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SIMULATING DESIGN PROCESSES TO INCREASE MANAGERS' UNDERSTANDING

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1. Introduction

Beginning a design project is challenging. Managers need to understand where the risks lie in the new process. They need to plan tasks and allocate resources to them. Most products are designed by modification, so that designers have some idea what the target product will look like. Design managers can draw on this to describe what tasks they will need to undertake and the information that will be required to do so. However this is not enough, they need to find a sequence of tasks that minimises the risk of running over time and over budget with given resources. Inefficiencies arise when resources are used inappropriately or are missing, thereby delaying (or holding up) the process. As design processes almost inevitably involve iteration and failure of individual tasks, the best route through a process, is one that takes account of likely failure.

Existing planning tools and methods in common use in engineering industry force project managers to treat engineering design processes as deterministic, assuming every task will be successful, every refinement will need a known number of iterations, and every specification choice is fixed from the outset of the project. Yet engineering design processes are characterised by uncertainty, both in the eventual form of the solution, and the means and method by which this solution will be reached. This study is grounded in empirical studies of design planning practise in three large UK companies, where we conducted interviews and observations with over 15 designers and design managers in each company (Eckert and Clarkson, 2003). The task plans we saw in our studies were all deterministic, a major reason being the absence of any alternative to the current tools supporting Gantt charts and PERT-style arrow and box diagrams. Engineers are under pressure from their managers to produce optimistic plans and treat them as certain. This is because iteration is seen as a failure to persuade engineers to create a satisfactory solution in the time available, rather than an optimal solution in a longer time (as would be the natural inclination of most engineers).

The results of this type of planning are well known: time and budget overruns; unnecessary rework; and reductions in the quality of the design produced. Engineers we observed tried to compensate: by building slack into their plans, either openly as rework or by stealth as pessimistic estimates of expected durations; and by planning at a low level of detail, for example, describing a two year project using a resolution of months to hide uncertainty in this and other projects. While these measures might help to cope with uncertainty, they seriously undermine the accountability of projects, providing unreliable data for internal process assessment and external tendering.

This paper discusses an alternative probabilistic view of the design process, the exploration of which is supported by a simulation based on the Signposting framework for design process modelling (Clarkson and Hamilton, 2001). Familiar process planning tools and methods such as the critical path method and Gantt chart are revisited from a probabilistic perspective. Finally, the view of a plan as a set of contingencies rather than a single pattern of events is presented. These concepts do not replace deterministic methods and representations for the purposes of planning, but, in offering a new perspective, complement the existing tools.

2. Modelling design processes

Designers in industry typically model their processes using the Process Evaluation and Review Technique (PERT) and critical path method (CPM), which are the two best known examples of the more general Precedence Diagramming Method (PDM). In all these methods activities are shown as nodes or boxes on a network and arrows joining the nodes signify the flow of information or material from one task to another. Neither approach allows probabilistic values in its present form.

Design Structure Matrixes (DSMs) are used in some large US corporation as well as parts of the construction industry (Austin *et al.*, 2000). They were originally developed by Steward (1981) and further developed by a number of researchers, most notably the DSM group at MIT (Eppinger *et al.*, 1994; Browning, 2001). In its most basic form, a DSM is a square matrix indicating connectivity within a set of entities of homogenous type. The list of entities is repeated as both row and column headings, and marks in the matrix indicate connections (see Figure 1). Applications of the DSM have included product modelling (links between systems or components), team modelling (modelling links between people or teams) and process modelling (precedence links between tasks). In the usual notation, marks below the diagonal indicate forward flows of information and marks above it indicate feedback or iteration. Algorithms to reorder the matrix such that iteration is removed or reduced have been developed, and visualisation techniques such as banding (indicating parallelisable tasks), tearing (selectively removing key links to remove iteration) and block diagonalisation or triangularisation (high-lighting iterative loops inherent in the process, which remain even after reordering) further extend the value of the basic approach, without adding to the complexity of the model. The simple marks in the DSM can be replaced by numbers indicating the relative probability of input change, iteration, etc. Browning and Eppinger (2002), and Carrascosa *et al.* (1998) have extended the DSM methodology through the creation of simulation-based analysis tools to generate information about the likely costs and durations of the project.

