INTERNATIONAL CONFERENCE ON ENGINEERING DESIGN
ICED 03 STOCKHOLM, AUGUST 19-21, 2003

THE SIMULATED DESIGN PROCESS

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Abstract

The Signposting modelling framework provides the opportunity for companies to build models of their design processes that incorporate the inherent unpredictability of outcomes. While the modelling exercise itself provides insight, the greatest value comes from the analysis of the combined effects of the uncertainty in all of the individual activities in the process. This paper presents the architecture of a prototype simulation tool, designed to analyse the most recent generation of Signposting models, incorporating concurrency and resourcing effects. The tool can help increase the designers' and managers' understanding of design process issues, both before and during a project.

The key heuristics concerning task selection and the evaluation of the consequences of task outcomes are presented. The simulation may be used in both the evaluation of a proposed process, and also in the optimisation of the process to reduce cost or time. Output from the simulation takes the form of a comprehensive log file, in order to facilitate post-processing to answer the specific questions of a particular audience, but a number of standard data visualisations have been developed to give access to key information quickly.

Keywords: planning and workflow methodology, risk analysis, design management

1 Introduction

New product development is the major source of risk for most engineering companies – no other aspect of their operations is so uncertain and so critical for the business. Risk assessment techniques for the handling of technical risk, such as FMEA, are well established in industry, even if many companies are still seeking to improve and refine their application. Process risk is less well understood, and the tools for its assessment and management are not widely available. A tool that can provide estimates of cost and duration for a proposed new product development would be of value to both the strategic management of a company, who might be trying to select which of a range of possible projects to pursue, and also to the operational management responsible for planning the execution of projects [1], who could use it to investigate which process factors can be varied to reduce the cost or duration.

Predicting the outcome of a design process is made difficult by a number of factors, most notably the low quantity and applicability of precedent information. Typically a company will have seen a relatively small number of previous generations of any type of product, perhaps none if the product is entirely new. The quantity of information available about the progress of previous projects will be limited and will depend on the degree of similarity between two products or two processes within the company. Even if information about past projects is available, advances in the technology of the product (e.g. new materials) or the design process (e.g. new CAD tools) may mean that it is difficult to extrapolate to a future design project.

To overcome this difficulty, just as finite element analysis analyses complex geometries by decomposition into a number of simpler, better understood elements, we can break the design process down into its component tasks, for which greater precedent is typically available. For example, while a company might have designed only five or six new cars over the past decade, within those projects hundreds, if not thousands of individual finite element analyses, component drawing tasks and other activities will have been completed. From this knowledge, whether previously collected by the company or embodied in the designers who have carried out the tasks, estimates of likely costs, timing and outcomes can reasonably be obtained. Breaking the analogy with FEA, while in that case the simple elements can be completely understood and their behaviour expressed in deterministic form, the complexity of a design task, even though less than the parent process, means that significant elements affecting the outcome (designer understanding, insight, inspiration) can never be entirely captured. Hence the task cannot be modelled as a purely deterministic element; the outcome will appear to have a random element to account for the action of factors beyond the scope of the modelling.

2 Overview of the simulation

Researched in Cambridge, the Signposting system [2] provides a framework for modelling tasks as stochastic mappings between input and output process states. This framework supports a number of factors including alternative tasks/methods, resourcing constraints and effects, a distinction between essential and valuable input information, and modelling learning during the design process.

Although previous research [3],[4] has resulted in the creation of a number of software tools, the new additions to the signposting model, particularly the move from serial-process single designer/teams to concurrent, resource limited multiple designer/teams, were unsupported by the existing tools. This created the need for a new analysis tool, and the decision to adopt a simulation based approach was made, for three principal reasons:

- A simulation can provide extremely rich data, minimally constraining the questions that could be answered through post processing of the results.
- The stochastic nature of the model lends itself to a population based evaluation technique.
- The simulation approach makes it easiest to verify the internal logic of the model, as the code is a reflection of the actual process.

