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DESIGN CUSTOMISATION IN MULTI-PROJECT ENVIRONMENTS: USING PROCESS SIMULATION TO EXPLORE THE ISSUES

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ABSTRACT

Adapting a design to the needs of a specific customer can be seen as a process in which an existing product is changed to incorporate desired properties and to exclude undesired ones. In a multi-project environment, many such projects are typically in execution at any given time and must compete for limited resources. Various strategies and approaches may be taken to organise such multi-project systems in order to maximise their effectiveness. This paper identifies and discusses several such strategies and shows how simulation can be used to explore their effectiveness in different contexts. Based on a case study of a simple, yet real customisation environment, we outline a discrete-event Monte-Carlo simulation model that we developed and which we argue can be used to explore some of the main issues. Although based on a simple example. we propose that the basic structure of our model could be used to derive insights for multi-project customisation environments in complex engineering domains.

KEYWORDS

Design customisation, platform strategy, design process simulation

1. INTRODUCTION

Responding to requests for customised products, or to invitations to tender for new designs, can be a headache for companies. Ideally, the new product should be easily–or at least predictably–designed, adapted and produced. However, depending on the business model of the company, requests for customised products can also pose a serious challenge–potentially requiring significant investment to generate the information required to respond with confidence.

If the company sells a stock range and can meet the customer's request from this range, a customisation request is straightforward. Other business models, common in engineering, involve a product configurator which allows the customer to select from a set of predefined options. For example, most automotive companies offer a set of options for each of their models, allowing the customer to select simple options such as finish as well as more complex options–such as the engine. However, this requires considerable design effort, which only pays back when the same components can be used across an entire product platform.

Companies which do not sell such large volumes must meet customisation needs through a combination of: 1) maintaining a range of products, i.e., pre-customising by anticipating likely order requests; 2) ensuring, through design, that products are easily-customisable; 3) modifying products on-demand to meet the needs of specific customers: and 4) knowing when to reject a request. For such companies, it is important to assess how much effort they should place into the maintenance of a range or the design of a configurable or flexible product, as opposed to meeting demand for customisation by making successive modifications to existing products when orders come in. It is therefore important for companies to accurately assess the ability to meet individual customisation requests within the chosen strategy and cost bracket.

The issues outlined above are of great concern to companies, particularly in the current economic climate when they don't dare to turn away customers, but also can't afford to accept orders that jeopardise other orders or their on-going development processes. These problems can be exaggerated in small businesses which make bespoke products. In such companies there is often little time to spare to invest in platform development if products are offered at competitive prices.

This paper uses the design and manufacturing process for hand-bags to illustrate how the simulation of multiple intertwined processes can help a company to select the appropriate customisation strategy. In particular, we focus on developing a simulation model of intertwined customisation processes based on this case study. In section 2, the challenges of making modifications to a design are outlined, some strategies for managing customisation processes are identified based on the work of Fricke et al. (2000), and the need to explore these strategies in a customisation–rather than engineering change–context is highlighted. Our simulation-based approach to do this is explained in section 3. The case study on which the model is based is discussed in section 4. Section 5 details the modelling and simulation of the case study environment. Section 6 discusses the implications for complex engineering. Section 7 concludes.

2. BACKGROUND

2.1. Design changes as a foundation of customisation

Adapting a design to the needs of a specific customer can be seen as a process in which an existing product is changed to incorporate desired properties and to exclude undesired ones. Such change processes are not just limited to customisation, but are a fundamental part of all design. New products are designed by modification from existing ones. Designs are changed throughout the design process. After a core product has been released, different variants are often generated for slightly different markets, and bespoke versions may be produced for individual customers. Drawing on interviews with engineers and managers from 13 companies in 7 industries, Fricke et al. (2000) estimate that 30% of all work in these companies arose from changes of one form or another.

Change is not only critical, but also difficult to manage. Its occurrence is hard to predict, as it is often driven by the emerging needs and problems of the customers; or by problems with the procuring occurring in particular circumstances. This is exacerbated in companies with a large number of different customers. The cost of the implementation is The cost and duration of customisation processes are both variable and difficult to predict, due in part to *change propagation*. Empirical studies (Terwiesch and Loch, 1999; Eckert et al. 2004; Rowell et al. 2009) have highlighted how changes initiated in one area of a product have a tendency to propagate unexpectedly, requiring additional knock-on change to many other aspects of the product. These studies also suggest that, when changes snowball or avalanche requiring many unexpected changes to other parts, development projects can be severely delayed and over budget.

Change propagation contributes to variability and unpredictability in customisation processes in several ways, including:

- **Variability arising from lack of knowledge about the ways components are linked**. While designers typically have a good sense of the geometric relationships in their products, understanding the other functions or behavioural effects, such as heat flow, requires considerable experience (Jarratt et al. 2004). Many designers may not have the knowledge required to assess when components are connected in a way which could cause propagation.
- **Variability due to propagation between linked components.** Whether a component does pass a change on to another component depends not only on connections between components, but also: a) on the nature of the change and b) on the state of that particular component at the time (see Eckert et al. 2004). For example a beam can carry a certain amount of additional load, however whether it an carry a specific amount of additional loads depends on the other loads it is carrying and the condition under which it needs to carry this load.
- **Variability due to constraints.** Changes do not only arise from the direct couplings between components, but also from the

constraints that are placed on products, such as regulations or safety requirements.

