Computer Supported Cooperative Work **10:** 29–74, 2001.

The Communication Bottleneck in Knitwear Design: Analysis and Computing Solutions

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(Received 21 December 1998)

Abstract. Communication between different members of a design team often poses difficulties. This paper reports on the results of a detailed empirical study of communication in over twenty British, German and Italian knitwear companies. The knitwear design process is shared by the designers, who plan the visual and tactile appearance of the garments, and the technicians, who have to realise the garment on a knitting machine. They comprise a typical but small design team whose members have different backgrounds and expertise. Knitwear design allows a detailed analysis of the causes and effects of communication breakdown. Designers specify their designs inaccurately, incompletely and inconsistently; technicians interpret these specifications according to their previous experience of similar designs, and produce garments very different from the designers' original intentions. Knitwear is inherently difficult to describe, as no simple and complete notation exists; and the relationship between visual appearance and structure and technical properties of knitted fabric is subtle and complex. Designers and technicians have different cognitive approaches and are very different people. At the same time the interaction between designers and technicians is badly managed in many companies. This paper argues that improving the accuracy and reliability of designers' specifications would significantly enhance the design process. It concludes with a description of the architecture of an intelligent automatic design system that generates technically correct designs from the designers' customary notations.

Key words: automatic design, communication, design, ethnography, knitwear, notation, team working

1. Introduction

The strength of a design team often lies in its diversity, but diversity can also made teamwork problematic. Every person has a particular personality and works in a different way; each brings different expertise and experience to the task. Designers with different expertise and areas of responsibility can have radically different conceptions of designs and the activities involved in producing them. How different members of a design team communicate is a major factor influencing any collaborative design process, and communication breakdowns can cause severe problems. How do patterns of interaction and the means by which ideas are communicated influence the success of design processes?

This paper presents the results of an ethnographic study of the patterns of communication observed in the knitwear industry with an analysis of the diverse factors contributing to the communication breakdown. It discusses how computer support for collaborative design can alleviate these problems.

1.1. KNITWEAR DESIGN AS A DOMAIN

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. While being an important industry in its own right, the knitwear industry shares important characteristics with both other aesthetic design industries and engineering design. Knitwear design is shared primarily between the designers, who design the visual and tactile appearance of a garment based on fashion trends and customer requirements, and the knitwear technicians, who are responsible for programming knitting machines to realise these design ideas. The knitwear design process is essentially linear: the key communication act is the hand-over of design specifications to a different team member (usually but not always nearby). Significant inefficiencies in the design process stem from problems in the communication between designers and technicians: partly from the fact that it *is* a hand-over between separate people doing separate activities; and partly from the form that the specifications take. For the comprehension of this paper it is essential to note that knitwear design is not an activity carried out jointly and concurrently by the designers and the technicians, but that technicians are expected to realise design ideas in whose creation they have not been involved.

The designers undertake the conceptual design of the garment, which as in other industries is usually skeletal, vague and tentative. In developing the knitting machine programs the knitwear technicians work out the detailed design of the fabric. Pattern cutters construct the cutting pattern for the shape of the garment and assemble the sample garment thus defining the details of the shape. The background and training of the person constructing the cutting pattern varies; in the UK they have often risen from shop floor sewing and fabric cutting tasks and are therefore referred to by their old title as "pattern cutter" or "make up person". In some smaller companies the designers do this job. The division of labour between the knitwear technicians and the pattern cutters is changing, as more and more knitwear is not cut to shape, but knitted to shape. Both technicians and make up people play an important role in detailed design; however what they do is not recognised as designing in the culture of the knitwear industry. 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. A typical knitwear company has two or three designers, one or two knitwear technicians and one pattern cutter, who also does some garment make up. The largest companies we visited had seven or eight designers and a design director, about four technicians to program the machines, and one dedicated pattern cutter. Some of the smaller ones use freelance designers and only have one technician.

The analysis of the causes of failures of communication in the industrial knitwear design process presented in this paper forms one part of a detailed analysis of the structure of the process (Eckert, 1997), which was intended to guide the development of intelligent support systems for knitwear design (Eckert and Stacey, 1995; Eckert et al., 1998, 2000).

1.2. OVERVIEW OVER THE PAPER

Section 2 places the study of the knitwear design process discussed in this paper in the context of other empirical studies of work processes in particular in design (section 2.1), before explaining the methodology employed in this study (section 2.2) and the range of companies and experts it has covered (section 2.3). Section 3 provides a more detailed description of the technical characteristics of knitwear which affect communication (section 3.1), gives an overview over the knitwear design process (section 3.2), outlines the characteristics of commercial CAD systems for knitwear (section 3.2) and describes the interaction between designers and technicians in this industry (section 3.4). The failure of these two groups to communicate successfully is analysed in section 4, which looks at different factors contributing to communication breakdown. Intrinsic problems concerning the effort and commitment involved in communicating early design ideas are discussed in section 4.1; and in describing knitwear in section 4.2. Section 4.3 looks at cognitive factors, while section 4.4 addresses organisational factors and section 4.5 cultural and social factors contributing to the communication bottleneck. The section concludes with a reflection on international differences and the relative importance of these factors. Section 5 presents a computer tool that enables the designers to build clear and unambiguous representations of garment shapes. Section 6 summarises the results of the study and draws conclusions for other fields.

2. The study

While ethnographic studies of design processes are becoming increasingly popular in other domains, this paper reports on the first detailed study of the knitwear industry, which has included visits to over 25 different companies. The methodology draws both on ethnography and knowledge level modelling.

Knitwear design in many respects is engineering design of complex products in a nutshell. It shares the interaction of technical constraints with aesthetic considerations and material properties. Knitwear is never designed in isolation; every design is deeply influenced by the context created by previous and contemporaneous designs, as well as by the wider design culture, and in turn contributes to this context. There is a constant tension between being sufficiently different from other products to attract customers and being sufficiently similar to be bought and worn with other garments; the garment must fit within the envelope of acceptable designs in a particular fashion. In the same way engineering products need to be sufficiently different from other products to fulfil a specific market need or simply to attract customers, while being similar enough that they meet needs the customers recognise, and can be used in conjunction with other products.

2.1. Background of research in other fields

The study presented in this paper has been the first extensive study of the knitwear industry, and one of the first large ethnographic studies of the textile industry. Pycock and Bowers (1996) have looked at the organisation of the tailored clothes division of a mail-order company. As no design occurs in the mail-order companies themselves the emphasis of this study was on quality control, which is the main challenge faced by all mail-order companies. Scaife et al. (1994) developed a prototype system to record and modify design information in a database, based on a detailed study of the tailored fashion industry, in which they identified the lack of consistent recording of design information as a major problem. Alas, the fashion industry has still not taken these findings on board, and tends to reassemble most of the information associated with a design when it is modified. Mäkirinne-Crofts et al. (1996) also remark on the lack of recording and reuse of design information. They investigated the potential for improving computer systems for fashion designers, basing their analysis on forty-five structured interviews with designers and a questionnaire. They developed a theory of the fashion design process and of creativity in general, based on quantum mechanics (from an uncritical reading of Penrose (1989)), psychoanalysis, and mother-child bonding in early infancy. They view idea generation as the ‘the great mystery’.

Ethnographic studies are increasingly employed to as a method to inform the development of information systems and other software tools, especially CSCW systems (see Viller and Sommerville, 1999, for a review and a description of an ethnography-informed approach to system design). Meyer (1991) has combined ethnographic observation with conventional knowledge acquisition techniques in expert system development.

Ethnographic or participatory observation approaches have been applied to the design of artifacts, most famously by Bucciarelli (1988, 1994) and Henderson (1999), and within the German design research tradition by Badke-Schaub and Frankenberger (for example 1999). Some other studies rely on interviews (for instance Busby, 1998). However much of the research on teamwork in design is based on experiments (for example Tang, 1989, 1991; Kvan et al., 1997; Cross and Cross, 1997; Ullman et al., 1997). These experiments have varying relationships to real-life design. Minneman’s (1991) research combined an extensive observational study with experiments in which people from different fields of expertise were required to develop design by work in parallel in small groups in separate rooms, exchanging messages by sending emissaries. Valkenburg and Dorst (1998) studied team working in a student competition.

Software design has been studied extensively from a work studies perspective by people who are interested in building computer support systems (see for an overview and example Symon, 1998). While software development as a design activity has many characteristics in common with visuospatial design domains, such as engineering, architecture or knitwear design, it differs in some fundamental ways. Software design does not generate a physical product: the elements of a software product are purely functional. The representation designers use to express designs is the medium for generating code, so the distinction between designing and making is blurred. Although paper and pencil notations are used to express designs more abstractly, they share the structural characteristics of the code. Not only is visuospatial thinking not an essential part of software development, but software developers do not have the problem of needing to translate design ideas into a different form to express them, nor of needing to abstract away from concretely imagined design ideas. Similarly software design does not involve the issues of dealing with and communicating uncertainty and provisionality inherent in visuospatial design (Stacey and Eckert, 2000). Apart from the problems involved in understanding the users' requirements, software development does not normally involve bridging divisions between alternative ways of understanding designs or dealing with multiple readings of representations. Software design is well provided with conventions for expressing system designs, such as UML (Booch et al., 1998; see Fowler with Scott, 1999), and techniques for developing specifications and designs, which are understood and applied by a large fraction of the user community, as well as well-developed methodologies that string these together into procedures for organising projects and generating designs, such as SSADM (see for instance, Goodland with Slater, 1995), OMT (Rumbaugh et al., 1990) and the Unified Software Development Process (Jacobson et al., 1999). Engineering has some design methodologies, for example those of Pahl and Beitz (1996) and Ehrlenspiel (1995), but these mainly provide process guidance rather than a set of techniques for creating designs. In engineering drawing conventions play an extremely important role, but primarily for detail design and communication between designers and manufacturing engineers (see Henderson 1999, ch. 6). Knitwear design has no methodology, and as we discuss later no complete, consistent and manageable notation. Software can also be developed in an incremental and modular way, so that changes to the system can easily be integrated provided the interfaces between modules have been clearly defined; moreover building and testing prototypes is often an integral part of refining both requirements analyses and designs. Most other design domains require far more attention to integrating components and satisfying different sets of requirements and constraints simultaneously; and building prototypes to refine conceptual designs is usually infeasible.

Because of these differences we believe that software design is no more relevant to the problems discussed in this paper then any other work activity.

2.2. Methodology

The original objective of this research was to build an expert system supporting grading of garments through placing pattern elements automatically on a garment; therefore the author intended to apply classical artificial intelligence knowledge acquisition techniques (see Scott et al., 1991). However it was not possible to get a dedicated expert who was willing to put in the time required for a conventional knowledge elicitation process, therefore observations and interviews become the only feasible options for knowledge acquisition. In undertaking the research it became apparent that it was essential to understand how designers and technicians saw their own work and work context. As social and cognitive issues became increasingly important the author adopted a consciously ethnographic approach. Ethnographic research aims to understand how people in the observed group understand what they do. This involves maintaining a dual perspective: coming as far as possible to share the viewpoint of the insiders; while at the same time keeping an outsider's distance, questioning and analysing the insiders' assumptions in order to describe and explain what they take for granted (see Agar, 1980; Hammersley and Atkinson, 1995). An essential part of the author's research was developing a significant part of the knitwear designers' and technicians' expertise, perceptions and tacit skills.

Researchers concerned with applying the methodologies of the social sciences to system development disagree on what ethnography is (and hence on whether it includes what we have done) – some regard it as an approach to data collection (see for instance Dourish and Button, 1998); others reject this view, defining it as a style of reportage (see for instance, Anderson, 1994). For the pragmatic reason that we wish to relate our methodological approach to existing methodological viewpoints and techniques, we side with the data collection camp, but only our choice of phenomena to investigate and describe is in serious conflict with the aims and procedures of mainstream analytical ethnography (Lofland, 1995).

As the research reported in this paper sought to gather declarative and procedural knowledge of how to design, as well as cultural knowledge, the ethnographic approach to data gathering was combined with techniques drawn from artificial intelligence for analysing and describing problem solving knowledge. Both the need for a design support system to support a wide range of different designers with different styles and approaches, and the unavailability of data about the details of designers' cognitive processes, made cognitive modelling of design thinking an inappropriate approach for this project (see Smithers, 1996, for a relevant theoretical argument). Accordingly the project used hypothesis-driven ethnographic data collection to built knowledge level models of design. We later termed this approach *knowledge level ethnography* (Stacey and Eckert, 1999). The term *knowledge level* was introduced to artificial intelligence by Newell (1981), who describes a knowledge level model as a model of behaviour in terms of what an actor needs to *know* to be capable of doing what it needs to do. Knowledge level models analyse behaviour in terms of information, knowledge and competence to use it. This concept was extended and applied to knowledge acquisition for expert systems in the Common KADS methodology (for instance, Wielinga et al., 1992; Schreiber et al., 1993, 1999). Smithers (1996, 1998) applies the concept to design, arguing that the development of design support systems require theories of design behaviour formulated in terms of what designers *can* do and what designers *must* do.

