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USING SIMULATION TO SUPPORT PROCESS INTEGRATION AND AUTOMATION OF THE EARLY STAGES OF AEROSPACE DESIGN

Warren Kerley[1], Gareth Armstrong[2], Carla Pepe[2], Michael Moss[2] and P John Clarkson[1]
(1) University of Cambridge, UK
(2) Rolls-Royce, Civil Aerospace, Derby, UK

ABSTRACT

Computer-aided engineering (CAE) software tools for design representation, analysis and optimization play a central role in aerospace engineering. Increasingly these tools are being integrated to automate data transfer, thereby reducing design cycle times and increasing the power of design search and optimization techniques. The majority of work concerning process integration and design automation has focused on the technical issues involved in improving the capability and interoperability of design tools and the means of incorporating them into automated workflows. Of lesser concern has been assessing the performance of these workflows prior to implementation. This paper reports on research at Rolls-Royce that used process mapping and discrete event simulation to help design and predict the performance of an automated design system that is being developed for the early stages of civil aero engine design. The findings of this research are that process simulation can add value to mapping the design process by quantifying the expected outcomes of different implementation scenarios and, thereby, indicating opportunities for further process improvements.

Keywords: Process improvement, process integration, design automation, process simulation

1 INTRODUCTION

Computer-aided engineering (CAE) software tools for design representation, analysis and optimization play a central role in aerospace engineering. Originally these tools were standalone and significant effort was needed to translate the outputs from one into the inputs of another. Increasingly these tools are being integrated to automate the passing of data between them, thereby reducing design cycle times and increasing the power of design search and optimization techniques [1].

The majority of work concerning process integration and design automation has focused on the technical issues involved in improving the capability and interoperability of design tools and incorporating them into automated workflows. Of lesser concern has been assessing the management and organizational issues involved in implementing these workflows and the cost/benefits of different implementation scenarios [1]. One method for planning and assessing the impact of process redesign involved is to use process mapping and simulation.

The research reported in this paper investigates how process simulation can be used to support the design and implementation of engineering design systems which increase the automation of the design process through the integration of computer-based design synthesis and evaluation tools into coordinating workflows. The authors, working at Rolls-Royce, used process mapping and discrete event simulation to help design and predict the performance of an automated design system that is being developed by the company. The rationale for this new system is to reduce design cycle times, while maintaining or improving design quality, and, hence, reduce the commercial and technical risks involved in the early stages of designing civil aero engines. This research used an action/ participatory research approach in which the authors worked closely with Rolls-Royce personnel to develop and validate simulation models of the new system.

The paper is organized as follows. Section 2 reviews the existing literature concerning the state of the art in engineering process integration and design automation, and the specific issues involved in automating design workflows. It then considers the application of process mapping and simulation to this problem. Section 3 describes the background to the case study. Section 4 enumerates the research questions for this study. Section 5 describes the modeling intervention and its results. Section 6 discusses these results with respect to existing literature. Section 7 concludes the paper by summarizing the paper and outlining future work, both already planned at Rolls-Royce and suggested for later work by the preceding analysis.

2 BACKGROUND

2.1 Process Integration and Design Automation

Aerospace design is critically dependent on the use of computer-aided engineering (CAE) software tools, such as computer-aided design (CAD) workstations, computational fluid dynamics (CFD) and finite element analysis (FEA) codes for design evaluation [1]. CAE tools have greatly increased the productivity of designers, reducing design cycle times and allowing either higher fidelity analysis or more design options to be evaluated in any given period of time [1 p45, 2]. Nevertheless significant opportunities still exist to increase productivity by using more powerful hardware, developing new tools – such as parametric CAD [1 p45] – and linking, previously, freestanding tools together into integrated design systems.

Aerospace design is typically organized into conceptual, preliminary and detailed design phases. During conceptual design a large number of candidate product architectures are created and evaluated. From these a small number are selected and then refined at higher fidelity during preliminary design until a single design is chosen to be fully elaborated in the detailed design phase. Typically different tools are used in each phase, reflecting their different objectives and the need for increasing fidelity over time [2]. For example, in order to rapidly explore the design space during conceptual design, simple parametric design descriptions derived from empirical relationships have been preferred historically, as they are simple to generate and evaluate. A large number of product architectures can be quickly created and evaluated either manually or automatically using multi-objective design search and optimization (DSO) tools [1 p.45, 2, 3]. One disadvantage of this approach is that the approximations used in these low fidelity techniques can result in potential problems with the candidate architectures not being identified until later in the design process, by which time the options for remedial action are limited.

High fidelity CAE tools have tended not to be used for conceptual and preliminary design because of the elapsed time, human effort and costs of computing resources that it takes to use them. For example, it can take two or three weeks to create the geometry model and associated finite element mesh needed for a large-scale CFD analysis and then run the analysis and evaluate the results [1 p22]. Further work would then be required to extract the aero-thermal data and convert it into a format for use in another model, e.g. a thermo-mechanical one. However the technical obstacles to design process automation are being overcome in two ways: first reducing the effort required to create geometry models and associated FE meshes using knowledge based engineering and improved computing techniques; and, second, using commercial software – such as ModelCenter® and iSIGHT® – to provide the means to pass data electronically between different CAE tools as well as the methods to invoke these tools and mechanize their sequence of execution into an automated workflow. These automated workflows can either be manually controlled or executed by automated search and optimization tools, greatly enhancing an organization’s ability to perform design search and multidisciplinary, multi-objective optimization [1-3].