- **Variability due to change context**. **C**hanges rarely occur in isolation, but are linked through different patterns (see Ariyo, in press), whereby some changes give raise to many other changes simultaneously or a lead to a series of separate requests as designers become aware of them. Changes that arise at different points in this way can come together and require massive effort to resolve (Giffin et al., 2009). Ariyo et al. (2006) point out in this context that change propagation is affected by (1) system knowledge and experience (2) quality and timing of design decisions and (3) deficiencies in the information transmission process supporting the change activities.

There are thus multiple sources of variability and uncertainty which impact upon change propagation, and thus the cost, duration and organisation of the customisation process. This highlights the importance of understanding how design customisation processes can be organised not only to minimise expected duration, but also to minimise perceived variability in projects despite lack of knowledge and actual variability in occurrence and cost. Fricke et al. (2000) draw on case studies in 13 companies to suggest five strategies to manage engineering change effectively in the context of engineering products:

1. **Prevention** aims to reduce (or eliminate) the number of changes which arise from errors or as a consequence of other changes.
2. **Front-loading** is proposed by a number of authors (e.g. Lindemann et al. 1998 or Terwiesch and Loch, 1999). Early detection of changes will result in a lower overall impact and cost.
3. **Effectiveness** emphasises undertaking effective cost/benefit analysis for each proposed change. Not all engineering changes are immediate or mandatory; some change requests would be best avoided altogether if their cost and benefits were known.
4. **Efficiency** means that essential changes should be implemented as efficiently as possible by making the best use of limited resources such as time and cost. Fricke et al. (2000) suggest this could be improved by communicating changes as-soon-as-possible to all affected personnel.
5. **Learning and reviewing** emphasises that each change offers a chance to improve the design of a product, the product design process and the engineering change process. Thus, future changes can be made easier.

2.2. Applying change prevention strategies to customisation

Mass customisation has traditionally been approached from the business or technology perspective rather then a design perspective. Looking at the change management strategies proposed by Fricke et al. (2000) in the context of customisation reveals a number of research questions which we argue in forthcoming sections can be investigated through process simulation:

Prevention cannot be applied in a customisation environment since change is the core business, an opportunity rather than an exception to be avoided.

Front-loading: finds its equivalent in designing a product platform. In (mass) customisation a company typically offers a number of base designs and option packages, but sometimes also has to engage in design modification. It is very much a business decision where a company positions itself on the spectrum of offering a few simple options to offering a fully bespoke service. The big difference is that mass customisation typically deals with a very large number of small changes, while engineering change deals with fewer larger changes. However the issue of intertwined processes and their mutual effect still holds.

RQ1: When is a platform worthwhile in a customisation environment?

Effectiveness lies in only accepting changes with appropriate cost-benefit ratio. This requires the ability to predict the impact of changes across a highly connected product, as argued, in Eckert et al. (2004) in the context of a study of engineering change in the customisation of helicopters. Various tools have been developed to predict the impact of change, through parametric links Ollinger and Stahovich (2004), anticipating changes Cohen et al. (2000), probabilistic links (Clarkson et al. 2004; Keller et al. 2008). However Fricke et al. (2000) argue that a cost-benefit analysis for changes has to include “the entire product development system”, including cost, time and resource utilisation. More recently, authors such as Gärtner et al. (2008) and Ahmad et al. (2009) have begun to address this by proposing methods to assess changes by considering propagation through both connections in the product and information dependencies in the process. Most of these tools consider change as an isolated process. None of them explicitly considers the effect of the multi-project environment–factors such as resource loading and process variability–on the ultimate cost and predictability of change orders. However, queueing theory suggests that the ultimate predictability of change implementation process' duration will be influenced by variability in arrival and current workload as well as propagation effects. Furthermore it can be hypothesised that this could be influenced by structural characteristics of the customisation process and policies for managing it–in other words, that the customisation environment might be designed to improve project predictability and thus profitability.

RQ2: What impacts the predictability and the duration of change processes in a customisation environment?

Efficiency requires reducing the cost of changes by improving the implementation process. Any company is constrained by the resources it has available in term of people, production machines, etc. Change and customisation processes thus can't draw on all the people they would like at any time in a design process. They have to wait until people become available to work on the problem. In a multi-project environment, we thus hypothesised that resource management is one of the key characteristics that influence RQ2, and thus that providing a way to investigate different resource allocation policies offers an opportunity to manage not only individual projects, but also the entire system of customisation processes more effectively.

RQ3: What is the impact of resource allocation policy on predictability and performance of the entire system of customisation processes?

Learning and reviewing means investing in reducing the cost of subsequent changes. The cost of implementing unavoidable changes, such as customisation requests, can be minimised by appropriate design, based on past experiences and making use of "Design For Changeability" (Fricke, 2000, and Fricke and Schulz, 2005), which moves away from a design which is highly optimised to a single set of requirements and "Design for Variety" Martin and Ishii (2002), which builds in redundancy for further anticipated changes. At the heart of these activities is the systematic assessment of potential changes and the impact they might have for a given design or design alternative. By using this methodology during the concept design phase, a design team can identify a decoupled architecture, which will require less design effort for future generations of product.