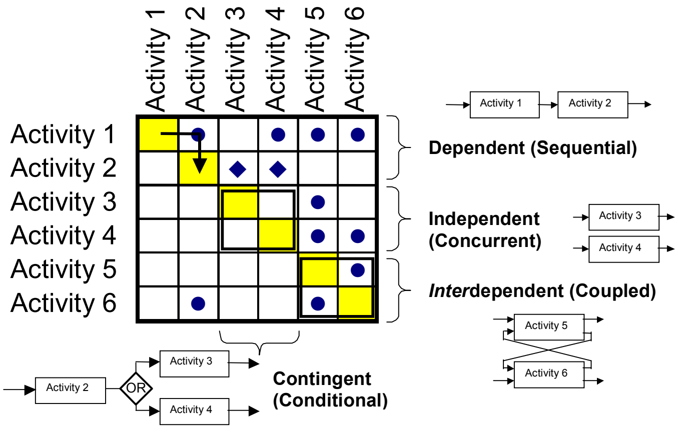

Figure 1 DSM from Browning (2001) © IEEE

3. The Signposting Approach

In industrial processes one task is often not finished before the next needs to start, leaving a model with many coupled tasks forming clusters. In response the signposting approach has been developed to allow modelling with provisional, uncertain information and to find routes through the process. Through simulation designers can be provided with an intuitive understanding of the distribution of likely process outcomes. Signposting models reflect specific tasks required for each project at what ever level of detail the designers or design managers choose. Other modelling approaches, such as Schabacker (2002), also use simulation to predict process behaviour, but model processes through a set of generic tasks, that is tailored to a specific process on a fairly high level.

3.1 The Model

Like DSM, Signposting models tasks through their input and output. However, parameters are now explicitly modelled. To break clusters parameters are assigned 'levels' that are required by and/or altered by tasks. These 'levels' do not represent the actual value of a parameter, but instead indicate the maturity and context within the design process of the information in the parameter. Initially this was used to show designers all the tasks for which they had parameters at sufficient levels, in order to them step by step through the process (Clarkson and Hamilton, 2000). However, often designers have many choices and need to know which task choice would lead to a solution with the lowest risk. Further research concentrated on planning routes through the design process. The model was then extended to include failure probabilities to account for iteration, and applied Markov chain techniques to identify the best policy for navigating through the process (Melo, 2002).

The present research extended the model to include resources, duration and cost values. In the current model tasks are described: in terms of mappings between 'input states' and 'output states' which are composed of parameters that represent the information of interest in the design process; the form and function of the design object; understanding or learning regarding the 'design space' of possible designs; the availability of resources (workforce, machinery, computing resource), etc. The types of information modelled as parameters, and the level of detail will depend on the interaction between: the concerns and interests of the modeller; the time and expense that can be spent on modelling; and the nature of the design project (single designer vs. team, degree of concurrency, amount of innovation etc.).

Signposting models have the potential to capture a greater amount of the implicit knowledge that a project manager may have regarding their process, than, for example, a 'Microsoft Project' description. The accuracy of this information will vary from one instance to another, but the simulation discussed later in this paper can perform a sensitivity analysis to show the effects of low-quality input to the model on the quality of process guidance and evaluation which results. Such a technique will never capture totally unpredicted process behaviour (e.g. a failure mode in a component test that had never been observed before), but it still offers a better view of the process than conventional techniques, which force planners to discard all but the most likely successful outcome of an activity. It has been commented on in our case studies that many process difficulties, while not expected, were not entirely unforeseen.