The structure of the program is shown in figure 1. There are three primary loops in the simulation code; the first is the loop responsible for simulation of individual iterations of the simulated design process; the second is the evaluation loop, which calls multiple iterations of the single process simulator in order to assemble a representative population [5], while tracking population statistics; the third, outermost loop is the optimisation loop, in which parameters of the model such as task precedence and resource allocation may be varied, calling the evaluation loop to test the effects of each alteration. Within the elements shown, there are many further loops and decisions.

The simulated processes have a range of costs, durations and other properties, due to:

1. Variation in the tasks chosen to be started when there are multiple possibilities;
2. Variation in the input information and resources to tasks, partly driven by 1. above;
3. Variation in the outcome of the task, whether success, failure or partial success/failure.

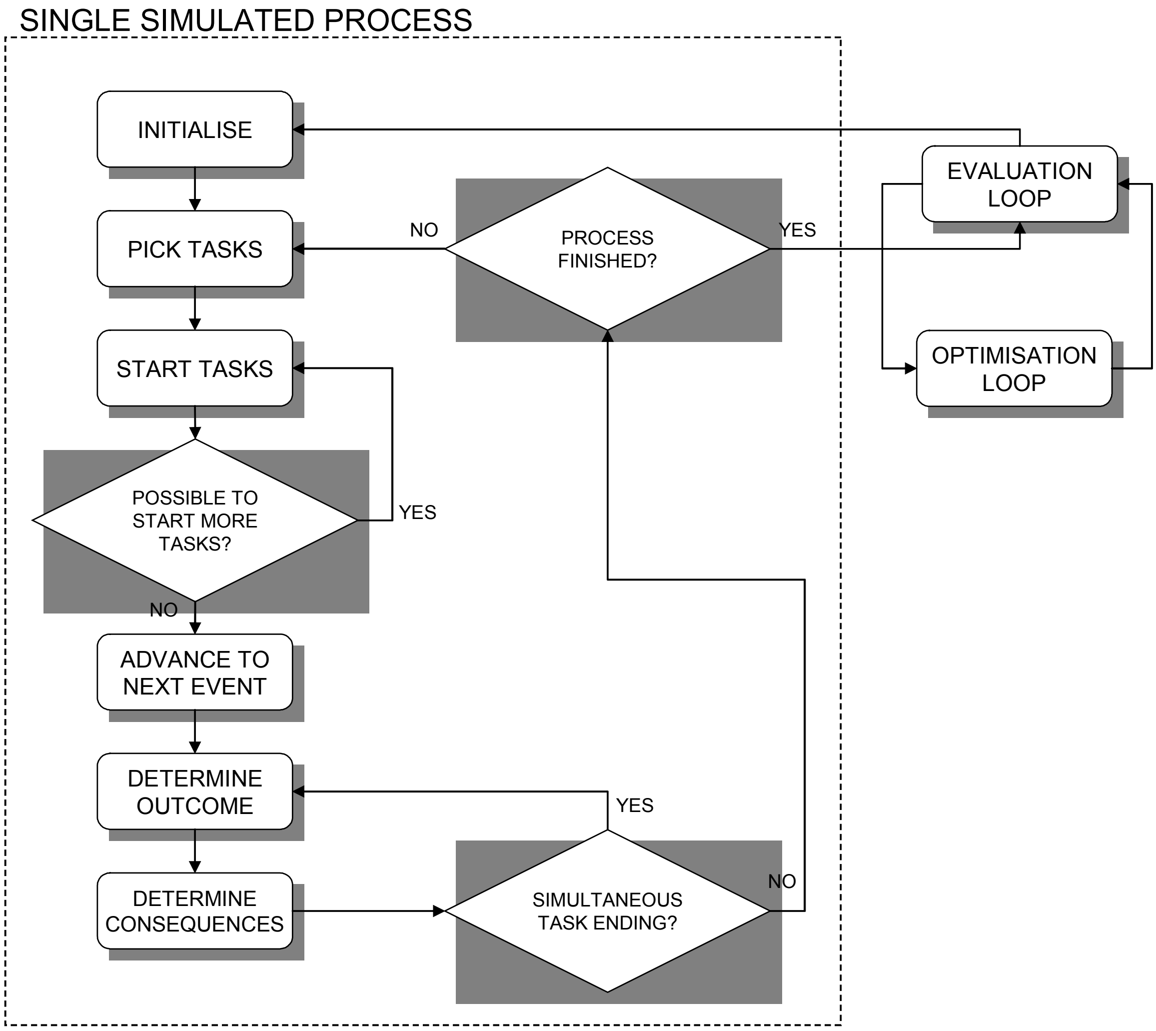

Figure 1. The overall structure of the design process simulation

2.1 Task Choice

Task choice is driven by three factors; possibility, preference, and other factors being equal, a random element. These issues are considered in turn to pick a single preferred task for the simulation engine to start at a given point in the process.

Possibility

Each task in the model being simulated has one or more valid input states, expressed in terms of the quality, availability or maturity of certain factors in the process; design data, resources, knowledge. These input states are compared to the process state at that instant in the simulation, and only those tasks for which all the input parameters are met or exceeded are possible. This produces a list of valid task/input state pairs – not all input states in any given task are possible.