Loch and Terwiesch (1999) argue that many activities in change processing can be viewed as slack, or "background work in the sense that it can be put aside at times of high pressure". This raises the question: when should platform maintenance be treated as slack? We hypothesised that spending time in platform maintenance should save time overall, even where multiple projects are awaiting attention; and furthermore that as more time is dedicated to platform maintenance, the system becomes more efficient until revenue-generating customisation projects are neglected to the point at which overall efficiency would begin to drop. Understanding how to locate this tipping point could help companies manage the effort expended in platform maintenance. This hypothesis led to the following research question:

RQ4: How much effort should be expended in maintaining project platforms, relative to executing customisation requests, to maximise benefit?

3. OUR APPROACH

The remainder of this paper aims to show how a simulation model can be structured to investigate these issues. We do not identify specific answers to the questions outlined above, as these answers will depend largely upon the characteristics of the product and of the company being studied. We develop a simulation model based on a study of a simple, yet real example of mass customisation practice. This simple example allows analysis and presentation of the issues involved at a depth which would not be feasible in a study of a complex engineering environment. We then reflect upon the applicability and implications of our model for studying the customisation of complex engineering products, and thereby indicate how it could be used to answer the questions identified above. Use of simulation to explore this type of problem (although not in the context of multiple customisation processes) is well-established in the PD process literature (Browning and Ramasesh, 2007).

Simulations are based on a simplified model of reality, which allows the investigation and statistical analysis of multiple process runs. This allows many questions to be explored which are difficult to consider empirically, due to the lack of sufficient data. In particular, discrete-event Monte-Carlo simulation is especially well-suited to study the impact of variability in input variables, such as arrival time and predictability, upon the whole system performance to be studied, as it randomly assigns potentially values in a very large number of runs thus expressing many of the possible real processes (Browning and Ramasesh, 2007). This paper uses the ASM simulation approach (Wynn et al. 2006) to construct a model of the customization process observed during the case study. The ASM is a task precedence notation in which tasks are assumed to begin once all input information is available, and produce output information which is consumed by successor tasks. The same modelling approach has been employed in our previous paper in this series, Eckert et al. (2008), in which it is explained in greater detail.

The case on which we based our model is that of a small business which produces bespoke bags, making and adapting his stock range designs, but also taking commissions for new designs for individual customers or bigger companies. The authors conducted three interviews with the designer-maker as well as numerous informal conversations as part of the ‘considerate design’ research project in which he participated.

The first interview was recorded and transcribed. It provided background information about the designer’s creative processes and the constraints he is facing in producing sustainable designs and as a small business producing locally. The second interview took over three hours; we elicited his design customisation and production process which is followed for every bag, including his estimated durations and failure risks for individual tasks. Finally a third telephone interview was used to gather numerical data which was used to calibrate the simulation and check it for sensibleness.

The case situation is described in detail below prior to introducing the model which was constructed.

4. CASE STUDY: PRODUCING PERSONALISED BAGS

Steven Harkin is an acclaimed UK accessories designer[1]. He has widely exhibited his work through galleries world-wide. He runs his own business designing and making a range of high-quality bags. At the time of writing he works with a full-time assistant.

4.1. Overview of the business environment

Harkin offers a range of basic designs, which are made to order in small batches by him and his assistant. When placing an order for a bag, the customer selects a colour combination from a range of organic leathers in different colours. While most orders are standard shapes and sizes, some are customised for individual customer measurements and other requests, such as custom fittings. Examples of different bags customised from two ranges are shown in Figure 1.

Figure 1. Examples of personalised bags by Steven Harkin, based on two different basic designs.

Harkin sells a significant fraction of his bags in trade fairs, where the buyers of independent shops purchase comparatively small orders. His orders therefore come in batches and, as with engineering

[1] http://www.stevenharkin.com/

customisation, with each order he takes he needs to give people a realistic estimate how long delivery will take.

While many of his ideas are derived from existing bags or other designed objects, Harkin responds to evolving fashion trends by developing additional bag ranges in each season. His process is therefore a mixture of customisation and new design. Because he designs and makes his own bags, the design and production are closely linked.

4.2. Overview of the design customisation process

Harkin starts the development of a major new bag with an idea and makes sketches such as that shown in Figure 2. The bags must be assembled from several pieces of leather; so he then makes paper cutting patterns for the main parts before making partial physical prototypes. This ensures that the 2D patterns assemble into the right 3D shapes, that they can be fitted into the machines used for joining, that seams are not unsightly and so on. Having great experience in designing and making bags, Harkin can switch smoothly between sketches, 2D cutting and a 3D prototype. Nevertheless, while he can visualise a bag before he begins to make it, a physical prototype using the right materials is necessary to see that the components can be reliably assembled. There are often several rounds of iteration involving experimentation with new materials and assembly techniques. Once the details are right, the fixtures and fittings must be developed. This can be time-consuming as the details can be quite intricate for some designs, as shown in Figure 3. This can be highly iterative as Harkin must source appropriate fittings, develop new assembly techniques, and ensure durability while maintaining pleasing aesthetics.

Finally, one or more complete prototypes are made to work out any final problems with the production process and define the assembly sequence. Samples may be made in several colour combinations, to be taken to trade shows to generate orders for customised versions of similar designs.