3.2 Signposting simulation

Once a Signposting model has been created, it can be analysed by means of simulation. The process simulation has its antecedences in complexity theory where simulation is used to gain a better understanding of the behaviour of complex systems. For each run the probabilities are picked at random, but by running 1000s of runs it is possible to generate an accurate profile of the probably distribution. The simulation code (see O'Donovan *et al*., 2003, for a technical discussion) works as a 'virtual project manager' choosing tasks, and then determining their outcome based on the input-output relationships captured in the task. The actual design is not created by this simulation process, but the contextual values of design information, performance, requirements and resources evolve according to the model as if a design was being created. Because tasks have randomly determined outcomes, and because the virtual project manager chooses a range of resource allocations and task sequences to test, the simulation is run a large number of times to generate a population of representative simulated process runs. For each member of this population, data is logged on a variety of performance metrics; cost, duration, tasks used and the resources allocated to them, task outcomes (successes and failures), quality of final design, etc. This allows the creation of diagrams showing the distribution of process costs and durations which are expected for the process (Figure 2). The interrogation of this data set, which may be very large, can also give useful insights into the likely outcome of the process and ways to improve it. However, the volume of the data generated is so large that post processing of the simulation results is necessary to prevent the user being overwhelmed, and it is here that the familiar tools of project management are useful. The simulation approach was validated with a process model of a team project that is run at the University of Cambridge, where students in multidisciplinary teams develop an autonomous robot. In addition, a model was developed and validated for part of the design processes in an aerospace company.

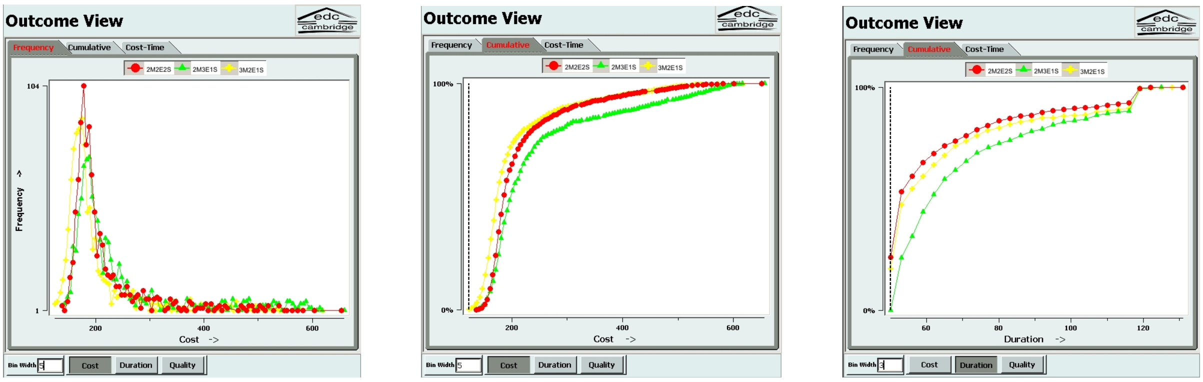

Figure 2. Typical simulation outputs including cost/frequency and distribution diagrams

4. Critical Path revisited

In a conventional plan, the concept of the critical path is useful in identifying key tasks. The critical path is the longest duration chain of precedent tasks in the process. Any delay to a task on the critical path will delay the overall duration of the project, making resource allocation particularly critical. There are many techniques associated with critical path analysis, such as determining the degree of 'float', or flexibility in start time, for each task. The concept of a conventional single critical path is incompatible with the signposting model and simulation. The random nature of the individual process runs means that the critical path may be different for each due to different task outcomes, despite the runs being based on the same process, run in the same configuration. Furthermore the resource constraints mean that the critical path is affected not only by the task precedences due to information input/output characteristics, but also due to choices in allocating resources. Nonetheless, while the concept of a critical path no longer applies to the processes generated by the simulation, we can extract from the simulation results measures of *task criticality* which serve many of the same purposes, and may even provide additional insights (Figure 3):

- *Task criticality* – likelihood. The likelihood of task criticality is the average number of instances per process in which the task is at some point the only activity being carried out. This indicates that the process is waiting for the task to be completed, whether because the task is using all the resources available, or because it is producing information needed in the subsequent tasks in the process.
- *Task criticality* – impact. The impact of the task criticality is the average length of time that the process is the only activity being executed, in each instance where this occurs.