All the input states that have been flagged as possible for each task are compared, and if any input state has a lower or equal value for every input parameter, compared to another valid input state for the task, and the lower values are not on resource parameters, then the task is invalid. This is necessary because the task with the highest values of input may not necessarily be the fastest, cheapest or most effective when considering the output – having completed other parts of a design can make a task easier, because more knowledge is available, *but* it could equally make the task harder because the possible solutions are more constrained, tolerance margins have been exhausted, etc. Available information cannot be ignored to make a task easier, but short staffing of a particular activity is a valid option.

For the list of remaining valid task / input states, the possible outcomes of the task are now considered. For the task to be useful, at least one possible outcome must have at least one output parameter at a higher quality/maturity level than the current process state. It doesn't matter if any outcomes produce a lower outcome – the possibility of failure is inevitable in some places in the design process.

Preference

The simulation code can incorporate preferences as to which tasks should be done in preference to, or before others. Within these tasks, the user can also express preferences for resourcing levels. These preferences can come from a number of sources

1. Direct input by the user of the simulation, to test a specific configuration of the process.
2. Optimised precedences generated by the previous Markov-chain model analysis tool.
3. The optimisation loop included in the simulation code itself.

These preferences are expressed in the form of a conditional precedence matrix. This is a square matrix with one column and row for each valid input state for each task. Each row lists the costs associated with picking that task, when the task in each column is also a valid possibility (figure 2.)