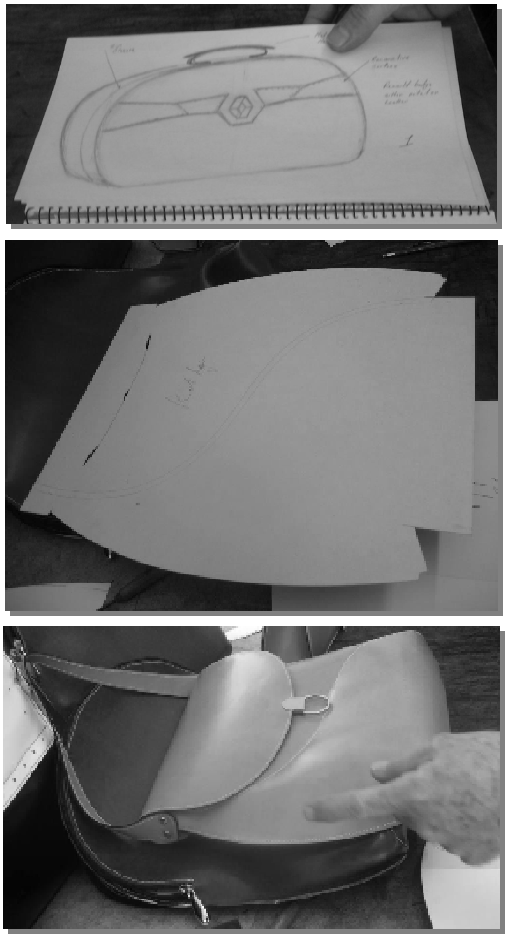

Figure 2. Successive stages in the development of a new design. 3D sketch (top). 2D cutting patterns (centre) Partial prototypes (bottom)

Figure 3. Example of an intricate detail

While drawing on experience of similar designs, the process but still involves significant overhead and variability arising from unpredictable design iterations. Customising existing designs is usually far more straightforward. In cases such as these, where the 3D shape is similar to an existing product and the material is in stock, the cost of customisation is very similar to producing a copy of an existing variant–as each item is hand-made anyway. Minor differences in shape or fittings can require different cutting patterns, increase the scope for mistakes and reduce economies of scale.

4.3. Detail of the customisation environment

Harkin spends roughly 300 working days per year designing and making bags, plus around 30 days attending trade fairs to generate orders. His assistant spends 180 working days per year on order processing. Of this time, they both spend 80% of the total time is spent manufacturing bags; and 12.5% on designing new bags and new ranges. The remainder of their time is spent in the administrative tasks related to running a small business.

Each order is expected to comprise 10 pieces, with a minimum of 5 pieces and a maximum of 50 pieces. Order processing can be divided into two main types. Firstly, fully-customised bags can be designed and then multiple copies of the new design produced. Secondly, bags can be ordered from the existing range or with minor customisations. To design a fully customised bag is expected to take around 3 working days. However, as explained above this process can take less time, or more if problems are encountered, many iterations are required, or time is spent on the details. We assume that minor customisations can be absorbed into the manufacturing process.

Production rate is also variable. However, this depends on the style of bag produced rather than process variability. For the large backpack range shown in Figure 1, only around 3 items may be made per day. For small items such as purses, which require less cutting and assembly, up to 20 items can be made in one working day.

On average, around 2 orders are received per normal business week. Each of these orders typically comprises between the minimum volume, i.e. 5 bags (eg. for a reorder) and the expected volume of 10 bags. Additionally, up to 10 large orders (between the expected and maximum volumes, 10 – 50 bags) are received per annum. At any given time, an average of three orders is being processed concurrently by Harkin and his assistant.

Besides designing and making his own bags, Harkin also designs on commission for companies, who either pay him for his time by the hour or more likely will request a fixed price for a certain number of designs. Whether he can afford to take or turn down these requests depends on the other commitments he has at the time.

4.4. Challenges

Designers like Steven Harkin often find it difficult to estimate the time it takes them to prepare a new design and make a new version. If they underestimate the cost of meeting a given order, they make very little profit. The pricing of Harkin's product is partly determined by the costs, but also by the prices that are charged for comparable products. At his market position he competes both with designer labels and with other craft designers.

Some of Harkin's ranges are more successful than others. While this is to some degree difficult to predict, the most successful designs are often those that Harkin works on for long periods of time to get the details exactly right. Thus, there is clear benefit to spending time in design iterations to create a more profitable product range. However, Harkin and his assistant work long hours to meet existing orders; and as a small business taking time away from the income-generating production process can be difficult to justify. As with the complex engineering processes, it is thus critical that Harkin can judge the benefits of time expended in platform creation and maintenance.

4.5. Comparison to complex engineering

Although the bag customisation process is clearly far simpler than that for, eg. aerospace customisation, many familiar issues arise: the need for iteration to explore possibilities and refine designs; the need to test production processes and to feedback production problems to alter the design; and the use of prior designs and experience as the basis to develop new ranges.

In terms of the multi-project environment, while many of the underlying challenges are very similar for larger engineering companies, the individuals in such companies are much more cushioned from their impact. In engineering companies the tasks are usually split between many more people, who all might have slack from other projects that they can invest carrying out a customization task. Although the product is far simpler, many of the basic issues outlined in Section 2 can be recognised in miniature in Harkin's business. Thus, it is a good proxy for showing how a simulation model can be constructed to explore the issues highlighted in Section 2 for more complex domains.

5. SIMULATING THE CUSTOMISATION PROCESS

The following sections progressively build up the model used to explore the research questions outlined in Section 2 after arguing that a design customisation process can be modelled and simulated in isolation to form the atomic building block for our approach. Due to lack of space and the very large range of questions which could be investigated by making small structural and parametric variations, we do not focus on specific simulation results. Rather, we focus on explaining the structure of our model which was constructed and validated based on the detail of the case study.