In this study of the knitwear industry the ethnographic approach provided a rich insight into social behaviour, organisational processes and culture in the companies observed, while AI knowledge description techniques were applied to describe designing behaviour. A basic understanding of the product was used to derive an initial model of the design process, which was then iteratively refined. The information gathering through observations and interviews hinged round gathering information contradicting the current models as well as information widening the scope of the current models, while assessing the typicality of behaviour. The process modelling concentrated on how information is created, combined, manipulated, and used to create an *information artefact*: a design. This involved understanding *how* information is generated and communicated, as well as *what* information is created and communicated, hence it modelled information flow rather than other aspects of social processes. (We don't share the view expressed by Henderson (1999) that information flow doesn't exist (or isn't a useful way to analyse design activities); however it is essential to remain aware that information flow is an emergent consequence of contingent and flexible human behaviour that is directed to achieving a variety of goals, not always compatible with the collective goals of the organisation (see Anderson, 1994).)

2.3. Data collection

This research draws on visits to thirteen British, nine German and three Italian knitwear companies, made over a period of four years. The interactions ranged from one-hour interviews with designers and technicians, to observations of design activities lasting up to one week; and involved over 80 designers and technicians. As the typical design time per garment adds up to about one day, it was possible to observe complete design episodes within the time scales permitted by the fieldwork. While the selection of companies was unavoidably opportunistic, the research aimed to get a balanced view of the industry, by investigating companies in different sectors of the market, and whenever possible comparing direct competitors. The enables generalisation and comparisons across the industry in Britain and Germany, and some international comparisons. The selected companies ranged from fashion leaders, such as Missoni and Escada, to the suppliers of mail order companies and retail chains at the cheapest end of the market; however most were suppliers to middle of the range retail chains. In about half of the companies it was possible to interview and observe both designers and technicians.

The author has also acquired some of the knowledge, skills and perceptions of the designers and technicians herself, by taking pattern cutting and design classes for undergraduate knitwear designers at De Montfort University, Leicester, attending knitting machine programming courses for professional knitwear technicians at Universal GmbH, and by designing garments.

2.4. COMMUNICATION SCENARIOS

Design communication can take many forms, and one should be wary of generalising from conclusions reached by studying one type of situation. Interactions between designers differ on at least the following dimensions:

- Time: synchronous in real time – asynchronous
- Location: co-located – remote
- Problem solving: separate – joint
- Expertise: shared expertise – complementary expertise
- Hierarchy: equivalent importance is attached to tasks carried out by the participants – the task of one participant is subordinate to the task of the other

Two factors are particularly important in understanding how communication works: the extent to which the participants share context and share expertise, and the tightness of the feedback loop. In face to face communication, failures of comprehension can be identified and corrected very quickly, and speech, gesture and sketches are used to explain and disambiguate each other (see Tang, 1989; Minneman, 1991; Neilson and Lee, 1994). In less tightly coupled exchanges, the need to prevent rather then correct misunderstanding is correspondingly greater.

Knitwear design is a small-scale example of the sequential ‘over-the-wall’ design processes that were once almost universal and are still common in engineering. In such processes organisational loyalties are to departments rather than projects. Different aspects of the design are developed in sequence, and the design is passed from department to department. Some tasks are subordinate to more central design processes: they have to deliver what is specified. The view of which task is subordinate to which can vary significantly between participants in a design process; this is a potential source of problems. The flow of information between tasks is ideally linear. The results of the main task are only changed if the subordinate task fails. Knitwear design has a linear information flow between the designers and the technicians. The technical realisation of a design is seen is subordinate to the aesthetic design.

In contrast concurrent design, which is now widely accepted as the most suitable approach to engineering design, is carried out by a team where different members have different roles, but design decisions are based on negotiated tradeoffs between different team members responsible for different aspects of the design. The object of concurrent engineering is to consider all the important factors early in the design process, to eliminate the mistakes and suboptimal choices that arise from neglecting important considerations in conceptual design. An important aspect of concurrent engineering is group loyalty to projects before departments. Kvan et al. (1997) present a cyclic model of collaboration in design teams, which fits the framework of concurrent engineering: (1) Joint meta-designing to plan the design process (2) Joint negotiation (3) Parallel separate activities (4) Joint evaluation of the new state of the design. In the past decade many engineering design processes have been reorganised to follow a concurrent design model. The distinction between concurrent engineering models and linear handover tasks is often one of granularity. The activities that are restructured to facilitate multidisciplinary input are on a much larger scale than the activities involved in joint problem solving and decision making. Individual tasks can still be organised in an asynchronous and solitary fashion. However restructuring group loyalties, processes and communication channels in the large can facilitate more joint designing activity. We know of one knitwear company where a concurrent engineering design process has been introduced, very successfully, but this is not generally known about in the industry, still less copied.

A global economy with competition for manufacturing work from low labour cost countries has let to a geographical diversification of design processes, so that many concurrent engineering processes now involve remote and asynchronous interactions with relatively few meetings. The same geographical distribution of work has happened in the textile industry, in the relationships between design companies and their customers and between design companies and their manufacturers (as illustrated for example in Pycock and Bowers, 1996). The interaction between designers and their sampling technicians in the knitwear industry has remained a handover task in a sequential design process in all but one of the observed companies. As many manufacturers have moved their sampling capacity away from their design location to their suppliers, the process has become geographically distributed and remained sequential. The reliance on communication through documents without interactive discussion has increased. In these situations companies have a dual need for recording information effectively: first to generate clear specifications that do not need interactive explanation; and second to enable designers to reuse and adapt previous design work more efficiently in the future (see Scaife et al., 1994).

CSCW research has concentrated on supporting collaborative designing, that is concurrent and synchronous, but remote, joint activities. Most of this work has aimed to develop technology that enables designers to create designs in shared workspaces (notably Tang and Minneman, 1990, 1991; Ishii and Kobayashi, 1992; Scrivener et al., 1993; Moran et al., 1998), and use the same modes of expression (especially, speech, sketching and gestures) in the same ways as they do in face-to-face interaction (Bly and Minneman, 1990; Minneman and Bly, 1990; see Tang, 1989, 1991; Minneman, 1991). The aim of both this and related work on supporting asynchronous collaborative design (Minneman and Harrison, 1999) is to provide information in its customary form as and when required (Minneman and Harrison, 1999, Wagner et al., 1999). However Hollan and Stornetta (1992) point out that communication processes are influenced by the medium; they question the assumption that systems for supporting remote communication should try to provide the same set of resources as face-to-face communication.

3. The communication bottleneck in knitwear design

This section outlines how the interaction between knitwear designers and knitwear technicians fits into the whole of the design process.

The textile industry is one of the world's major industries and the knitwear industry is a substantial component of it. Knitwear is designed, manufactured and sold in a wide range of countries, and is the subject of a large amount of international trade. This international trade intensifies cost pressures on the design process: western knitwear companies face severe competition in East Asia, primarily Hongkong and China; and in the late 1990s British retailers have put their suppliers under intense pressure to manufacture abroad to reduce costs. At the same time, the knitwear design process is subject to severe time pressures. For all fashion-related products, the beginning of a new season in shops sets an unmoveable deadline for delivery of the final products. Due to the requirements of production and the retail chains' need to select co-ordinated collections, the design process for a season begins one to two years before garments reach the shops.

3.1. Intertwining of design and technical realisation

Design of all consumer products from cars to coffee cups involved a combination of product design, which is concerned with the visual and tactile appearance of the product, and which is driven by aesthetic considerations as well as functional requirements, and designing to meet technical considerations. However there are few products were the visual appearance and technical realisation are as closely linked as in knitwear design.

In knitwear the shapes of the garment pieces are designed at the same time as the fabric. The pieces are either knitted to shape ('fully fashioned knitwear'), or cut out from rectangular sheets of fabric ('cut-and-sew knitwear'); and then assembled into complete garments. Knitwear design thus combines the scope of fashion design, which is concerned with the shape of garments, and textile design, which creates fabric with woven or printed patterns.

Technical and aesthetic design can never be completely separated in knitwear, even though the work culture imposes a sharp separation through the division of labour between designers and knitwear technicians. A detailed analysis of the influence of the technical properties of knitwear on design is far beyond the scope of this paper. The complexity that knitted structures can have can be seen from textbooks on knitwear technology, for example Spencer (1989). In this paper we are only

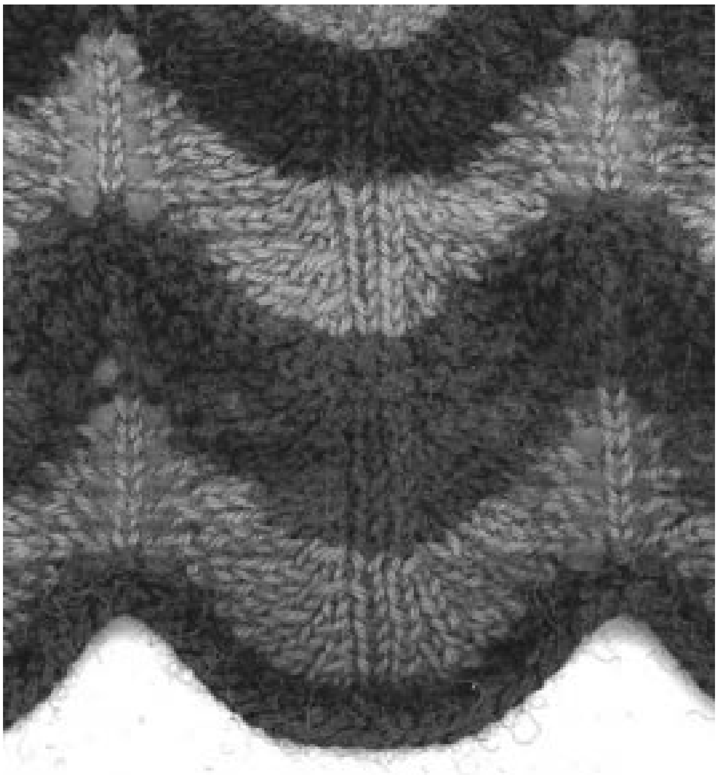


Figure 1. Lace wave pattern.

concerned with why the technical properties of knitted fabric make communicating conceptual designs of garments problematic.

The time it takes to knit a piece of fabric on an industrial knitting machine is a major contributor to the cost of the garment made from it, partly because of labour costs (of the machine operators) and partly because knitting machines are very expensive. Quite subtle changes to a knitted structure, or to the relative positions of design elements on a piece of fabric, can make dramatic differences to the knitting time.

The capabilities of each individual machine limit the space of possible designs; only people who work regularly with a machine know what it can and cannot do. What is possible also depends on the type of yarn; for instance mohair is relatively weak and will break if knitted into an elaborate cable, such as cable (ii) in Figure 2, while attempting the same cable in strong but unstretchable cotton would break the needles on the knitting machine.

The relationship between the stitches in a piece of knitted fabric and its size and shape depends primarily on the types and combinations of stitches. For simple stitch structures, such as knit and purl patterns[1] and straightforward multi-colour patterns (fair isle[2] and intarsia[3] patterns), the rows and columns of stitches

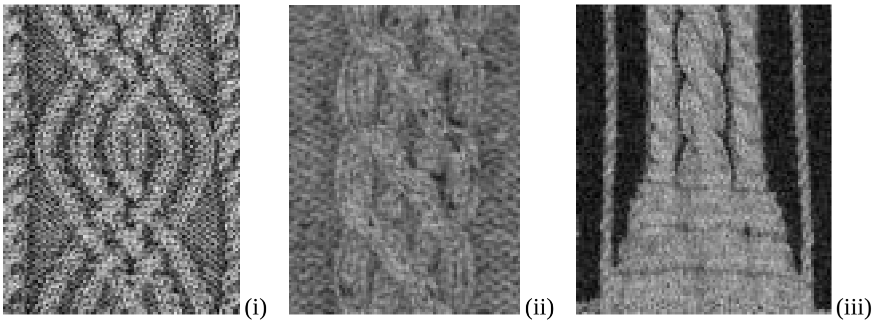


Figure 2. Technical realisation of cables technically routine: (i) standard arran Pattern; (ii) difficult technical problem: three groups of stitches crossed; (iii) technically impossible problem: cables with shadows.

are straight, so that relating conceptual design to implementation and predicting appearance from structure is relatively easy. Holes (in lace patterns) and other complex combinations of stitches cause the size and shape of stitches to vary, so that the rows and columns are not at all straight (see Figure 1). In some lace patterns the arrangement of the holes cause the rows to form undulating waves. In these cases appearance cannot easily be predicted from structure, nor can appropriate structures easily be derived from an intended appearance. It is also extremely difficult to predict by looking at a structure how hard it is to realise on a knitting machine. For example cable (i) in Figure 2 is a standard cable. A designer would be strongly discouraged from using cable (ii), because the yarn might break in crossing three strands. The shadow effect produced by a second colour in cable (iii) can only be achieved in hand knitting.

Fabric is often designed separately from the shape of the garment, and it is difficult to predict whether the pattern will fit onto a shape. Imagine a Fair Isle overall pattern with a small motif, say a swan, of 10 rows by 25 columns, which needs to be placed onto a simple set-in sleeve shape. Ideally the swans should not be cut. The width of the garment is however specified to be 105 stitches. What is the best placement? Can the garment width be changed?

The major sources of complexity and difficulty in knitwear design are predicting the shape and appearance of the fabric from a structural specification, and the reverse problem of understanding the structure from the visual appearance, as well as developing a structure to match a visual specification. They are thus the major sources of difficulties in design communication.

3.2. Computer support for knitwear design

Industrial knitting machines are among the world's most complex machine tools, with around 100 000 parts. An industrial knitting machine with CAD system can cost over £30 000. The major manufacturers of flatbed knitting machines are Shima Seiki in Japan, and Stoll and Universal in Germany.

