 GENERIC AND SPECIFIC PROCESS MODELS: LESSONS FROM MODELLING THE KNITWEAR DESIGN PROCESS

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ABSTRACT
Design process models are generated for a variety of purposes. Most design process models are abstract and only include large-scale tasks. This paper reports on the experience of building a generic hierarchical flow chart model of design processes in knitwear design based on a study of processes in 25 companies with a wide spectrum of market positions. The model shows tasks, decision point and iteration loops. It does not show differences in task duration and effort, or the frequency or depth of iteration, which account for the differences in the observed processes. Variations arise from the effort that individual companies invested in the design process and their willingness and ability to allow iteration. Detailed properties of the product also influenced iteration and the distribution of effort. This research shows that considerable modelling effort is required to capture characteristics of specific processes, but that generic models can be used as a starting point.

KEYWORDS
Design process models, comparisons between processes, process modelling, knitwear design

1. INTRODUCTION
Understanding design processes is the key to improving them in the future. However capturing and describing design processes is far from simple. While generic models of design processes have played an important part in the development of tools and methods, it is an understanding of specific processes that is needed to manage these processes efficiently and reduce the risks they involve. This paper discusses the question, at what level of detail variations between processes emerge. Based on a detailed study of the knitwear industry, this paper argues that it is possible to produce fairly detailed task and decision flowchart models, but such models do not show variations in task duration and iteration.

The paper discusses detailed process modelling for a particular industry, where observations and interviews in 25 companies (see section 2) have led to the development of a model of the design process comprising detailed hierarchical flow charts with over 140 tasks (see section 3). These are valid for all the companies that were studied. Differences lie in the duration of tasks, and the frequency of iteration and backtracking between these tasks, rather than in the tasks themselves. Even on one level deeper than the knitwear model many similarities exist. These models are still generic for an industry sector and hide the differences between individual companies and projects. This paper unpacks where these differences occur and what causes them in section 4, and reflects over the implications for design process modelling in general in section 5.

1.1. The purpose of process modelling
For the past 50 years the design research community has produced many generic descriptive and prescriptive models of design processes, at varying levels of detail (see Wynn and Clarkson (2005) for a review). While some models, such as Evans’s ship-design spiral (1959) are industry-specific, others, including the Asimov (1962) problem-solution-evaluation cycle, apply to all processes. However what all these models have in common is that they are not very detailed and don’t describe specific processes accurately. Design processes are modelled for a variety of different purposes, which all call for slightly different models. The generic models draw attention to particular feature of design process, or serve as guide to designers, as for example the Pahl and Beitz (1996) prescriptive description of how a design process should be conducted and what it should achieve.
at each point. Some processes are modelled to understand the requirements for computer support tools, or methods for processes or tasks. These models must be generic or at least have a wide scope to justify the development of the method or tool. For example the model discussed in this paper served to analyse communication and identify those points in the processes where the communication between knitwear designers and technician could be supported through an intelligent computer support tool (Eckert et al., 1999). Other models are generated to analyse aspects of a specific process in a specific company, for example to analyse information flow, task interfaces or bottlenecks. For example process Design Structure Matrices are generated for particular processes to analyse task sequences (Eppinger, 1994; see Browning, 2001 for a review) or signposting models to analyse iteration and rework (Wynn et al., 2005, Flanagan et al., 2005). The same model might apply to several projects, but might not reach beyond the scope of a particular company. To plan a project, the specific development process must be modelled to identify the risk and bottlenecks. Such models are highly specific. While they can be based on a generic model or an existing specific model their development requires considerable customization.

As the soft system community points out (Checkland, 1981), processes do not have an objective existence and are viewed in a different and personal way by each participant. Process models can be useful as a way to bring different views about processes out into the open and facilitate a discussion about the process. They are boundary objects (Star, 1989) that enable a negotiation about a process. However a consensus model of a process is not an objective depiction of a process, but a potentially useful aid in understanding, managing and supporting a process.

