AN OPTIMAL DESIGN PROCESS FOR AN ADEQUATE PRODUCT?

P. J. Clarkson

University of Cambridge
Department of Engineering
e-mail: pjc10@cam.ac.uk

Keywords: process modelling, robustness, optimisation

Abstract: *The 'optimal' or 'best' design process may be the shortest or cheapest process, or the one that leads to a particularly desirable product, or to a reliable and maintainable product, or to a manufacturable product, or some combination of all of these. It is likely to satisfy the aspirations of the organisation to invest an appropriate amount of resource in the development of a specific new market opportunity, set in the context of longer-term business goals. This paper describes the progress made in over ten years of research on process modelling undertaken at the Cambridge Engineering Design Centre to identify an 'optimal' design process with which to develop an 'adequate' product.*

1. INTRODUCTION

The goal of most businesses in the modern world is to provide desirable, and ultimately profitable, products and services. This is generally achieved by meeting customers' needs and/or expectations both at the point of purchase of the product or service and during its sustained use. Customer satisfaction may range from delight in acquiring an aesthetically pleasing object (e.g. a lamp) or in using a well designed tool (e.g. a good car) to the grudging acceptance of the 'good' value-for-money of an essential, but poor, service (e.g. telecommunications). Business success will depend on the immediate and sustained profitability of a portfolio of products and services, which will in turn depend upon the timely and cost-effective introduction of new market offerings.

This paper aims to explore the proposition that a significant contribution to business success might be derived from the use of an 'optimal' design process to develop an 'adequate' product by reflecting on progress made in over ten years of research on process modelling undertaken at the Cambridge Engineering Design Centre. It begins by describing the background to this research, then presents some of the achievements to date and concludes by describing the research challenges for the future.

2. BACKGROUND

The 'optimal' or 'best' design process may be the shortest or cheapest process, or the one that leads to a particularly desirable product, or to a reliable and maintainable product, or to a manufacturable product, or some combination of all of these. It is likely to satisfy the aspirations of the organisation to invest an appropriate amount of resource in the development of a specific new market opportunity, set in the context of longer-term business goals.

The introduction of a new 'widget-in-can' beer product was driven by the need to deliver an appealing product to market within ten months in order to meet the Christmas surge in sales. Infringement of competitors' patents had to be avoided whilst concurrently developing new product, manufacturing and assembly solutions. Development costs were expected to be significantly less than marketing costs and were ultimately paid back within weeks of a successful launch. The 'optimal' design process delivered a 'good' product on time and rejuvenated an ailing company.

The development of a prototype fire-fighter training unit (FFTU) for the UK Royal Navy was driven by the need to demonstrate the utility of a novel technological approach to fire-fighter training. The 'optimal' design process followed strict quality guidelines to deliver a demonstrable system with robust design and risk documentation. The development of the subsequent units was driven by the need to deliver a thirty-year training service. The 'optimal' design process in the latter case had to take particular account of the long-term safety, availability, reliability and maintainability (ARM) requirements for the FFTU in the context of a fixed-price service contract.

The supply of an adapted jet engine design as part of an aircraft fleet contract is driven by the need to meet a specified delivery target and to sustain a minimum level of performance through life. The new design will be based upon previous designs, with the introduction of new technology often contingent on its performance in 'test' engines. The 'optimal' design process will enable as much exploration and development of possible designs as is consistent with the need to deliver a product that meets regulatory approval on time.

These examples highlight the wide range of factors that may influence the design process, defining both what may be considered to be 'adequate' as a new product or service and what might be regarded as 'optimal' as a design process. However, since design is a dynamic process that is not easily defined beyond the key stages described in many text books, the 'optimal' process may seem more of an aspiration than a realistic goal. Hence, the following sections describe efforts that have been made to develop tools that assist in the definition of 'good' design processes for complex engineering products. The chronology of the actual research is broadly observed and the key research questions at each stage are highlighted.

The benefits of a dynamic model-based approach to design process improvement are explored through the description of research carried out over a period of ten years on the improvement of engineering design processes through process modelling and analysis. The research aims to support the design process by capturing, visualising and directing the 'specific' design process required to design a product rather than the 'official' process that designers are supposed to follow. The modelling approach proposed explicitly models information flows within the design process and drives the selection of tasks by the quality of the information that is available at any point in time.