Knitting machines are controlled by programs for knitting garments that are developed on highly sophisticated CAD systems produced by the knitting machine manufacturers; the capabilities of the CAD systems are a vital factor in selling the knitting machines themselves. These CAD systems provide visual programming environments in which designers or technicians can create schematic graphic depictions of garments using symbols or colour codes for different types of stitches. They use embedded expert systems to support automatic programming of industrial knitting machines by compiling their symbolic notations into machine instructions.

Despite marketing claims to the contrary, these CAD systems are primarily tools built by knitting machine manufacturers for knitting machine technicians to program knitting machines, rather than as design tools for designers. Using these systems requires considerable understanding of the technicalities of knitwear design. Working out how a knitted structure is created is a mental activity quite similar to programming in assembler. The first computerised knitting machines were programmed using assembler-like languages which required a thorough understanding of how stitches are formed. Modern CAD systems have graphical programming environments which compile into the earlier assembler-like programs. Knitwear technicians can modify programs on both levels, and can in principle create a wider variety of stitch structures working directly in the low level languages. However technicians now never develop the skills to do this, so in practice the range of designs they can create is restricted.

Modern CAD systems can generate simulations of knitted structures, but only when the program for knitting a garment or a piece of fabric is fully complete. Either the designers create the designs themselves or they have to communicate them to the technicians. Simulations provide faster feedback on the results of knitting machine programming than fabric swatches, but the initial communication problem remains. A designer described this process of simulation as “The Shima [CAD] system can knit the fabric onto paper”. Designers complain that computer simulation does not give the feel of the fabric, and they can visualise the fabric themselves, but praise it for communication and marketing purposes. In reality the CAD systems have become the medium of choice for designers to design colour patterns, where each colour in the CAD system stands for one colour on the garment, but designers very seldom use them for complex stitch structures or for defining shapes.

3.3. THE KNITWEAR DESIGN PROCESS

In current industrial practice knitwear design is a nearly a linear process (see Figure 3). Designers and technicians work mainly independently. There is no organisational provision for joint problem solving, even though some particular individuals work collaboratively. The author has encountered one exception mentioned above, where the design process has been re-engineered along concurrent engineering principles similar to those recommended by Eckert and Demaid (1997). This company's designers regard this change as a great improvement.

3.3.1. *The stakeholders and their social and educational background*

Three main participants share the knitwear design process: knitwear designers, knitting machine technicians and pattern cutters, see section 1.1. The have different tasks and outlook on life. They are very different people in most respects, who do not naturally interact outside their jobs. The designers who are responsible for the visual and tactile appearance and timeliness of the design are young university or polytechnic educated women with artistic aspirations in a job that is not highly paid. The knitwear technicians' task is to realise these design ideas on power knitting machines. Almost all knitwear technicians are men. They see themselves as working class, and have little interest in fashion or other artistic aspirations. They are typically recruited from knitting machine operators, and have no education beyond secondary school, even though the job is as challenging as other types of computer programming. Pattern cutters are typically women recruited from shop floor sewing, cutting or linking operatives, who have risen as far as is normally possible in their careers and feel they have fulfilled their career ambitions. Both technicians and pattern cutters are hard to replace, and usually stay for a long time in one company. They are better paid than designers, which contributes to their generally much higher job satisfaction. Designers and technicians rarely socialise. There are exceptions to this pattern, including companies where designers and technicians socialise. Eckert and Stacey (1994) present a more detailed analysis of the gender and other differences between designers and technicians, and their differences in aptitude for technical work and access to computer technology. When we wrote that paper, we had never heard of a female knitwear technician; we have since encountered one, who said she did not suffer from sex discrimination.

3.3.2. *The design process*

As Figure 3 illustrates, the designers begin working on a new season with what they call 'research': investigating the coming fashion trends and selecting the yarns used for all the garments in a season. They then plan the types of garments they intend to create for the season. At this point many fundamental design decision are made before anybody thinks that design has happened. The results of the research process are represented in so-called "mood boards" or "theme boards", which present a collection of images and sketches of possible garments that define parts of the range for a new season. Most designers begin what they think of as designing by designing fabric swatches, though many will already visualise concrete ideas for garments during research. A swatch is a sample piece of fabric that is a prototype of a motif or other stitch structure that is independent of garment shape. Shapes are often developed in parallel independently of the pattern placed on them. Many garments are later designed by selecting a shape and using stitch

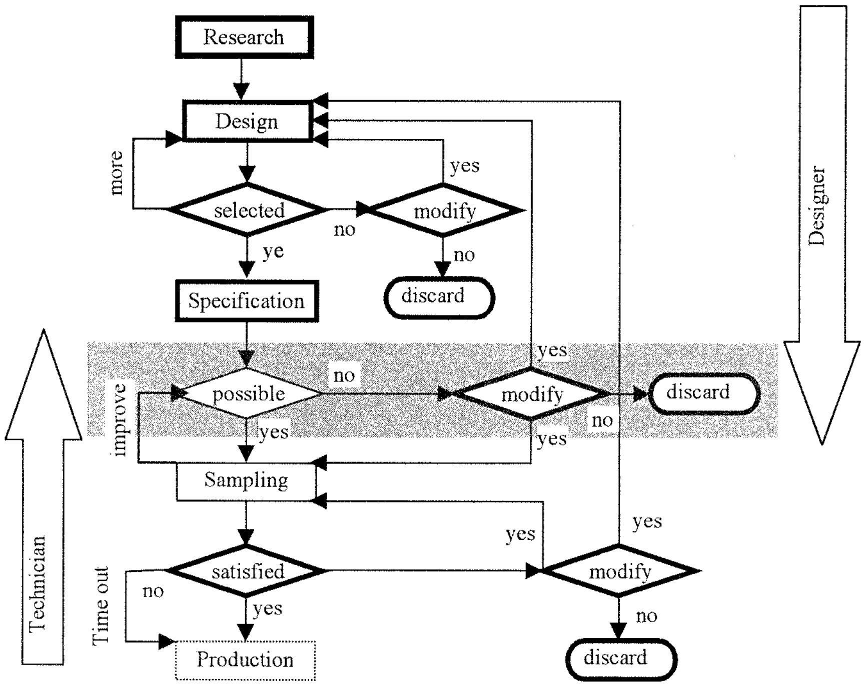


Figure 3. Basic stages of the knitwear design process.

structures developed in these earlier sample swatches, and supplementing them with additional swatches designed for the garment. Other garments are designed in a holistic way designing both shape and fabric at the same time. Swatches, shapes and garments are usually selected by the entire design team. Designers create specifications (see section 3.4.1) for each of the designs they want to see turned into sample garments, in the form of a *technical sketch* describing its shape and appearance, which is the conceptual design of a garment (Figure 4 shows an example).

In Figure 3 boxes with thick lines show tasks done by designers; boxes with thin lines show tasks done by technicians. The decisions in the shaded area are made either by the designers or the technicians, or the two together. The shaded area shows the area of collaboration between designers and technicians.

The technicians then take over the development. The knitwear technicians program the knitting machine and knit the prototype garment pieces. This involves doing a lot of detail design in the course of interpreting the technical sketch in structural terms; the technicians often deviate significantly from the designers' intentions. The pattern cutters create cutting patterns for the shape, and make up the complete sample garments (prototypes). The knitwear technicians have often already been in involved in creating fabric samples to select new yarns and knitting idea swatches for fabrics.

The technicians create complete swatches or garments that get as close as possible to what the technicians think the designers wanted, and present them to the designers. If an idea cannot be realised, the technicians often have to "prove" this, by showing unsuccessful attempts to produce what is asked for. Designers are usually only able to comment on the modifications made by the technicians when they have produced swatches or sample garments. Technicians generally try to develop designs as far as they can without "bothering" the designers. If they have problems with specified designs, they often only approach a designer if they feel they can offer the designer a suggestion for a solution, or can discuss alternatives fully. For example a designer specified the left-hand cable in Figure 8, but the yarn broke in several attempts to knit a swatch. The author observed the technician investing about two hours in producing a swatch of the right-hand cable, before going to look for the designer with all his swatches. As the designer was away, the technician approached her boss in the corridor, who had previously not been involved in the particular design, and explained what had happened and asked her whether he could use the successful, but very different cable. The author observed several similar episodes in other companies. Besides designs that are technically infeasible, designs that are too expensive to knit at a given price point need to be modified to make them cheaper. These simplifications are also done by technicians and can require several rounds of modifications.

Designers can accept the sampled version or comment on what they would like different. Designs are modified until they are good enough to be presented to a buyer or the company runs out of time. There is often insufficient time to refine a design until it really corresponds to the designers' original intentions, or to allow the designer to improve on their idea. Some very simple garments can be sold using the first sample. Other designs, like complex cable patterns or patterns of multi-coloured stripes which need to be balanced, often require many sample rounds. A typical garment would go through about three or four sample rounds. The finished sample garments are selected internally and often also by external buyers. Only once a decision has been made to produce a design will it be graded (reproduced in different sizes). At this point designs are sometimes adapted to make them cheaper to produce or reimplemented for another knitting machine.

3.3.3. *The efficiency of the process*

Practitioners do not normally comment on the efficiency of the process as such, unless they speak about improvements that they have achieved. However the design process appears to be inefficient by the following indicators:

- *Ratio of Design Ideas to Samples*: Ideas are cheap. Each designer produces hundreds or even thousands of design ideas in each season, which they visualise mentally as garments. In all of the three competing supplier companies to a large British retail chain that were observed by the author, only about 50 to 100 designs are specified as technical sketches and about a third of these are produced as sample garments. Of the 20 to 40 sample garments, the retail chain buys fewer than 10.

- *Technical feasibility of designs*: Almost all technicians complain about the designers' lack of technical knowledge. Only about 30% of all the designs specified as technical sketches can be turned into sample garments that can be manufactured at the specified price point. The technicians attribute this to the designers not understanding what can and cannot be done, and for how much knitting time.
- *Time pressure during sampling*: All participants in the knitwear design process complain about having to work overtime before presentation deadlines. They often have to settle for sub-optimal design or technical realisation because iterative improvement is infeasible.

3.4. INTERACTION BETWEEN DESIGNERS AND TECHNICIANS

The lack of interaction between designers and technicians is a major contributory factor to the inefficiency of the process, because designers specify designs which can not be knitted and designs are evolved through numerous sample rounds to a compromise between what the designer wants and what is not only technically feasible but affordable.

3.4.1. *Technical sketches*

The handover of designs is done through so-called *technical sketches*. A technical sketch is the formal specification of a design through which it enters a company's records and achieves official recognition as entity in the design process. It is written on a form occupying one side of a sheet of A4 paper, and comprises a brief written description of the type of garment (seldom more than a couple of phrases), a set of values for the dimensions of the garment, called measurements, and a freehand sketch (usually only one), usually of the front of the garment as though laid flat.

Technical sketches are classic instances of what Star (1989) terms *boundary objects*. These are documents and other objects that facilitate communication across the boundaries between interests and disciplines, because they can be read differently by people with different concerns and expertise, in terms of the different sets of entities, properties, relationships, and principles that make up what Bucciarelli (1988, 1994) terms different *object worlds*.

The most reliable part of the specification is the brief verbal description ("Ladies Viscose Chenille A line Tunic" in the technical sketch shown in Figure 4). Designers usually guess the measurements based on previous garments. These are often an *inaccurate* description of the designers' idea. The measurements are often *incomplete*, because the designers do not know a measurement or leave it out deliberately as an attempt (not always successful) to initiate a dialogue with the technicians and pattern cutters. The measurements are also mutually dependent, and can therefore be *inconsistent*. For example the style, the retailer-standard

REQUESTED BY: Helen | DATE ISSUED: 13/4/94. | REQ. COMPLETE: | F/F GAUGE: | N/F GAUGE: 7gg 2ends | PURPOSE: TWO | SAMPLE No. 784 | AMOUNT: 9/10

FULL DESCRIPTION: Ladies Viscose Chenille A line Tunic

NECK STYLE & METHOD OF ATTACHMENT: [illegible] blanket edged neck

SLEEVE SHAPE: Shaped

RIBS | BASED ON 7768

YARNS: 5.5 Viscose chenille [illegible] Baldini

	GAUGE	STITCH LENGTH	ROUGH MAKE UP INST./COMMENTS
BODY GAUGE			
RIB GAUGE			

FINISHING INST. Steam [illegible]

WEIGHTS

DATE TO DYE | LOT No.

B/CODE	SIZE 12	REQ.	ACTUAL	B/CODE	SIZE	REQ.	ACTUAL
	FRONT LENGTH	76			BACK NECK OVERALL		
	ACROSS FRONT	35			SHOULDER SEAM	10	
	CHEST WIDTH	47			WELT DEPTH		
	WELT WIDTH	64			CUFF/ARMBAND DEPTH		
	UNDERARM	46			NECK RIB DEPTH		
	ARMHOLE	20			STRAPPING WIDTH		
	A/H FASH./F. RAG				STOLLING WIDTH		
	HOR. SADDLE/B. RAG.				POCKET DEPTH		
	A/H LINK/VERT. SADDLE				POCKET WIDTH		
	SLEEVE WIDEST	17			POCKET TOP		
	ELBOW WIDTH	13			COLLAR DEPTH		
	CUFF WIDTH	14			COLLAR WIDTH		
	NECK DROP	8			BUTTONS No./TYPE		
	BACK NECK SEAM-SEAM	16			FINISHED WEIGHT		

SKETCH:

Figure 4. Industrial example of a technical sketch.