1.2. Knitwear design

The model in this paper describes the process with which individual knitted garments and knitwear collections are developed. Designing knitwear is generally much simpler than designing engineering products, but both industries share important characteristics.

Knitwear design is the creation of a technically complex product according to aesthetic considerations – the relationship between the appearance of a knitted structure and its structural characteristics is subtle and complex. In knitwear the shape of the garment and the fabric are generated together. Historically many garments were knitted as straight panels and cut into shape. This is cut-and-sew knitwear. Modern knitting machines can shape the garment pieces while knitting the fabric. They have reached the full scope of hand knitting – producing fully fashioned knitwear. The creation of knitted fabric draws on many historic patterns, and inspirations from different fields (Eckert and Stacey, 2003).

Knitwear designs are typically developed in collections of garments between two and six times a year. In most companies, the collections are reasonably coherent with shared colour schemes and shared pattern elements.

While knitwear is an important industry in its own right, the knitwear design process shares important characteristics with other aesthetic design processes such as graphic design, and with engineering processes. Knitwear design is performed primarily by:

- Knitwear designers who do the conceptual design by defining the visual and tactile appearance of a garment based on fashion trends and customer requirements.
- Knitwear technicians, who carry out the detailed design of the pattern and increasingly the shape of the garment, by using a CAD system to create programs for computer-controlled knitting machines to knit garment pieces or strips of fabric. They must also make sure that the design knits at a constant quality in the specified yarn.
- Make up people, who assemble sample garments and who traditionally constructed garment shapes.

The knitwear design team is small compared with those designing complex engineering products, but is typical in that different team members have different responsibilities, interests and expertise, but their collaboration is essential for the success of the product.

2. METHODOLOGY

To understand the scope of the models and the validity of the issues arising from them, it is important to understand how they were developed, and how they relate to experiences of modelling and analysing processes in other industries.

2.1. The studies of knitwear design

This research draws on observations in thirteen British, nine German and three Italian knitwear companies, made over a period of five years between
The interactions ranged from one-hour interviews with designers and technicians, to observations of design activities lasting up to one week. As far as possible interviews were recorded and transcribed; other observations were summarised immediately after the session.

The knitwear studies comprised two stages. The first phases concentrated on modelling the design process and understanding communication between designers and technicians in the knitwear industry (see Eckert, 2000; Eckert and Stacey, 2001) to inform the development of an intelligent support tool to aid the communication between knitwear designers and technicians, described by Eckert et al. (1999). The models that this paper reflects over were part of the author’s PhD thesis (Eckert, 1997). The second phase of knitwear studies concentrated on the use of sources of inspiration throughout the knitwear design process, which was informed by this process model (Eckert and Stacey, 2003). Many of the original companies were revisited.

### 2.2. Modelling the knitwear design processes

Process modelling is not part of research culture in artistic design domains as it is in engineering design with its long tradition of prescriptive and descriptive design models. Following Smithers (1998) we adopted a knowledge level approach, modelling processes in terms of what designers can do and must do. A knowledge level model describes a process in terms of the knowledge and information required to undertake definable tasks. The model is defined in terms of a network of tasks. The tasks are described in terms of the domain knowledge and the task knowledge required, and the information created through the transformation processes involved in executing a task. The concept of knowledge level models has originally been introduced by Allen Newell (1981) as a contribution to cognitive psychology: models of behaviour in terms of what actors need to know in order to be capable of doing what they do. This competence-based view has been extended by the CommonKADS group as a tool for knowledge engineering (see Schreiber et al., 2000).