5.1. Simulating a single customisation and production process

In the TMCE 2008 conference we used an isolated model of this type to show how simulation can be used to assess the circumstances under which different mass-customisation strategies become economically viable (Eckert et al, 2008), thereby showing how RQ1 can be explored. In that paper, the problem was analysed in terms of 1) the total number of customised products the company expects to sell; and 2) the trade-off between the up-front investment of designing a customisable platform vs. the additional unit cost required to adapt individual products to the customer's requirements. This was achieved by assuming that effort expended up-front to develop a product platform or ensure flexibility of a new design reduces the duration and variability of each task within the single customisation process. In other words, a certain upfront investment reduces the unit cost of each item produced (Eckert et al, 2008). Simulation was then used to calculate the break-even point for different types of platform; each of which was considered to reduce the effort in different types of task at a different up-front cost. This sub-section describes a single customisation and production process for bags.

The isolated customisation process, which is part of the overall order response process, was developed in-situ during the second interview with Harkin and reviewed with him at that time, see Figure 4. The model comprises 14 tasks, each between 30 minutes and 1 day in duration. Certain tasks may generate information that is fed back to earlier in the process, thus requiring rework of a block of one or more intermediate activities and any nested iteration loops. These rework-generating tasks are shown as diamonds in Figure 4.

Nominal task durations were elicited from Harkin in terms of minimum, expected and maximum values which formed the parameters of a triangular probability density functions (PDFs) or uniform PDFs, depending on the task. Probabilities of rework were also elicited for tasks which could drive iteration. Harkin was asked to consider the duration of each task in isolation, i.e. assuming that no other work was ongoing, for the process of designing a complex bag such as the backpack. These values are tabulated in the appendix.

In overview, the simulation of the customisation process is based on the following assumptions:

1. The process begins with the need for customisation.
2. Receipt of the customisation request provides information allowing the first task, to be attempted.
3. When complete, each task creates new information and the successor task(s) become available to attempt. Where a task has multiple predecessors, all predecessors must be completed prior to beginning the task.
4. When an iteration task (diamond in Figure 4) is completed, the outcome is determined stochastically according to the probability of iteration. If iteration is required, the task pointed to by the arrow emerging upwards from the diamond is re-attempted – with all its successors. Otherwise, the tasks following the black arrows emerging from the diamond are attempted next. Following iteration, the diamond will eventually be encountered again and the procedure is repeated. If iteration is not required, the next downstream task is attempted immediately.
5. At some points in the workflow, certain tasks are possible to attempt concurrently. In these situations, unless sufficient resource is available to attempt both the task with least duration is executed first.

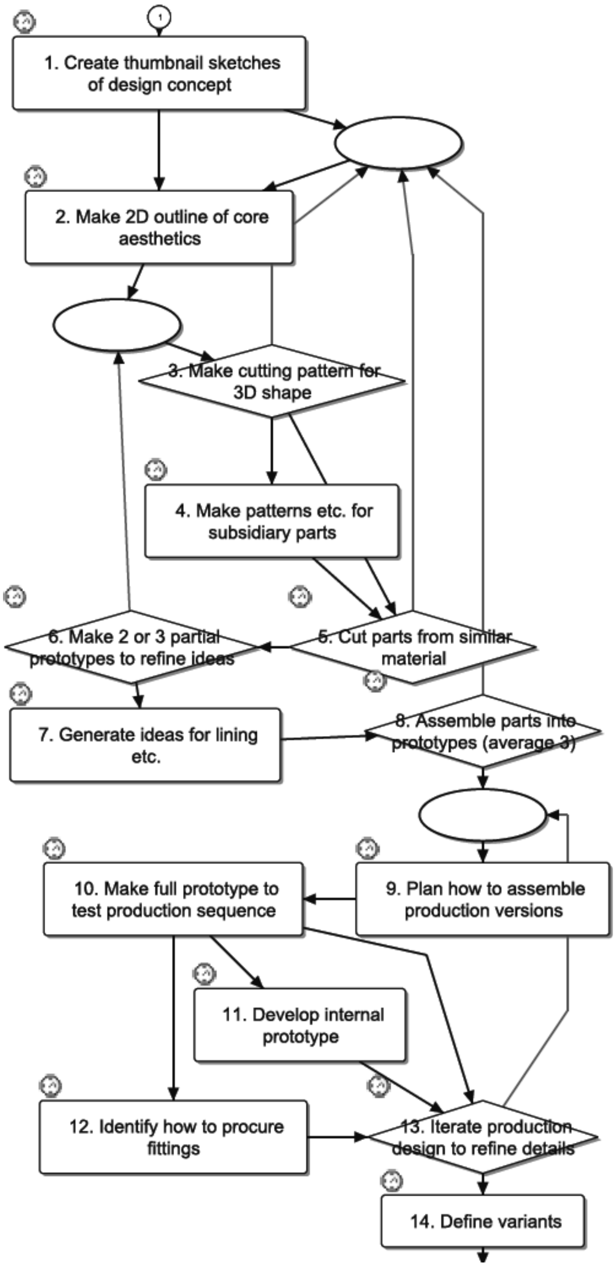

Figure 4. Model of the single customisation process

The single customisation process of Figure 4 was nested in the context of the whole order processing process, as shown in Figure 5. This allows simulation of the entire process of meeting an order request. The model was parameterised with the details of the order, allowing for the following realistic scenarios:

1. **Does the request require a completely new design or is it a simple customisation process?**

   The decision point entitled `Customisation or production` in Figure 5 causes the customisation sub-process to be bypassed for orders requiring only minor customisations, thereby assuming that such customisations can be absorbed within the production process without additional cost.