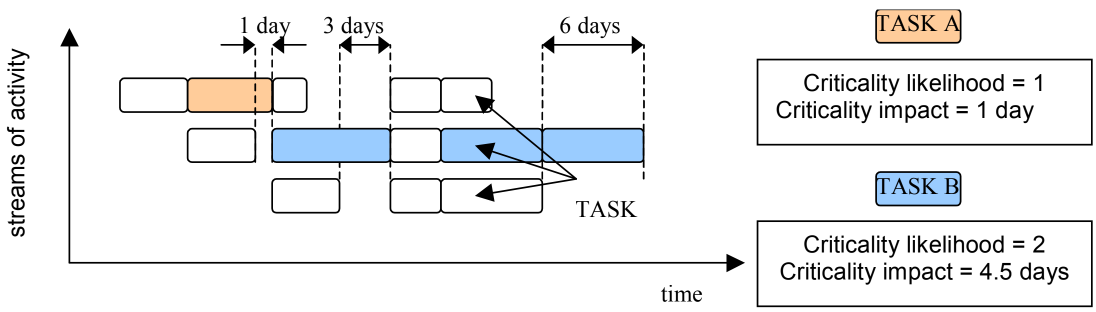

Figure 3. Criticality likelihood and impact

5. Gannt Charts revisited

To give further insight into how best to optimise the resource allocation, a view of the task timing which takes into account the statistical properties of the process is needed. The most basic Gannt chart representation shows tasks as simple boxes, but often a taper is used at trailing edge to indicate either uncertainty in the finish date, or a tailing off of the resources allocated or rate of working on a specific task. Taking inspiration from this representation, the analysis tool provides a similar view of the process which takes into account the probabilistic nature of task timing in the extended signposting model.

Because of variation in the duration and outcomes of tasks, both the start and end time of each instance of a task are uncertain. In order to summarise the timing of the tasks across the thousands of individual simulated process runs which make up the sample population, the time taken for the longest of these process runs is divided into 1000 time index points. For every instance of a task in every process, the number of times that the task is in progress during the period of time between time index point *i* and *i+1* is recorded. Dividing this count by the number of simulated runs in the sample population gives the probability across all instances of the development process that the given task is in progress (Figure 4).

