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USING SIMULATION TO SUPPORT INTEGRATION OF LIFE-CYCLE ENGINEERING ACTIVITIES INTO AN EXISTING DESIGN PROCESS: A CASE STUDY

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1. Introduction

Life-cycle engineering (LCE) aims 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 inevitably requires change to the product design process because it is estimated that 70-80% of all life-cycle costs are determined during design (Dimache et al., 2007). These changes involve the integration of new requirements, particularly those related to service, into the existing process. This is difficult when the design process is already tightly integrated and constrained by the need to meet existing requirements. This is typically the case for companies which develop complex, high-performance products (such as those found in the aerospace industry) using concurrent engineering (CE) practices. The design processes in such companies are particularly complex due to their iterative nature and the need to co-ordinate the work of specialist teams.

This paper is concerned with how such companies can approach integrating LCE into the design process when already using CE techniques. We argue that this can be facilitated using a structured approach that uses process simulation to support process mapping activities. We illustrate this through a 12-month case study conducted with a major UK manufacturer of capital equipment.

The paper proceeds as follows. Section 2 introduces the case study and the problems we set out to address. Section 3 lays out the argument for applying process modelling and simulation and outlines the Applied Signposting Model (ASM) which we used. Section 4 discusses the case study in depth. Section 5 highlights our findings regarding the use of process simulation to support LCE process development, discusses the implications of these findings and suggests areas for further work prior to concluding in Section 6.

2. Case study background and objectives

Like many other firms, the case study company increasingly offers its products under total service agreements. Under these agreements, customers only pay for the time that the product is in use and responsibility for service and maintenance remains with the company. The company therefore has a strong incentive to ensure that the total life-cycle costs (LCC) of the product over its entire lifetime are as low as possible. The company aims to achieve this by incorporating 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 company's customers expect price commitments at the earliest stages in the design process – and therefore the earlier life-cycle costs are considered the greater is the opportunity to manage the financial risks associated with each project.

In the case study company, 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. Implementing LCE from the outset of the design process would require this team to be more closely integrated with the commercial and service design teams and would involve a greater emphasis on life-cycle considerations.

It was recognised that this integration 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. In order to understand the extra co-ordination and to create a canonical process that could guide product development in future, the company needed the revised conceptual design process to be formalised. To meet the requirements of a wider quality management programme, the company also required the new process to incorporate systems engineering principles by being structured as a V-model (Sage and Armstrong, 2000) and to conform to the company's existing stage-gate approach (similar to Cooper, 2001).

The objective of the case study was therefore to formalise and evaluate the proposed changes to the conceptual design process. In particular, the following specific questions were asked:

- **Structure of the new process.** What changes should be made to the structure of the existing process? What new information and activities are required? How should these new tasks be incorporated and what effect does this have on the existing process structure and information flows?
- **Resourcing the new process.** What extra resources are required to perform the process? What and how much extra work will each team have to do?
- **Performance of the new process.** How long will the revised process take to produce a conceptual product 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?

2.1 Research challenges

The difficulty of answering these questions gave rise to the main research challenges of the study:

- **Developing a mutual understanding of the new process amongst its participants and other stakeholders.** This is difficult because of the implicit, distributed nature of process knowledge, the concurrency and iterative nature of the design process and the need to incorporate new tasks into the currently ill-defined process.
- **Evaluating the impact of process change on key performance metrics such as project duration and cost.** It is important to highlight that this is a challenging issue since the additional LCE tasks are not independent of the existing design process – they involve the evaluation of design deliverables and may lead to design tasks being revisited. The duration of the new process could not therefore be estimated simply by summing that of the existing process with the duration of the additional LCE tasks, since these new tasks can interact in a potentially complex way with the existing process through the mechanisms of design iteration and task concurrency. This is illustrated in Figure 1 below.