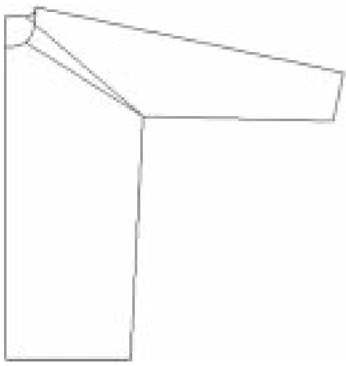


Figure 5. Raglan sleeve.

distance from neck to wrist, the shoulder width and the sleeve width (given by the designer) together determine the shape of the sleeve, but often other measurements are given (see Eckert and Bez, 2000, for a mathematical explanation). It is relatively unusual for designers to put in the necessary effort to ensure that their sets of measurements are accurate and consistent. Pycock and Bowers (1996) draw attention to over-specification in garment shape specification, which is likely to involve inconsistent specification of mutually dependent values, as a major source of consumer dissatisfaction with garments, because suppliers produce sub-optimal shapes that comply with as many measurements as possible rather then focusing on the desired effect.

The designers often complain that the technicians ignore their sketches. Technicians often do not take information from sketches, even when they cannot get the information from any other part of the specification. For example the exact shape of a raglan sleeve can be seen most easily from a sketch, as specifying in any other way requires a description of the intersection between a line and a curve (see Figure 5). Designers sometimes supplement technical sketches with garments, swatches or photographs of garments. These supplements are likely to get lost during photocopying.

3.4.2. *Ambiguity of technical sketches*

A typical technical sketch is highly ambiguous. Not only is the freehand sketch itself ambiguous, but it also often contradicts what is specified through the measurements and the verbal description. For example in Figure 4, the sketch shows one straight sleeve and one that is narrower at the elbow. The elbow measurement is also less than the cuff measurement. During the observation the pattern cutter constructed a straight sleeve.

Knitwear designers have no way to disambiguate their technical sketches by indicating the intentions behind the elements of their specification in terms of their importance or degree of commitment or intended precision. This is the key to resolving many problems in asynchronous communication. We discuss this issue elsewhere in relation to a typology of forms of imprecision in design specifications (Stacey and Eckert, 2000). By contrast section 5 proposes a different approach to design support: trying to eliminate ambiguity in design descriptions by using a design support system that generates consistent, complete and unambiguous garment shape specifications.

The inherent ambiguity of sketches is well known to researchers studying collaborative design, although some analyses of the role of ambiguity in communication (notably Minneman, 1991) conflate ambiguity with indication of imprecision and provisionality (see Stacey and Eckert, 2000). Studies of designers using sketches to develop designs jointly in meetings by Tang (1989, 1991; Tang and Leifer, 1988), Bly (1988), Minneman (1991) and Neilson and Lee (1994) have shown that designers use speech, sketches and gestures in combination, using each mode to explain and disambiguate the others. In individual design, sketches often serve as external memory. Sketching also facilitates idea development, because designers can reinterpret their externalisations to mean or suggest something they did not intend when drawing them (for instance Schön, 1983; Goldschmidt, 1991, 1994; Goel, 1995; see Purcell and Gero, 1998, for an excellent survey of research on sketching in design). McFadzean et al. (1999) point out that this reinterpretation is driven by dissatisfaction with the current design. For this, vagueness and ambiguity can be an advantage. However, in asynchronous, sequential design – like knitwear design – ambiguity can be a major obstacle to successful communication (Stacey et al., 1999; Stacey and Eckert, 2000).

3.4.3. *Interpretation of specifications rather than negotiation*

The negotiation of meaning is a very important part of social activity, which is widely discussed by social scientists, including researchers on CSCW for design (notably Minneman, 1991). In this research tradition, negotiation constitutes a paradigm for understanding communication. In a negotiation process a proposal is followed by a reaction to it and possibly by a counter-proposal, which in turn might be followed by another proposal. Negotiation of understanding happens on two different levels:

- Negotiation for clarification, where different parties negotiate to reach an understanding of each other’s position.
- Negotiation for joint problem solving, where different parties negotiate a joint solution, with the aim of satisfying as many as possible of their own concerns and objectives, which might involve a change of position or a compromise by either party, as well as clarification.

The role of ambiguity (see Stacey and Eckert, 2000) is very different on these two levels of negotiations. In negotiations for clarification it is important to understand the scope of vagueness and imprecision in an expression to understand which aspects of a design each party is committed to. In negotiation for joint problem solving ambiguity can play an important role in facilitating exploring and sparking of creativity through reinterpretation, in the same way as it does in some individual design activities (see above). Only when negotiation for joint problem solving occurs “everything is up for negotiation” as Minneman (1991) claims. Negotiation for clarification is often a necessary step towards negotiation for joint problem solving. In a sequential problem solving situation, where a design is handed over to someone who is expected to develop it further (such as knitwear design), negotiation for clarity only occurs when it is perceived to be necessary, that is, when ambiguity is recognised and not one interpretation (ones own) taken for granted.

In many knitwear companies technical sketches are produced in batches and handed over to technicians without further explanation. Designers often rely on earlier unrecorded discussions to give the technician a context for each design. It is an important part of the culture that technicians try to work as far as possible without “bothering” the designers. As long as technicians think they know what a designer wants they pursue it as far as possible. There are very few clarification conversations or discussions about design alternatives before the technicians have tried to generate a swatch. Technicians do not see it as their role to “tell designers what to do”, as little as they think that the designers should tell them how to program machines. The technicians and designers both see a technician as the person who realises the designers’ intentions. The shaded area in Figure 3 could give the misleading impression that there is a negotiation over each specification before the technicians begin to program the knitting machine. The evaluation – modification cycle in developing samples from a specification is typically done by the technicians alone; and the designers are only involved when the technician fails to find a solution to the problem of meeting the specification. Negotiation only begins when the design has failed, either because it was technically infeasible or the result that the technicians have produced does not correspond to what the designer had in mind. The design is then discarded or the designers and technicians discuss alternatives. Again this is often done in such a way that the designers tell the technicians what they want to have done. However we have also observed isolated occasions when the technicians proposed solutions.

Designers sometimes leave measurements out deliberately to force technicians to come and talk to them. This is not guaranteed to succeed. This is the only deliberate use of vagueness in specifications that we have observed. Designers would want to generate unambiguous specifications, but can’t do so given the time constraints. Increasingly knitwear designers for preference use CAD systems to specify designs that are within their competence (primarily colour patterns), even if the CAD system they use is not compatible with the company’s knitting machines, primarily so they can produce unambiguous specifications. Knitwear designers often have problems getting CAD training, because it is expensive and the managers of knitwear companies sometimes perceive technical knowledge as harmful (Eckert and Stacey, 1994; Eckert et al., 1999b).

Contradictions between measurements, verbal description and sketch are resolved by the design technicians through an implicit prioritisation of the components of the specification. They accept the verbal description, which is the most abstract, as correct and prioritise the measurements according to the extent to which they are independent of human anatomy. They accept the length and the width of the garment, but almost as a rule ignore designers' specifications of neck width. Technicians claim not to use the sketches, and designers complain about technicians ignoring sketches. However, technicians take the proportion and balance of pattern elements on a garment from the sketches, as these aspects of the design are not specified in any other way.

The technicians' interpretation is influenced by the designs that they have produced in the past, which for them are the standard exemplars of categories. For the designers, the standard meanings of their category terms come from the shapes and features used in an emerging fashion, in fashion forecasting materials, catwalk garments, and other companies' garments. These define the space of acceptable designs for their target market in the season they are designing for. For example designers complain that no matter what raglan sleeve they specify, the same sleeve comes back on a sample. With the discrepancy in the seasons designers and technicians are working on, the frames of reference of designers and technicians can be three or four seasons apart. The shapes that the designers specify are the final shapes of the garments, whereas the cutting patterns that the pattern cutters construct are the shapes the fabric pieces need to have to achieve these shapes. From these pieces complete samples are produced. Designers cannot tell whether their garment designs fail to come out as they had envisioned them because of inadequacies in their specifications, or because something else has gone wrong. Therefore they have little chance to learn how to improve the quality of the their specifications. As designers and technicians get to know each other over years they will of course get better at understanding each other. However the lack of clear and specific feedback slows the learning process. Busby (1998) describes similar problems in engineering.

3.4.4. *Mutual distrust as an effect of communication failure*

Designers and technicians are often dissatisfied with each other. Designers are frustrated that their specifications are ignored, while technicians feel that they cannot get designers to give them the information that they need. Technicians do not trust the designers' specifications, because they know from experience that the designers often define impossible designs. Several technicians have quoted 30% as the ratio of designs that are technically possible in the chosen yarn on an available machine at the intended price point. With some justification technicians attribute the fact that designers specify impossible designs to their lack of technical aptitude and knowledge.

Many designers complain that if they specify a new structure, the technicians' initial reaction is “that can not be done”. Later the technician comes back with an entirely satisfactory solution (which may be a significant modification of the designers' original request). Some designers assert that technicians will say that a design is impossible to program because they are unwilling to put in the effort to develop something difficult. Technicians complain that they often have to waste time to prove to a designer that a certain design can not be produced, when this is entirely obvious to them from the beginning.

4. Reasons for communication breakdown

Differences in responsibilities, interests, expertise, culture and language can be overcome if the participants in a design process have a notation in which to say exactly what they mean, if the notation is complete, precise, and cost-effective to use. Conceptual designs are by nature incomplete, imprecise and provisional. Communicating them inevitably involves a certain degree of uncertainty; but this does not mean that the representations used to convey imprecise and provisional ideas are necessarily vague or ambiguous (Stacey and Eckert, 2000). But saying exactly what one means requires that the recipients of ones communications can understand them appropriately; reading pictures and diagrams is a learned skill. As Henderson (1999) illustrates, the use of CAD systems can severely disrupt design communication: completeness and exactitude isn't enough – messages and communicative objects must match the interpretive skills of the recipients, and convey the information they actually need. But given sufficient shared expertise, and representations that tightly constrain their interpretations, it is possible to communicate effectively between object worlds.

Knitwear designers and technicians are not so fortunate. They do not have any exact model with which to communicate a knitted structure short of an actual knitted structure. All the available notations are either incomplete, clumsy or very complex (see section 4.2.1). Information about complex knitted structures is inherently difficult to communicate – harder than in other branches of textile design – because the relationship between the combination of stitches in a knitted structure and its size, shape and appearance is subtle, and dependent of the technical properties of the yarn. However difficulties in communication between designers and technicians arise from a number of different factors. Designing appropriate computer support tools and strategies for collaborative design requires an understanding of all aspects of the problem.

4.1. Effort and commitment in communicating conceptual designs

In most design domains an accurate description requires a large investment of effort in working out details, and so a high degree of commitment to a design (Cross, 1989). It is a well-known problem in engineering that designers frequently pick the first plausible solution and work it out in detail, without ever searching for alternatives. This can be attributed partly to the difficulty of specifying designs at the earliest stages of development exactly enough for them to be evaluated. Moreover needing to commit to details in order to create a representation of a design forces designers to make decisions prematurely that they would prefer to defer. In knitwear design the problem is somewhat different. Designers typically produce technical sketches for a very large numbers of designs, without putting a great deal of effort into any one. Designers together with managers and sometimes buyers narrow these down to a small subset for further development, before they seek any kind of technical input from the technicians. The limited investment of effort in describing each design restricts the ability of the technicians to interpret the designers' intentions, because designers don't put enough effort into precision and consistency to eliminate the ambiguity stemming from sloppy descriptions.

4.1.1. *Greater accuracy entails greater commitment*

Many designers explore options at the conceptual design stage by generating and evaluating mental images, often without any sketching; and sketches created as part of idea generation may be unintelligible to anyone else. Aesthetic aspects of visual appearance, such as exact shapes of curves, and balance and proportions of colours and design elements, are difficult or impossible to convey by words.

A detailed and accurate specification of a design requires committing a significant chunk of the designer's time to a specific design. A detailed sketch that contains clear information for technical implementation needs to be drawn to scale with all parts in proportion, and details need to be worked out. For example a detailed sketch of garment with an animal border would require working out how many animals knitted in the chosen yarn fit on the desired shape, which can be rarely be decided before the fabric has been sampled. Accurate sketches are also against the ethos of fashion drawings, which use distortion as a means to express style. As they put effort into a design solution, they also become more emotionally attached to that solution. As we argue in section 4.2, knitwear does not have an intuitive and easy notation for specifying designs accurately. So by working out a design sufficiently to specify it accurately, with a sketch or in a symbolic notation, the designers have to devote quite a long time to it, and make a mapping between their mental representation and the representation they are using on screen or on paper. The degree of precision and reliability is proportional to effort. By investing this time into a specific design, designers have to change focus away from conceptual design: in the case of knitwear designers, thinking about their requirements, their sources of inspiration, and the demands of fashion.

4.1.2. *Conflict in the intended degree of detail in a sketch*

An important problem faced by knitwear technicians is that it is often hard to interpret from a sketch which aspects of a design are specified accurately, and what is deliberately left vague.

Knitwear designers often use sketches to specify aspects of a design that would otherwise be difficult to describe, for example the angle of a raglan sleeve (see section 3.4.1). The rest of the sketch of the garment is often just a placeholder providing the context for the particular aspects that are unusual or important.