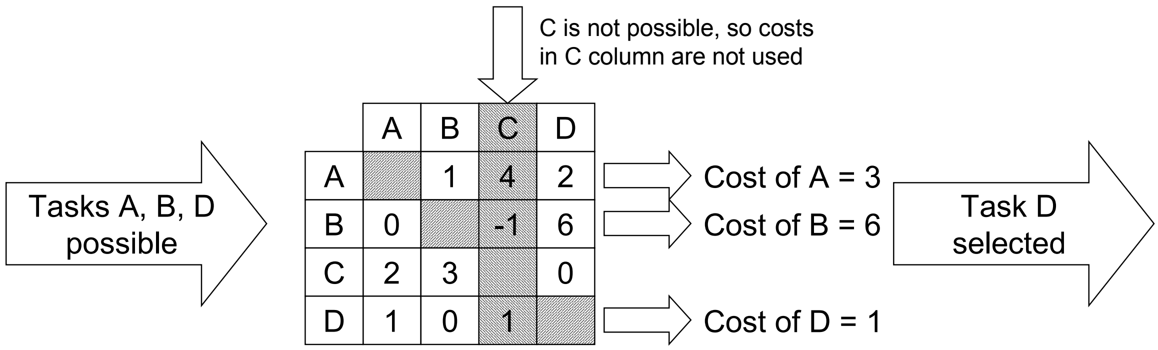

Figure 2. Using the conditional precedence matrix to pick a task

The conditional precedence matrix is a powerful representation, as it can capture not only simple precedence, e.g. A follows B, but also conditional precedence, e.g. A before B if C is possible, B before A if not. It is less useful as a visual or manual representation than conventional precedence matrices [6], but as a data structure it is very useful.

Random factor

The preferences expressed in the conditional precedence matrix may assign equal costs to more than one task. In this case a single task is picked from the remaining possibilities, with equal likelihood attached to each. This random factor ensures that the population of simulated processes is as diverse as possible within the constraints and assumptions of the model.

2.2 Task outcomes and effects

At the point of simulated completion of a task the simulation picks an outcome from those linked to the active input state for the task, in accordance with the probabilities assigned in the model to each outcome. The process state is updated with the new values of parameter quality/maturity indicated by the outcome and any resources required by the finished task are returned to the pool. In the case of task success, where the only effect of the outcome is to improve the process state, this is the end of the process. However, in the case of task failure, in which information previously assumed to be of high quality / maturity is found to be unsatisfactory, the simulation must evaluate the consequences of the failure.

The direct consequence is that the tasks that originally generated the invalidated information must be repeated (although possibly faster / cheaper with the benefit of learning). The indirect consequence is that any tasks which were performed using the assumed high-quality information as an input must also be repeated. The tasks thus invalidated may then have knock on effects of their own, and a chain of consequences must be evaluated (figure 3).

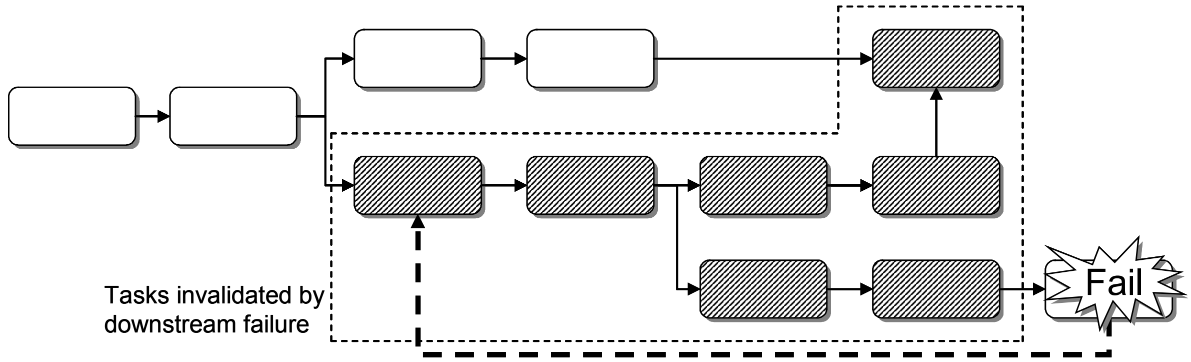

Figure 3. Task failure can cause a cascade of invalidated tasks

2.3 The process dimension of quality

By default, the simulation of a single design process run proceeds until it reaches the end state of the model, defined in terms of the quality/maturity level of the design parameters of interest. To allow the crude investigation of the tradeoffs between process duration and budget and quality of outcome, the concept of minimal and maximal end states was introduced to the model. A minimal end state represents the minimum quality of design that could be manufactured and sold to customers. This includes safety and legislative requirements, and basic functional performance, but does not factor in relative performance to competitor products, commercial viability, etc. Because signposting abstracts the actual product, we are not trying to measure the quality of a product in any physical sense, with all the attendant difficulties that this would bring. Instead it is sufficient to be able to say 'after X iterations we typically have a product that we could release' or 'if another two weeks were spent on fine tuning we could improve Y aspect of the product's performance'. The maximal end state in contrast, represents the peak product performance that could realistically be expected, a product that would be highly competitive in the present and future market, and a level of performance beyond which there would be no value in investing in further development.