Nevertheless these integrated design systems have to be designed and decisions made about the level of automation and manual intervention. In simple terms, from an efficiency perspective, the more automated the design process is, and therefore the less human intervention there is, the better. However a number of issues can be identified with this. Firstly upstream tools may not be able to provide downstream tools with all the data they require [3]: a particular problem is that different tools may be at different levels of fidelity resulting in data compatibility issues [2]. Secondly a standardized workflow that is centrally designed, implemented and maintained can be problematic if it needs to be adapted quickly to match the specific product architecture being produced [4]. Thirdly it is not possible to automate all the decision-making in the design process, given the creativity, judgment and social interactions required during design. There is considerable debate about how prescribed the engineering design process can be and therefore how scripted the workflows in an integrated tools environment can be. [e.g. 1 p51, 4-7]. Proponents of the two camps have argued over the merits of the ‘map’ approach (shared information spaces that provide contextual guidance and support) and the ‘script’ tradition (automated workflow systems with the ability to deal with contingencies that script a set of sequential and parallel tasks) [8]. Most integration solutions try to balance the pros and cons of each. Integration companies that allow best of breed solutions attempt to simplify this process by providing development environments and management tools [4]. The onus therefore rests on the organization to determine which design tools to use and how to integrate them. According to Keane and Nair, “Such decisions depend heavily on the complexity of the products being produced and also any regulatory framework that must be adhered to. Leading contractors in the aerospace sector may well continue to prefer DSO systems to be controlled within parametric CAD packages in a closely supervised fashion, rather than place geometric definition in the background with designers focusing mainly on automated search mechanisms” [1 p51]. Successfully implementing information systems, such as an integrated design system, typically involves modeling the process to redesign the workflow and allocate responsibilities between humans and computers [9].

2.2 Activity-Based Process Modeling

Activity-based process modeling is a commonly used method for process redesign and assumes that the process being designed can be conceptualized as a network of discrete, interconnected tasks [10]. Activity-based modeling involves both representing (mapping) the process and evaluating it. The nodes (tasks) and edges (information flows) of the network can be documented in a number of different ways. The most common diagrammatic representation is the process flowchart although there are a large number of modeling notations for process mapping such as IDEF0 and SySML. Alternatively, design structure matrices (DSMs) [11] are increasingly being used in the engineering design domain.

The simplest form of model evaluation is by visual inspection of the process map. Greater insights may be possible if quantitative data can be incorporated into the model and then analyzed using either mathematical techniques or using computer-based simulation [12]. A large number of commercial and academic tools exist for process modeling and simulation. The authors used the ASM method of discrete event simulation (DES) implemented in the CAM (formerly P3) software tool [13], although there are many other alternatives that could have been used for the same purpose.

The remainder of this paper presents a case study at Rolls-Royce, where discrete event process simulation was used to evaluate the process design for an automated design system for the early stage design of civil aero engines.

3 CASE STUDY BACKGROUND

Before describing the research intervention (Section 4 onwards), and in order to put that intervention in context, this section provides background information about the case study company, its current ‘as-is’ design processes and the ‘to-be’ process that it intends to implement.

3.1 Rolls-Royce

Rolls-Royce is a world leading manufacturer of civil aero engines. Like other aerospace companies, it is investing significant effort in reducing the commercial and technical risks throughout the product lifecycle by being able to more thoroughly evaluate a wider selection of architectures at an earlier stage of the development process. This is particularly important during the preliminary design stage as aircraft manufacturers expect the company to be able to commit to the technical performance of the engine, as well as its unit and lifecycle costs, within a few months of them approaching Rolls-Royce with a request for proposal (RFP).

3.2 Current ‘As-Is’ Design Process

The current preliminary design process sees project engineers using experience and judgment to define and analyze various aspects of the product as required in order to reduce the risk of the product not meeting the customer requirements. In order to do this they will typically use low fidelity techniques to test their assumptions, with occasional use of higher fidelity analysis (with support from specialist analysts) to investigate areas which are perceived to be high risk (e.g. due to use of novel technology). Once the product architecture has been demonstrated to meet the requirements with enough confidence, approval is given to proceed to a more detailed design phase where high fidelity analysis will be routinely used on the entire product. Typically commitments will have been made on product attributes (e.g. efficiency, cost, weight), interface positions, and component materials, meaning that if any significant issues are uncovered at this stage, the options for significantly changing the architecture are limited and so the ability to deliver an optimal solution can be hampered.

Consequently the better the analysis at this stage, the lower the risk of design rework being required later on.

3.3 Proposed 'to-be' Process

Recognizing that it is not realistic to increase the time available for the conceptual and preliminary design phases, the logical step is to enable more high fidelity analysis to be done in the existing timescales. The strategy for achieving this has two main workstreams, both of which are building on existing work within the company. Firstly Rolls-Royce is using knowledge management techniques to capture and communicate understanding of the capabilities of various engine technologies, this knowledge is then embedded in knowledge-based engineering (KBE) tools which enable new architectures to be rapidly evaluated against criteria based on physical principles and experience. Secondly it is using integration methods and tools such as iSIGHT® [14] to combine various tools into automated workflows. In their most basic form, these workflows enable a single product architecture to be quickly and easily evaluated for multiple attributes; however using methods such as design of experiments (DOE), an automated study can be run by varying a wide range of input parameters in order to evaluate a range of architectures throughout the design space and find an optimal, robust solution.