3. CHRONOLOGY

The research on began in 1995 with a PhD studentship sponsored by Westland helicopters and continues today with a team of more than 10 researchers.

In this paper, we explore the dynamic nature of the design process revealed through ten years of empirical studies and through literature. We describe research using the Signposting approach to model dynamic process behaviour. This research includes the development of a system to guide the adaptive design of a helicopter blade; a real-time process management system which supports the integration of proprietary compressor design codes; and a model-based approach to support planning practice in collaborative design projects (Figure 1).

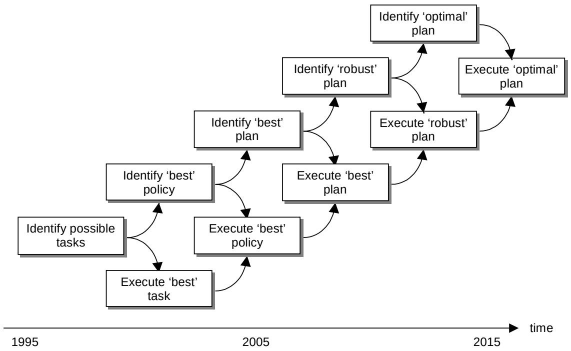

Fig.1. *The development of Signposting*

4. IDENTIFYING POSSIBLE TASKS

Early attempts at capturing design processes within a number of organisations found that current off-the-shelf approaches were lacking in their ability to capture complex engineering design processes. This led directly to the development of a new approach to process mapping.

4.1. A passive parameter-driven model

Westlands are recognised as world-leaders in the development of helicopter rotor-blades and developed the burp-tip rotor blade to improve the aerodynamic performance and hence lift and load-capacity of their aircraft. They had tried to capture the rotor-blade design process themselves and found that the highly iterative process could not be adequately described with conventional stage-based process models [1]. Through a series of interviews and months of observations it become clear that rotor blade design process was data-driven and consisted of repeating the same or similar tasks with ever more accurate input data [2]. Subsequently, a tool (known as Signposting) was developed (see Figure 2 for notation) that provided designers with a list of tasks that they could carry out at any point in the design process, given the availability of appropriate information [1].

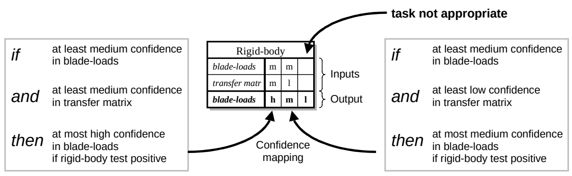

Fig.2. *The basic element of a Signposting model*

A subsequent tool (Figure 3) was successfully evaluated in Westlands.

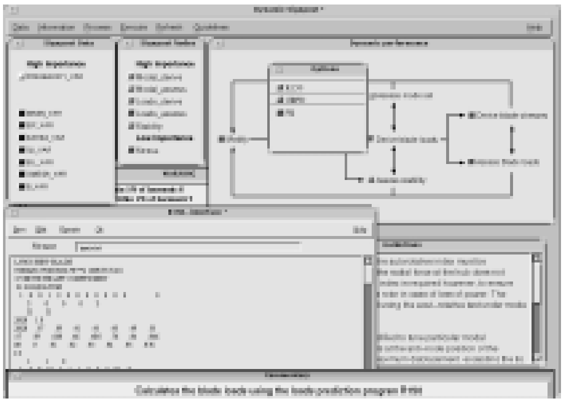

Fig.3. *An early Signposting tool*

4.2. An active parameter-driven model

In 1997 the same core idea was applied to the conceptual design of steam-turbine compressor blades. It soon become clear that turbine blade design was a lengthy process, not only because it was highly iterative, but also because designers had to use many separate computational tools, manually transferring information between them.

A subsequent version of the Signposting tool (Figure 4) integrated these disparate analysis tools and provided real-time data management for early conceptual design, incorporating a sensitivity analysis to identify the most appropriate task to advance the design towards its performance goals [3]. Again interviews and observation provided understanding and data for the study.