In addition to the two end states, two limits are placed on the cost and duration of the project. The target budget / delivery time represents the amount of money / time that the company intends to spend on developing the new product, and the maximum budget / delivery time is the most money / time that could possibly be devoted to the project before it is cancelled or the company runs out of resources.

The simulation implements different end conditions depending on the state of the budget:

- Below target time / cost, the design proceeds unless the maximal end state is reached.
- Above target time / cost, but below the maxima, the process proceeds until the minimal end state is reached, at which point it terminates.
- Above maximum time / cost all projects are halted. Any project which has failed to complete in this time is considered to have failed.

From the point of view of the simulation this provides a useful limit to the length of any run, but modification of the budgets also allows the average product quality and risk of failure to be evaluated for a number of business cases. A number of characteristic regimes of product development can be observed under this end conditions (figure 4.).

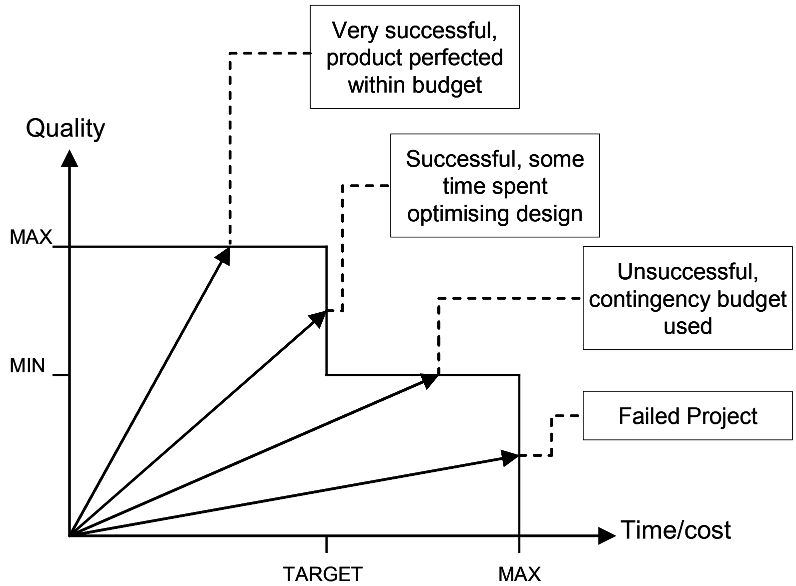

Figure 4. Interaction between time/cost budgets and min/max process end states

2.4 Resource profile events

In large scale engineering design processes particularly, it is common to see variation in the staffing levels over the course of a project, driven both by the needs of the project, with fewer needed during conceptual design phases, and also by competition for resource with other projects, for example engineers being gradually released from a project nearing completion into a project that is starting up.

This facet of design process management is incorporated through 'resource events' which are inserted into the simulated project timeline and add or remove resources at set times. The effects of these resource level variations on the process cost, timing and output quality can be investigated, allowing managers in industry to begin to quantify the benefits of deploying people into a project at specific times.

2.5 Gateway controlled process

Many industrial design processes are not directly controlled by a drive towards the finished design, but instead through intermediate goals and gateways. This can be simulated by setting intermediate end states in the process, which the simulation will strive to reach, and at each gateway updating the end state to the next gateway. The optimisation loop determines a separate conditional precedence matrix for each process phase.

Incorporating this factor into the simulation allows a user to investigate the effects on the process of setting different gateways, developing understanding of the tradeoffs between control of the process and the deviation from the optimal process.