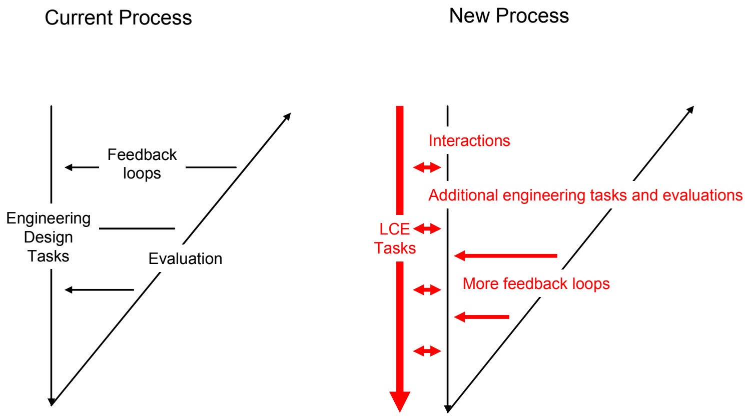

Figure 1. The new LCE tasks interact in a complex way with the existing CE design process, through the mechanisms of iteration and task concurrency. Understanding the impact of a proposed change is therefore difficult

3. Process modelling and simulation

In overview, the case study objectives were met by constructing a model of the existing design process and using this description to localise the proposed life-cycle engineering activities within the workflow. Simulation was then used as a tool to explore the consequences of the proposed change. This section introduces the modelling and simulation methods prior to discussing their application in Section 4.

The 'Applied Signposting Model' (Wynn et al., 2006) was chosen as the basis of this research. This approach is implemented in the 'P3 Signposting' modelling and analysis software developed in Cambridge. Although other academic and commercial tools are available and could have been used instead, P3 was considered to hold three advantages in the context of this particular study:

- **It provides visualisation tools to explore simulation results.** For instance, it is possible to select processes which satisfy certain criteria (such as those which fall within a given range of durations and which incorporate a certain number of iterations of a given task) and view Gantt charts of these individual outcomes. This allows the model behaviour to be studied and validated in depth; as discussed in Sections 4 and 5 this is an important aspect of our approach.
- **It incorporates features necessary to simulate the iterative interactions between the proposed LCE activities and the existing design process.** These features, outlined in Section 3.2 below, are not available in commercial simulation tools.
- **As the tool has been developed within the authors' research group, it would be possible to accommodate new requirements if they were encountered during the study.** In particular, it would be possible to write additional modules to perform any specific analyses which became necessary. This flexibility was considered to outweigh the usability and reliability benefits which might be gained from using a commercial package.

The ASM modelling approach is described in full by Wynn *et al.* (2006). Those features of the ASM which are relevant to this paper are summarised below.

3.1 Overview of the Applied Signposting Model

The ASM provides a formal process modelling language which may be manipulated using a number of different views, of which the primary representation is the formal flowchart diagram shown in Figure 3. The following basic element types are available in this notation:

- **Parameters** (blue ellipses) represent the packages of information which are created and updated as tasks are attempted.
- **Simple tasks** (yellow rectangles) convert one set of input parameters into one set of output parameters, in a specified time and using specified resources.
- **Compound tasks** (red rectangles) comprise one set of inputs which is required to start the task and multiple sets of outputs, of which one set is selected and activated when the task is completed. They are used to represent the selection of alternative process routes; for instance, to choose between a high-fidelity or low-fidelity analysis on consecutive iterations.
- **Iteration constructs** (green diamonds) represent evaluation tasks. They comprise sets of outputs which must each be tagged as either *success* or *failure*. Failure scenarios are then indicated by red arrows emerging from the task. They lead to the modification of information which was previously made available by upstream tasks, and are treated as a special case by the simulation algorithm (Section 3.2).
- **Sub-processes** (orange rectangles) are hierarchical groupings of tasks and parameters which may be expanded and collapsed to facilitate construction of large models.

Task properties such as task duration and outcome may be specified as probability distributions or as functions of *process variables*. A process variable is a numeric representation of some aspect of process state. For instance, the number of iterations of a task may be modelled using a process variable x, and the duration of that task specified as a function of x to account for reducing duration on subsequent attempts.

Simulation proceeds according to the task properties and the structure of the information flow network. It is based on the following discrete-event algorithm:

1. All parameters which are specified as inputs to the model, or which are not produced by any task, are initialised to the *updated* state. All other parameters are initialised to the *unavailable* state.
2. Each task is considered to identify those which are *recommended* to attempt immediately. The conditions under which a task is recommended to attempt are part of the task's configuration; most usually requiring some subset of the inputs to be *updated* and the remainder to be *available.* If no tasks are possible, the simulation finishes.
3. Tasks are started one at a time until no more tasks are *recommended*. When a task is started, all its inputs which were *updated* are downgraded to *available* status. It will thus not be recommended to attempt again unless one or more inputs is subsequently updated by iteration.
4. The simulation clock is advanced to the next time at which a task is due for completion. The task is completed by selecting a single set of outputs according to logic specified in the task's definition, and making all outputs in that set *updated.* Since this might make some successor tasks *recommended*, Step 2 is revisited.