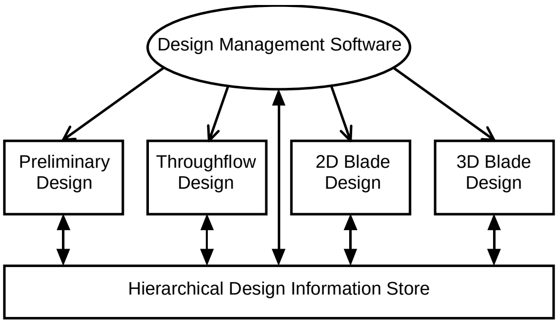

Fig.4. *A framework for a dynamic Signposting tool*

5. IDENTIFYING THE 'BEST' POLICY

Identifying tasks that will progress a design provides an instantaneous view of the design process that takes no account of the relative risk incurred in choosing a particular option. A better approach would be to select a task based on some knowledge of process risk.

5.1. Risk-based route finding

Identification of the 'best' route through the design process was addressed in a theoretical research project on route planning which utilised Markow chains to identify policies for navigating the design process (Figure 5). This research introduced the notion of probabilistic task failure, where each task can either succeed and advance the design, fail in its execution without changing the design or produce results that reduce the designer's confidence in the design [4].

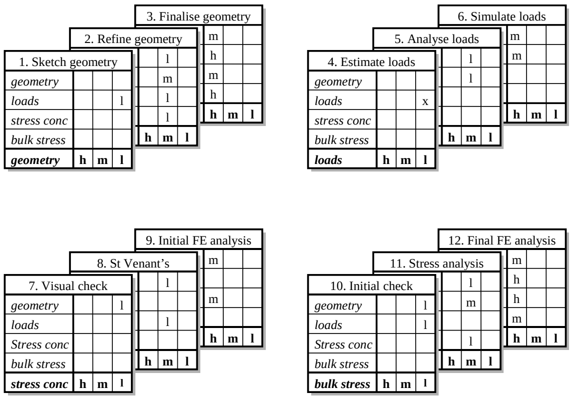

Fig.5. *A simple 12-task model*

Much effort was also spent in visualising networks of alternate paths through a given set of tasks as a means to articulate the best policy [5]. Figure 6 shows the best policy for the tasks shown in Figure 5. Policies could also be represented as soft dependencies in the Signposting model in contrast to the hard dependencies defined by critical data flows.

The research was informed by a study on design process planning within a sports car manufacturer, by undertaking interviews with 18 engineers and design managers regarding how design processes were planned and what functions the resulting plans carried out [6]. This was complemented by a further 17 interviews carried out in an automotive consultancy.

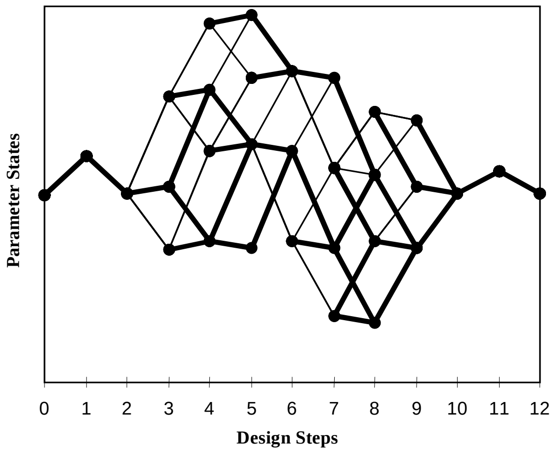

Fig.6. *Best policies (in bold) for the 12-task model*

5.2. Simulation-based route finding

Design processes are full of uncertainty and, as a result, it is difficult to identify all the tasks, and their ordering, at the beginning of a process and assume that this process will be followed. Design managers are interested in the risk associated with alternative design routes, which may be estimated through simulations of the design process (Figure 7).