3 Interpreting the simulation results

The range of questions that can be asked by a user of the simulation is almost limitless. Rather than constrain the questions that can be asked, the simulation can write a log file at either a process or task level, capturing all of the simulated events. The post-processing of these log files will allow almost any user question to be answered without the need to modify the simulation code itself. The programming of the post-processor is not complicated, but to improve the accessibility of the simulation software, a number of pre-prepared visualisations have been developed.

Views of population cost / duration – As the simulation calculates the cost and duration of the each process in a large population to arrive at a representative result, the information available is much richer than simply an average value. A frequency distribution (figure 5.) indicates not only the mostly likely cost/duration outcome, but also how the other outcomes are distributed around it. This could show, for example, that a certain process with a low average cost has a wide range of possible outcomes, and hence a significant risk of running over budget, while a different process with a higher average cost has less variance, and hence a lower chance of running over budget.

A contour plot of cost and duration together (figure 5.) could be produced, but the points are likely to lie closely clustered along a line with a gradient related to the average cost per day for an engineer working on the project. This is because, for most design tasks, the variance of cost and duration are strongly related, as the principal cost is related to the engineer resource allocated to the activity. More variation will be observed in processes where there is a greater variance of pay-levels among the participants, or where significant non-time-rated costs, such as the construction of prototypes or outsourced tests, are present. The simulation does not currently support a random element in the cost or duration of tasks, even though the underlying signposting framework does.

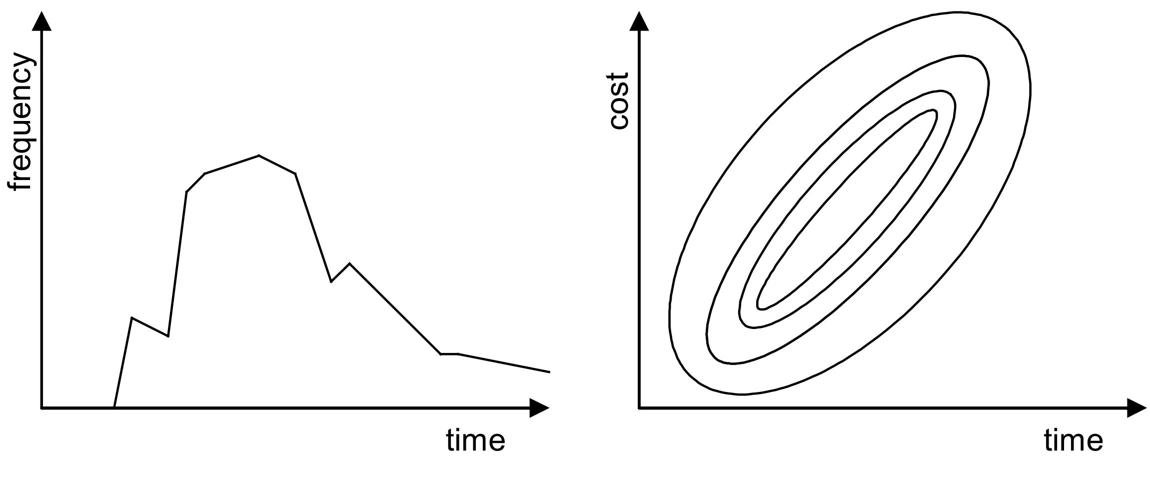

Figure 5. Views of time, and cost/time for a single process configuration

Views of cost / duration trade-offs – Concurrent engineering offers the potential for faster completion of projects, but at a greater cost due to tasks necessary to correct the output of activities begun with incomplete or estimated information. By generating a population of different simulated processes with different resource level profiles and task precedences, a scatter plot of average costs and durations for each process configuration can be drawn. This indicates the potential for improvement, holding cost or duration constant, suggesting whether process acceleration or cost-cutting initiatives are likely to be more productive (figure 6.).