2. **Is the request for ‘complex’ or ‘simple’ bags?**

   Complex bags include the backpacks in Figure 1, and simple ones the grab-bags in Figure 1 (bottom). We assume that the duration for all customisation tasks in a ‘simple’ order is scaled to $^{1}/_{3}$ of the duration picked from the probability distribution specified in the appendix. The complex/simple flag also determines the time required for the ‘Make one item’ task in Figure 5; 4 hours per complex bag or 0.6 hours per simple bag.

3. **The number of units required.** This governs the number of repetitions of the ‘Make one item’ task visible in Figure 5.

The model forms the basis of a Monte-Carlo simulation of a given order processing process in isolation. The behaviour of the simulation is governed by the values of the 3 order parameters given above.

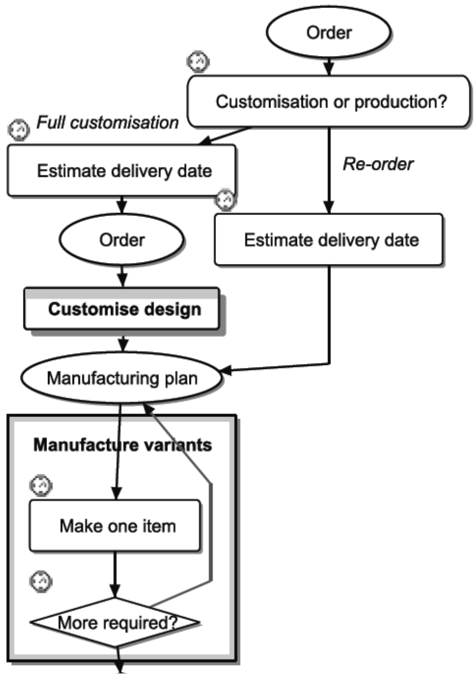

Figure 5. Model of the entire order-processing process. The customisation process of Figure 4 defines the content of the closed sub-process labelled ‘Customise design’

Simulation of the process model in Figure 5 was calibrated by triangulating the individual task durations and failure probabilities against the aggregate numerical data given by Harkin in Section 4.3 for four cases: simple customisation and production; simple production only; complex customisation and production; complex production only. To illustrate, results for the `*complex customisation and production*` case are shown in Figure 6. Examination of the results for all four combinations given above indicated that the simulation was a feasible representation of the process.

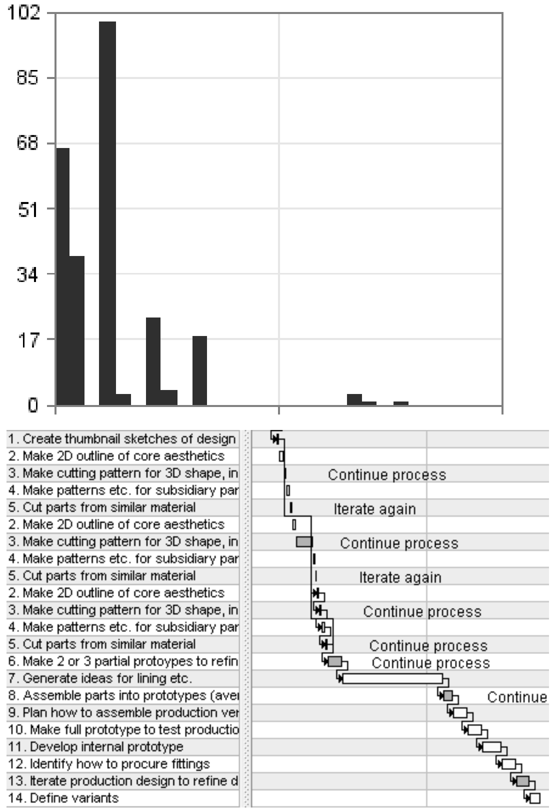

Figure 6. Results from simulating a single customisation and production process. Histogram of total duration (top) and detail of the single outcome for the modal case (bottom).

5.2. Simulating multiple, concurrent customisation processes

To construct a multi-project simulation to explore RQ1, RQ2 and RQ3, the order-processing process described in Section 5.1 was treated as a black box with only the three input parameters listed above. The following additional assumptions were made to compose the multi-project simulation from this model:

1. **Order requests arrive at intervals.** The time between one request and the next is distributed uniformly with a range between 5 days and 9 days. When an order request is accepted, Harkin must indicate the time it will take to fulfill that order.
2. **Each order request received is processed using an instance of the single process simulated above.** Thus, multiple overlapping processes are typically in execution at any given time.
3. **Tasks within processes are interleaved.** When Harkin or his assistant complete any given task, they choose the next task to attempt by considering the *priority* of each project.

This model of interleaving tasks to overlap projects was considered appropriate since Harkin had indicated that he and his assistant would mostly complete each task he started for a given project in one attempt, before moving onto another task. An additional complexity, which is not considered in our model, was Harkin's indication that production of different orders is often organised such that multiple operations of the same type can be performed together to improve efficiency.