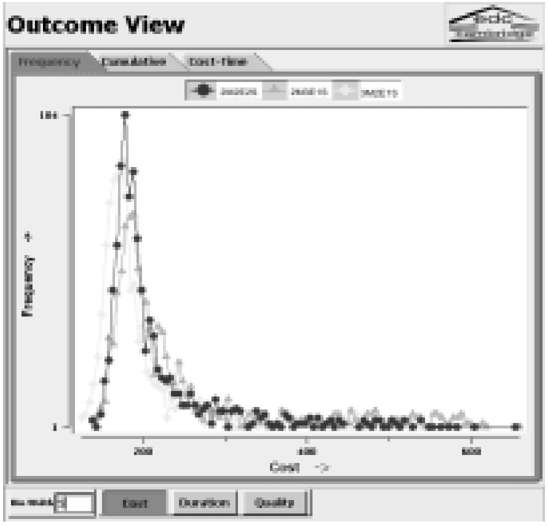

Fig.7. *Typical process simulation output*

This research drew on complexity theory and involved the analysis of many design project plans in the automotive consultancy. An evaluation model was built of an in-house process of a jet engine component design combined with four interviews with design experts in the company [7].

6. IDENTIFYING THE 'BEST' PLAN

The best policy provides support in selecting the best next task during execution of a design process. A more pragmatic approach would be to select the best route or plan before the process commences. This is the main tenet of process planning.

6.1. Design process capture

To introduce process risk assessment techniques in industry it is vital that designers and design managers can build knowledge-rich process models and benefit from the process of model building itself. Based on experiences gained through a seven month secondment to Rolls-Royce, a tool was developed that enables designers to capture detailed hierarchical design process models [8]. These models can be viewed as flowcharts (Figure 8) or DSMs (Figure 9) and, using the simulation approached developed earlier, translated into Gantt charts (Figure 10).

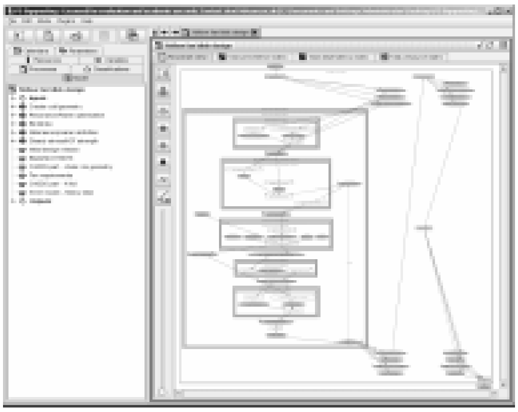

Fig.8. *A hierarchical process capture tool*

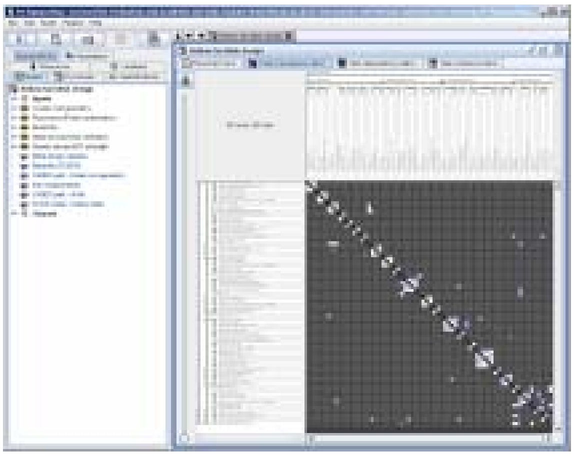

Fig.9. *A DSM for the process in Figure 8*

This tool has subsequently been developed further to support a variety of explicit definitions of process iteration. These range from the original Signposting formulation to descriptions that show a specific number of iterations or a probability of task success.

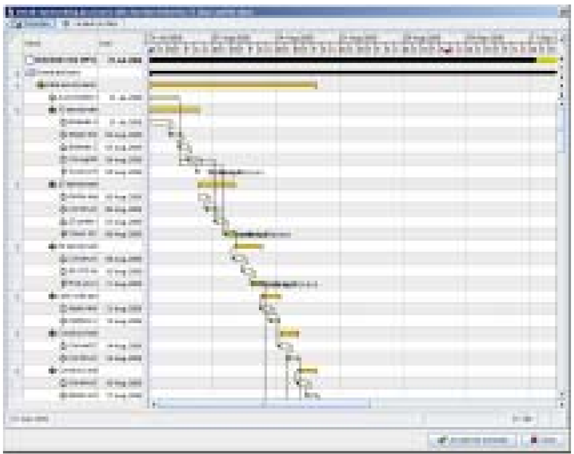

Fig.10. *A Gantt chart for the process in Figure 8*

The tool also supports the attachment of embedded task definitions allowing active task execution.