Usually knowledge level models for knowledge systems are built using AI knowledge acquisition techniques. However, in this research it has not been possible to procure dedicated expert time. While designers were willing to interact and contribute to this research, expert system knowledge acquisition was alien to their culture. Therefore an ethnographic approach was employed. The special emphasis of ethnography is the dual perspective of the participant observer, to look at everything from the viewpoint of the insider, while remaining conscious of being an outsider with an analytical perspective (see Agar, 1980). Spradley and McCurby (1972) define the perspective of ethnography as “instead of asking ‘What do I see these people doing?’ [the ethnographer] must ask ‘What do these people see themselves doing?’”. Many different ethnographic accounts of the same observed phenomena may be valid, and they may couched in terms strange to the people observed, but the test of validity is that an ethnographic account should ring true to the people it describes.

For this research ethnography and knowledge level modelling was combined in a bootstrapping approach, that we called knowledge level ethnography (Stacey and Eckert, 1999). The logical structure of the process arising from the properties of the product was used as starting point for an iterative approach to modelling. The models were falsified and thus refined from each empirical study to the next until a stable process model was reached. Each time divergent behaviour was seen, it was incorporated into the model (or discarded, if it was on the wrong level of granularity). The aim of these models was to develop a detailed, but general model, at the level of the detail, where the behaviour of companies was similar. The models were also discussed in detail with a design educator and a practising knitwear designer to make sure that nothing was missed and the vocabulary chosen to describe tasks was generally accessible.

### 2.3. The range of companies

The companies covered a broad range of market sectors, from leading fashion companies, such as Escada and Missoni, to the suppliers of the cheap mail order companies. Technical innovation in the knitwear industry often occurs in the so-called golf market, where high development costs can be passed on to the customer to pay for subtly different, but expensive looking products. The bulk of the study was conducted with suppliers to a high street retailer, who were operating in a highly fought-over market environment, and had very tight price targets, but also an in-depth understanding of market trends.

In addition, several craft knitters were interviewed, however these will be excluded from the discussion of process models, as their processes are not driven
by technical execution and quality of the final products in the same way as the industrial processes, as they follow a different business model.

3. MODEL OF THE KNITWEAR DESIGN PROCESS

Based on the empirical studies outline above, a detailed generic process model was developed, that accurately describes all the observed processes.

3.1. The modelling approach

The model comprises a hierarchical set of what are essentially flowcharts for the knitwear design process. They model tasks and decision points, and show tasks and tasks ordering, decisions points and potential iterative loops and exit points for particular garments. A task input-output model (like an IDEF0 model (United States Air Force, 1992) or a signposting model (Clarkson and Hamilton, 2000)) was not necessary, because very few documents were passed between the participants. The aim of many tasks is to increase the understanding of the designers and technicians, either through research\(^1\) or the generation of samples. This knowledge was rarely expressed in any formal way, and the outputs of the tasks, such as swatches or collections of images, served as a medium of communication (see Eckert and Stacey, 2001, for a discussion of communication through objects in the knitwear industry).

The model captures all the steps that collections and particular garments need to go through from researching ideas to being selected for mass production by the customer. Many of these tasks are shared between all the garments, for example research or sampling. As the process progresses the tasks become more specific to particular garments; however as shortcomings with particular garments and omissions in the planned collection become apparent as the process progresses, earlier tasks might be repeated and designs might go through the entire process again in an accelerated manner.

The timescale and therefore the iteration loops of the process are dictated by the delivery time of the collection. Fashion products need to be ready to go to shops at fixed times of the year to fit into seasonal sale cycles. Schedules are met by controlling the number and depth of iteration cycles, by compromising the quality of the design execution. As fashion is not safety critical (in contrast to many engineering products) and has very few objective success criteria, it is possible to bring sub-optimal garments to the market.

3.2. Detailed hierarchical models

This section provides an overview of the knitwear model generated. It describes the overall design process of designing an individual garment, as well as entire collection. In knitwear design the whole process is very similar to the process for designing a particular part. The emphasis and durations of tasks and iteration loops change, but the same logic applies to the overall process as to its parts. The design process was modelled at the level of detail where the process was generic to all companies visited and all garment types. The model includes all the iteration loops that have been observed, even if particular paths are very rare, but not impossible in a particular company.

