Redesigning the design process through interactive simulation: A case study of life-cycle engineering in jet engine conceptual design

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Abstract: Many aerospace companies are currently making the transition to providing fully-integrated product-service offerings in which their products are designed from the outset with lifecycle considerations in mind. Based on a case study at Rolls-Royce, Civil Aerospace, this paper demonstrates how an interactive approach to process simulation can be used to support the redesign of existing design processes in order to incorporate life-cycle engineering (LCE) considerations. The case study provides insights into the problems of redesigning the conceptual stages of a complex, concurrent engineering design process and the practical value of process simulation as a tool to support the specification of process changes in the context of engineering design. The paper also illustrates how development of a simulation model can provide significant benefit to companies through the understanding of process behaviour that is gained through validating the behaviour of the model using different design and iteration scenarios.

Keywords: Jet engine design, Life-Cycle Engineering (LCE), process change, design process simulation, Applied Signposting Model (ASM)

1 Introduction

Engineering companies have traditionally sold products, which customers purchased and owned until they were decommissioned or re-sold. Companies also provided warranties and spare parts to these customers, who were responsible for maintaining the products that they had purchased. However, this business model is changing because of the increased servitization of manufacturing industry (Baines et al., 2009) – i.e., the move from selling products to selling product-service systems (PSS) (Baines et al., 2007). Manufacturers are being driven to offer services in conjunction with their products for various economic, customer and competitive reasons (Gebauer, 2007; Oliva and Kallenberg, 2003) and aerospace companies are seen as leading this trend (Johnstone et al., 2009; Ward and Graves, 2007). Aircraft and their engines are now frequently leased, or operated on service contracts, with the manufacturer retaining ownership of the product and being responsible for its maintenance over its entire life. In order to maximise profitability in these circumstances, there is a strong incentive for companies to design products and services together with the full product life-cycle in mind from the outset. This requires companies to address a wide range of strategic, commercial, operational, structural, people and information systems factors (Ward and Graves, 2007). Cultural changes are required to develop the necessary customer and market-orientation among engineers and promote cooperation and interaction between the product and service sides of the business (Grant, 2009; Johnstone et al., 2009). At the same time, tools and techniques are needed for service design, organisational design and organisational transformation (Baines et al., 2009).

In this paper, we consider the use of activity-based process modelling as a technique for organisation design and transformation. We draw on a case study at Rolls-Royce, Civil Aerospace, to argue that the complex design process changes required to integrate life-cycle engineering (LCE) activities (Wanyama et al., 2003) into an existing design process, can be facilitated using an iterative and interactive approach that uses process simulation alongside less formal process mapping activities. Section 2 provides an overview of life-cycle engineering and of process mapping and simulation as a method to help design and evaluate the types of process changes that LCE introduction requires. Section 3 provides an overview of the modelling methodology used by the authors. Section 4 introduces the case study on which the paper is based. It provides a high-level overview of the jet engine design process, describes the business context of the modelling and simulation work undertaken at Rolls-Royce, Civil Aerospace. Section 5 describes the process modelling intervention. Section 6 then details part of this work in depth to illustrate the main argument of this paper: how process simulation was applied in the context of the study and the benefits which were drawn from our simulation approach. Section 7 reflects on the case study and shows how the business-oriented objectives were met through iterative and interactive application of process modelling and simulation. It then discusses the limitations of this specific case study. Section 8 reflects more generally on the insights gained from the study and their implications for the application of process mapping and simulation to improving complex engineering design processes. Section 9 concludes the paper.

2 Background

2.1 Life-cycle engineering

Rather than simply selling products, engineering companies are increasing selling their customers combinations of products and services to meet their needs, generally referred to as Product-Service Systems (PSS). Mont (2002: 239) defines a PSS as a "system of products, services, supporting networks and infrastructure that is designed to be competitive, satisfy customer needs and have a lower environmental impact than traditional business models". The PSS approach recognises that products and services have to be designed in conjunction to provide an integrated solution, no matter whether the business concerns are purely customer-focused or also bring in other stakeholder objectives, such as environmental sustainability (Oliva and Kallenberg, 2003). Not only do designers have to have to consider how products and services perform together in the context of the customers' operations and processes (Davies, 2003), they also have to design the PSS with the full lifecycle in mind (Ishii, 1995).

This paper focuses on one aspect of PSS development, namely Life-Cycle Engineering (LCE) (Ishii, 1995; Janz and Westkämper, 2007; Wanyama et al., 2003). The objective of LCE is to develop more profitable products and services by considering the economics of the entire product life-cycle while satisfying customer, technical, regulatory and ecological requirements (Janz and Westkämper, 2007). Implementing LCE typically requires change to the product design process because the majority of life-cycle costs – some authors estimate 70-80% – are determined during design (Dimache et al., 2007; Newnes et al., 2008). These changes involve the incorporation of additional product requirements, particularly those related to service, into the existing product design process.

In order to identify, understand and incorporate these requirements into the product design, integration is needed between the different departments and functions involved in design, development and provision, which involves new processes and other organisational changes (Grant, 2009; Johnstone et al., 2009; Ward and Graves, 2007). Incorporating LCE into an existing design process is difficult when that process is already highly complex, tightly integrated and constrained by the need to meet many existing requirements. This is typically the case for companies which develop complex, high-performance products such as those found in the aerospace industry. The design processes in such companies are particularly complex due to their iterative nature (Browning et al., 2006), emphasis on Concurrent Engineering (CE) practices (Ainscough and Yazdani, 2000; Maylor, 1997), and the need to co-ordinate the work of specialist teams (Eckert et al., 2008). Participants often have limited overview of how these processes operate, due in part to the specialised nature of most design work and due to designers' focus on the product, rather than the way it is designed (Flanagan et al., 2007). Thus, when planning to integrate LCE considerations into existing ways of working, it is necessary first to understand the design process which is actually followed, and then to build a consensus among process participants on what changes will need to be made.

2.2 Process mapping and simulation as an interactive design tool

Process modelling is a widely recognised and accepted approach for visualising processes and supporting the planning of process change (e.g. Browning and Ramasesh, 2007; Curtis et al., 1992). The activity-based modelling approach – which is widely used in industry and considered in this paper – views a design process as a system which can be decomposed into a network of interconnected elements such as tasks, deliverables and resources. This contrasts with system dynamics modelling (e.g. Chuang and Chen, 2009) which conceptualises a system in terms of feedback loops and the stocks and flows of entities. Activity-based models can be used for several purposes, including: process visualisation; process planning; process execution and control; and process development and improvement (Browning and Ramasesh, 2007). Activity-based modelling of design processes is predicated on the assumption that, despite the novelty and ambiguity involved in specific projects, design processes have an underlying, repeatable structure that can be identified and therefore modelled (Browning et al., 2006).

Activity-based models can take a number of forms and be analysed in a number of different ways (Browning and Ramasesh, 2007). Many process models used by industry in practice take the form of process flowcharts which are analysed by inspection (Vergidis et al., 2008). Nevertheless there are an increasing number of modelling software tools that allow process simulation, such as ARIS (Scheer, 2000) and Simul8 (Concannon et al., 2003); although the number that are specifically designed for simulating engineering design processes is limited (see for example Wynn et al., 2006).