However, the technicians do not know which parts of the sketches contain the important information, and so should be taken seriously and studied carefully. Designers frequently complain that technicians ignore their sketches, and produce designs just like those they have always produced, applying standard procedures according to the category descriptions. This can be attributed to the failure of the technicians to recognise the intended degree of detail and precision with which design features are depicted in sketches. This is largely due to the conflict in degree of accuracy to be found both between sketches and between parts of the same sketch. The problem might be alleviated by explicit indications of how seriously to take different parts of the sketches, but we have never observed anyone trying that approach.

4.2. DESCRIPTIONS OF KNITTED STRUCTURES

None of the ways of representing knitwear used in the industry are at the same time unambiguous, complete, and easy to read and write. Each possible notation is a compromise and leaves scope for interpretation. In industrial practice designers communicate their ideas to technicians in a number of ways.

4.2.1. *Describing knitwear*

Currently no notation exists for knitwear that is complete, unambiguous and easy to use. Knitwear is often described by reference to other knitted garments or pictures of garments. Communication by reference is used amongst designers who share the some cultural references as well as strong visual memories, and therefore can reconstruct the visuospatial properties of the design from a verbal reference to a commonly known design and an explanation of the changes to it. But such descriptions are hard to understand for technicians who are not involved in fashion research, and therefore don't share the same reference points. Eckert and Stacey (2000) argue that references to other objects form a language for design. Garments, swatches or photographs are often attached to design specifications. Sometimes technicians physically take the fabric apart to reverse engineer it; otherwise they have to reconstruct it by inferring structure from appearance, which can be difficult. Designers often use drawings or sketches, which as we note above are inherently ambiguous. They also use made-up notations, such as crosses for colour patterns, which need to be interpreted according to context.

Designers often describe swatches or changes to designs during later sampling rounds verbally. All observed companies did produce technical sketches for the formal handover, but one company we heard of did also do this verbally. Hand knitting notations, such as the schematic diagrams and instructions found in knitting magazines for amateurs, are not used by professional designers, because they express designs as a sequence of hand knitting actions, which are totally different to machine knitting operations.

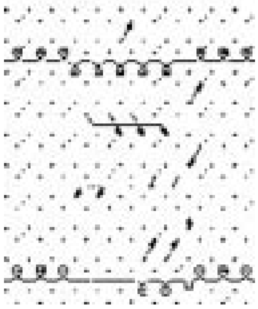


Figure 6. Loop description of part of a cable pattern (Universal, 1996).

The only complete and accurate notation is a so-called loop description, which describes the structure in terms of the how the stitches look on a knitting machine looking at the needle beds from the top, thus showing the path of the yarn. However this requires technical knowledge to use, is extremely lengthy and does not show the appearance of the fabric. Designers cannot generate this notation and would find it extremely difficult to understand.

Most CAD systems (see section 3.2) use different colours for different types of stitches. However there are more different types of stitches then there are easily differentiable colours. Using the colour coding requires familiarity with the code and some understanding of the technicalities of creating knitted structures. Colour coding camouflages the original colours of multicoloured designs; and makes certain parts of the design more salient than others. With suitable familiarity with the codes, colour coding is the fastest way to specify stitch structures, and is the most accurate notation that gives an impression of the visual appearance of the fabric. As the colour code expresses the structural form of the design, it is necessary to work out how something can be knitted, before it can be expressed in the colour code. Designers typically don't have this expertise. The arbitrary choice of colour codes by the knitting machine manufacturers makes some features more salient than other equally important features; for example the white stitches in Figure 8 stand for cross over to the right and the blue stitches stand for cross over to the left. The colour codes lose the visual coherence of pattern elements.

Knitwear designers and knitwear technicians do have not a notation in common that both understand and can use fluently.

4.2.2. *The only model of a knitted structure is a knitted structure*

Model house designs are built from cardboard, model car designs are made in reusable clay, but is not possible to create a mock up of a knitted garment in another material to communicate the design without creating knitted fabric. Only a swatch can communicate accurately both an intended visual appearance and the structural properties of a fabric. A swatch can also be taken apart to give information about the creation process. As the simulation programs require complete

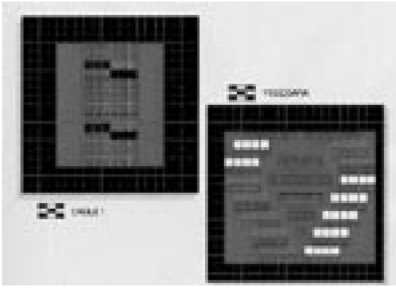


Figure 7. Colour coded structure (cable pattern on the right) (Shima Seiki, 1996).

knitting machine instructions (see section 3.2), they do not solve the problem of communicating design ideas before they have been developed into complete designs.

4.3. Cognitive factors

The specifications discussed in this paper are the manifestations of the designers' mental images of their design ideas. Mental images are extremely difficult to research or observe; however designers' and technicians' powers of visualisation are reflected in their attitudes to commercial simulation software (see section 3.2). Both designers and technicians can mentally visualise knitted structures and manipulate them. Experienced designers have commented to the author that visualisation ability is the most important talent a designer requires. Designers can visualise garments on different people and imagine the drape of garments. Technicians can visualise complex knitting operations, such as the creation of cable patterns. However, the way in which both groups visualise designs is different: designers think in terms of visual and sometimes tactile emergent properties whereas technicians think in terms of the structural characteristics of fabrics.

4.3.1. *The difficulty of describing mental images*

The problem of communicating a mental image of a design to someone else is comparable to trying to explain a picture over the telephone. Our language can express symbols and categories, but is inadequate for the task of describing subtleties of shape and texture, and can be ambiguous. Even when the explanation is long and detailed, a listener who does not see a picture still only has a partial understanding of what it might look like. It is possible to recognise a picture from a description, but unlikely that a complex picture can be recreated from a verbal account no matter how detailed. But this is exactly what needs to happen in the design process: the mental model that the designer has of a garment needs to be translated into a garment by someone else. As a designer has phrased it: "the technicians need to knit what the designers think".

4.3.2. *Different mental representations of designs*

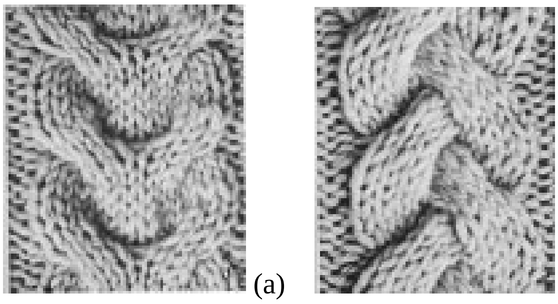
It is always difficult to access mental models. The following remarks rely on comments made by designers about their they visualise their designs, and answers to debriefing questions given by designers who participated in an experiment on adaptation of sources of inspiration (Eckert and Stacey, 1999). Inferences can also be drawn from the way designers and technicians talk about the fabrics and designs.

The designers think primarily in terms of the visual and tactile appearance of the fabric or the garment. They design to achieve an effect. They talk to each other about the effects they are trying to create, for example a crochet effect, or an ocean wave look. These effects are emergent perceptual properties of the fabric. The designers have to force themselves to think about the structural properties required to achieve the desired effect. They see a design primarily as an overall concept within the context of fashion, which fulfils a function and expresses a pre-decided mood. Designers think in terms of complete garments or swatches from the time they start looking at yarns and forecasting material. For example one designer commented that as she looks at yarns in a yarn show she pictures them as garments that she would make from them and experiences the exposure to materials as the most creative time in the entire design season. They have the subjective sensation of seeing complete designs as pictures of garments. One should be wary of making assumptions about how much detail and how many different aspects of a design a subjectively complete image includes. Some designers see garments in colours, often from their current standard colour palette; others are not initially aware of colours or see colour contrasts (one designer commented that she sees a black and white image), and then colour in their images. Designers have no names for many concepts they use to conceive designs (such as complex shapes), and describe them by describing changes to other objects (Eckert and Stacey, 2000).

Technicians think about and describe knitwear in terms of the structure of the pattern, i.e. as combinations of stitch types, or as combinations of machine operations. For example when the technician talked about the “crochet” pattern, mentioned above, he described it as a racking pattern, referring to the technique he used – rather cleverly – to create it. When technicians are suggesting alterations to a fabric they sometimes try to maintain the structural characteristics of the fabric and not the visual appearance. For example the author has observed a technician changing a cable pattern from Figure 8(a) to Figure 8(b), because in the specified design the yarn broke as a result of crossing two adjacent cables in opposite directions. The visual effect of these cables is very different, even though they are structurally very similar. For the technicians the emergent properties are the goal of the reasoning process, not the beginning.

4.3.3. *No overlapping expertise*

Knitwear designers don’t receive much technical training in the construction of knitted structures or programming CAD systems during knitwear design courses



(a) (b)

Figure 8. Different appearance of cable patterns with similar structural properties (taken from Burda, 1975).

at college. Universities cannot afford the hardware to give each student adequate access to CAD systems or power knitting machines, and the manufacturers do not offer educational licences for their CAD software. Many knitwear designers in industry are trained in fashion or textile design and are not taught knitwear any in depth. Of all the designers included in this study only two were able to program power machines, but never did any programming. Most British designers used the CAD systems sometimes to enter colour designs. When the issue was raised, all British designers commented that they regret their lack of technical knowledge and would like to have to time to learn more about knitting machine programming, while their German counterparts did not considers programming at all relevant. Designers acquire technical knowledge piecemeal through practical experience of seeing how their designs are realised, and therefore explain technical issues by reference to the designs that had incorporated certain features. This knowledge is not systematically passed on to younger colleagues. Many technicians have commented to the author that they would like their designers to have greater technical knowledge, so that they know what is feasible and cheap, and what is not; they think that better technical training for designers would be the single thing that would improve the design process the most.

Technicians do most of the detailed design of knitted garments when they are translating the designers' rough specifications into fabric or shapes. Technicians don't have design training. They rarely have an interest in fashion and don't follow design developments. Only one company the author has visited takes technicians along to fashion and yarn shows; it proved beneficial to them. With practice technicians learn design principles, such as balance of pattern elements or colours. They adapt to company house styles and learn to fit into the style of individual designers.

4.4. Organisational factors

The organisation of the knitwear design process in industry creates communication difficulties, some of which could be alleviated by better management (see Eckert and Demaid, 1997).

4.4.1. *Getting hold of each other*

In many companies the offices of the designers and technicians are quite a long way apart. The technicians' offices are close to the sample machines, which are often kept close to the production to enable the technicians to attend to production machines. Designers often are located elsewhere in a quiet corner of the site, as knitting machines are very noisy. Seeing each other takes effort. In several companies designers and technicians noticed it as a relief when moved closer together. Designers and technicians often have to wait a long time until they can catch up with each other when they need critical input. For example a technician needs to show an unsuccessful swatch to a designer before trying a different solution. The machine is set up, the program is loaded and two minutes designer time is required. If the technician cannot find the designer, he has to begin a new task and think his way into a new problem. Designers are often in internal meetings, seeing buyers, customers or yarn sales people, at shows and on shopping trips, and are therefore out of their offices. In most companies there are fewer technicians than designers, so the designers have to wait until the technicians have finished a task for a colleague. Interaction is very much more efficient and successful in the one company the author has visited that has reorganised its design process according to concurrent engineering principles and located its technicians next to the designers.

4.4.2. *Overlap of seasons – different frames of reference*

The fashion of each season is defined by the garments that are created for it and the sources of inspiration used for them (Eckert, 1997b). For the designers these garments and objects set the context and subtly influence their perception. Designers comment that designs often look dated to them by the time they reach the shops. The mental context for technicians is provided by the garments that they are currently working on or have recently worked on. As designers and technicians are working on different seasons, they work in different contexts.

A season lasts for 6 months from January to June and July to December. Many companies have now moved to four seasons a year; however they still have the one and a half years time span between research and sale. Figure 9 shows a simplified picture of the activities occurring in a company during one season. The season N on sale is given as a reference point. Production on a season continues for a while before production moves on the to the next season N + 1. The technicians sample the season N + 1 until it has reached production, and assist with production problems of season N. At the same time they produce swatches for designers for season N + 2. The designers are engaged in design for season N + 2 and begin the research for season N + 3. When technicians encounter problems in sampling, the designers have moved a full year ahead in their fashion context. Designers and technicians are working with different frames of reference and interpret assertions accordingly. Designers would like to concentrate fully on the research on the new season and are primarily interested in the new work, but they are often interrupted

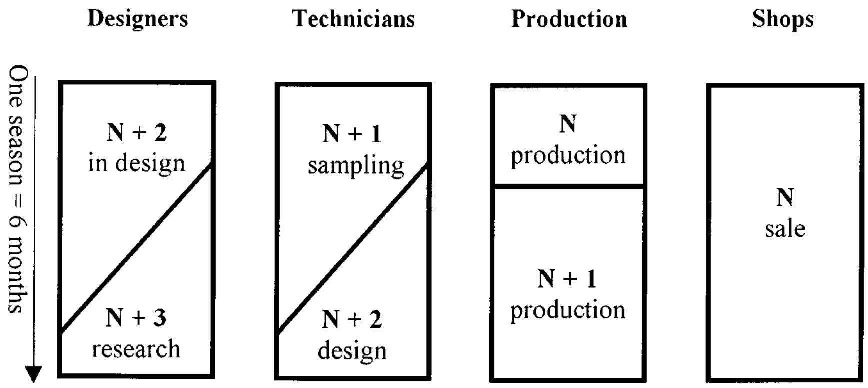


Figure 9. Parallel activities during one season.

to sort out problems with the previous season's garments. Many designers complain that they spend more time troubleshooting the previous season than researching the new season, but not in an organised manner. The problems created by the overlap of seasons are increased by last minute adjustments to ranges for presentations to buyers, which require new designs or modifications to existing designs. Both groups require each other's support at times when it is not convenient for the other group. This leads to inefficiency and frustration.