6.2. Characteristics of good processes

Companies need to make trade-offs between process time and product quality and are therefore interested in trading off product and process risk. A detailed study in an off-road diesel engine manufacturer involved one months observation over a period of 6 months and about 40 interviews with designers, managers and support staff, led to an inclusion of product quality measures into the process models.

The same study also made it clear that it is difficult to evaluate objectively the structural properties of design processes models, i.e. to identify those process constructs that commonly succeed (or fail), using real industrial models. Therefore a model generator was developed that creates and perturbs models to investigate the relative robustness of models of different characteristic types.

7. IDENTIFYING A 'ROBUST' PLAN

Process models based on flow-charts derived from designers are typically over-constrained when compared to the earlier Signposting models. They are likely to contain dependencies between tasks that are a reflection of the designer's preference rather than the absolute need to pass data between tasks. This allows the possibility of identifying better plans for a given process.

Any given plan, if executed many times, is likely to show a variation in performance, as measured in terms of process or product performance (Figure 11a, curve I). If that variation can be reduced the process will become more immune to external disturbances (Figure 11b, curve II), i.e. more robust. It is possible that further improvements in robustness may be achieved if some of the designer's preferences (Figure 11c, curve I) can be relaxed. This should lead to a greater number of design process possibilities (Figure 11c, curve III) within which a better performing subset of plans may be found (Figure 11c, curve II).

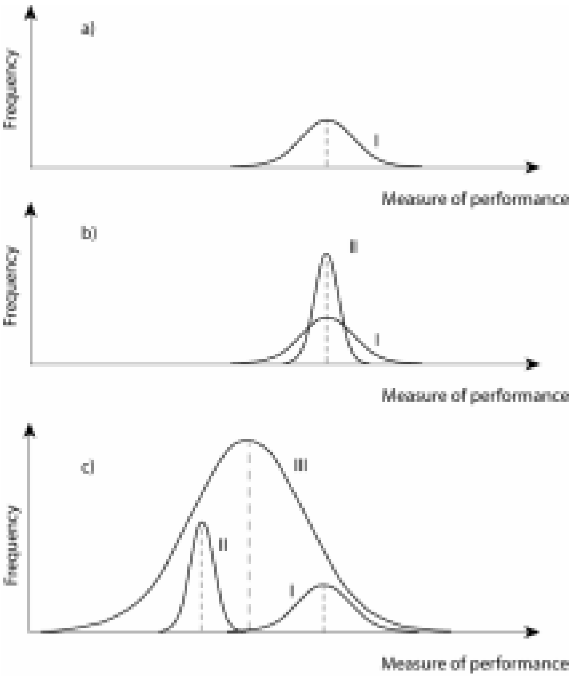

Fig.11. *Searching for a more robust process*

This approach sounds fine in theory, but in practice it is not clear how better, more robust, plans can be identified. In addition, it is not at all clear how a single project plan can be derived that represents the characteristics of a set of similar plans, i.e. how can the distribution shown as curve II in Figure 11c be represented by a single Gantt chart?

8. IDENTIFYING AN 'OPTIMAL' PLAN

Most of the research to date has focused on improving the performance of the design process in terms of measurable characteristics, such as time and cost, of the process itself. However, as mentioned earlier, it is also important to consider the impact of the process on the measurable performance of the product, for example its weight or reliability.

Future research will focus on attributing product performance to specific process tasks, hence enabling the investigation of product performance variance against process plan. This is turn leads to the possibility of adopting multi-objective multi-criteria optimisation techniques to identify the trade-offs between product and process performance.

9. SUMMARY

The research presented in this paper reflects the Cambridge Engineering Design Centre's preferred approach to combining the development of applied solutions for industry with theoretical research.

We wish to understand how design processes work in industry and how we can support their planning and execution through computer tools that capture, visualise, 'optimise' and manage the design process. The intended outcome of the research is a suite of robust industrial software tools.