The benefits of process simulation have been widely discussed in the literature (see Vergidis et al., 2008). However, a survey conducted by Melão and Pidd (2003) found that many organisations do not make use of process simulation, even when they are aware of or trained in its methods. This paper demonstrates some of the benefits of simulating design processes based on process flowcharts. In particular, we will argue that constructing a simulation requires modellers and domain experts to consider the implications of a proposed process change in much greater detail than a descriptive flowchart model alone. We use an example to show that many of these implications are not immediately obvious and can easily be overlooked when considering a purely descriptive model. Drawing on the case study, we argue that their consideration helps build a better understanding and achieve stakeholder buy-in to proposed changes than can be achieved through non-simulation modelling methods. In this context, simulation is viewed as an interactive method to support the design of processes through several iterations with significant stakeholder involvement.

3 Modelling methodology

This paper reflects upon a modelling intervention performed by the authors at Rolls-Royce, Civil Aerospace between in November 2005 and April 2008. In overview an activity-based model of the activities, information flows and resources in the existing conceptual design process was constructed using the Applied Signposting Method (ASM) implemented in the P3 software platform (Wynn et al., 2006), now known as Cambridge Advanced Modeller (CAM). The ASM method has been developed by the authors and provides a formal modelling language that combines a process flowcharting notation for process mapping (as shown in Figure 1 below) with functionality to perform discrete event simulations of these models. Task properties, such as task duration and outcome, may be specified as probability distributions or programmed for greater control over the simulation behaviour. For example, the duration of a task might be programmed to reflect a reduction in duration on each consecutive attempt. Simulation then proceeds according to the task properties and the structure of the information flow network. The steps taken to construct the simulation model are outlined in Figure 2.

<Insert Figure 1 here>

<Insert Figure 2 here>

The modelling intervention started with the researchers agreeing the objectives for the work with the company. Data was then gathered broadly about the current ("as-is") design process and the changes to be incorporated into future ("to-be") situation. The model scope and conceptual model structure were then agreed between the researchers and the company. A descriptive model was then constructed. This description was then used to localise the proposed life-cycle engineering activities within the workflow. The resulting model indicated when life-cycle costing activities had to be undertaken to assure the economic viability of the product. Simulation was then used to explore the consequences of the proposed change in detail and thereby build an improved understanding of the new process among the various stakeholders prior to its implementation in practice. In practice the whole process was highly iterative both within and between each of the steps shown in Figure 2 above.

The next section describes the background of the case study. This is followed in Sections 5 and 6 with a more detailed description of how the authors applied this modelling methodology in this particular case.

4 Case study background

Rolls-Royce, Civil Aerospace, is a world-leading manufacturer of jet engines for the civil aerospace sector. Like many other engineering firms, it increasingly offers its products under total service agreements. Under programmes such as Power By The Hour® and TotalCare® its customers pay for the time they use the product and responsibility for servicing or maintaining the jet engine remains with the company. The risk of ownership is transferred from the customer to Rolls-Royce allowing the customers to concentrate on their own core competencies. Rolls-Royce therefore has a strong incentive to ensure that the total lifecycle costs of an engine fleet over its entire lifetime are as low as possible.

4.1 Designing Jet Engines

The process of designing a jet engine takes many years and involves teams of hundreds of engineers within Rolls-Royce and across its supply chain. There are thousands of separate components which, when integrated, must deliver an optimum mix of performance characteristics in relation to the various requirements for the engine. These requirements, many of which are in conflict, include engine thrust, fuel consumption, weight, performance degradation over time due to engine deterioration, unit and maintenance costs and legislative requirements that must be met for engine certification, such as those concerning noise, emissions and safety (Kirk, 2003). Consequently, the design of a jet engine is a complex, multi-objective process. It is highly constrained by multiple requirements, established solution principles, design tools and ways of working. It is also complicated by "cliff-edge effects": discontinuities in the design space due to the discrete nature of some of the key parameters, such as the number of blade rows in a compressor stage (Jarrett et al., 2007). Small changes in one design parameter can move the whole design a long way from the desired performance characteristics (Eckert et al., 2005). The search for the best mix of design attributes results in an iterative "fine tuning" process as the repercussions of design decisions become evident. Many of these characteristics are common to other engineering design domains, such as helicopter rotor blade design (Clarkson and Hamilton, 2000).

In order to handle the complexity involved, jet engine design is evolutionary based on successive modification within product families, each of which has a common underlying architecture e.g. Rolls-Royce's Trent series for wide-bodied commercial aircraft (Kirk, 2003). Designers can make design decisions based on correlations with existing designs and the experience of actual operation of those existing designs. One benefit of this evolutionary design approach is to reduce the risk associated with early design decisions, since such decisions can have consequences which are only revealed much later in the process. Another consequence is that the processes by which new engines are developed remain relatively similar across product generations, even during the early conceptual design process which is usually associated with ill-defined activities and information flows. This in turn makes the design process amenable to process modelling and structured, systems engineering, process improvement techniques.

4.2 Design for Service Programme

In 2002 Rolls-Royce made a strategic decision to offer all new engines under its TotalCare® offering, whereby airlines purchase flight time at a predefined rate. Although older engines and some contracts on new engines will still be offered on a maintenance time and spare part basis, the company is expecting to move predominantly to these total care contracts. The profitability of these contracts depends on establishing the right cost per-hour for the fleet of engines and designing the engine accordingly. Rolls-Royce identified that there was a significant opportunity to reduce the costs associated with both planned and unplanned engine maintenance. These costs not only include the time and materials cost of the maintenance itself – e.g. the repair or replacement of worn out or damaged components – but also the lost revenue when an engine is not flying. The key to reducing these costs is "understanding the engine's deterioration mechanisms, controlling their rate of occurrence and impact, and ensuring effective and low cost restoration of capability at overhaul" (Harrison, 2006). Components should be designed so that their lives correspond to multiples of the planned intervals between engine overhauls. For example, a component that lasts 1.9 intervals has to be replaced at every overhaul and nearly half of its potential life is thrown away (Eckert et al., 2008). Engineers have been educated in the importance of "Design for Service" and a programme instigated to develop LCC analysis tools for their use. As LCC critically depends on extrapolating reliable data from past products to current designs, significant investments have been made to make service information available to them. Engineers have been placed at the overhaul bases to gain an understanding of service issues. Service information is documented and stored in databases for design engineers to access. Service information for components with a significant impact on LCC – such as those which operate at very high temperatures and therefore have limited lives – is specifically gathered and analyzed by the service design team, leading to high-level design decisions for these components such as life targets and coatings.

4.3 LCE during Jet Engine Conceptual Design

Building upon the Design for Service programme already underway, Rolls-Royce, Civil Aerospace, aims to incorporate life-cycle engineering considerations from the outset of the product and service design process. This focus on early-stage conceptual design arises from two considerations. Firstly, from an engineering perspective there is greatest scope for innovation at this stage and therefore the possibility to consider and evaluate radically different product configurations which might better meet the trade-off between LCC and other design objectives. Secondly, the aircraft manufacturers expect price commitments at the earliest stages in the design process as they require an explicit hourly rate early on to include in the overall cost of ownership offering to their customers. Therefore the earlier life-cycle costs are considered the greater is the opportunity to manage the financial risks associated with each project.