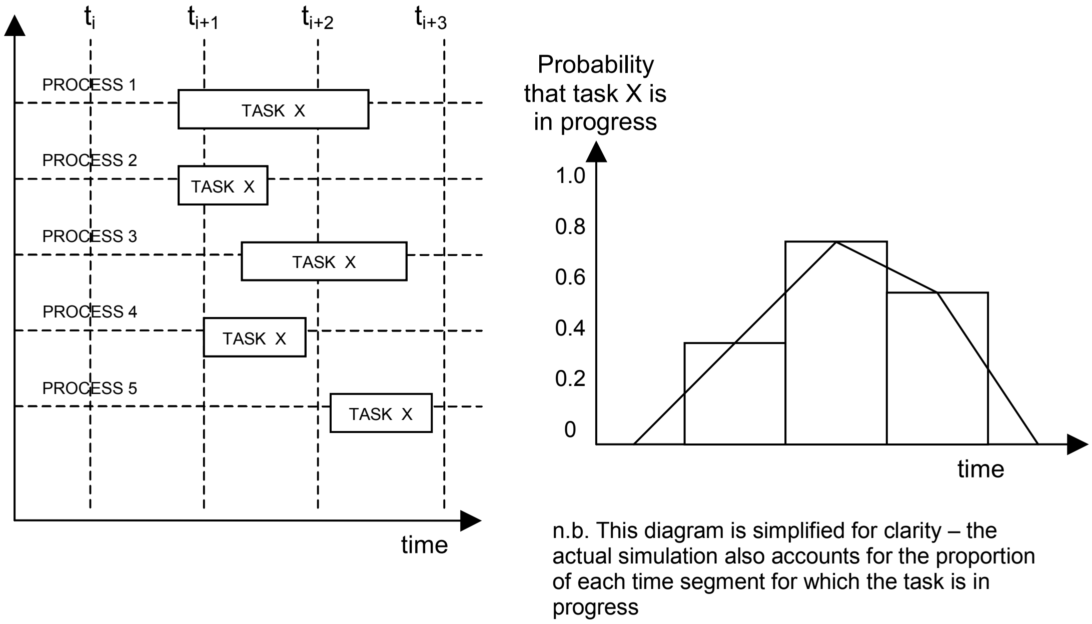

Figure 4. Summarizing the task timings

The data can be viewed with the probability curves overlaid or displayed separately in a stack as in Figure 5. In the sequential tasks shown, it can be clearly seen that as Task1 draws to an end there is a corresponding rise in the probability of Task 2 task being in progress, as would be expected.

6. Discussion and Conclusions

Design processes are riddles with uncertainty. Designers and design managers are well aware of this, but they still have to plan their projects. Conventional project planning takes an optimistic approach assuming all tasks will be completed in the allocated time. While Gantt charts and Perts charts likely to become inaccurate as soon as they are created, they perform an important function in indicating the order in which tasks are performed. Ideally this information would be combined with a more accurate understanding of the uncertainties in the process.

The signposting model is a probabilistic approach to modelling design processes. It requires far more knowledge to build then conventional models, but also forces the designer to think more deeply. The analysis gives designers an understanding of the properties of the design. They can identify critical tasks and those tasks that might not be on the critical paths, but which could have huge impact if they were on the critical path. The signposting tool is still under development, however, at the moment we are developing an interface to allow easier input of task information and to show multiple simulation outputs. Only when an integrated suite of programmes has been developed will it be possible to judge in detail whether the tools that are discussed in this paper will make a difference in industrial practise.

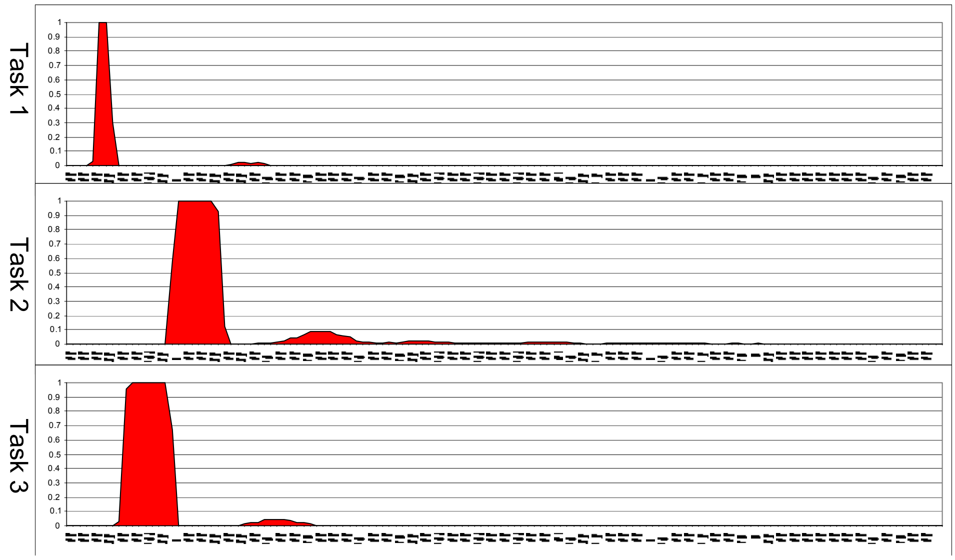

Figure 5. Viewing task timing information (screenshot) – A simulation gantt chard

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