4.4.3. *Record keeping*

The lack of design records has been identified by Scaife et al. (1994) as a major problem in other parts of the textile industry. Our findings in the knitwear industry confirm this. During the design process the only records are technical sketches, such as the one shown in Figure 4. Most designers initially produce sketches for their designs, but they usually don't keep them or show them to the technicians. Conversations between the designers and the technicians are informal and unrecorded. Perry and Sanderson (1998) have highlighted the equal importance of informal communication in engineering companies' design processes.

Knitwear companies don't keep many records of the designs of previous seasons. Some companies keep all finished sample garments, others only sold garments or selected designs. The technical sketches are kept for one or two years and are then thrown out. Successful swatches are seldom kept in any organised manner, and swatches of previous versions of fabrics are not kept. Theme and mood boards are recycled after the end of the season; and are never used for communication between designers and technicians. The records are kept in the memory of the participants. Yet designers and technicians frequently use old designs to describe new designs in terms of changes to them (Eckert and Stacey, 2000), and copy measurements from old designs or technical sketches. New designers have to put significant effort into learning the house style, so that their style fits in with their colleagues' style and the requirements of the target customers. This is highly problematic as many designers don't stay in a job for more than three years, because they are afraid of burning out and can often only advance their career through changing jobs (Eckert et al., 1999b).

4.5. Cultural and social factors

The social organisation of the knitwear industry and the cultural attitudes and beliefs of its participants are not responsible for the communication problems, but they do little to counteract them. Designers and technicians typically come from very different social groups. Managers have rarely been designers or technicians in the past and therefore don't have the skills and attitudes to counteract differences between the groups. Eckert and Stacey (1994) present a much more detailed discussion of the social and cultural influences in the industry and its attitudes to creativity.

4.5.1. *View of creativity*

In both universities and industry the view is held by some people that excessive technical knowledge restricts the designers' creativity. There is some justification for this view, as technically experienced designers tend to design to the ability of the machine, rather than push it to its limits by demanding novel designs. With increasing expertise designers acquire a repertoire of design components which they include in new designs as a way of working quickly under time pressure. They acquire procedures for creating certain types of design efficiently, and also shy away from types of designs that have proved problematic in the past. In Eckert et al. (1999b) we discuss this in more detail in the context of designer burnout. However there is no evidence that the creativity as such is restricted, rather that designers have found ways to design feasible designs fast and are rewarded more for this than for novelty.

4.5.2. *Skill profile of design managers*

Only in the last few years the largest of the British knitwear companies included designers in the management of the company by creating the job of design manager. The other managers tend to be male and usually have degrees in textile technology or business studies, or have neither a degree nor any training in textiles, but have risen from sales. They cannot assess technical arguments and often have only a partial understanding of fashion; and have little understanding of design thinking. Therefore they cannot mediate between designers and technicians. The fashion industry has also no theory or methods for managing processes or generating designs, as engineering does, that could be used to guide managers and explain design acts abstractly to them.

4.5.3. *Power struggles between the designers and the technicians*

Most companies declare that they are committed to realising the designers' intentions as closely as possible, because the design ultimately sells the garments. However they rarely give the designers formal power over the design process. It is difficult to find skilled technicians, because few people able to program highly complex CAD systems are to be found operating knitting machines on the shop floor. Colleges and universities produce a surplus of designers, and designers find it difficult to get a job. Companies don't have problems recruiting skilled designers, but sometimes find it difficult to find designers with management skills. This difference in job security gives the technicians power over the designers who know that if they antagonise the technicians, they are likely to leave and not the technicians.

4.6. Some International Differences

The analysis presented in this paper applies equally to knitwear design in Britain and Germany. (The three Italian companies visited in this study were too few and too idiosyncratic to draw general conclusions from them, but are significant for an understanding of the industry as a whole). However there are some differences between these countries resulting from their different training patterns and labour costs. In Britain most knitwear designers are trained at least to some extent in knitwear design and know at least in principle how to operate a knitting machine, by being taught how to operate a hand knitting machine. Usually student designers don't have access to power knitting machines, but have their fabrics made by college technicians. They are interested in the construction of knitted garments and often express great regret that they don't have the time to learn more about the technical side of knitting. On the other hand Germany does not have specific knitwear design degrees and most German knitwear designers are trained as fashion designers (tailored garments) and do not know about the technical side of knitting; nor do they consider it their job. In consequence German designers often reuse stitch structures from other designs or from swatches that they buy. This is compensated for by the better theoretical understanding of the German knitwear technicians, resulting from the high standard of a training comprising three-year apprenticeships – often at the knitting machine manufacturers' headquarters – and a year of professional training. By contrast the British technicians are trained on the job and through courses put on by the knitting machine manufacturers. In consequence German designers and technicians discuss design problems less than their British counterparts.

Due to high salary levels and strict legislation on issues like overtime many German companies have moved their production abroad since the early 1990s and only kept a sampling department in Germany. In recent years some companies have also closed down their sampling departments and sample at their suppliers. If the designers and technicians are no longer in the same company and do not speak the same language the need for accurate written specifications increases. The high Sterling exchange rate is forcing British knitwear companies to do the same.

The Italian knitwear industry has on the whole a different division of labour. Italy does not have specific knitwear design degrees, and many knitwear companies hire British knitwear design graduates as fulltime or freelance designers. Knitting machine programs are often developed in dedicated software houses that specialise in programming knitwear machines of all kinds. Top range German companies use these Italian software houses and Italian manufacturers in spite of high labour costs in Italy, because they are most able to push the capabilities of machines to their extremes.

4.7. RELATIVE IMPORTANCE OF THE REASONS FOR COMMUNICATION BREAKDOWN

The difficulty of expressing conceptual ideas in knitwear is at the heart of the communication problem. As there is no complete and accurate representation of a complex knitted structure other than a knitted structure (and reverse engineering a swatch is not a trivial task), communicating a design with the precision and accuracy needed to avoid confusion is very time-consuming and would disrupt the creative process. The existing relatively complete and precise notations can't be used before the detailed design is done.

The imprecision and ambiguity inherent in most of the means of expressing designs gives scope for interpretation. The interpretation is likely to differ from the original idea, if the recipient's frame of reference differs from that of the sender. As technicians do not share the designers' research on target seasons, they interpret designs based on what they have done in the past.

The most fundamental problem is, however, that the industry in general does not recognise that a communication problem exists, and therefore does nothing to counteract it. In the few companies that have seen the problem, designers and technicians have actively worked on finding a shared language, for example by defining a common vocabulary for cables. Once a communication problem is identified, each group can put effort into finding ways to clarify their ideas as much as possible, and develop a mechanism of interaction through frequent meetings or an intermediary person. In general this improves the communication situation, but does not change the culture of bulk handovers of technical sketches with little or no explanation.

The culture of the knitwear industry does very little to create a common understanding. Designers are not taught to program knitting machines and technicians don't take part in fashion research. Moreover, misunderstandings are viewed as incompetence or unwillingness to try. Facilitating frequent easy interaction can help, as designers and technicians become more familiar with each other's work and tasks.

Even though knitwear designers and technicians come from extremely different social groups (section 3.3.1) this is not the cause of the communication problem, but merely a factor in the lack of compensation for the communication problems inherent in the division of labour in knitwear design. If designers and technicians came from more similar groups they would be more likely to socialise and talk about their work; thus addressing problems as they arise in an informal manner. Common interests, and similar backgrounds and ages would give the two groups a greater shared understanding of cultural references, such as fashion trends or inspiration material.

4.8. WHY THE PROBLEM PERSISTS IN INDUSTRY

Good practice in the textile industry does not spread from company to company, because there is little discussion between companies on processes; and the people moving between companies either don't have the power to change the culture, as is the case with designers and technicians, or the understanding to recognise process problems, as is the case with managers.

The underlying problem is that no one in the textile industry has a theory of design process, or a way of sharing knowledge between companies about design processes. The issue is barely touched in the few existing trade journals, such as *Textile Horizons* or *Knitting International*, which concentrate on technical issues or global changes. There is no intellectual interest in design processes in textiles, either in university textile departments or in industry, comparable to that shown by many engineers and architects; nor much teaching of design management in either design courses or textile management courses.

5. The role of computers in overcoming the communication bottleneck

Computers have already played a significant role in easing the communication difficulties in the knitwear industry by facilitating exchange of information electronically through standard tools like E-mail and providing consistent representations of knitted structures. But the available computer tools (see section 3.2) still have major limitations as support for conceptual design, because designers find it difficult and time consuming to translate their ideas into forms the systems can use, even if they have the expertise to do so, which most designers do not. However, a CAD system that turns the incomplete and inaccurate specification the designers currently produce into clear and accurate representations of their ideas could break this bottleneck.

5.1. Effect of existing computer support on communication in knitwear design

So far the main contribution by commercial CAD systems to facilitating design communication has been to make the creation and specification of colour patterns significantly easier, so that designers can define their own colour patterns. Designs that were a matter of weeks twenty years ago are now completed in a few hours. If the designers are willing to invest the necessary time and effort these designs are communicated precisely. For more complex designs, designers would have to acquire the skills of the technicians to program the machines. This would upset the division of tasks in the industry; and would increase the workload of the designers. Technicians now spend much less time on the programming of simple designs. However the basic work pattern has remained the same. Technicians have commented that their workload has remained the same over the years, because the designs have become more complex as computer technology has made programming easier. The increased level of technical complexity of the designs makes efficient communication more important than ever before.

5.2. Approach to computer support for communication

As we argue in section 3.4 the communication problems in knitwear industry arise from incorrect interpretations of incomplete, inconsistent and inaccurate specification. The problems can therefore partially be partially be overcome by a computer program that aids the designers in creating complete and correct specifications quickly; and enables them to elicit technical feedback fast. Eckert (1997; Eckert and Stacey, 1995; Eckert et al., 2000) proposes a system to create conceptual designs of garments automatically from designers' customary specifications (category descriptions and sets of measurements). These suggestions can be evaluated visually and edited by the designers while maintaining internal consistency. The design that the knitwear designers pass on to the technicians corresponds to the designers' intentions, is technically correct and complete; and can be presented in multiple representations. An automatically generated design solution has a reliably consistent quality of specification, and the generators and the receivers can learn to interpret and trust it (See Eckert et al., 1999a, for a discussion of the role of generative systems in design processes and design cognition).

Designers are used to receiving suggestions for designs, because technicians present them with completed implementations of their conceptual designs after a considerable time delay. Professional designers are highly skilled in evaluating their own and other designs on a variety of aesthetic and technical criteria, by perceptually appreciating the characteristics of designs, more than by reasoning about them (Schön, 1983; Schön and Wiggins, 1992). This enables them to recognise good or technically correct designs, even if they could not create them, and to see in which ways designs should be amended. Presenting possible designs visually exploits the designers' highly developed skills in the perceptual evaluation of designs (Eckert et al., 1999b).

This similar fast feedback approach has been introduced in fashion information systems, such as the Gerber GERBERsuite system,[4] where designers can specify a design for a tailored garment through modifications to older designs, and receive initial costing feedback by manipulating a two dimensional outline of the garment and adding and deleting standard features. Doing this for a knitted garment is far more complex than for a woven garment, because its feasibility and cost depend on details of the stitch structures and the placement of design elements on the shape. Describing modifications to an existing garment would not provide enough information to generate costing feedback, because seemingly small changes to the design can require radically different technical solutions, and different materials can behave very differently.

5.3. A PROTOTYPE GARMENT SHAPE DESIGN SYSTEM

Traditionally garment shapes are constructed in industry using a manual craft approach. The pattern cutters use measurements provided by the designers to derive the dimensions of the garment; they have remarkable tacit skills in drawing curves for armholes and sleeves that have exactly the same lengths and the right shape within company parameters. To create automatic solution suggestions from categories and dimensions, the construction of garment shapes needs to be modelled mathematically, to guarantee that two curves that need to be joined have the same lengths, or lengths in a specified ratio. The mathematical model needs to enable the design support system to meet the following requirements:

- design starts from the specification of shape categories and measurements, or from shape categories and default values;
- designs are easy to edit both by direct manipulation of diagram elements and by changing measurement values, so that users can modify the solution suggestions;
- the system highlights and modifies inconsistent input measurements;
- the system allows easy use of the intelligent completion of values;
- the system maintains domain constraints;
- the system is adaptable to individual company styles.

To fit into the designers' customary working practices and thinking style, garment shapes need to be presented as two-dimensional outlines as in the technical sketches, so that the proportions are easily visible. These can be translated into cutting patterns for individual shapes, which is often a better representation for editing details, as well as into a set of measurements. These shapes represent the final shape of the garment independent of fabric properties. They could be used by technicians as a starting point to create the final cutting pattern or the shape of the garment piece for a specific fabric.