Conceptual design is performed at the outset of a project prior to contracts being signed with customers and prior to the large-scale commitment of engineering resources. Currently the majority of this early, conceptual design work is carried out by a single team which specialises in this area, and which draws on the specialist expertise of other engineering teams as required. Ensuring LCE considerations are addressed from the outset of the design process would require this team to be more closely integrated with the commercial and service design teams.

It was recognised by Rolls-Royce that this would necessitate changes to the conceptual design process. In particular, there would need to be greater interaction between the conceptual product design team and the team responsible for specifying life-cycle cost requirements. To achieve this within the existing time constraints for design, the two teams would have to work concurrently and co-ordinate their work to set the product requirements and subsequently to evaluate the resulting designs. This would require additional design tasks and feasibility evaluations and, therefore, could result in additional design iteration, which could be problematic if it extended the design time. Consequently the company engaged the authors to model the early stages of the conceptual design process of a new civil jet engine.

5 The modelling intervention

The authors' modelling intervention followed the steps shown in Figure 2 and outlined in Section 3 above.

5.1 Objectives

The objective of the modelling was to transform the high-level LCE objectives outlined above into an understanding among the process stakeholders of how, by whom and when in the process they would be implemented. The proposed changes to the conceptual design process would be formalised in a model – resulting in a documented, canonical process which could be followed by future projects. In particular, Rolls-Royce asked the researchers to address the following questions:

1. *Structure of the new process.* What changes should be made to the structure of the existing process to incorporate LCE considerations? What new tasks will be performed by the conceptual designers and what information will be needed to support effective LCE? How should these new tasks be incorporated and what effect does this have on the existing process structure and information flows?
2. *Resourcing the new process.* Will additional resources be required to design new engines when LCE considerations are incorporated into the process? How much extra work will each team have to do? How much will this cost?
3. *Performance of the new process.* How long will the revised process take to produce an engine conceptual design? How does this compare with the current process and with customer expectations of responsiveness to Requests For Information (RFIs) and Requests For Proposal (RFPs), which are used by the customer to gather information about supplier capabilities?

5.2 Data Gathering

The starting point for integrating the LCE activities was to gain an overview of the existing (“as-is”) process. Although it was recognised that all projects would be different, as a starting point the Trent 1000 engine was chosen as a reference project for which the conceptual design phase was complete. 34 semi-structured knowledge elicitation interviews were conducted with 27 different personnel who had worked on this project in various roles and levels of seniority (see Table 1 for a breakdown by business function). This was supplemented by studying process documentation suggested by the interviewees. Once the data for the “as-is” process was obtained, the remaining steps, including iterations, took just over 12 months. Most of the information needed for the later steps was elicited from 10 key stakeholders in the process, each with their own domain of expertise.

<Insert Table 1 here>

5.3 Model scoping and structuring

The next step was to determine the scope and overall structure of the models:

Scope. The broad scope of the process to be modelled had been determined *a priori* by the overall objective of incorporating LCE considerations into conceptual design. Nevertheless, due to time limitations and the project's focus on changing the engineering design process, the researchers agreed with Rolls-Royce to concentrate modelling on the product design tasks and indicate their interactions with business and service teams, rather than model all three elements in similar detail. The first two stages (identification of product needs to concept release) of the design process of the Trent 1000 engine were modelled using the Applied Signposting approach and the P3 software (Wynn et al., 2006). Development of the desired “to-be” process proceeded in parallel with refinement of the “as-is” model, since they needed to be comparable for evaluation purposes.

Structure. The structure of the model was developed in stages. Firstly, it was recognised that conceptual product design was divided into phases, corresponding to the company’s stage-gate approach (c.f. Cooper, 2001), through which a large number of candidate designs were evaluated, refined and rejected until a single conceptual design was selected. Secondly, each of these phases could be represented as a systems engineering V-model (Sage and Armstrong, 2000) comprising design followed by verification and validation. Thirdly, each phase involved increasingly detailed design of a decreasing number of candidate solutions. Consequently, the structure of each phase was similar but constructed from tasks and parameters specific to that phase.

Structuring the model was difficult and time-consuming because of the need to represent the process in a form that was understandable and useable by both the modellers and process stakeholders. This required careful consideration by the researchers doing the modelling of how many tasks to use in the model, as well as identifying a way to arrange these tasks graphically to aid comprehension. The desire to have a small model to simplify modelling and presentation was balanced against the need to represent the process in sufficient detail to show the necessary activities and interactions between teams. In the case of the process being modelled, it was concluded that around 50 tasks were needed to achieve this. Comprehension was aided by laying out the model to indicate the design phases and the systems engineering V-model substructures within it. Although some parts of the model were decomposed hierarchically, nevertheless it remained a relatively flat structure due to the high connectivity between tasks. This complexity of information flows prevented effective partitioning into sub-processes with well-defined interfaces (see Austin et al., 1999, for example, concerning model partitioning)

5.4 Mapping the process

The relevant, additional LCE tasks had to be added by the modellers to the existing "as-is" tasks. The proposed activities which would be needed to set requirements for LCC, to design for these LCC requirements and to calculate the LCC of the conceptual design were elicited. These activities were then localised within the process by discussing the "as-is" and "to-be" models with the stakeholders. Focal points of this process were the "top 20 LCC" components, which were those components expected to have to the greatest impact on the LCC calculations. Given the requirement to do more detailed lifing and costing analyses of the "top 20 LCC" components, tasks had to be brought forward from later in the design process. The positioning of these within the "as-is" process was driven by the information dependencies i.e. what information was needed for a task to be performed. The principle was that additional tasks would be done as early as they possibly could be. This required some faith that the analyses could actually be performed at this point in the process. The addition of these LCE tasks also allowed identification of the knock-on consequence that greater participation of certain organisational units would be required during the early conceptual design phase. This process of knowledge elicitation, localisation and model validation was conducted through workshops, poster sessions and follow-up interviews in which both models were presented

Figure 1 shows a partial view of the "to-be" process model (tasks and parameter names are disguised due to commercial sensitivity). Although the model cannot be presented in detail due to space and confidentiality constraints, this overview indicates the complexity of the process in terms of the interdependence of activities and the number of iteration constructs and compound tasks. This highlights the complexity of possible responses when iteration does occur; and hence the need to carefully consider iteration when evaluating the impact of the proposed change. We used simulation to support this.

5.5 Simulating the mapped process

Once the overall structures of the "as-is" and "to-be" process models were agreed they were used as the basis for process simulation. Estimated task durations, estimated probabilities of rework and resource limitations were elicited from the process stakeholders and incorporated into a separate simulateable version of the process model. Monte Carlo simulations were then executed to calculate process durations and resource requirements from these models. The results were fed back to stakeholders for validation and discussion and were subsequently used to refine both descriptive and simulation models.