The process falls into three distinct stages: research, design and sampling, which are shown by the background colour in the flowcharts\(^2\). Decisions are often made collectively, but are colour-coded here by their principal task owners. Alternative tasks, as for example in the first row of Figure 1 are drawn in parallel.

The process was modelled in fourteen diagrams at three levels of detail. The model has about 140 tasks and 85 decision points.

The Overall process: level 1

Figure 1 shows the entire knitwear design process from fashion research to the selection for garments for final production. Designers and their customers begin the process in parallel by researching the fashion of the season they work on by attending yarn shows and fashion shows, studying forecasting materials and studying the garments of competitors and market leaders.

Once briefed by the buyers the designers begin specific research for the themes and styles that they will work on. The activities of the two research phases blend into each other, but have a different focus. Initially designers try to familiarize themselves with all the fashion trends for the coming season, later they work on ideas for garments in their specific collection and research yarns for it.

To select yarns and try out first ideas, technicians produce little fabric samples, called swatches. Based

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\(^1\)The term research has a very loose meaning in artistic design domains, covering market research, and searches for ideas for designs as well as studies of what other companies are doing.

\(^2\)The tasks are colour-coded by task owner. Designers are red, technicians blue and pattern cutters green.
on the research designers have carried out and the feel and technical feasibility of the swatches\(^3\), a set of yarns is selected for the season. Now the designers can plan their entire collection, developing a framework with a high level description of the garments they want to produce. For example – to simplify - they might specify that a collection will have six jumpers (one plain, one intarsia, two colour patterns, two texture patterns), etc. Now designers and technicians work on further swatches, testing colour combinations and textures. Those that the designers like and fit the context of the coming fashion are incorporated into designs for specific garments. With ideas for concrete designs in mind, further swatches are generated to test fabrics for specific designs. Each design is described with a brief written description, measurements (that is, parameter values) and a free-hand sketch, in a technical sketch. The designers now hand the responsibility for a specific design over to the knitting machine technicians. The technicians work on getting the fabric for the entire garment piece worked out, while the pattern cutters work out the shape (in more modern processes the technicians do the two tasks sequentially). With all the pieces in place the technicians bring the shape and the fabric together and modify both slightly until the garment looks similar to their interpretation of the technical sketch. The garment is then shown to the designers and refined until the designers are satisfied or the technicians run out of time. The garment is then approved by the designers and later by the buyer. As Figure 1 indicates, failure to meet approval at any of these stages can lead to long iterative cycles.

**Swatch Sampling: Level 2**

The top level process described in Figure 1 comprises tasks that can be broken down into more detailed task descriptions.

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\(^3\)Swatches are fabric or garment piece samples.
sign framework task, and for the design of a particular garment. The technicians receive input at varying levels of detail. Sometimes designers provide them with a grid representation of the pattern they want to generate or they give them an example of the knitted structure they want to achieve in the form of an existing swatch, garment or picture. However sometimes the technicians are only provided with a picture of an object or a verbal instruction, and have to work the details out themselves. Each of these different ways of generating swatches could be again broken down into an additional flowchart with the same number of tasks as the sampling flowchart itself.

Programming the Knitting Machine: level 3

Once the technicians have gained access to the CAD system they can optimize the knitting operations and set up the knitting machine to knit the sample. Figure 3 shows a further breakdown of the knitting machine programming operations, which are a part of the knitting of samples. While this is not a model for a specific make of knitting machine, some of the tasks, such as the “optimization of traverse” have been automated in modern knitting machines. The more automated programming environments of modern knitting machines follow the same task logic. If problems occur, any of these tasks may need to be carried out manually by the technician.

4. DIFFERENCES BETWEEN PROCESSES

The process model discussed in the previous section applies to all companies. The top two levels are entirely generic. The level 3 flowcharts differ for the type of knitting machine and corresponding CAD system employed. However the processes are by no means the same in every company and for every garment. This section will discuss how and where differences in the processes occur.