In addition to improving the design of individual components, this new approach will also support the study of larger systems (e.g. at assembly, sub-system and product level) by reducing the time and effort required to define and analyze the entire system concurrently. It is recognized that risks exist, as an automated workflow can be very specific to a particular product concept. The mitigation for this risk is to make the workflow as modular as possible (e.g. modules based on engine subsystems) in order to make it modifiable for different product concepts.

3.4 Process Design and Implementation Approach (As-Is to To-Be)

The development of the individual tools and integrated workflows is being overseen by a specialist systems design team. They are responsible for understanding the requirements of the end-users (e.g. the project engineers who will use the design system) and then liaising with the specialists who are responsible for developing the methods and tools used for the various analyses at different levels of fidelity.

Once the methods and tools that will meet the end-users' requirements have been identified, the information is used to create a series of process maps (e.g., one for each major engine sub-system, see Figure 1 below) that provide: the design phases and participating teams; the specific design tasks, their order and information flows between them; the people involved; the design synthesis and analysis tools used; and, finally, the major decision points and iteration paths in the process. These process maps can then be used to review the functionality of the proposed workflow to determine if the end-users and specialists agree that the individual tools can be integrated together to meet the requirements.

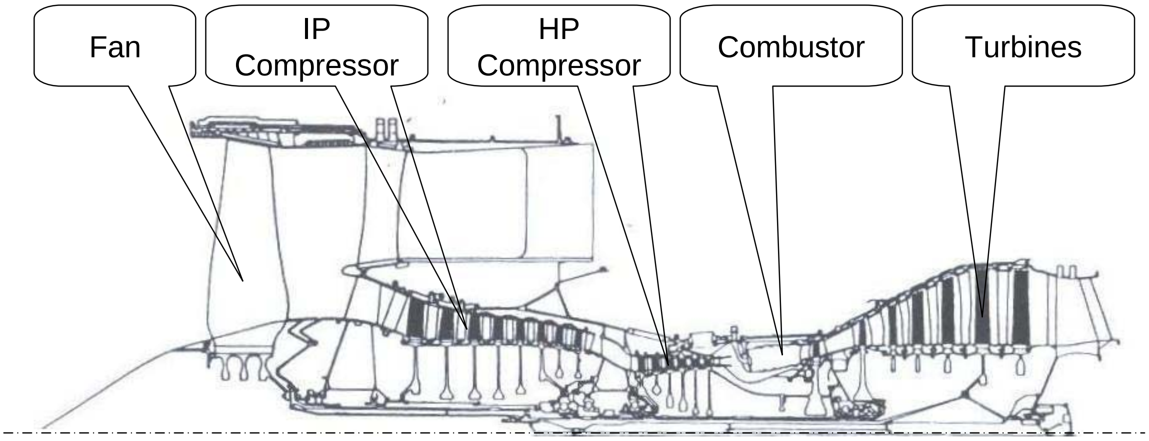

Figure 1. Example engine cross-section with selected subsystems indicated (modified from [15 p50])

This work is largely qualitative and the quantification of time and resource required to carry out the 'to-be' process as defined has not been determined with a high degree of confidence. As a proof of concept to demonstrate the benefits of process simulation, the authors converted the process map that they had created for the fan sub-system into an ASM process simulation [13]. The research questions and intervention used are explained in the next two sections.

4 RESEARCH QUESTIONS

A process map by itself can answer the question of how to coordinate a part-automated and part-human driven process. The questions that Rolls-Royce expected the simulation to answer were: How long will preliminary design of the fan sub-system take under various scenarios, for example involving different levels of automation? What is the probability distribution for these durations? What are the critical paths and bottlenecks in the process? What will the cost of the process be in terms of the human and computing resources deployed? How can the process be improved (e.g. by investment in new tools and methods or by using more and/or more powerful computer resources)

From an academic perspective the generalizable questions that the researchers were interested in were: What information can these models provide? How suitable is process simulation as a method to support the design of automated design process workflows? What are the limitations and issues involved in creating models of this type?

5 THE MODELING INTERVENTION

The research methodology used to perform this intervention can be seen as a form of action research, where the researchers were actively involved in the development of the new design system. Taking the process map of the fans sub-system already developed by the authors for Rolls-Royce, the steps then followed were to:

- Convert the process map into a structure that could be simulated;
- Gather data to populate the simulation model;
- Determine process scenarios for the model;
- Run these scenarios;
- Verify and validate the model and results;
- Make recommendations and propose future work.

Each of these steps is described below. Although they are presented in sequence there was a certain amount of iteration, as is usual in simulation modeling exercises such as this [16].