Different versions of the models were used for process visualisation and for process simulation, since these two objectives place conflicting requirements upon the model. For visualisation, the models needed to be as concise as possible in order to minimise the cognitive demands on process stakeholders and the time taken to review and understand them. This could be achieved since the models could be relatively informal and still be interpreted in a consistent way by the stakeholders, because they had developed a common understanding of the representational scheme and an agreement of the behaviour of particular tasks.

In contrast, simulation models are a form of computer program. The model must, therefore, be fully specified and formally correct to behave as intended. Once this had been achieved, the simulation was used to calculate the additional duration and designereffort implied by the “to-be” model. A number of different scenarios were considered and the simulation results were presented in a number of different ways – such as histograms and Gantt charts (see Figures 3 and 4 below) – in order to consider the impact of these changes. Since the modelling exercise had involved examination of multiple scenarios, certain ranges of duration and effort were expected by this point and the quantitative outputs of simulation were viewed as a validation of the model and of the “to-be” process rather than as a result of the analysis. Other questions related to the new skills and capabilities required by the teams were addressed through discussions revolving around model development and interpretation of the simulation results.

<Insert Figure 3 here>

<Insert Figure 4 here>

To summarise, the objective of process simulation was not to create a perfect simulacrum of the process. Instead, it was to provide enough information to the stakeholders to facilitate debate and support them in making evidence-based judgements about the feasibility and consequences of implementing the suggested changes. As explained in the following section, using simulation in conjunction with process mapping provided value to Rolls-Royce beyond just using descriptive models alone.

6 Value of process simulation

6.1 Challenges and benefits of constructing the simulation models

The increased formalism required to build simulation models, although possibly challenging for modellers, leads to benefits for the stakeholders above those obtained from simply constructing process flow diagrams and analysing these by inspection. In our case, the increased formalism led to two specific challenges:

- Incorporating the contingency of task behaviour. The behaviours of many tasks in the process (e.g. the duration of a particular task or the likelihood of an evaluation resulting in rework) are contingent upon factors such as the maturity of the design and the time remaining for the whole design process. This dynamic behaviour was elicited from the process stakeholders and subsequently modelled using ASM process variables. For instance, specifying a task to behave differently on first and subsequent iterations required explicit incorporation of additional rules which had been implicitly assumed (or in some cases not recognised) in the descriptive model used for process visualisation.
- Understanding the implications of information flow structure. When an iteration construct fails during simulation, the ASM logic ensures that downstream tasks are invalidated and repeated as appropriate. Since this involves parsing the information flows in the process map, these flows must be structured correctly to ensure the simulation behaves as intended. Due to the relatively complex flow of the “to-be” process, careful consideration of the structure of interdependencies was required to achieve this.

Incorporating the contingency of task behaviour and understanding the implications of information flow structure, in order to be able to the interactive analysis, were relatively time-consuming aspect of the modelling process. However, this activity generated significant insight into the design process as it required the modellers and Rolls-Royce stakeholders to ask specific questions about not only how the process was organised and what the information dependencies among tasks might be – the focus data gathering (step 2), and model scoping and structuring (step 3) – but also about how it might be expected to behave both in ideal conditions and following rework.

Once issues related to the information structure and contingent task behaviour had been resolved and an executable simulation model had been created then it was possible to use the model as an interactive process design tool. The structure and process variables could be changed to reflect different design and iteration scenarios, creating a powerful tool to perform many different "what-if" analyses. The benefits of this are illustrated in the example that follows.

6.2 Example of using the simulation to build understanding of the new process

A key consideration for the "to-be" process was that the addition of the extra tasks needed to estimate the life-cycle cost from the conceptual engine design should not compromise Rolls-Royce's ability to respond in a timely manner to aircraft manufacturers' requests for information (RFIs) and requests for proposal (RFP). Running the simulation model allowed estimates to be made of the estimated process duration and the variation in that duration.

Initially, the simulation suggested that the "to-be" process would take far longer than would be commercially acceptable to meet customer expectations for RFIs and RFPs. Particularly concerning was the length of time the extra LCE-related analyses would take. This led to a detailed examination of the model and discussion about how the "to-be" timescales could be reduced. Errors were found in how the process had been modelled for simulation; for example, concurrent tasks that were implicit in the visualisation had been modelled sequentially in the simulation. Once these issues were resolved, task durations and iteration probabilities were re-examined. The assumptions of different parties were also revisited for consistency – for instance, by asking if the task behaviours represented a radically new product or an incremental development based on an existing design. Some tasks were relocated earlier in the process and allowed to start with incomplete information to increase concurrency. Some had their durations decreased through allocation of extra resources, where this was possible. In other cases the need for new software tools to perform design analyses more rapidly was recognised and the durations of the corresponding tasks were reduced accordingly.

The simulation results clearly highlighted what and where the "problem" tasks were and facilitated a discussion about what should be done to address the issues that arose from them. By inspecting the task sequence within individual simulation runs, the critical path through the process was identified. Focusing on critical path tasks, discussions were had with the process experts about how the activities could be further speeded up or moved off the critical path. These discussions identified, for example, that the development of a particular analysis model that provided inputs to the component lifing models had a long duration and was positioned in the process flow after some key components were designed. It was recognised that this single task could actually be performed as two tasks: the creation of the majority of the model and then updates to incorporate specific data about the components of interest (see Figure 5 below). Splitting the task in the "to-be" model allowed the creation element to be performed in parallel with the component designs, thereby saving significant process time. This representation also better reflected the effects of iteration and rework given that the whole analysis model would not be updated if a component design changed, only the parameter related to the changed component. This change, in turn, had a knock on effect that tasks which fed the model creation with parameters had to be split in the same way and repositioned within the model structure. In this way the flow structure of the model was improved to better reflect how the process would need to be performed in a timely manner and what the effects of iteration would be.

<Insert Figure 5 here>

The need to represent – and therefore perform in the new process – the development of the analysis model as separate creation and update steps would have been difficult without the use of simulation. At this point in the process there are multiple concurrent activities. In a semi-formal, descriptive model, the interdependencies between these parallel activities can be inferred. In our example, the original definition of the analysis model development activity was ambiguous, so it was subsequently allocated a long duration taking into account all the things that the task could include. The formality of a simulation model requires the modeller to understand exactly what the timings of relationships between parallel tasks are and at what points they need to exchange information. This typically requires the tasks to be broken down into smaller elements for simulation, but also means that the users of the model have a better understanding of exactly what is required by when.

To summarise, the interaction between the simulation model and the design of the new, "to-be" process can be seen as a form of triangulation between the process' requirements, the model and the real-life process being designed (see Figure 6 below). When the simulation model does not provide the results expected – in our example, acceptable process duration – then it provides a starting point for investigating what is "wrong" with the design. The "to-be" process can then be changed, providing that the process experts believe that the change in the process as represented in the model can actually be performed in real life; albeit if this requires a change to how the task was performed in the past, such as in this example of splitting the development of the analysis model into two phases, such that the initial creation of the model can be concurrent with the design of the components that will be incorporated into the model subsequently.

