impact on the business performance and consequent economic achievement of Rolls-Royce, a global company supporting the civil and defence aerospace, marine and energy markets worldwide. Their Chief Safety and Reliability Engineer says: "*The importance of [using 4Cast to determine acceptability of the reliability characterisation of our latest engine designs] is that the results from this exercise have now been used in life-cycle cost estimations that underpin the business case for the engine type being evaluated. Decisions are being made based on results which 4Cast has contributed. … The importance of gaining confidence in the engine before entry into service cannot be stressed enough and … the role that 4Cast plays in Rolls-Royce in achieving this is evident.*"

5. Sources to corroborate the impact

1. Reliability Target Lines for the Trent XWB LP Turbine (IRP01215, 25th Feb 2011), Anuzis, P, Rolls-Royce Aerospace
2. Guidance for ALP C.2.6/13 "Setting Design Targets for Reliability", Anuzis, P, Rolls-Royce Aerospace
3. Rolls-Royce Airlines Local Procedure (ALP C.2.6/13) *Reliability Target Lines*, Anuzis, P
4. Industrial Trent MK3 DLE Secondary Ring – Thermal Fatigue, Thomas, D
5. Overview of Reliability Target Setting and Assessment of Design Status, Anuzis, P
6. Letter of corroboration from Chief Safety and Reliability Engineer, Rolls-Royce