4.1. Different key behaviours

The main differentiating factor between the processes in individual companies was how much effort they spend on the process for the number of garments that they produce per season. At the lower end of the market companies do not have dedicated sampling machines. Garments need to be developed on production machines and expensive sampling is not economically viable. The number of designers and technicians varies between companies at different ends of the market. Where companies producing cheap garments at the bottom end of the market typically employ a freelance designer, top-end companies have a whole team of designers, technicians, and possibly placement students to come up with new ideas. A typical high street supplier, which targets the middle of the market, would generate for each collection about 1000 ideas for designs, produce about 200 swatches and 50 full garment samples for 20 garments in a collection (accurate figures are impossible to obtain, because ideas are not recorded and swatches are shared between seasons and collections, but not systematically kept). This corresponds to an average of four swatches per sample garment. At the higher end of the market a far larger number of swatches was often generated to create innovative stitch structures or employ novel yarns, which require much more testing. By contrast, the designs are technically much less challenging at the lower end of the market. If bottom-end companies employed interesting stitch structures they either used the same ones or slight variations for years, or make use of the freely available patterns provided by knitting machine manufacturers.4

4This is similar to the difference between using clipart and
The hallmarks of expensive garments are a tremendous attention to detail and a fine sense of changes in fashion. As knitwear does not have objective evaluation criteria (as long as the garment does not fall to pieces and fits the wearer roughly), the love and eye for detail determines the quality of the product.

Fashion companies iteratively refine their understanding of emerging fashion by looking at the new products produced by their market leaders and competitors. As the more upmarket companies release garments, the company who follow them see which of the trends they had earlier identified are taken up by others. While all companies can make mistakes in their predictions, more fashion-oriented companies are more willing to change garments or collections late in the design process to adapt to changes in fashion. Last minute additions or modifications to collection can be very stressful and regularly require designers and technicians to work overtime before collections are released. While research and design tasks can be accelerated the time to make a swatch can not be accelerated, because it depends on physical processes.

Companies vary in the range of garments that they produce for each season. This is almost independent of the position in the market place. Greater variety does not necessarily lead to greater effort. Rather effort is determined by the number of new features that are introduced into the collection. Sampling new shapes or patterns and using materials with different properties required more rounds of iteration than the reuse of standard shapes or patterns. For example, if a company tries to develop an innovative neckline, they can produce dozens of samples, until they have made it work in a particular material. Assessing how much effort will be required for innovation is very difficult when the design framework is decided, so that companies can find themselves with unexpectedly difficult collections to produce.

4.2. Effect of different key behaviours on processes

The essential differences between the key behaviours manifest themselves in processes in the following ways:

- **Effort spent on tasks**: While all companies go through the same tasks, the time and resources spent on the tasks vary greatly. For example, the top-end companies put considerable effort into re-developing one’s own artwork.

- **Number of iteration loops**: Iteration in many ways is driven by dissatisfaction. Therefore attention to detail and to some extent exact positioning in the fashion market drive the number of iterations on each task.

- **Depth of iteration loops**: As the process progresses iteration loops can go further back in the design process and therefore potentially become far more costly. More upmarket companies are more willing to go further back in the process. Instead of solving perceived problems in designs on a localized level, they systematically question the entire collection. For example they might do more research towards the end of the process to check whether a design is still up-to-date and possibly incorporate new designs into the collection to catch an emerging trend. They might also consider introducing new yarns, thus going through the whole cycle from swatch sampling again.

- **Tasks in iteration loops**: Even with long iteration loops, it is not always necessary to go through all of the stages. For example swatch sampling occurs three times in different roles in the process. When a new yarn is introduced late, it is possible either to work immediately on a specific garment or go through the sampling process all over again.