<Insert Figure 6 here>

7 How simulation helped meet the case study objectives

To wrap-up the case study description, a number of objectives were set for the process mapping and simulation work in subsection 5.1, which were met as follows:

1. *Structure of the new process.* Process mapping was used to develop the majority of the structure in the process models. This structure was then refined and improved, first by the added formalisation imposed by the process modelling tool and then by consideration of the results of the simulation analyses (as described in the preceding section).
2. *Resourcing the new process.* Process mapping was used to identify the participating teams in the "as-is" and "to-be" processes. Simulation modelling then was used to calculate the resourcing levels that would be needed in each of these teams at any point during the concept design phase.
3. *Performance of the new process.* Process simulation provided an interactive tool for calculating overall process times (as probability distributions) and schedules and critical paths (in the form of Gantt charts). Although the overall critical path and process duration could have been calculated from inspection of the descriptive, flowchart model, process simulation provided a quick way to evaluate multiple scenarios and also provided measures of the possible ranges of durations and the sensitivity of the critical path to these variations.

It can be seen therefore that process mapping and process simulation were used in complementary manner to develop the stakeholders' understanding of how LCE considerations could be incorporated into the existing conceptual design process and what the likely implications of this would be. Process mapping alone would not have led to the same depth of insight. Conversely, a "black box" simulation model would not have allowed the same level of interaction between the modellers and Rolls-Royce.

7.1 Limitations of the case study

A simulation-based process improvement project of the type presented here must inevitably include a combination of quantitative guidance derived through simulation with a significant amount of qualitative evaluation and interpretation by the modellers and other stakeholders. In our study, we evaluated duration and cost using the model and addressed questions of how this might affect design quality through discussion outside the model. There was also no attempt to quantify the reduction in life-cycle costs which might be gained by designing products using the new process – in other words, the performance of the new process was assessed but we did not attempt to evaluate how well it would meet its objectives. Again this would require subjective assessment on the part of the stakeholders. These limitations highlight opportunities for further research to investigate how the quality of a process' output can be quantified with respect to performance-oriented variables, such as the time expended, cost accumulated, structure and timing of iterations and resource allocations (see for example Grebici et al., 2008; Kreimeyer et al., 2008).

The other area that has not been considered in this paper is how the changes suggested by this work would be implemented. At present the organisation is in flux, working out the best way to respond to the needs of a more integrated design and service community. It is often difficult for individuals to see the relevance of their work in reducing life cycle costs; whether that is in product engineering, service design or in product and service operations. For example in the area of product engineering, the traditional design goals are challenging in themselves and so achieving the best emphasis on lifecycle cost during early conceptual design in relation to other issues, such as increasing engine performance, is difficult. Formal mechanisms such as organizational structures, processes and rewards can be translated into individual goals and targets for life cycle engineering (LCE). In addition activities such as specific design for service training and the use of cross-team component reviews are a means to challenge existing ways of thinking (Harrison, 2006). It is also expected that ongoing research projects with academic partners, such as the authors' work on developing a new product design process, will play an important role in increasing awareness of design for service and, through the participation of key Rolls-Royce stakeholders in the development of new processes and tools, support the desired cultural changes.

8 Reflection on the use of design process simulation as an interactive process design tool

Design process changes are often implemented through process mapping exercises followed by refinement in practice (see for example Vergidis et al., 2008). This is a potentially risky approach given that concurrent engineering practice demands that new initiatives such as life-cycle engineering are incorporated into existing processes without detrimental effect on either the design being produced or the performance of the process itself. The case study presented in this paper has demonstrated how simulation can enhance process mapping activities by supporting the development of a deeper understanding of the processes being modelled and thereby in evaluating the likely impact of changes.

8.1 A (relatively) simple model for a complex process

Coupled with simulation methods, process modelling allows the impact of proposed changes to be estimated despite potentially complex interactions with the existing tasks. If process modelling is to be used to understand – and support management of – an existing or new process then the model needs to capture the complexity of the design process in terms of the activities, participants and the interactions between them, without making the model itself so complex that it is unusable. This involves determining the appropriate level of abstraction and attending to the important behavioural characteristics of the process, in this case the concurrency and interdependency of activities and the nature and frequency of the iterations of the design as it develops over time. Once an "as-is" understanding of the current process has been developed then it should be possible to model a "to-be" process that supports the need for incremental, evolutionary process change.

However, many companies are concerned about the time, costs and unfamiliar capabilities required for simulation modelling (Melão and Pidd, 2000). Simulation can be particularly difficult to apply to design process improvement activities due to the uncertainty and complexity of such processes and the difficulty of modelling them. On the other hand, this study has shown that process maps and simulations do not have to reflect the full complexity of the design process in order to be useful. In our study much of the knowledge surrounding the model was not explicitly represented. While this simplified the process representation, ongoing involvement of the process stakeholders was required to understand and develop the model, which significantly slowed down its development and validation. This distinguishes this type of simulation from that of more well-defined processes (such as manufacturing production lines) in which the modeller can develop sufficient understanding of the process to explore the implications of the model themselves.

8.2 A (relatively)"open box" approach

> *"Learning about the processes of the interactions that go on within a complex environment, the relationships between the variables, is probably the dominating characteristic of interest in simulation modelling" (Paul and Hlupic, 1994: 642)*

In the case study, process simulation was used to build upon and enhance descriptive process mapping activities by providing a focus to question and elaborate the stakeholders' understanding of the process behaviour. The process model was viewed as largely an "open box" in that a detailed understanding of the mechanisms underlying process behaviour was developed through a combination of process visualisation and in-depth examination of simulation results to highlight the impact of changes in detailed terms; although the detailed simulation mechanisms themselves were "black box" in that they were only understood in detail by the modellers. Nevertheless, in this way, specific recommendations for process change were developed based on a detailed, shared understanding of not just the predicted outcomes of the proposed change but also the reasons and justification for these predictions. This led to one of the key conclusions of the study: that the process of constructing a simulation model can provide significant benefit as a means to develop insights into process behaviour – even if the numerical results are of limited utility in themselves. We view this as complementary to the commonly articulated belief that the main benefit of descriptive process mapping lies in developing insight into the process, and not in the resulting document (e.g. Box, 1979).

8.3 Comparison with other work in this area

Comparing our approach against existing literature, most published research in simulation-based design process improvement concentrates on the development of specific analytical techniques rather than applications in practice (see Browning and Ramasesh, 2007 for a review). The representation of the task behaviours and interactions in these simulation models tends to be relatively simple and the same rules are applied across the whole model. Unlike in our approach, in most cases of design process simulation reported in the literature: all tasks are modelled in the same way (e.g. using stochastic probability distributions to describe task durations); the model is reported as a "black box" in that the implications of structures within the model are not analysed in detail and exceptions are not discussed on a case-by-case basis; and the benefits of the technique are illustrated in terms of summary metrics with only limited discussion of how the improved process could be implemented in practice. A good example of this type of work is Browning and Eppinger (2002). These approaches seem to be particularly useful for designing new processes or significantly restructuring existing processes. In contrast, we contend that the approach described in this paper is more appropriate when incorporating relatively small changes into an existing, well-established and well-understood process structure, as it is aims to model the specific peculiarities of the existing process and support analyses of how proposed changes will affect these.

9 Conclusions

This paper has discussed a case study in which process simulation was applied to support the integration of life-cycle engineering activities into the existing design process at a major UK manufacturer of capital equipment. Although the discussion has focused around implementing LCE, the same approach could be applied to support any change to a concurrent engineering design process.