5.1 Create the Simulation Model Structure

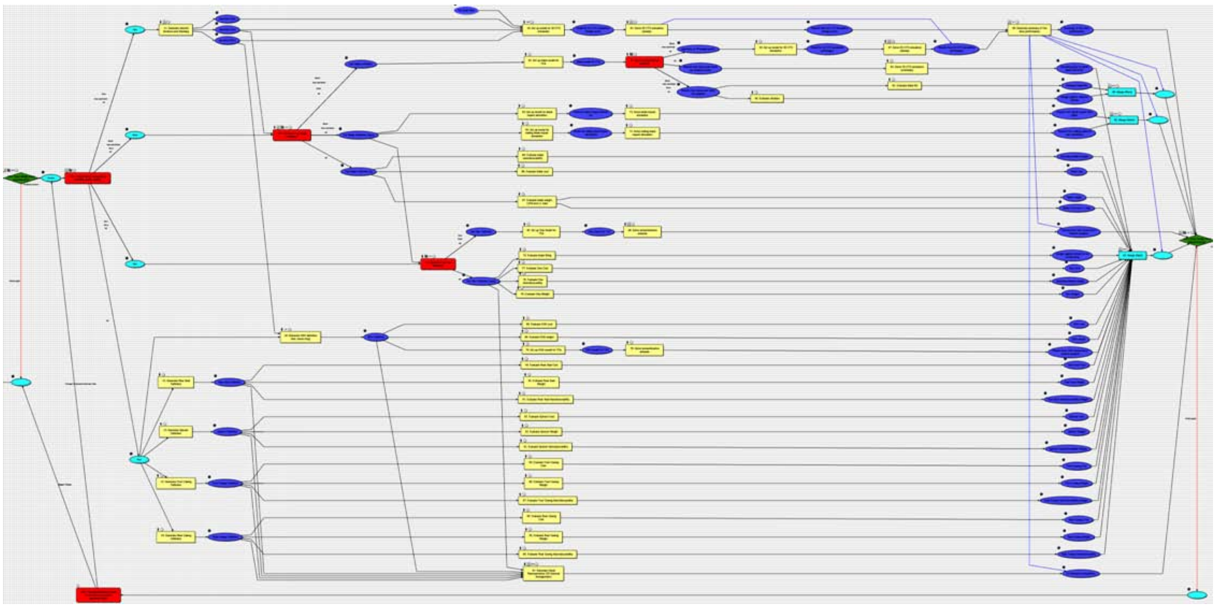

Figure 2. Part of the fans sub-system process map after modifications for simulation

The fans process map was initially created using drawing objects in MS-Excel. This method was chosen initially as a quick and easy method to create the diagram to facilitate discussions, however it quickly became apparent that the scale of the process maps was larger than MS Excel could handle effectively. Following a survey of alternative modeling tools, the process maps were re-created in the simulation modeling tool (see Figure 2 above). In addition to providing an improved modeling environment, this was also a necessary step to enable simulations of the process to be run, albeit with some additions to the process flow to make the model execute in the way expected [c.f. 16].

5.2 Gather Data

Once the sequence of tasks had been mapped and could be executed in the simulation software, the next step was to populate the simulation model with various data which were gathered from Roll-Royce specialists who had experience of the methods and tools being simulated. These data comprised expected tasks durations and the human and IT resources required to perform each design task. These data had to be estimated – given that this was a model of an intended ‘to-be’ process, rather than an existing process – based on current practice. In line with lean principles and value stream mapping practice [17], total task durations were split between waiting time, people (manual) time, queuing time and solver (computing time). Individual task times were then determined depending on: 1) the level of task automation, which might, for example, reduce manual time to zero; and 2) whether this was the first time the task had been performed or whether it was being reworked, which again could save manual time as the computational model of the design would already have been prepared for execution and would only require new input data.

5.3 Determine Process Scenarios

Besides the individual task durations and resources, the model had to allow for the different number of times that any design task might be performed. Tasks in the model were logically grouped into ‘swimlanes’ based on their function: aerodynamic design of the fan blades (which determines their external shape), mechanical design of the fan blades (which determines their mechanical properties), design of the disc that holds the whole set of fan blades and connects them to the rest of the engine, design of blade root which attaches the fan blade to the disc; and, finally, a variety of other design tasks such as determining the weight and cost of the various fan components. A plausible scenario for doing the complete design using the various methods and tools – but only one of many possibilities in practice – is to build it up by starting with the aerodynamic design. Once a set of suitable candidate designs have been identified, the mechanical design is then performed for these blade profiles. The aerodynamic and mechanical design of each blade is then refined in tandem. Once the basic blade design is complete the disc is then designed, followed by the root fixing. Finally the design of the blades, disc, roots and all other factors is then refined. Each of these stages involves a number of iterations. This type of scenario was modeled stochastically based on estimates of the likelihood of a certain number of iterations of the design being needed at each stage.