4.3. Implications for planning

Knitwear design does not have a fixed number of iterations the process needs to go through or a fixed number of times a task need to be undertaken. Knitwear companies continue with their design process until they run out of time. The quality of individual garments is uneven in many collections. While high-end companies’ collections normally only contain very well executed, up-to-the-minute garments,
other collections have some excellent pieces and some less impressive designs.

The process is never explicitly written down or planned on a task level. Especially technicians in all companies struggle with scheduling the tasks they are carrying out. They understand the process in very much the way it has been modelled here, but do not have an explicit model of task iterations and durations for the entire process. They don’t, as such, plan the process, but try to do their best for each milestone, which is set by buyer meetings or internal selection meetings. In many ways technician have to be responsive to the needs of the designers and provide them with swatches or garments as and when requested. For the rest of their workload, technicians apply several key heuristics for planning their work-load:

- Work on the difficult designs first, to make sure they work out.
- Work on the simple ones first to make sure most of the collection is done.
- Work on the design that seems most urgent in an entirely responsive mode.

Which heuristic they follow very much seems to be a matter of personal preference as opposed to an explicitly discussed strategy.

4.4. Influences on all processes

One of the main factors influencing design processes in general are the characteristics of the product that is being designed. Knitwear is no exception. Different garments require different processes to design them. Simple garments clearly require less iteration during the process. A plain garment with a simple shape might only need one fabric swatch knitted before the whole product is developed. Other garments with complicated shapes need many whole garment samples, while some require samples only for aspects of the garment. As fashion changes the balance of tasks changes as well. For example the 1990s saw very few intarsia garments, which require whole garment swatches. The changes in fashion affect primarily the way ideas are generated and the number of swatches generated at different times in the design process. Even with a spread of garments the way collections are developed in terms of task duration and iteration varies with fashion.

There was a marked difference in the design processes between different countries arising from the skill levels of the different participants and thus the division of labour between designers and technicians. Generally good technicians are harder to find than designers, shifting the balance to power towards technicians. In the UK designers are trained in the technical aspects of knitwear design and try to engage in the detailed development of the stitch structures. In contrast the German designers in the study were uninterested in the technical realization of the garment pieces and provided technicians with images or sketches. The German technicians, who were better trained than their UK counterparts, did most of the detailed design. This affects the iteration loops between tasks. Where a UK technician would try to get designer approval, which could result in a redesign, a German technician might iterate within one task. In Italy designs were worked out by a designer – often trained in the UK – and then sent out to an independent knitting machine programming company. This model places a far greater onus on the designer to develop good descriptions of their design ideas, thus increasing the duration and iteration on the detailed design and technical sketch task.

Over the last few years the knitwear industry world wide has changed beyond recognition. Most western European mills have been closed down and production has been moved increasingly further east. However, the designs are still created in Europe, but production and sometimes sampling is moved off-shore. This again affects the effort that needs to be put into specifying garments. As technicians and designers don’t know each other anymore, they won’t be able to interpret each others descriptions correctly. With production off-shore, companies have very little margin for error in their collection planning. With garments produced locally, it was possible to put a small run into shops and gain feedback on the designs at the last minute. Due to current off-shoring trends, there is much less scope for long iteration cycles once the technical sketches are released.

5. SUMMARY AND IMPLICATIONS

The knitwear design model is a descriptive analysis of observed behaviour, and is not comparable to prescriptive generic models of engineering design, such as the Pahl and Beitz (1984) model. The level of detail and number of tasks is comparable to engineering process models generated for particular components of complex products, for example the turbine cooling design process (Bell et al, 2006), where the models describe the practice in one company, and obtaining a model from a competitor company would compromise confidentiality agreements.
The purpose of this section is not to compare processes in knitwear and engineering design, but to draw lessons for process modelling.

The knitwear model refers to an entire industry sector that produces homogenous products. Compared to engineering products in most sectors, the knitted garments are remarkably similar: they are produced on one type of machine with very similar CAD systems. The materials they are made of are far more similar than the wide range of materials one would find in engineering. As fashion changes new variations on existing themes are generated. While real innovations do occur they are subtle changes, unless they affect the entire industry sector at once. Variations affecting the knitwear design process are likely to be amplified in other design domains where the products are more varied.