In this paper, we have argued that, to develop changes to CE design processes through simulation, an in-depth understanding of the process is required. In many cases, such as in our case study, the existing process will be long-established and the changes required will be incremental rather than revolutionary. It is therefore essential that the existing process and proposed changes are well understood if the changes are to not have a detrimental effect and are to be implemented successfully. In the case study our approach led to an understanding of not just the process structure but also of its behaviour, due to the depth of engagement with the mechanics of the simulation model. This required the modellers and process stakeholders within the company to ask detailed questions and enabled them to develop a greater understanding of the current process and of the impact of changes.

In conclusion, the contributions of this paper are twofold. Firstly, through an in-depth case study with an industry partner, we have demonstrated the practical value of process simulation as a tool to support the specification of changes to a complex, concurrent engineering design process. This complements existing literature in design process simulation, which focuses mostly on the development of models and analyses with less emphasis on studying their application to real-life improvement projects over an extended time period in industry. Secondly, we have shown how development of a design process simulation model can provide significant benefit to companies, not just in terms of the numerical results of simulation analysis, but through the understanding of process behaviour which is gained through validating the behaviour of the model in different iteration scenarios. We present this as complementary to the view that a key benefit of process mapping lies in the understanding and negotiated agreement gained through constructing a model.

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References

Ainscough, M. and Yazdani, B. (2000) 'Concurrent engineering within British industry', *Concurrent Engineering: Research and Applications*, Vol. 8, No. 1, pp. 2-11.

Austin, S., Baldwin, A., Li, B. and Waskett, P. (1999) 'Analytical Design Planning Technique: a model of the detailed building design process', *Design Studies*, Vol. 20, No. 3, pp. 279-296.

Baines, T.S., Lightfoot, H.W., Benedettini, O. and Kay, J.M. (2009) 'The servitization of manufacturing: A review of literature and reflection on future challenges', *Journal of Manufacturing Technology and Management*, Vol. 20, No. 5, pp. 547-567.

Baines, T.S., Lightfoot, H.W., Evans, S., Neely, A., Greenough, R., Peppard, J., Roy, R., Shehab, E., Braganza, A., Tiwari, A., Alcock, J.R., Angus, J.P., Bastl, M., Cousens, A., Irving, P., Johnson, M., Kingston, J., Lockett, H., Martinez, V., Michele, P., Tranfield, D., Walton, I.M. and Wilson, H. (2007) 'State-of-the-art in product-service systems', *Proceedings of the Institution of Mechanical Engineers Part B - Journal of Engineering Manufacture*, Vol. 221, No. 10, pp. 1543-1552.

Box, G.E.P. (1979) 'Robustness in scientific model building', in Launer, R.L. and Wilkinson, G.N. (Eds.): *Robustness in Statistics*, Academic Press, New York, pp. 201-236.

Browning, T.R. and Eppinger, S.D. (2002) 'Modeling impacts of process architecture on cost and schedule risk in product development', *IEEE Transactions on Engineering Management*, Vol. 49, No. 4, pp. 428-442.

Browning, T.R., Fricke, E. and Negele, H. (2006) 'Key concepts in modeling product development processes', *Systems Engineering*, Vol. 9, No. 2, pp. 104-128.

Browning, T.R. and Ramasesh, R.V. (2007) 'A survey of activity network-based process models for managing development projects', *Production and Operations Management*, Vol. 16, No. 2, pp. 217-240.

Chuang, H.H.-C. and Chen, M.-K. (2009) 'A system dynamics analysis of the interactions between multidimensional collaboration and collaborative product development cycle', *International Journal of Services and Operations Management*, Vol. 5, No. 5, pp. 637-661.

Clarkson, P.J. and Hamilton, J.R. (2000) ''Signposting', a parameter-driven task-based model of the design process', *Research in Engineering Design*, Vol. 12, No. 1, pp. 18-38.

Concannon, K., Elder, M., Hunter, K. and Tremble, J. (2003) *Simulation Modeling with SIMUL8*. Visual Thinking International Ltd., Boston, MA.

Cooper, R.G. (2001) *Winning at New Products: Accelerating the Process from Idea to Launch*. Perseus, Reading, MA.

Curtis, B., Kellner, M.I. and Over, J. (1992) 'Process modeling', *Communications of the ACM*, Vol. 35, No. 9, pp. 75-90.

Davies, A. (2003) 'Integrated solutions: The changing business of systems integration', in Pencipe, A., Davies, A. and Hobday, M. (Eds.): *The Business of Systems Integration*, Oxford University Press, Oxford, pp. 333-368.

Dimache, A., Dimache, L., Zoldi, E. and Roche, T. (2007) 'Life cycle cost estimation tool for decision-making in the early phases of the design process': *14th CIRP Conference on Life Cycle Engineering*, Waseda University, Tokyo, Japan, pp. 455-459.

Eckert, C., Kerley, W., Clarkson, P.J. and Moss, M. (2008) 'Design for Service: The New Challenge for Long-Life Products': *Proceedings of TMCE 2008 Symposium*, Izmir, Turkey, pp. 1087-1099.

Eckert, C.M., Clarkson, P.J. and Earl, C.F. (2005) 'Predictability of change in engineering: a complexity view': *2005 ASME International Design Engineering Technical Conferences (IDECTC/CIE2005)*, Long Beach, CA, pp. 341-350.

Flanagan, T., Eckert, C. and Clarkson, P.J. (2007) 'Externalizing tacit overview knowledge: A model-based approach to supporting design teams', *Artificial Intelligence for Engineering Design, Analysis and Manufacturing*, Vol. 21, No. 3, pp. 227–242.

Gebauer, H. (2007) 'The logic for increasing service revenue in prodcut manufacturing companies', *International Journal of Services and Operations Management*, Vol. 3, No. 4, pp. 394-410.

Grant, S.B. (2009) 'Developing a market-oriented culture: an aerospace case study', *International Journal of Services and Operations Management*, Vol. 5, No. 2, pp. 209-231.

Grebici, K., Goh, Y.M. and McMahon, C. (2008) 'Uncertainty and risk reduction in engineering design embodiment processes': *International Design Conference - Design 2008*, Dubrovnik, Croatia, pp. 143-156.

Harrison, A. (2006) 'Design for service - Harmonising product design with a service strategy': *GT2006 ASME Turbo Expo 2006: Power for Land, Sea and Air*, Barcelona, Spain.

Ishii, K. (1995) 'Life-cycle engineering design', *Journal of Vibration and Acoustics*, Vol. 117, No. B, pp. 42-47.

Janz, D. and Westkämper, E. (2007) 'Design to life cycle by value-oriented life cycle costing': *14th CIRP Conference on Life Cycle Engineering*, Waseda University, Tokyo, Japan, pp. 461-466.

Jarrett, J.P., Dawes, W.N. and Clarkson, P.J. (2007) 'An approach to integrated multi-disciplinary turbomachinery design', *ASME Journal of Turbomachinery*, Vol. 129, No. 3, pp. 488-494.