The research originally arose from the practical needs of companies to understand and improve their processes. Interestingly, a common observation has been that even the most successful companies often struggle to describe the very processes by which the products that bring them success are generated. There would appear to be room for improvement.

The research has continued to involve close collaboration with industry, both to ground it in the needs of industry and to gain immediate feedback on the tools under development.

Our current research approach may be summarised as a continual cycle of modelling, simulation, improvement and application. (Figure 12).

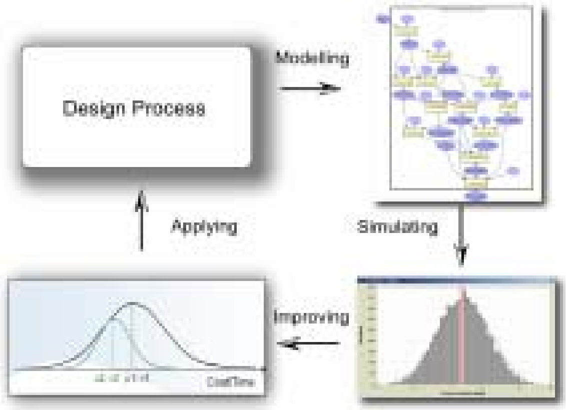

Fig.12. *A framework for process improvement*

Process modelling represents the critical starting point of the improvement cycle. Good models are essential and research efforts remain focussed on understanding how best to model the intended design process, balancing the desire to build an information-rich model suitable for simulation, with the cost of data collection. Graphical elicitation techniques are important as they find favour with designers and design managers alike.

Process simulation is generally straightforward. However, the challenge remains to choose which process parameters to vary and to identify some basis for the range and type of variation. Again, sophistication has to be traded against accuracy and the cost of data collection. Simulation is unlikely to produce results with absolute accuracy, but can be very effective at identifying links between process performance and process attributes, such as task ordering, and design resource capability.

Process improvement remains a challenging task. There is still much research required to explore the link between process simulation and process improvement. In particular, there is a need to understand how to identify robust processes, both in terms or design process performance and subsequent product performance.

Finally, it is important to identify practical means by which robust processes may be described to designers and design managers. It is likely that traditional Gantt and PERT charts will continue to have significant influence is this area, but research will also focus on identifying alternative descriptions.

Common to all of these steps is a desire to provide designers with practical, easy-to-use tools that allow them to capture, visualise and manage the design process.

In summary, the Cambridge Engineering Design Centre is committed to developing practical process improvement tools that will challenge current planning approaches.

Acknowledgements: the work presented in this papers represents the efforts of the author's many PhD students and Research Associates who have contributed to the development of the Signposting concept over the past 10 years.

The research has also been informed throughout by studies in six companies: a major aeroengine manufacturer; a manufacturer of diesel engines for power generation and off-road vehicle applications; an industrial chemicals manufacturer; an automotive engineering company; an automotive consultancy within a steel company; and a large European aircraft manufacturer.

References

[1] Clarkson P.J., Hamilton J.R., *Signposting: a parameter-driven task-based model of the design process*, Research in Engineering Design 12(1) pp. 18-38, 2001.

[2] Hamilton J.R., *The Capture and Representation of Knowledge to Support Aerospace Design*, PhD thesis, University of Cambridge, 1998.

[3] Jarrett J.P., *Technology or methodology? An approach to designing better turbomachinery*, PhD thesis, University of Cambridge, 2000.

[4] Melo A.F., *A State-Action Model for Design Process Planning*, PhD thesis, University of Cambridge, 2002.

[5] Clarkson P.J., Melo A.F., Eckert C.M., *Visualization Techniques to Assist Design Process Planning*. ICED'01, Glasgow, Scotland, 2001.

[6] Eckert C.M., Clarkson P.J., *The Reality of Design Process Planning*, ICED03, Stockholm, Sweden, 2003.

[7] O'Donovan B.D., *Modelling and Simulating Design Processes*, PhD thesis, University of Cambridge Department of Engineering, (2004).

[8] Wynn D.C., Clarkson P.J., Eckert C.M., *A Model-based approach to improve planning practice in collaborative aerospace design*, Proceedings of ASME IDETC/CIE, Long Beach, California, USA, 2005.