The analysis of the knitwear design process model has shown that even if a process is modelled in considerable detail, variations between individual projects do not always show up as differences in models. This section abstracts from knitwear to other fields and discusses the implications of this work for process modelling in general.

5.1. Process modelling

Since 1999 the author has carried out several detailed studies in engineering design companies to understand communication between design teams, planning in industry and changes to existing products (Eckert, Clarkson and Zanker, 2004; Eckert and Clarkson, 2003). Overall nearly 100 engineers and engineering managers in seven large UK aerospace and automotive companies were interviewed. These studies were intertwined with process model building exercises carried out by other researchers in the same research group (Wynn et al. 2005, Flanagan et al. 2005). The models were parameter-based task models following a signposting approach (Clarkson and Hamilton, 2000). Unlike the knitwear model, these models tried to capture a specific process to guide the designer through the process and to find the best route through the process. However the involvement with partner companies has been going on for several projects.

In engineering the number of companies that cover the same product range is much smaller than in the textile industry. For example there are only three jet engine manufacturers and less than ten big players in diesel engine design development worldwide. As the competition is stronger, it is very unlikely that competitors would share their process knowledge in any degree of detail. However sharing process models across projects is very important. As differences manifest themselves mainly in task duration and iteration, it would be possible to develop generic industry sector models as a starting point for detailed process modelling and process planning. To establish specific risks, these models would have to be hierarchical with a clear understanding of the relationships between component models at different levels of hierarchy.

5.2. Abstracting away from knitwear

Differences between companies, seasons and products are reflected in the details of the design process:

- The product or product spread;
- The position of the company in the marketplace;
- The skill-level and potential commitment of the participants;
- The attention to detail;
- Willingness to adapt to emerging requirements;
- Ownership of tasks and the division of labour;
- The degree of collaboration between participants in the design process.

In terms of processes these differences manifested themselves in the following areas:

- Effort involved in tasks;
- Number of iterations through the tasks;
- Frequency of iteration loops;
- Depth of iteration loops.

Real differences between processes in different companies only became apparent at a very detailed level, and depend strongly on detailed properties of the products.

The knitwear models are a formal representation of the participants’ own understanding of the design process. As the knitwear design processes are not formally planned or scheduled, these models also don’t contain the information required for planning.

5.3. Implications for engineering design process modelling

Process models are generated for a purpose and then serve mainly that purpose. The knitwear design models were generated to understand communication in the design process by modelling interfaces between stakeholders and iteration loops, with the view of building a generic tool. These types of flowchart models are useful for understanding the processes on a high level. They serve to analyse communication,
feedback and co-operation and allow management to scrutinise the division of labour. In knitwear design with a small number of participants this is relatively straightforward; however in far more complex engineering processes, processes can be improved by minimizing the need to communicate and collaborate across teams (see Sosa et al., 2003, for an analysis of communication and task connectivity). However, flowcharts are not sufficient to facilitate planning.

The knitwear design models raise questions about the appropriate level of detail in which to model tasks:

- **Detail of task breakdown:** How detailed does a model have to be to show up potential problems? In knitwear, the differences in processes appeared only at a fairly detailed and product specific level. At the next level of detail the process model would need to differentiate between different types of garment. The variant models for garment types would still apply to garments produced in different companies, but would no longer be generic for the sector.

- **Overall versus component specific process:** The distinction between the process with which the overall product is designed and the process with which its components are designed is often not clear in models. The knitwear model describes both the design of an entire collection and an individual garment. The same applies in engineering design, where, on one level of detail, the process for the entire product is similar to the process for its components, but the different technical properties of the components lead to very different sub-processes.