3.2 Iteration in the Applied Signposting simulation

The basic scheme outlined above is appropriate for modelling independent streams of tasks which may include sequences of tasks repeated in an ordered process of iterative refinement. However, it is insufficient to model complex CE processes where there are concurrent, interdependent streams of activity and tasks are attempted based on incomplete information because of the need to compress project schedules. In this situation, the failure of an iteration construct in one stream (which might represent an LCE evaluation activity) may invalidate information in others. When this occurs, the model should identify all tasks which were attempted based on these assumptions and ensure that these are executed again in the simulation.

The ASM views this type of iteration as a special case – propagated rework whose initiating cause is the failure of an iteration construct. When such a task fails during the simulation, the network of tasks is processed to identify all *updated* parameters anywhere downstream of those which were directly updated by the failure. All such parameters are set to *available* and any tasks in progress which were based on the invalidated parameters are immediately interrupted. This has the effect of requiring all tasks 'downstream' of the information which was updated by the failure to be attempted again.

4. Applying process modelling and simulation to support LCE introduction

The case study objectives were met by applying four steps which were subsequently revisited in a process of iterative refinement (Figure 2). This approach is discussed in Subsections 4.1-4.5 below prior to reflecting upon lessons learned in Section 5.

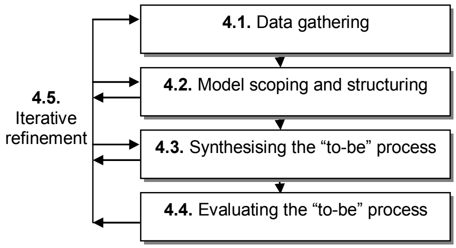

Figure 2. An overview of the iterative approach used for process modelling and simulation

4.1 Data gathering

The starting point for integrating the LCE activities was to model the existing ('as-is') process. Although it was recognised that all projects would be different, as a starting point a reference project was chosen 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. 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.

4.2 Model scoping and structuring

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

- **Scope.** To a large extent the scope of the process to be modelled had been determined *a priori* by the focus on conceptual design (Section 2). Additionally, due to time limitations and the project's focus on changing the engineering design process, it was decided 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.
- **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, 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 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 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. 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. Although some parts of the model were decomposed hierarchically, nevertheless it remained a relatively flat structure due to the high connectivity and interdependence between tasks which prevented effective partitioning.

4.3 Synthesising the 'to-be' process

Development of the 'to-be' process proceeded in parallel with refinement of the 'as-is' model, since they needed to be comparable for evaluation purposes. 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. 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. The 'to-be' model at this stage contained roughly 75 tasks of which 15 represented evaluation activities (compared with roughly 50 tasks in the 'as-is', of which 10 represented evaluations). The increased size of the model was a direct consequence of the increased process complexity which arose from incorporating LCE tasks.

Figure 3 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.

4.4 Evaluating the 'to-be' 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. 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.