Johnstone, S., Dainty, A. and Wilkinson, A. (2009) 'Integrating products and services through life: an aerospace experience', *International Journal of Operations & Production Management*, Vol. 29, No. 5, pp. 520-538.

Kerley, W.P., Eckert, C.M., Moss, M.A. and Clarkson, P.J. (2008) 'Using Simulation to Support Integration of Life-Cycle Engineering Activities into an Existing Design Process: A Case Study': *International Design Conference (Design 2008)*, Dubrovnik, Croatia, pp. 1033-1042.

Kirk, G.E. (2003) 'The design of the Rolls-Royce Trent 500 aeroengine': *International Conference on Engineering Design ICED 03*, Stockholm.

Kreimeyer, M., Deubzer, F., Herfeld, U. and Lindemann, U. (2008) 'Strategies towards maturity of product information objects to manage concurrent engineering processes': *Proceedings of TMCE 2008 Symposium*, Izmir, Turkey, pp. 925-939.

Maylor, H. (1997) 'Concurrent new product development: an empirical assessment', *International Journal of Operations & Production Management*, Vol. 17, No. 12, pp. 1196-1214.

Melão, N. and Pidd, M. (2000) 'A conceptual framework for understanding business processes and business process modelling', *Information Systems Journal*, Vol. 10, No. 2, pp. 105-129.

Melão, N. and Pidd, M. (2003) 'Use of business process simulation: A survey of practitioners', *Journal of the Operational Research Society*, Vol. 54, No. 1, pp. 2-10.

Mont, O.K. (2002) 'Clarifying the concept of product-service system', *Journal of Cleaner Production*, Vol. 10, No. 3, pp. 237-245.

Newnes, L.B., Cheung, A.R.M.W.M., Marsh, R., Lanham, J.D., Saravi, M.E. and Bradbery, R.W. (2008) 'Predicting the whole-life cost of a product at the conceptual design stage ', *Journal of Engineering Design*, Vol. 19, No. 2, pp. 99-112.

Oliva, R. and Kallenberg, R. (2003) 'Managing the transition from products to services', *International Journal of Service Industry Management*, Vol. 14, No. 2, pp. 160-172.

Paul, R.J. and Hlupic, V. (1994) 'The CASM environment revisited', in Tew, J.D., Manivannan, S., Sadowski, D.A. and Selia, A.F. (Eds.): *Proceedings of the 1994 Winter Simulation Conference*, Orlando, pp. 641-647.

Sage, A.P. and Armstrong, J.E. (2000) *Introduction to Systems Engineering*. Wiley-Interscience, New York.

Scheer, A.-W. (2000) *ARIS: Business Process Modeling*. Springer, Berlin.

Vergidis, K., Tiwari, A. and Majeed, B. (2008) 'Business process analysis and optimization: Beyond reengineering', *IEEE Transactions on Systems, Management and Cybernetics - Part C: Applications and Reviews*, Vol. 38, No. 1, pp. 69-82.

Wanyama, W., Ertas, A., Zhang, H.-C. and Erkwaro-Osire, S. (2003) 'Life-cycle engineering: issues, tools and research', *International Journal of Computer Integrated Manufacturing*, Vol. 16, No. 4-5, pp. 307-316.

Ward, Y. and Graves, A. (2007) 'Through-life management: the provision of total customer solutions in the aerospace industry', *International Journal of Services Technology and Management*, Vol. 8, No. 6, pp. 455-477.

Wynn, D.C., Eckert, C.M. and Clarkson, P.J. (2006) 'Applied signposting: A modeling framework to support design process improvement': *IDETC/CIE 2006 ASME 2006 International Design Engineering Technical Conferences & Computers and Information in Engineering Conference*, Philadelphia, Pennsylvannia, USA.

Figure 1 A partial view of the "to-be" process model, illustrating the first of three levels of detail. Task names modified to protect confidentiality (Kerley et al., 2008)

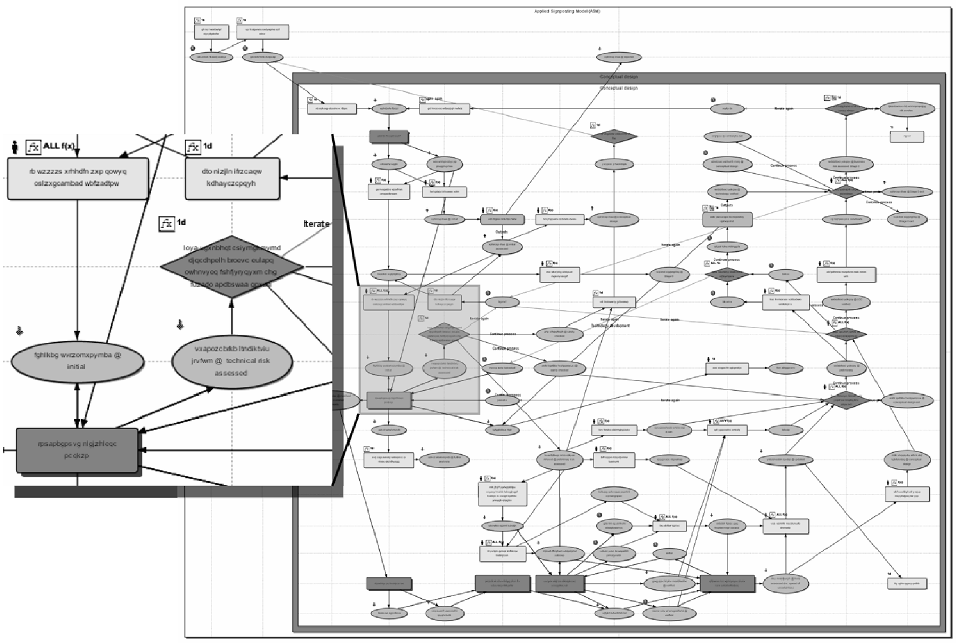

Figure 2 An overview of the iterative approach used for process mapping and simulation

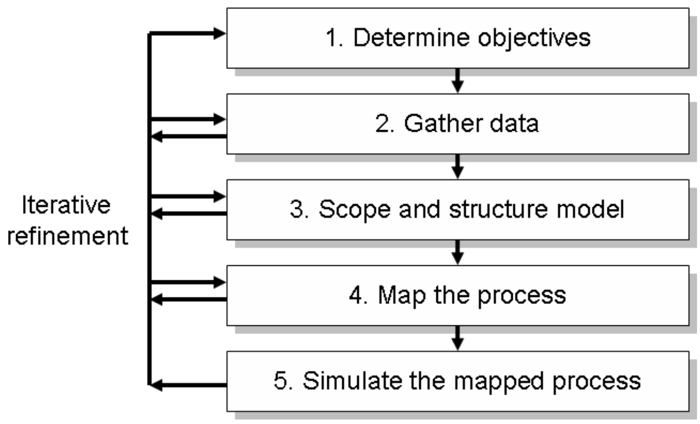

Figure 3 Histograms comparing expected duration ranges for two engine design scenarios. Scenario descriptions and actual durations have been removed to protect confidentiality