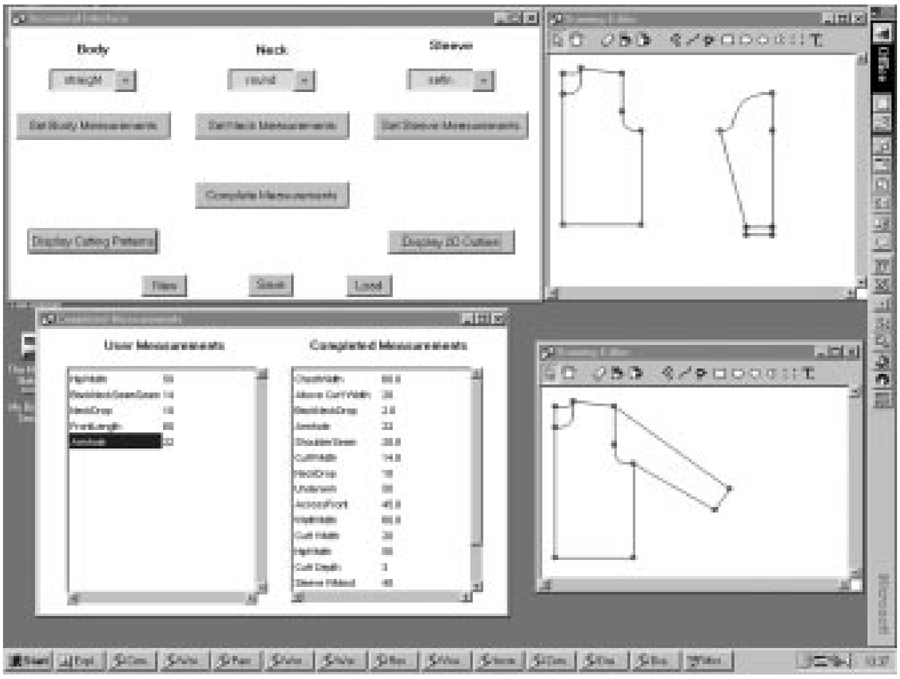


Figure 10. Prototype system.

Figure 10 shows a prototype system implemented by the author in VisualWorks®, which is an implementation of Smalltalk-80, to specify garment shapes based on incomplete input data. The user can specify the garment shape by choosing the category for the body, neck and sleeve. The user is asked to put in specific values for the measurements for a garment of the chosen category. All measurement inputs are optional. Missing values are completed using default values for a given category. The system could sensibly be extended using case based reasoning (see Kolodner, 1993, for an introduction; and Voss (1996) and Voss et al. (1996) for a detailed review of current case-based reasoning systems with special reference to their use in design). Mathematical models (see Eckert and Bez, 2000) are employed to generate garment shapes, that are consistent and conform to the constraints on the shapes of knitted garments arising from the behaviour of knitted fabric. The shape is displayed as a two-dimensional outline of the garment and as a cutting pattern (that is, small versions of the outlines of the garment pieces). It takes less than a minute to specify a garment shape with the tool. Informal evaluations by designers are highly encouraging, and the development of the prototype system into a commercial product as part of a commercial CAD system is under negotiation.

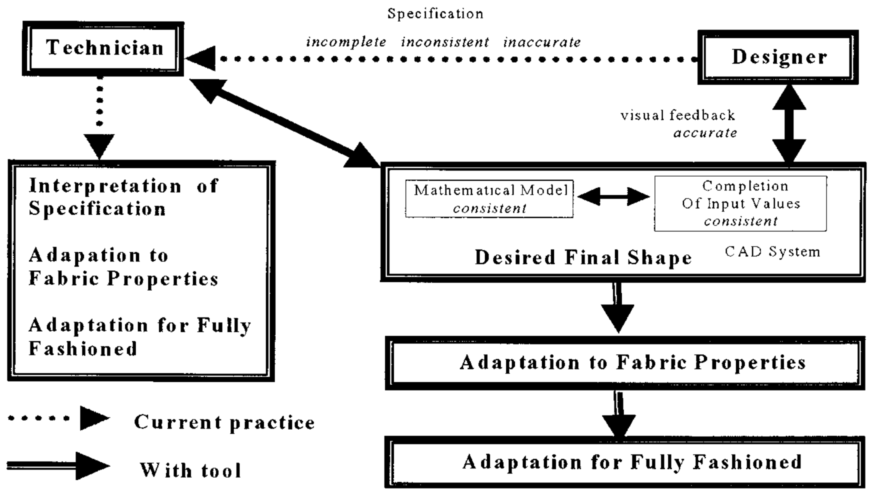


Figure 11. Mathematical model to improve the communication process.

5.4. Expected effect on the design process

The grey dashed arrows in Figure 11 show current design practice. A designer hands a specification that may be incomplete, inaccurate and inconsistent to the technician, and the technician interprets the specification and makes all the necessary adjustments for customers, fabric properties and shaping instructions in the course of detailed design.

The black arrows show the process using the prototype system. The tool enables the designer to generate a description of the shape of the final garment, which they can modify until it corresponds to what they want. Technical consistency is built into the model. This specification can then be handed to the technicians, who can make adjustments to the shape for fabric properties and so on. Discussion of changes to the garment shape can be grounded in an accurate representation. The tool will reduce the number of samples needed to reach the same standard of design quality. However, it is reasonable to expect that this technical innovation like previous innovations will lead to more complex products, rather than to a reduction in workload.

6. Conclusions

In knitwear design aesthetic design is inseparable from technical realisation (see section 3.2). Neither knitwear designers nor technicians, who program the industrial knitting machines, understand both aspects of design, which limits what they can imagine as well as what they can do (see section 4.3.3). We have observed that difficulties in communication between designers and technicians are jointly caused by a variety of different factors, and that the failure of knitwear designers to communicate design ideas successfully to technicians has profound effects on the design process:

- many design ideas are discarded, because they are wrongly interpreted during sampling;
- many specified design are not technically feasible at a given price point;
- Sub-optimal designs reach the market, because time to improve designs runs out.

6.1. COMMUNICATION IN KNITWEAR DESIGN

Knitwear designers generate designs in intensive bursts and produce the specifications for most designs together. The specifications recorded in designers' *technical sketches* are typically incomplete, inaccurate and inconsistent (see section 3.4.1), which makes them ambiguous. Technicians interpret these specifications to do the detailed design work involved in developing programs to knit the garments; and plan their own tasks according to the effort that they expect is required by each garment. Only when a problem occurs do they contact designers to discuss possible solutions. This situation is typical of many old-fashioned design processes, where a design is handed over from one person to the next; and communication only happens when problems occur.

In the large majority of knitwear companies, technicians do not participate in developing ideas or designing ranges. Designers and technicians do not negotiate about the forms that designs should take, either before or during the initial hand-over of designs in the form of technical sketches. Contact and discussion occurs once a design has failed; and both designers and technicians spend considerable time in trouble shooting. However designers often don't know why a design has failed. They cannot unpack the influence of the adjustments made by the technicians for technical reasons from the influence of faults in their own specifications, so they get no feedback on the quality of their specifications from which to learn how to meet the technicians' needs.

6.2. CAUSES OF COMMUNICATION PROBLEMS

The communication problems have many different causes, none of which is solely responsible for the problems in the knitwear culture.

The key problem in knitwear is that designers cannot provide the information the technicians need with the means available to them. That is, the drawing conventions and notations used in the knitwear industry will not convey this information, without the designers either leaving a lot of scope for misinterpretation, or investing an excessive amount of effort (section 4.1.1), or making detailed design decisions and solving technical implementation problems for which designers don't have the expertise (section 4.3.3). A key issue is communicating priorities and spaces for development and negotiation (see section 4.1.2). Henderson (1999) has highlighted this as being a significant problem in some engineering design processes. The conclusion we draw from this is that when interaction between the participants in a design process or other complex information manipulation activity is problematic, understanding and resolving problems involves understanding both the participants' information needs and the channels and means by which information is conveyed. Problems that appear to have other causes may be due to mismatches between the participants' information needs, the expressive power of notations and other verbal and visual representations and the skills in understanding these possessed by the different participants, as well as the participants' understanding of what information their colleagues need.

Designers and technicians have very different mental models underlying their creation and interpretation of descriptions of garment designs. Designers think in terms of the visual and tactile appearance of a design, in terms of the style of a future season. Technicians think in terms of the structural properties of knitted fabrics, which designers are often not familiar with. In consequence they interpret the boundary objects through which they communicate (the technical sketches) very differently. The designers' limited understanding of how the technicians will interpret their specifications restricts their ability to provide effective indications of what changes and elaborations in detailed design are acceptable. Bucciarelli (1988, 1994) has pointed out the importance in engineering design of communication between object worlds – the sets of things, properties, relationships and principles with which people think (see also Henderson, 1999). The author has encountered similar fundamental differences in mental models between systems engineers and mechanical engineers in a helicopter design team; when the issue was discussed in a meeting they were quite startled by descriptions of how their colleagues thought. The conclusion we draw from this is that investigations of communication problems in other industries where people with substantially different expertise work together need to examine the object worlds and mental models of the different participants, to understand both what their information needs are, and how they interpret messages, sketches and other communicative objects.

The organisation and management of the design process in most knitwear companies, and the cultural beliefs and attitudes of the participants do little to counteract these problems. In engineering design awareness of the need for managerial support for communication is greater than in knitwear design. However, there is still a long way to go before the information needs of engineers are fully understood and efficiently and effectively met.

The participants in the knitwear industry do not recognise the nature of their communication problems; they assume that misinterpretations are inherent in the way knitwear is generated. Problems stemming from the intrinsic difficulty of communicating knitwear designs with quickly drawn sketches and the available notations are often blamed on other factors such as the personal relationships between individuals. The conclusion we draw from this is that explicit reflection and discussion of communication problems by the participants are an essential part of resolving them.

6.3. Removing the need to interpret ambiguous specifications

Communication between designers and technicians can be supported and enhanced by removing the need to interpret vague and ambiguous representations, which is a major cause of inefficiencies in the knitwear industry. In this paper we present a prototype design support system that enables knitwear designers to produce accurate and technically consistent garment shape specifications in less time than producing handwritten technical sketches to do the same job.

Acknowledgements

Claudia Eckert's research has been supported by SERC ACME grant GR/J 40331 for the knitwear project at the University of Loughborough Department of Computer Studies; by ESRC grant L12730100173 for the MIND project at the Open University Computing Department; and by Open University Research Development Fund grant 717 at the Open University Department of Design and Innovation. The author is deeply indebted to her PhD supervisors, Prof. Nigel Cross and Dr. Jeff Johnson of the Department of Design and Innovation at The Open University, and Dr. Helmut Bez at the Loughborough University Department of Computer Studies. This paper has greatly benefited from conversations and comments on previous drafts by Dr Martin Stacey of the Department of Computer and Information Sciences, De Montfort University, Milton Keynes. The support of Graham Perkins of the Department of Computer and Information Sciences, De Montfort University, Milton Keynes, in developing the prototype was invaluable. We are greatly indebted to all the designers and technicians who gave their time to talk to us and allowed us to observe them working.

Notes

1. *Knit* stitches are the standard stitches that make up most or all of most knitted garments; *single jersey* fabric consisting only of knit stitches is very common, for instance as T-shirt material. *Purl* stitches are 'back-to-front' knit stitches.
2. Two colour pattern.
3. *Intarsia* patterns comprise regions of fabric knitted with different yarns.
4. See http://www.gerbertechnology.com.

References

Agar, M. (1980): *The Professional Stranger: An Informal Introduction to Ethnography*. London, UK: Academic Press.

Anderson, R.J. (1994): Representations and Requirements: The Value of Ethnography in System Design. *Human-Computer Interaction*, vol. 8, pp. 151–182.

Badke-Schaub, P. and E. Frankenberger (1999): Analysis of Design Projects, *Design Studies* vol. 20, no. 5, pp. 465–480.

Booch, G., I. Jacobson and J. Rumbaugh (1998): *Unified Modeling Language User Guide*. Reading, MA: Addison-Wesley.

Bucciarelli, L.L. (1988): An Ethnographic Perspective on Engineering Design, *Design Studies*, vol. 9, pp. 159–168.

Bucciarelli, L.L. (1994): *Designing Engineers*. Cambridge, MA: MIT Press.

Burda (1975): *Freude am Stricken*. Offenburg, Germany: Verlag Aenne Burda GmbH & Co., p. 74.

Burda (1988): *Grosses Strickmusterhelf*. Offenburg, Germany: Verlag Aenne Burda GmbH & Co.

Busby, J.S. (1998): The Neglect of Feedback in Engineering Design Organisations, *Design Studies*, vol. 19, pp. 103–117.

Bly, S.A. (1988): A Use of Drawing Surfaces in Different Collaborative Settings, *Proceedings of CSCW'88*. Portland, OR: ACM Press, pp. 250–256.

Bly, S.A and S.L. Minneman (1990): Commune: A Shared Drawing Surface, Proceedings of the Office Information System Conference. Boston, MA, pp. 184–193.

Cross, N.G. (1989): *Engineering Design Methods*. Chichester, UK: John Wiley.

Cross, N.G. and A.C. Cross (1995): Observation of Teamwork and Social Processes in Design. *Design Studies*, vol. 16, pp.143–170.

Dourish, P. and G. Button (1998): On "Technomethodology": Foundational Relationships Between Ethnomethodology and System Design. *Human-Computer Interaction*, vol. 13, pp. 395–432.

Eckert, C.M. (1997): *Intelligent Support for Knitwear Design*, PhD Thesis, Department of Design and Innovation, Milton Keynes, UK: The Open University.

Eckert, C.M. (1997b): 'Design Inspiration and Design Performance', *Proceedings of the 78th World Conference of the Textile Institute*, Thessaloniki, Greece: The Textile Institute, vol. 1, pp. 369–387.