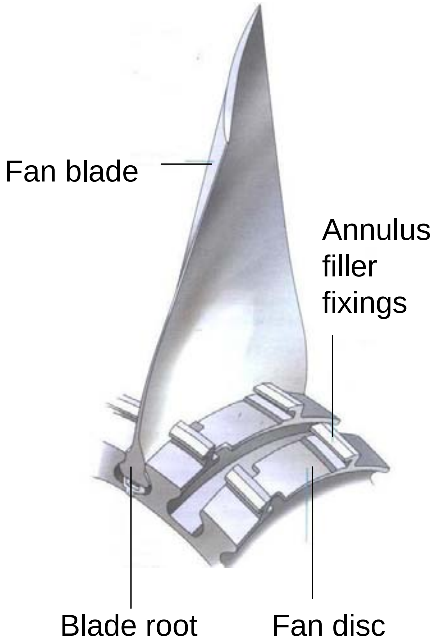

Figure 3a. Fan system [18] and Figure 3b. Fan blade showing fixings [19 p103]

5.4 Run Simulations and Evaluate Results

Once the simulation model structure had been determined, and data for various scenarios gathered, five simulation scenarios were run using discrete event simulation and Monte Carlo methods. These five scenarios were:

1. Straight through processing for a manual process;
2. Straight through processing for a fully automated process;
3. A manual process (using the scenario describe in 5.3 above, which is selective about which tasks are run);
4. An automated process, assuming that all tasks will be run each time;
5. An automated process allowing for the benefits of parallel design (i.e. reduced numbers of iterations/ executions of each design task).

Although probability distribution functions (pdfs) could have been used for the task durations for the simulation runs, point estimates were used for durations and variation was limited to the number of iterations in each Monte Carlo simulation run. This was sufficient for the analysis that was performed. In other applications the use of duration ranges might be required to make the scenarios more realistic.

Scenarios 1 and 2 provided information about the absolute minimum amount of time to produce and analyze a single product architecture using, firstly, existing tools and methods and then, secondly, with the proposed automated workflow. A comparison of these two scenarios validated that automating each of the tasks could, in principle, lead to a significantly shorter process duration (roughly half the time), all other factors (i.e. the sequence of tasks and the number of times they were performed) being equal. The remaining three scenarios were intended to simulate actual design process performance. The key evaluation criterion was whether the process could be performed within the required timescales for preliminary design.

Scenario 3 set the baseline for how quickly a fan could be designed using the existing mix of manual and automated methods and tools. As expected the elapsed time was far in excess of that required if an architecture was going to be analyzed at the required fidelity by the preliminary design team.

The two ‘automation’ scenarios, with a much higher level of design process automation and integration, made different assumptions about the number of times that certain tasks would need to be performed. In scenario 4, all elements of the design process – blade aerodynamics, blade mechanical design, disc, root and other – were performed in parallel the same number of times as the total number of iterations in the manual scenario. This was the worst case from a schedule perspective but would be expected to produce a significantly better architecture as more design evaluations would be performed in each iteration. However the time elapsed was significantly longer (+40%) than in the manual scenario (scenario 3). This was because of complex 3D CFD and FEA design evaluations that defined the critical path which were not being selectively performed and were now being repeated more times than before. We needed to identify what could be gained from running aerodynamic, mechanical and disc design in parallel e.g. how many of the early aero runs are mechanically unviable (and would be spotted earlier). Scenario 5 addressed this by assuming that by running evaluations in parallel the total number of iterations could be reduced to the same number of aerodynamic design passes. Although this significantly reduced the total elapsed time (half of Scenario 4 and -35% of Scenario 3), it was still significantly more than the target.

5.5 Model Verification and Validation

Care was taken throughout that the data input into the model were the same as those provided and consistent with those provided for a parallel value stream mapping (VSM) exercise.

The model was validated through a meeting between the authors and members of the fan design team, some of whom had provided us with the information and data used to construct the model. The fan design personnel confirmed the face validity of the model based on the reasonableness of the assumptions and the correspondence of the simulation results with their experience of the design process on projects in the past i.e. that the critical path seemed reasonable and the overall process durations seemed right.

5.6 Recommendations and Proposed Next Steps

Having run the five process scenarios the researchers were then in a much better position to understand the process behavior and make suggestions for how it should be executed and improved. We were able to identify the critical path activities and run a number of ‘what-if’ analyses using the simulation model. First we were able to quantify the savings from skipping the longest critical path tasks. We were also able to quantify the time savings that would be achieved by Rolls-Royce, if they invested in more computer hardware. This would reduce how much the teams had to share computing resources and, therefore, the amount of queuing time before computational model runs, which was a significant factor in slowing the process down.

Other possibilities for speeding the process up, which were prompted by, but not analyzed using, the simulation model were: more powerful computers to reduce solver (computing time); more intelligence related to the expected number of times needed to run each task (when planning) and which tasks could be skipped in any run (both for planning and during actual execution of the design system). Some of this would require a better understanding of the benefits of design task parallelism.

Further work that could have been performed using the model included:

- Determine computational resource usage profiles;
- Incorporate conditional probabilities to allow for, for example, the degree of technical challenge involved in the design project as a whole (e.g. novel engine architecture vs. scaling of existing design). There could also, potentially, have been more realistic task selection based on number of passes and tasks already performed.

6 DISCUSSION

Having described the modeling intervention that was performed, this section evaluates the intervention in the light of the research questions posed in Section 4 and discusses what we have learnt as a result of doing this research project.

The generalizable questions that the researchers were interested in were: What information can these models provide? How suitable is process simulation as a method to support the design of automated design process workflows? What are the limitations and issues involved in creating models of this type? These three questions are addressed in the sub-sections that follow.