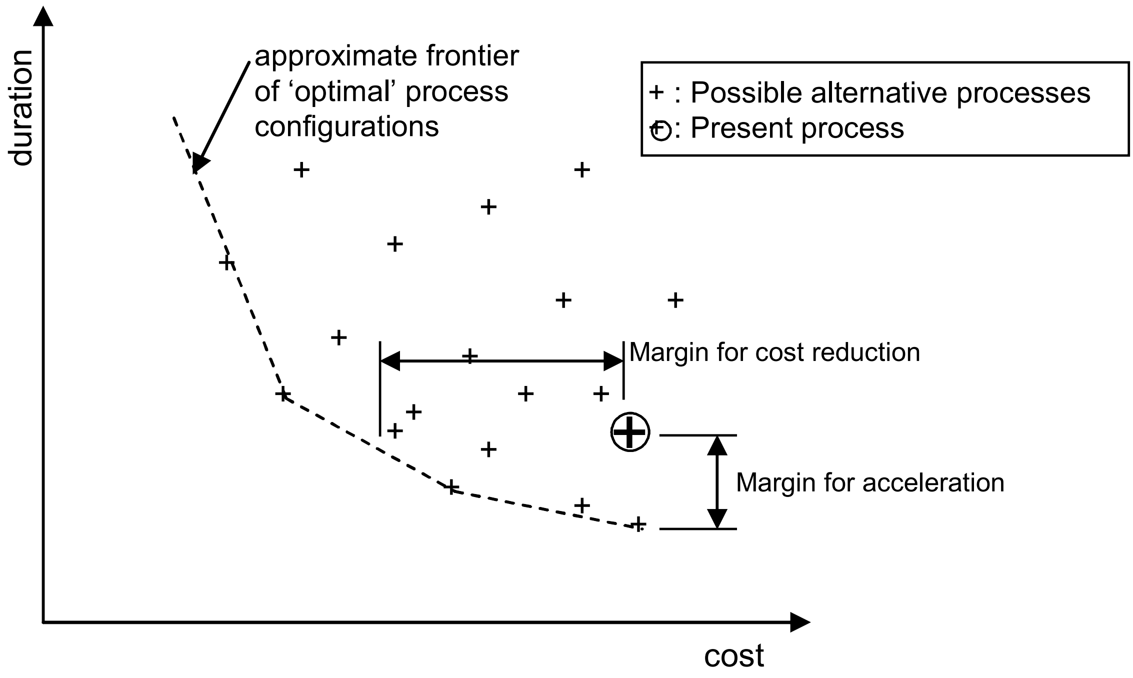

Figure 6. Views of cost/duration trade-offs

Views of cost / duration / quality tradeoffs – By setting different end points for the design process, the average cost of finishing a project to different levels of quality can be shown. This will be of value to company management in market positioning of new products.

4 Simulation for process optimisation

Although previous signposting tools provided the ability to optimise the sequencing of tasks in a serial process, the results of this analysis are indicative rather than definitive when considering the sequencing of a concurrent process. The results of the Markov chain analysis can be used, in the form of a conditional precedence matrix, but it was desirable to make concurrent-process based optimisation available.

Optimisation via the simulation is based on perturbation of the precedence matrix around a reference point. To optimise the running of the simulation, the parameters which drive the optimisation are determined at run time from two, more easily understood, measures:

- The percentage change in the cost/duration which will be considered insignificant
- The confidence level desired for the precedence guidance (e.g. 99% of precedences correctly indicated)

The optimisation proceeds in stages, with each stage taking a new reference process configuration to perturb about. Firstly in each stage, a large reference population is simulated – as we are trying to determine whether there is a difference between the reference mean cost/duration and the perturbed mean cost/duration, it is most efficient to increase the size of the reference population relative to the individual comparison populations, as it will be used several times. The size of the reference set is not input directly by the user, as the required size for a given accuracy of optimisation will vary depending on the individual model. Instead, as the reference set is generated it is compared to a portion of itself, and the generation stops once the conclusion can be reached that the population means are the same, given the accuracy requirements set above.