Eckert, C.M. and H.E. Bez (2000): A Garment Design System Using Constrained Bézier Curves, *International Journal of Clothing Science & Technology*, vol.12, No 2, pp. 134–143.

Eckert, C.M., N.G. Cross and J.H. Johnson (1998): Intelligent Support for Communication Difficulties in Conceptual Design. *Proceedings of Computer Aided Conceptual Design '98*, Lancaster, UK: Lancaster University Engineering Design Centre, pp. 267–284.

Eckert, C.M., N.G. Cross and J.H. Johnson (2000): Intelligent Support for Communication in Design Teams: Garment Shape Specifications in the Knitwear Industry, *Design Studies*, vol. 21, pp. 99–112.

Eckert, C.M. and A. Demaid (1997): Concurrent Design, *Proceedings of the 78th World Conference of the Textile Institute*. Thessaloniki, Greece: The Textile Institute, vol. 3, pp. 101–122.

Eckert, C.M., I. Kelly and M.K. Stacey (1999): Interactive Generative Systems for Conceptual Design: An Empirical Perspective, *Artificial Intelligence for Engineering Design, Analysis and Manufacturing*, vol. 13, pp. 303–320.

Eckert, C.M. and M.K. Stacey (1994): CAD Systems and the Division of Labour in Knitwear Design. In A. Adam, J. Emms, E. Green and J. Owen (eds.): *Women, Work and Computerization: Breaking Old Boundaries – Building New Forms*. Amsterdam, The Netherlands: North-Holland, pp. 409–422.

Eckert, C.M. and M.K. Stacey (1995): An Architecture for the Intelligent Support of Knitwears Design. In J.E.E. Sharpe (ed.): *AI System Support for Conceptual Design*. Berlin, Germany: Springer-Verlag, pp. 71–92.

Eckert, C.M. and M.K. Stacey (1999): Adaptation of Sources of Inspiration in Knitwear Design. Cambridge University Engineering Department, Technical Report CUED/C-EDC/TR80.

Eckert, C.M. and M.K. Stacey (2000): Sources of Inspiration: a Language of Design, *Design Studies*, vol. 21, pp. 523–538.

Eckert, C.M., M.K. Stacey and J. Wiley (1999b): Expertise and Designer Burnout, *Proceedings of the 12th International Conference on Engineering Design*. Munich, Germany: Technical University of Munich, vol. 1, pp. 195–200.

Ehrlenspiel, K. (1995): *Integrierte Produktentwicklung*, Munich, Germany: Carl Hanser Verlag.

Fowler, M. and K. Scott (1999): *UML Distilled*, 2nd ed. Reading, MA: Addison-Wesley.

Goel, V. (1995): *Sketches of Thought*. Cambridge, MA: MIT Press.

Goldschmidt, G. (1991): The Dialectics of Sketching. *Creativity Research Journal*, vol. 4, pp. 123–143.

Goldschmidt, G. (1994): On Visual Design Thinking: The Vis Kids of Architecture. *Design Studies*, vol. 15, pp. 158–174.

Goodland, M. and C. Slater (1995): *SSADM Version 4: A Practical Approach*. Maidenhead, UK: McGraw-Hill.

Henderson, K. (1999): On Line and on Paper. Cambridge, MA: MIT Press.

Hammersley M. and P. Atkinson (1995): *Ethnography: Principles in Practice*. London, UK: Routledge.

Hollan, J. and S. Stornetta (1992): Beyond Being There. *Proceedings of CHI'92*, Monterey, CA: ACM Press, pp. 119–125.

Ishii, H. and K. Minoru (1992): ClearBoard: A Seamless Medium for Shared Drawing and Conversation with Eye Contact, *Proceedings of CHI'92*. Monterey, CA: ACM Press, pp. 525–532.

Jacobson, I., G. Booch and J. Rumbaugh (1999): *The Unified Software Development Process*. Reading, MA: Addison-Wesley.

Kolodner, J. (1993): *Case-Based Reasoning*, San Mateo, CA: Morgan Kaufmann.

Kvan, T., R. West and A.H. Vera (1997): Tools and Channels of Communication: Dealing with the Effects of Computer Mediation on Design Communication. *Proceedings of Creative Collaboration in Virtual Communities '97*, Sydney, Australia: University of Sydney. *http://www.arch.su.edu/kcdc/conferences/VC97/papers/west.html*

Lofland, J. (1995): Analytic Ethnography: Features, Failings, and Futures, *Journal of Contemporary Ethnography*, vol. 24, no.1, pp. 30–67.

Mäkirinne-Croft, P., W. Godwin and S. Saadat (1996): *A Conceptual Model of the Fashion Design Process*, Cheltenham & Gloucester College of Higher Education, Report for: EPSRC/DIP GR/H84475.

McFadzean, J., N.G. Cross and J.H. Johnson (1999): Notation and Cognition in Conceptual Sketching, *Proceedings of VR'99, Visual and Spatial Reasoning in Design*. Cambridge, MA: MIT Press.

Meyer, M. (1992): How to Apply the Anthropological Observation Technique of Participatory Observation to Knowledge Acquisition for Expert Systems, *IEEE Transactions on Systems, Men, and Cybernetics*, vol. 22 no. 5 pp. 983–991.

Minneman, S.L. (1991): *The Social Construction of a Technical Reality: Empirical Studies of Group Engineering Design Practice*, PhD Thesis, Department of Mechanical Engineering, Stanford University, Stanford, CA. Xerox Palo Alto Research Center report SSL-91-22.

Minneman, S.L. and S.A. Bly (1990): Experiences in the Development of Multi-user Drawing Tools. *Proceedings of the Third Guelph Symposium on Computer Mediated Communication*, Guelph, Canada, pp. 154–167.

Minneman, S.L. and S. Harrison (1999): The DrawStream Station: A Tool for Distributed and Asynchronous Chats About Sketches and Artifacts, *Proceedings of HCI'99*, Munich, Germany, pp. 221–225.

Moran, T.P., W. van Melle and P. Chiu, P. (1998): Spatial Interpretation of Domain Objects Integrated into a Freeform Electronic Whiteboard, Proceedings of UIST 98, San Francisco: ACM Press, pp. 175–184.

Neilson, I. and J. Lee (1994): Conversations with Graphics: Implications for the Design of Natural Language/Graphics Interfaces, *International Journal of Human-Computer Studies*, vol. 40, pp. 509–541.

Newell, A. (1981): The Knowledge Level, *AI Magazine*, vol. 1, no. 2, pp. 1–20. Also published in *Artificial Intelligence*, vol. 18, pp. 87–127, 1982.

Pahl, G. and W. Beitz (1996): *Engineering Design*, trans. K. Wallace, L. Blessing and F. Bauert. London, UK: Springer.

Penrose, R. (1989): *The Emperor's New Mind*. Oxford, UK: Oxford University Press.

Perry, M. and D. Sanderson (1998): Coordinating Joint Design Work: the Role of Communication and Artefacts. *Design Studies*, vol. 19, pp. 273–288.

Purcell. A.T. and J.S. Gero (1998): Drawings and the Design Process. *Design Studies*, vol. 19, pp. 389–430.

Pycock, J. and J. Bowers (1996): Getting Others to Get it Right: An Ethnography of Design Work in the Fashion Industry, *Proceedings of Computer Supported Collaborative Work '96*, Cambridge MA: ACM Press.

Rumbaugh, J., M. Blaha, W. Premerlani, F. Eddy and W. Lorensen (1990): *Object-Oriented Modeling and Design*. Englewood Cliffs, NJ: Prentice-Hall.

Scaife, M., E. Curtis and C. Hill (1994): Interdisciplinary Collaboration: A Case Study of Software Development for Fashion Designers, *Interacting with Computers*, vol. 6, pp. 395–410.

Schön, D.A. (1983): *The Reflective Practitioner: How Professionals Think in Action*. New York, NY: Basic Books.

Schön, D.A. and G.A. Wiggins (1992): Kinds of Seeing and Their Function in Designing. *Design Studies*, vol. 13, pp. 135–156.

Schreiber, A.Th., H. Akkermans, A. Anjewierden, R. de Hoog, N. Shadbolt, W. van de Velde and R. Wielinga (1999): *Knowledge Engineering and Management*. Cambridge, MA: MIT Press.

Schreiber, A.Th., R. Wielinga and J.A. Breuker (1993): *KADS: A Principled Approach to Knowledge-Based System Development*. London, UK: Academic Press.

Scrivener, S., S. Clark, A. Clarke, J. Connolly, S. Garner, H. Palmén, M. Smyth and A. Schappo (1993): Real-Time Communication Between Dispersed Work Groups Via Speech and Drawing. *Wirtschaftsinformatik*, vol. 35, no. 2, pp. 149–156.

Scott A.C., J.E. Clayton and E.L. Gibson (1991): *A Practical Guide to Knowledge Acquisition*, Reading, MA: Addison-Wesley.

Shima Seiki (1996): *Total Knitting System*, Sales Brochure, Shima Seiki Europe, Milton Keynes, UK.

Spencer, D. (1989): *Knitting Technology*, Oxford, UK: Butterworth-Heinemann.

Smithers, T. (1996): On Knowledge Level Theories of Design Process. In J.S. Gero and F. Sudweeks (eds.): *Artifical Intelligence in Design '96*. Dordrecht, The Netherlands: Kluwer Academic Publishers, pp. 561–579.

Smithers, T. (1998): Towards Knowledge Level Theories of Design Process. In J.S. Gero and F. Sudweeks (eds.): *Artifical Intelligence in Design '96*, Dordrecht, The Netherlands, Kluwer Academic Publishers, pp. 3–21.

Stacey, M.K. and C.M. Eckert (1999): An Ethnographic Methodology for Design Process Analysis. *Proceedings of the 12th International Conference on Engineering Design*. Munich, Germany: Technical University of Munich, vol. 3, pp. 1565–1570.

Stacey, M.K. and C.M. Eckert (2000): Against Ambiguity. *COOP 2000 Workshop Proceedings: The Role of Objects in Design Collaboration: Communicating through Physical and Virtual Objects*, Sophia Antipolis, France: INRIA.

Stacey, M.K., C.M. Eckert and J. McFadzean (1999): Sketch Interpretation in Design Communication. *Proceedings of the 12th International Conference on Engineering Design*. Munich, Germany: Technical University of Munich, vol. 2, pp. 923–928.

Star, S.L. (1989): The Structure of Ill-Structured Solutions: Heterogeneous Problem-Solving, Boundary Objects, and Distributed Artificial Intelligence. In L. Gasser and M.N. Huhns (eds.): *Distributed Artificial Intelligence*, vol. 2, Menlo Park, CA: Morgan Kaufmann, pp. 37–54.

Symon, G. (1998): The Work of IT System Developers in Context: An Organisational Case Study, *Human-Computer Interaction*, vol. 13, pp. 33–71.

Tang, J.C. (1989): *Listing, Drawing and Gesturing in Design: A Study of the Use of Shared Workspaces by Design Teams*. PhD Thesis, Department of Mechanical Engineering, Stanford University, Stanford, CA. Xerox Palo Alto Research Center report SSL-89-3.

Tang, J.C. (1991): Findings from Observational Studues of Collaborative Work. *International Journal of Man-Machine Studies*, vol. 34, pp. 143–160.

Tang, J.C. and L. Leifer (1988): A Framework for Understanding the Workspace Activity of Design Teams. *Proceedings of CSCW'88*. Portland, OR: ACM Press, pp. 226–232.

Tang, J.C. and S.L. Minneman (1990): VideoDraw: Video Interface for Collaborative Drawing, *Proceedings of CHI'90*, Seattle, WA: ACM Press, pp. 313–320.

Tang, J.C. and S.L. Minneman (1991): VideoWhiteboard: Video Shadows to Support Remote Collaboration, *Proceedings of CHI'91*, New Orleans, LA: ACM Press, pp. 313–320.

Ullman, D., D. Herling and B. D'Ambrosio (1997): What to Do Next: Using Problem Status to Determine the Course of Action, *Research in Engineering Design*, vol. 9, pp. 214–227.

Universal (1996): *Pattern Presentation Unit*, Sales Brochure, Universal Maschinenfabrik, Westhausen, Germany.

Viller, S. and I. Sommerville (1999): 'Coherence: An Approach to Representing Ethnographic Analyses in System Design', *Human-Computer Interaction*, vol. 14, pp. 9–41.

Valkenburg R. and K. Dorst (1998): The Reflective Practice of Design Teams. *Design Studies*, vol. 19, pp. 249–271.

Voss, A. (1996): Towards a Methodology for Case Adaptation, *Proceedings of 12th European Conference on Artificial Intelligence*, Chichester, UK: John Wiley.

Voss, A., B. Bartsch-Spörl and and R. Oxman (1996): A Study of Case Adaptation Systems. In J.S. Gero and F. Sudweeks (eds.): *Artificial Intelligence in Design '98*. Dordrecht, The Netherlands: Kluwer Academic Publishers, pp. 173–189.

Wagner, I., M. Buscher, P. Morgensen and D. Shapiro (1999): Spaces for Creating Context and Awareness – Designing a Collaborative Virtual Work Space for (Landscape) Architects. *Proceedings of HCI'99*, Munich, Germany, pp. 283–287.

Wielinga, B.J., A.Th. Schreiber and J.A. Breuker (1992): KADS: A Modelling Approach to Knowledge Engineering. *Knowledge Acquisition*, vol. 4, pp. 5–53.