In our model, the priority of a given project is related to the perceived progress to date, relative to the date at which delivery was promised. The expected date at which each task is completed was obtained from the simulation results for the customisation process presented in Figure 3. Using the data from a process with modal duration selected from these results, as given in Figure 4 the time at which each task was completed was calculated as a fraction of the total process time. This value, unique to each task i of the modelled process is referenced in the following text as $t_{i(expected)}$. The values are given in the appendix and summarised graphically in Figure 7.

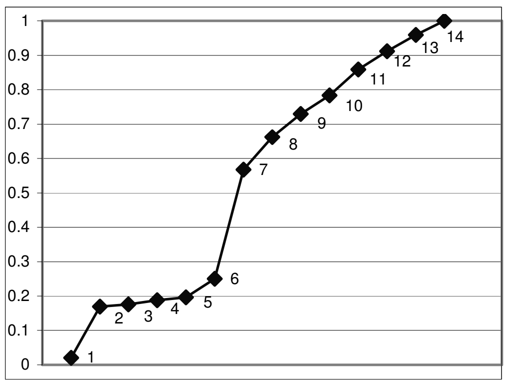

Figure 7. Values of $t_{i(expected)}$ indicate fraction of time through project at which each task is expected to be completed.

Using these values for $t_{i(expected)}$, the priority of every task *i* in each project *j* is dynamically calculated at each step of the simulation according to Equation 1:

$$\Pr iority_{ij} = \frac{\dfrac{t_{(elapsed)} - t_{j(start)}}{t_{j(required)} - t_{j(start)}}}{t_{i(\exp ected)}} \quad [1]$$

where:

- $t_{j(start)}$ *is the date the* j^{th} *project was started, ie. the date when the order was received.*
- $t_{j(required)}$ *is the required delivery date of the* j^{th} *project, a commitment made when the order was received.*
- $t_{(elapsed)}$ *is the current date.*
- $t_{i(\exp ected)}$ *is the expected fractional time at which the* i^{th} *task should be completed.*

Equation 1 is arranged such that, as time progresses, the priority of the next pending task in each project will increase. When the priority is higher than all other pending tasks, the task is executed. The next pending task in that project will have lower priority, since $t_{i(\exp ected)}$ will be greater as shown in Figure 4; hence the resource may be allocated to another project which is now falling further behind. This prioritisation function simulates a basic work-balancing strategy of focusing on those projects which begin to fall behind following iterations or delayed tasks.

The validity of the simulation was checked by triangulating the order arrival parameters with the expected number of projects in progress at any time, as elicited from Harkin.

To illustrate, consider Figure 8. This shows the results from a simulation in which it was assumed that all projects are accepted with the same nominal time commitment of 3.3 days. 20 order requests were simulated; this proved sufficient for the behaviour of the simulated system to stabilise. Figure 9 shows how the simulated lead time of subsequent processes (the lead time for each successive process is shown in a darker color) increases and the variability remains similar until a stable state is reached, at which each project requires a modal value of 9 days to deliver. This is commensurate with the expectations from the case study.

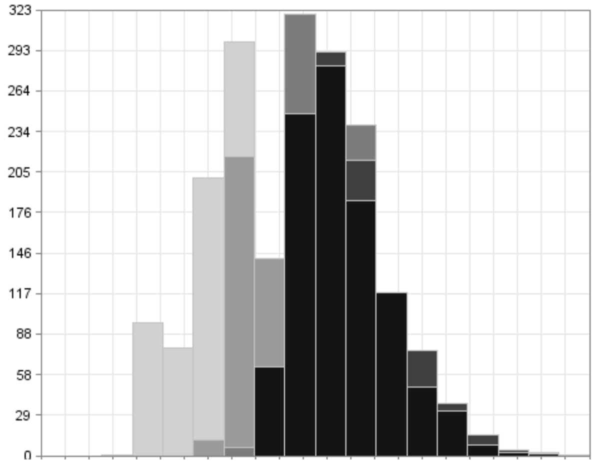

Figure 9 Results from simulating multiple concurrent customization processes, showing that the total duration of each consecutive processes reaches a stable value after 4-5 processes have been simulated.

The model outlined above can be used to explore research questions RQ2 and RQ3 for a given customisation process. For instance, the policy for making commitments to delivering projects within certain timescales – for choosing values of $t_{j(required)}$ when each order is received – can be modified. The values for $t_{i(expected)}$ and the policy for balancing resources are assumptions of our model which could equally be varied to explore their effect. For instance, a more sophisticated strategy for choosing $t_{j(required)}$, is to commit to shorter projects in periods of lower demand.

The resulting simulation model may be extended to explore many of the assumptions in its construction. For instance, to explore the impact of process variability on lead time, simulations can be conducted in which the probabilities of iteration within the customisation process, or the variance in order arrival time are treated as independent variables and systematically varied.

This scheme is arranged to explore problems associated with how platform maintenance (an indirectly value-added activity) competes with project tasks (directly value-added activities). It allows exploration of issues such as: when should platform maintenance be prioritised, even though projects are waiting for resource? How does this depend on project workload, platform utility, variability and the difficult associated with the platform?

6. DISCUSSION

The customisation process system that was modelled in this paper is simple, but real. It covered a generic set of tasks that Harkin believed he would follow to meet most orders.