- **Iteration: repetition, refinement and rework:** Tasks are repeated for three fundamentally different reasons. Rework occurs when there was a mistake in the tasks or the input parameters have changed. Refinement takes place when a task is repeated to improve the design, without an obvious mistake to eradicate. Often designers can only decide what they want once they see a sample and suggest modifications to it. Repetition happens when the same task is carried out for a different purpose. The knitwear model mixes these types of iteration, as individual garments or swatches are rejected and thus reworked. The knitwear process model also mixes activities that are carried out for groups of designs and activities that are carried out separately for each design in turn. On the level of the activities that need to be carried out the three types of iteration are identical; however the difference from a planning point of view is great (see Flanagan et al., 2005, for a detailed discussion of the planning implications).

This implies that different components require a different level of detail in the model, making the process models uneven in terms of granularity.

One of the main roles of process models is in analysing the risk in processes, especially the risk of task failure. This requires that processes are modelled in sufficient detail that individual task failures that can lead to bottlenecks are captured. If the model is too coarse, potential failure of a subtask and the resulting iteration is hidden in a task. For example the knitwear technicians produce garment samples until they run out of time. They iterate through this task frequently without this showing up in the process model. In an engineering design process, with objective delivery criteria this can lead to high risk, if there is insufficient time for iteration. In the knitwear models there is variation in the depth and frequency of deep iteration loops. If tasks are not modelled in sufficient detail, these deep iteration loops are often overlooked, or can be hidden in iteration loops that are followed for different reasons, hiding a potentially critical interaction.

As the knitwear process model has shown, variation does not only occur across companies but also between collections within a single company. The same applies to individual engineering projects. This makes predicting process duration or process iteration very difficult. Most planning is carried out through similarity references to other designs. The relationship between planning and similarity is not straightforward. A detailed model could highlight where divergence occurs; a high level model allows planning with aggregate experience values.

### 5.4. Building specific models

Generic models at a sufficient level of detail can be used as a starting point for building rich specific models, in a similar way to process building blocks (Bichlmaier, 2000). In addition to understanding the organisation and the available resources, it is necessary to analyse the specific properties of the product that needs to be designed. The degree of innovation and likely problems influence the duration of tasks and likelihood of iteration, even if the tasks are generic. As the process progresses and uncertainty accumulates, companies are likely to change tasks in a process to meet given goals. Process models influence the processes that they model, because they draw attention to characteristics and bottlenecks in
the process. As the participants respond to those problems, they change the process, thus rendering the model inaccurate.

Many modelling approaches do not allow the inclusion of task duration and iteration information. The flowcharts used in the knitwear models do not include durations. Conventional Gantt and Pert charts typically only include repetition iteration omitting rework and refinement iteration. DSMs (Eppinger et al., 1994) include sequential information, showing dependency loops, but do not contain task iterations. Signposting models (Clarkson and Hamilton, 2000) include duration, dependency and rework information, thus being very knowledge intensive. In process modelling it is vital to decide whether the purpose of the model merits the effort required in building either very detailed or very specific models.

6. CONCLUSION

The knitwear example has shown that it is possible to build detailed generic models, which have validity beyond a particular instance of a project or a company. These models can be built to support the development of generic computer support tools and the management of particular processes or to provide an explicit starting point for negotiation. A generic model can only be a starting point for process planning or risk assessment. However, it might be possible to identify the locations and forms of normal variations in a generic model. It does not capture a process at the level where behaviour diverges for a particular project, therefore not allowing an assessment of specific risks. Key risks arise from the way tasks are reworked and iterated and the depth and frequency of iteration loops, which are determined both by the characteristics of the product and the setup of an organization.

In the near future the knitwear design process will be modelled in the P3 software (Wynn et al., 2005), which generates flowcharts based on task and parameter models following a signposting approach (Clarkson and Hamilton, 2000). Here duration and failure probabilities can be modelled; however for knitwear these have to be estimates by the author, as this information has not been obtained in the original interviews and observations.

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