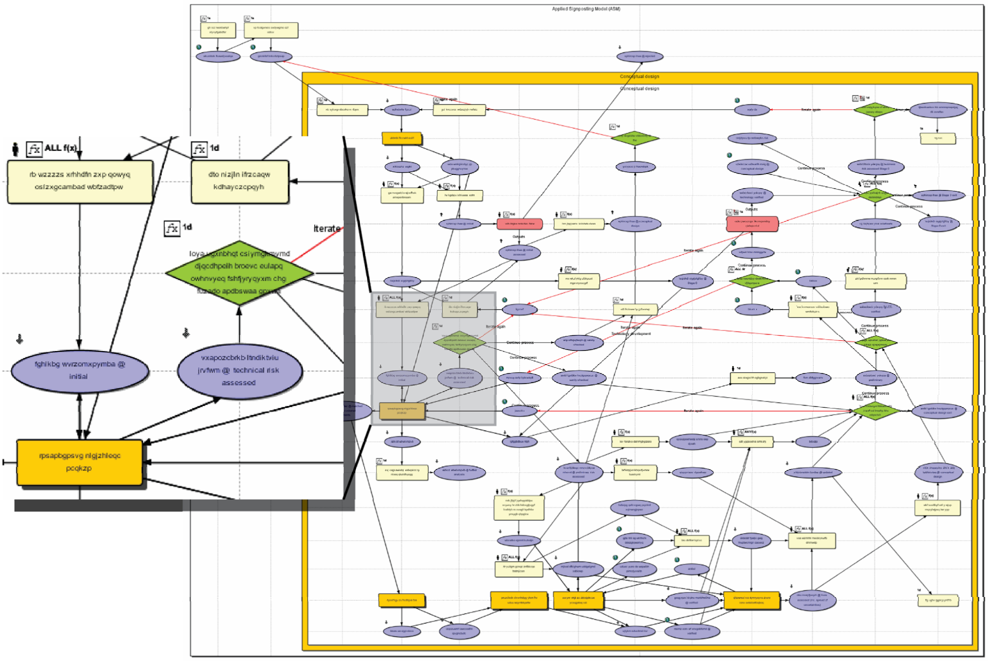

Figure 3. A partial view of the 'to-be' process model, illustrating the first of three levels of detail. Task names modified to protect confidentiality

Different versions of the models were used for process visualisation and for process simulation, since these two objectives were found to 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, when used for simulation, models are a form of computer program interpreted by the ASM simulation algorithm. The individual elements from which a model is constructed have simple behaviours determined by a small number of rules; the complexity in process behaviour then arises from the interactions between these rules and the model structure. The model must therefore be fully specified and formally correct to behave as intended. This formalism required a more detailed model (increasing the total number of tasks to about 85).
Two particular challenges arose while constructing the simulation models:

- **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 (described in Section 3.2). However, since this is based on an algorithm parsing the information flows in the model, 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.

Resolving these issues was a relatively time-consuming aspect of the modelling process. However, this activity generated significant insight into the design process as it required the modellers and other stakeholders to ask specific questions about not only how the process was organised and what the information dependencies among tasks might be – the focus of steps 4.1 and 4.2 – but also about how it might be expected to behave both in ideal conditions and following rework. Once this had been achieved, the simulation was used to calculate the additional duration and designer-effort implied by the 'to-be' model. However, since the modelling exercise had involved examination of multiple iteration scenarios, certain ranges of these values were expected by this point and the figures were viewed as a validation of the model and 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.
To summarise, the objective of this step 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.

4.5 Iterative refinement

The procedure outlined in steps 4.1-4.4 above was highly iterative, as models were refined and the need for more information was recognised following each discussion. The process modelling exercise required the participants to consider the process behaviour carefully, while the simulation of these processes provided data to refine these models and to compare the 'as-is' and 'to-be' cases. Refinement of the 'to-be' model continued throughout the study. In particular, significant refinement was required once simulation results were available, since many consequences were only revealed through this analysis.

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. 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. Assumptions across the various teams were also revisited – 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.

Throughout this process the modellers and stakeholders were learning from one another. The focused model-building and simulation activities led to a more refined model as well as a better-corroborated and agreed understanding of the proposed process and of the challenges which would be faced in its introduction. This bi-directional learning was viewed as critical for both the development of adequate models and to support the implementation of the recommended process at a later date. The development of a more explicit, negotiated understanding was seen by company stakeholders as a key benefit of the case study.

5. Reflection

Design process changes are often implemented through process modelling exercises followed by refinement in practice. This is a 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 modelling activities by supporting the development of a deeper understanding of the processes being modelled and thereby in evaluating the likely impact of changes.

5.1 A (relatively) simple model for a complex process

Process modelling is a widely recognised and accepted approach for visualising processes and supporting the planning of process change (Curtis et al., 1992; Browning and Ramasesh, 2007). Coupled with simulation methods, process modelling allows the impact of proposed changes to be estimated despite potentially complex interactions with the existing tasks. 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 models and simulations do not have to reflect the full complexity of the design process in order to be useful. Our study also highlighted that the representation of a process is shared between the model and the users of the model – and that much of the knowledge surrounding the model is 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 lines) in which the modeller can develop sufficient understanding of the process to explore the implications of the model themselves.

5.2 An 'open box' approach

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 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 – for instance, by highlighting that a given evaluation activity was poorly placed due to its propensity to interrupt other work. 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.

5.3 Comparison to 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 describing how they have been applied in practice. 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. In most cases 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.

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.

5.4 Limitations and further work

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.

6. 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 conclusion, the contributions of this paper are twofold. Firstly, through a significant 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. 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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