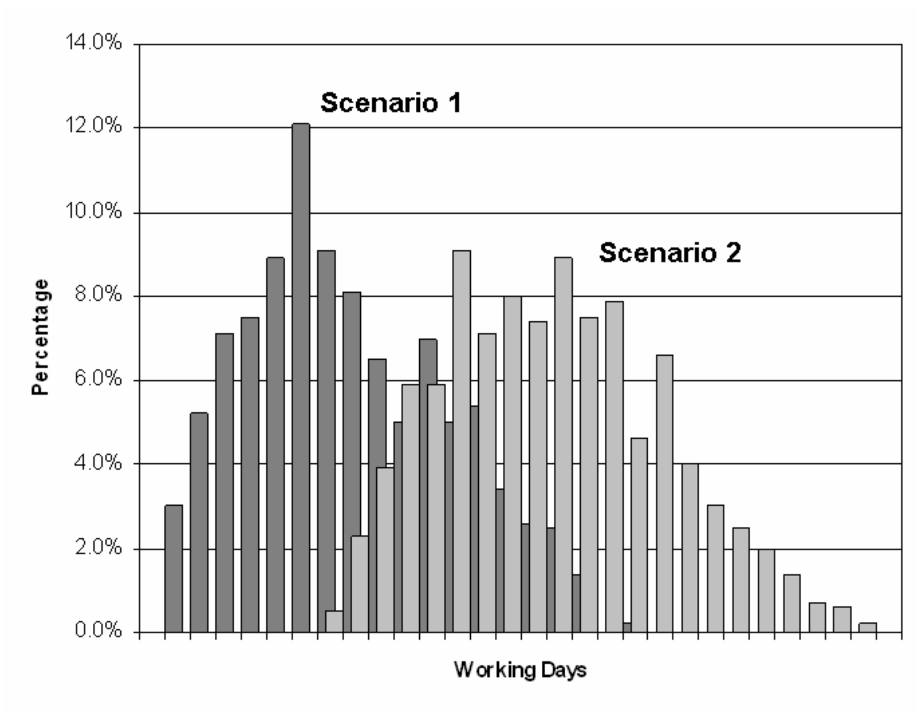

Figure 4 Example Gantt chart fragment from a single simulation run. Task names have been disguised to protect confidentiality. Gantt charts like this were used to analyse the critical path in different design scenarios.

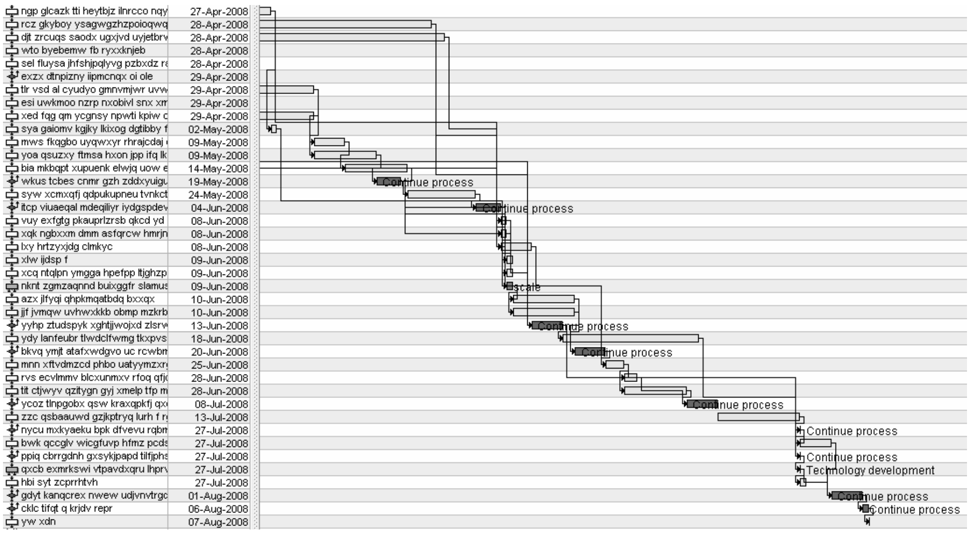

Figure 5 Example of splitting a task as originally modelled to reduce time on the critical path

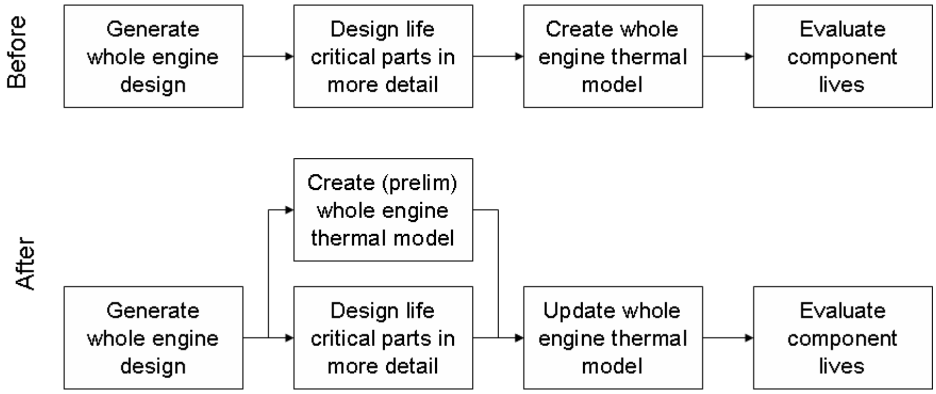

Figure 6 The triangulation of model results with expected performance

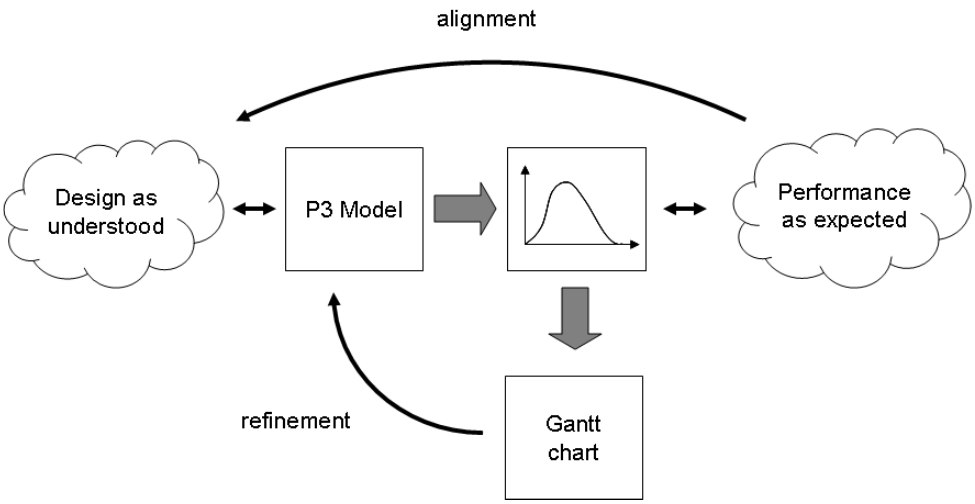

Table 1 Breakdown of interviewees by business function for the Trent 1000

Function	**Nr**
Project management	3
Engineering (Product Development)	11
Marketing (inc. Business Development)	8
Services	5
Total	27