We have argued that Harkin's business provides a good proxy for investigating similar issues in other industries. In particular, it has been possible to understand the entire business model, elicit detailed information from which a realistic model could be built, and to feedback the model for validation by the process participants. Despite the simple case, the resulting model is of similar complexity to that used by other authors (eg. Adler et al., 1995) to study this type of problem in far more complex engineering domains. However, since it was unnecessary to make large simplifications to render the analysis tractable, the model parameters could be tuned in a realistic way and the findings more easily validated against the process characteristics described in Section 4.3.

The structure of the simulations presented in this paper draw on the findings of our long-term research on engineering change in collaboration with amongst others a leading diesel engine company, who produce 1000s of different versions of 3 basic engine designs (see for example Jarratt et al., 2004). Some of the challenges of putting together tenders discussed in earlier sections have been observed in our original study on engineering in helicopters (Eckert, et al. 2004). These studies indicate that *engineering* change processes can be modelled in the same way as the simpler customisation processes we studied here – ie. as a change process generic to the company or industry being considered. This approach has previously been taken by Maull, 1992.

However, although many features of the environment we studied are similar in type, if not in scope to that of complex engineering, others remain different. One such issue is the information dependencies which occur between complex design customisation projects that, depending on how customisation is interpreted, could have lead times spanning several years. Another is the propensity for change not only to be initiated from orders, but also from emergent issues within the process and from change to requirements once the project has been started. A third is the far more complex structure of information dependencies within individual projects; this should be taken into account when determining how to resource those projects. One way of addressing these issues would be to describe the specific activities that are required to carry out each particular processes, rather than basing the model on a generic description of the isolated process; however this would likely not be feasible to do in practice. In the literature, most other models used to answer policy-level questions such as those we consider use a simple basic structure (eg. Adler et al., 1995), even when applied to study very complex domains. One interesting opportunity for further work is thus to explore the degree to which reducing the detail in the simulation model (eg. by aggregating multiple tasks and iterations into one activity with more uncertain duration) affects the conclusions which can be, or should be drawn. This could be explored using the bag customisation model, as a detailed and realistic model is available against which the results of simulating simplified versions could be compared.

Despite these limitations, we believe that the basic structure of the approach we have presented here has potential to help understand the issues relating to customisation processes as they are manifested in complex engineering domains.

Process simulation in product development has attracted much interest over the last few years (Browning and Ramasesh, 2007 give a comprehensive review). However, most authors focus on simulating individual design processes and relatively few simulate multiple intertwined processes. Although other authors have simulated design processes, our approach differs in applying process modelling and simulation methods to explore the problem associated with customisation in a multi-project environment.

7. CONCLUSIONS

Companies which offer customisable or configurable products must make decisions about how to price multiple orders which are processed concurrently. This is related to questions of how much effort to put into designing configurable platforms up-front. Through a simple, yet empirically grounded example this paper shows how design process simulation can offer insights into the risk associated with multiple orders and help to understand the dependencies between different orders. We have focused on the structure of our model, rather than particular simulation results as we believe this has the greater interest to the engineering community given the simple case study on which it is based.

Research Question 4 will be addressed in further work. Learning and reviewing could be modelled in different ways, for example as a reduction in task duration. However the issue of updating and revising the platform is critical in mass customisation, as many products, like handbags are subject to fashion, therefore the platforms ability to support the currently range could be modelled as decaying over time. Successfully completed projects could be seen as a "utility buffer", from which ideas can be transferred to the platform.

Although the structure of our model is based closely on the case study, and the results arising from simulation have been shown to be reasonable in this context, much further work is required to fully develop our approach and validate its usefulness. We aim to achieve this by applying our model directly to investigate specific issues related to the customisation of complex products in engineering design.

In the case study we have been able to models all the significant tasks in the process. In the more complex engineering process, it will be necessary to identify those tasks and parameters, which are required in the simulation before the outset of the modelling activity to ensure the effort involved in model building remains reasonable.

APPENDIX

	ID	Name	Predecessors	Duration	$t_{i(expected)}$	Iteration likelihood/ tasks revisited
PRODUCT DESIGN	1	Create thumbnail sketches of design concept	N/A	30s / 4hr	0.0203	
	2	Make 2D outline of core aesthetics	1	10m / 45m / 4hr	0.1689	
	3	***Make cutting pattern for 3D shape, inc. gusset etc.***	***2***	***90m***	**0.1757**	***0.2 / 2-3***
	4	Make patterns etc. for subsidiary parts	3	1hr / 2hr	0.1878	
	5	***Cut parts from similar material***	***3,4***	***30m 70m 90m***	**0.1959**	***0.2 / 2-5***
	6	***Make 2 or 3 partial prototypes to refine ideas***	***5***	***2 hr / 8hr***	**0.2500**	***0.2 / 3-6***
	7	Generate ideas for lining etc.	6	30m 70m 90m	0.5676	
	8	***Assemble parts into prototypes (average 3)***	***5,7***	***4hr 10hr***	**0.6622**	***0.2 / 2-8***
PROCESS DESIGN	9	Plan how to assemble production versions	8	8hr	0.7297	
	10	Make full prototype to test production sequence	8,9	8hr	0.7838	
	11	Develop internal prototype	10	8hr	0.8591	
	12	Identify how to procure fittings	10	8hr	0.9122	
	13	***Iterate production design to refine details***	***10,11,12***	***0***	**0.9595**	***0.15 / 9-13***
	14	Define variants	13	5hr 6hr	1.0000	

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