6.1 Value of Information Provided

Simulation modeling is a skilled activity and takes a long time. It is important, therefore, that it adds value above flowcharting (inspection) or any other analysis technique (e.g. critical path analysis using MS-Project, say). The questions that Rolls-Royce expected the simulation to answer were: How long will preliminary design of the fan take (under various scenarios, for example involving different levels of automation and/or novelty of product concept)? What is the probability distribution for these durations? What are the critical paths and bottlenecks in the process? What will the cost of the process be in terms of the human and computing resources deployed? How can the process be improved (e.g. by investment in new tools and methods or by using more and/or more powerful computer resources)?

As described above, these questions were answered and insights were gained into the need for: 1) selective task execution in the fully automated process and 2) increased IT investment in order to reduce queuing times due to shared computer resources and to speed up computation times. It could be argued whether or not Rolls-Royce would have identified these points as easily without the use of the simulation, nevertheless, from the perspective of the information provided, the simulation modeling was considered by the fans design team to have given them valuable insights and, thereby, added value. Although simulation of this type can be used for other forms of process analysis – for example to refine process structure [16] – there seems to be clear benefit in the particular application described in this paper given the quantitative results it provides.

6.2 Suitability of the Technique

Other, more general points can be made about the suitability of this type of intervention for supporting the development of automated workflows for preliminary design processes. It should be recognized that discrete event simulation is considered a relatively ‘hard’ modeling technique, which may be unsuited to describing more complex, less structured processes [20]; however, in this particular application, simulation is being used to support a ‘hard’ approach to systems development i.e. requirements leading to specification to implementation and then evaluation, without too much comparison with existing artifacts. There therefore seems to be a good fit between problem and analysis technique. Specific points to consider are: 1) the more limited degree of abstraction involved than in other applications of simulation modeling; and 2) the ability to do the modeling without the need for an intermediate ‘as-is’ process modeling exercise.

Less abstraction than in some other applications

There is relatively little discussion within the engineering design community about the appropriateness of ‘hard’ process modeling techniques. Much of the work considering the appropriateness of different modeling approaches comes from the more general, business process management (BPM) literatures [e.g. 12, 20]. That notwithstanding, in our opinion, the workflow automation problem described in this paper is particular suited to the hard process modeling techniques we employed; particularly compared with using process mapping and simulation of manual – and therefore less structured – process typically encountered in early stage design. Whereas in less structured processes, with high levels of social interaction, the model is an approximation to the information flows, task boundaries and timings, in an automated process the tasks are much more clearly defined (i.e. preparation and execution of particular codes) and the information flows are known (either input at the beginning or output at the end of a task and defined in the interfaces). Consequently the model can be an exact facsimile of the process structure (tasks and information dependencies). There is no fuzziness about what information is passed, when it is passed or what it is used for.

No ‘as-is’ model required to develop ‘to-be’ solution

The ‘hardness’ of the problem, perhaps even more so than in other systems integration projects (e.g. in the software engineering field) also means that no ‘as-is’ process is explicitly needed for design and evaluation of the proposed ‘to-be’ process. This is useful, particularly when there is no agreed structure amongst the designers to describe the ‘as-is’ process. Instead the ‘to-be’ process is based on a logical sequencing of tasks based on information dependencies. Consequently the ‘to-be’ process can be derived from scratch, based on data about the information flows. Tasks can all be identified and sequenced based on their input/output information dependencies. If multiple tasks use the same information then this information needs to be defined upfront and decisions made using preliminary information. This is the approach taken in the DSM literature [e.g. 11, 21]. Browning [11] argues that this focus on information flows is a strength of DSM methods compared with flowcharting and allows the accurate construction of process models. Our work suggests that process flowcharts can accurately reflect information flows provided explicit consideration is given to information dependencies in the modeling notation used, such as in the ASM approach that we used or other process flow notations such as Event Process Chains (EPC) and IDEF0.

It should be noted, however, that without an ‘as-is’ model, evaluation of the ‘to-be’ is done based on absolute (rather than relative/comparative) criteria. It is not possible, therefore, to make detailed comparisons at the individual task or sub-process level. Instead whole process comparisons will be made based on time, cost and – potentially – quality considerations.

6.3 Limitations of the Technique

To date, the work reported in this paper has only considered processing time and cost. Scenarios have assumed simple rules for the number of passes/ iterations of the design. The decision points have been modeled stochastically using simple rules (e.g. a choice from a small range of values). Results are how long a number of passes will take rather than how many passes can be done in certain (predetermined) amount of time (say a certain number of months) The focus has been on technical feasibility (i.e. can the process run in the time available?) Ideally more intelligence is required for: 1) a full cost/benefit analysis; 2) conditional probabilities for iteration based on what has happened already; and 3) an assessment of the quality of the design/ risks carried forward to later stages in the design process. This quality information is also needed to do a proper cost benefit analysis of the new system; although it is not unusual for this not to be done. Each of these three points is a topic for research and is discussed in the subsections that follow.

Lack of cost/benefit analysis

The analysis performed has only considered, in a limited way, the efficiency benefits (specifically time savings) that will result from implementing the proposed automated workflow for the design of the fan sub-system. The total costs and benefits have not been determined. In particular we are concerned to identify all the costs and benefits involved in process automation, which may include: the cost of the developing the design system; the upfront costs of developing models that are not used; the qualitative change in the information available for computational design modeling due to doing it earlier; and, the effect on the quality of decision making due to automation and earlier modeling runs.