During the generation of the reference set the possibilities in the process, the points at which more than one task competes for limited resource to be started are recorded. Only these entries in the conditional precedence matrix need be evaluated. It is important to restrict the number of evaluations performed, as simulation is highly demanding of processor time.

Each of the entries in the precedence matrix observed as a possible influence on process performance is perturbed from the reference value in turn, and the effect on the average cost or duration is determined by comparison to the reference set; positive, negative or no effect. Positive effects have 1 subtracted from their cost in the new precedence matrix, while negative effects have a 1 added to their cost.

The optimisation routines have been applied to existing signposting models and have obtained process configurations with a total cost and duration 5% lower than the average process configuration.

5 Robustness of the simulation results

A simulation can produce apparently useful results, but the validity of the model can be difficult to prove [7]. One of the challenges of the signposting modelling approach is the difficulty of finding reliable information on the characteristics of each task involved in the design process. The uncertainty in the average duration of a particular task, or the likelihood of each of the potential task outcomes, can never be entirely removed. If this uncertainty can be represented however, the effects on the outcome of the simulation can be evaluated.

Unfortunately, local sensitivity analysis is insufficient to indicate the potential effects of variation in the model parameters, because of the non-linear behaviour of the model – for example, an increase in the duration of a task will have no effect on the total duration of the project, until it reaches such a length that it moves onto the critical path. The mode of evaluation of effects will depend on how many key uncertainties there are in the signposting model being simulated. For investigation of a single uncertain parameter, a process population can be created at each of a range of points within its possible range, and the results can be averaged or graphed. If more than one parameter is uncertain, as would commonly be the case, outright evaluation of the process properties for every combination of possible model values rapidly becomes impractical. For these cases, rather than generate a whole population for each combination of model values, the uncertain model values can be randomly assigned within the limits at the start of each separate simulated process. The overall population then represents the spread of results expected given the uncertainty in the model, although the effect of individual factors cannot be determined.

6 Discussion

Simulation offers a new way for engineers in industry to understand and improve their processes. At present the approach allows specific questions to be posed and answered, but in the future it is hoped that a real-time interactive version of the simulation can be made available, allowing engineers to interact directly with the configuration of their design processes and to receive feedback on the effects in real-time. For this to be possible, major improvements in the efficiency of the simulation must be made, possibly requiring a move away from a pure Monte-Carlo approach, or the implementation of a database of pre-generated data and interpolation between known points.

Acknowledgements

The authors wish to thank the UK Engineering and Physical Sciences Research Council (grant GR/R64100/01) for funding this research.

References

[1] Eckert C.M. and Clarkson P.J., "Planning Design Processes in Industry: Initial Observations", Computer-based Design, Engineering Design Conference 2002, London, 2002, pp.637-646.

[2] O'Donovan B.D., Clarkson P.J. and Eckert C.M. "Signposting: Modelling uncertainty in Design Processes" Proceedings of ICED '03, Stockholm, 2003.

[3] Jarrett J. P., Clarkson P.J. et al., "Accelerating turbomachinery design", Proceedings of ASME International Gas Turbine Institute TURBO EXPO 2002, Amsterdam, Netherlands, 2002.

[4] Clarkson P.J., Melo A., et al., "Signposting for Design Process Improvement", Proceedings of Artificial Intelligence in Design '00, Worcester, MA, USA, 2000, pp.333-354.

[5] Hatman, T.S., "Mathematical Fortune-Telling", Complexity, Vol 6, No. 5, 2001, pp27-40.

[6] Eppinger S., Whitney D., Smith R. and Gebala D., "A Model-Based Method for Organising Tasks in Product Development", Research in Engineering Design, Vol. 6, 1994, pp.1-13.

[7] Johnson J., "The "Can You Trust It?" Problem of Simulation Science in the Design of Socio-technical Systems", Complexity, Vol. 6, No. 2, 2001, pp.34-40.

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