Assessment of the benefits of automated workflows is known to be a challenging problem. “Besides quantitative benefits such as decreasing cycle times, reduced personnel cost and (if workflow and document management are combined) document storage space and paper cost, qualitative aspects have to be taken into account as well. These figures include shorter time to market due to process improvement, higher process quality due to decreased error rates and faster response to customer inquiries. Moreover, while most costs from the introduction of a workflow management system are generated during the system introduction phase, the benefits are generated over a much longer period of time” [22 p1].

Conditional probabilities

The second issue is a more realistic representation of the decision points in the process simulation model, which would require conditional probabilities for iteration to be incorporated into it. Conditional probabilities would require an understanding of what is the best way to search the design space with the number of analyses left. In order to model the decision points it is, therefore, necessary to: obtain a better understanding of the subjective criteria used during design evaluations and selection of which analyses are to be repeated; determine how these may be affected by process automation; and, consequently, how the new process may respond to these challenges.

To give an idea of what this involves, the criteria used for evaluations are often subjective related to the perceived risk – based on previous experience – of an architecture failing to meet specification at a later design stage and, therefore, having to be reworked. Risky architectures have parameters that fall outside of previous experience. If an architecture is considered risky then:

- It may be developed to a higher fidelity i.e. more detailed analyses or rig tests to check it. In other words, if, for example, a component is over temperature, then look at it in more detail. More performance parameters generated for an architecture as a result of the analysis or testing will identify more ‘out of experience’ ones, if they exist.
- More architecture may be evaluated to more fully explore the design space so that fewer unknown possibilities will remain. This is robust design and understanding the effects of variations (e.g. in manufacturing), which involves modeling at the extremes, rather than just at the peak or nominal value.

In this way, confidence in an architecture is built up through a combination of the chosen concept(s)/ architecture(s) being worked to a sufficient level of fidelity (detail, consistency, risk…) and sufficient alternatives being evaluated and rationally discarded to give confidence that those chosen are better, or even optimal. If a design review concludes that the risk is too high, then the architecture is iterated; otherwise the architecture (with associated risks) is passed on to the following design phase.

Assessment of quality

There is also the need to consider the interdependencies and trade-offs between time, cost and quality from a project management perspective. Determining the likelihood of later iteration, and the added time and costs incurred from any iteration, involves an understanding of the trade-off between time and cost (resources) against quality of the architecture in terms of the design risks carried forward. There is, therefore, a need to assess the quality of the design system and particularly the quality of the architecture it produces. From a modeling and design process management point of view the key questions are: What is the expected quality of the architecture i.e. design risk carried forward? What are the trade-offs between time, cost and design quality [23]?

The process modeling literature mainly uses time as the process metric of interest and most of the work to date has concentrated on simulating project schedule. This is a significant limitation given the time, cost and quality ‘iron triangle’ of project management and the trade-offs that this involves. In general there is little about how to model design quality/ risk [24]. The case study results above have shown that this will come from a strong understanding of the evaluations that are made at the decision points (i.e. the conditional probabilities previously described above).

In the case of the remaining design risks at the end of the process, there seem to be a number of ways forward:

- Develop/ determine quantitative measures of risk and estimate the remaining risk level based on the simulation model and the various scenarios investigated using it. Currently Rolls-Royce use high/medium/low (HML) scoring of individual risk probability and impact, which are multiplied together and then summed to give a total risk score [25].

- Make a quantitative estimate of the change in the number of risks that will be carried forward and a qualitative assessment of the likely magnitude of these risks.
- Argue that the proposed process does not increase either the number or magnitude (likelihood multiplied by impact) of the risks and therefore, the proposed process is no worse (qualitatively) than the existing 'as-is' process.

Ideally, when determining the overall risk, all factors should be considered i.e. all costs, all quality and risk considerations, and all schedule issues.

7 CONCLUSION

This paper has considered the increasing automation of early stage design workflows and the application of process simulation as a means of analyzing the impact of this increased automation, through a case study at Rolls-Royce. In summary, the key factors that emerge from this work are:

- The benefits of process simulation as a planning tool for design process integration and automation. The assessment of these benefits was, however, subjective and further work is needed to better assess the cost/benefits of simulation modeling interventions of the type described in this paper.
- The need for research into how decision making in design processes can be more faithfully reflected in simulation models beyond unconditional stochastic probabilities of iteration.
- The need for a method to better evaluate and model the risks being carried forward to later design stages and how these risks change between 'as-is' and 'to-be' processes.

Note that this paper has concentrated on the 'hard', technical aspects of systems design and process modeling. No real consideration has been given to either the implementation of the design system or to the human factors involved in its use in practice, such as how the actual work of, and social interactions between, designers will be affected [1]. This is an organizational design and change problem and not one that is amenable to the process modeling techniques that we employed.

As for Rolls-Royce, the next steps following on from this work are: first, to implement the 'to-be' process for the fans subsystem, taking into account the insights provided by the simulation modeling described in this paper; and, second, to extend the technique to the analysis and design of other subsystems within the automated design system being developed, such as the compressor or turbine.

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REFERENCES

[1] Keane, A.J. and Nair, P.B., Computational Approaches for Aerospace Design. (John Wiley & Sons, Chichester, 2005).

[2] Price, M., Raghunathan, S. and Curran, R., An integrated systems engineering approach to aircraft design. Progress in Aerospace Sciences, 2006, 42(4), pp331-376.

[3] Davies, D. and McMahon, C.A., Design representations for multiple-viewpoint analysis with a focus on conceptual aircraft design. In ICED'05. Melbourne, August 15-18, 2005.

[4] Abrahamson, S., Integrated design in a service marketplace. Computer-Aided Design, 2000, 32(2), pp97-107.

[5] Dellen, B., Maurer, F. and Pews, G., Knowledge-based techniques to increase the flexibility of workflow management. Data & Knowledge Engineering, 1997, 23(3), pp269-295.

[6] Davis, J.G., Subrahmanian, E., Konda, S., Granger, H., Collins, M. and Westerberg, A.W., Creating shared information spaces to support collaborative design work. Information Systems Frontiers, 2001, 3(3), pp377-392.

[7] Duffy, A.H.B., Andreasen, M.M., MacCallum, K.J. and Reijers, L.N., Design coordination for concurrent engineering. Journal of Engineering Design, 1993, 4(4), pp251-265.

[8] Schmidt, K., Of maps and scripts: The status of formal constructs in cooperative work. Information and Software Technology, 1999, 41(6), pp319–329.

[9] Curtis, B., Kellner, M.I. and Over, J., Process modeling. Communications of the ACM, 1992, 35(9), pp75-90.

[10] Browning, T.R. and Ramasesh, R.V., A survey of activity network-based process models for managing development projects. Production and Operations Management, 2007, 16(2), pp217-240.

[11] Browning, T.R., Process integration using the Design Structure Matrix. Systems Engineering, 2002, 5(3), pp180-193.
[12] Vergidis, K., Tiwari, A. and Majeed, B., Business process analysis and optimization: Beyond reengineering. IEEE Transactions on Systems, Management and Cybernetics - Part C: Applications and Reviews, 2008, 38(1), pp69-82.
[13] Wynn, D.C., Eckert, C.M. and Clarkson, P.J., Applied signposting: A modeling framework to support design process improvement. In IDETC/CIE 2006 ASME 2006 International Design Engineering Technical Conferences & Computers and Information in Engineering Conference. Philadelphia, Pennsylvannia, USA, September 10-13 2006.
[14] Koch, P.N., Evans, J.P. and Powell, D., Interdigitation for effective design space exploration using iSIGHT. Structural and Multidisciplinary Optimization, 2002, 23(2), pp111-126.
[15] Cumpsty, N., Jet Propulsion. (Cambridge University Press, Cambridge, UK, 2003).
[16] Kerley, W., Wynn, D.C., Eckert, C. and Clarkson, P.J., Redesigning the design process through interactive simulation: a case study of life-cycle engineering in F conceptual design. International Journal of Services and Operations Management, 2011, In press.
[17] Morgan, J.M. and Liker, J.K., The Toyota Product Development System: Integrating People, Process and Technology. (Productivity Press, New York, 2006).
[18] Rolls-Royce plc. The Rolls-Royce Trent 1000 powers the Boeing 787 [online]. Available from: http://www.rolls-royce.com/press/assets/prg.jsp [22 December 2010]
[19] Rolls-Royce plc. The Jet Engine. (Rolls-Royce plc, London, 2005).
[20] Melão, N. and Pidd, M., A conceptual framework for understanding business processes and business process modelling. Information Systems Journal, 2000, 10(2), pp105-129.
[21] Browning, T.R., Fricke, E. and Negele, H., Key concepts in modeling product development processes. Systems Engineering, 2006, 9(2), pp104-128.
[22] zur Muehlen, M. and Rosemann, M., Workflow-based process monitoring and controlling - technical and organizational issues. In Proceedings of the 33rd Hawaii International Conference on System Sciences. Hawaii.
[23] O'Donnell, F.J. and Duffy, A.H.B., Design Performance. (Springer, London, 2005).
[24] Kerley, W.P. and Clarkson, P.J., Modelling the quality of engineering designs. In Heisig, P., Clarkson, P.J. and Vajna, S., eds. Modelling and Management of Engineering Processes, pp153-164 (Springer, London, 2010).
[25] Kloss-Grote, B. and Moss, M., How to measure the effectiveness of risk management in engineering design projects? Presentation of RMPASS: a new method for assessing risk management performance and the impact of knowledge management - including a few results. Research in Engineering Design, 2008, 19(2-3), pp71-100.

Contact: Warren Kerley
University of Cambridge
Engineering Design Centre, Department of Engineering
Trumpington Street
Cambridge, CB2 1PZ
UK
Phone: +44 (0) 1223 765 107
Fax: +44 (0) 1223 766 963
E-mail: wpk21@cam.ac.uk
URL: http://www-edc.eng.cam.ac.uk/people/wpk21.html

Warren is a research associate in the Engineering Design Centre at the University of Cambridge. He is currently researching the issues involved in designing complex socio-technical systems, such as those involved in engineering design. He has a particular interest in the application of process mapping and simulation tools to help understand and improve these systems.