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Acknowledgements

Intelligent Support for Knitwear Design



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Thesis submitted for the degree of Doctor of Philosophy

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Date of submission: 10th September 1997

September 1997

Date of award: 7th November 1997

Acknowledgements

A PhD is an epic journey in search of the holy grail of academic knowledge; and mine more so than most. As in so many fantasy stories the journey begins with the enthusiasm and encouragement of those who have already achieved the goal (Simon Holland). The journey has many desperate moments and encounters with evil wizards, wicked witches and false friends; and detours in false directions. But it also has the joys of loyal and unconditional support from travelling companions (my partner and now husband Martin Stacey) and a wise guide through the application domain (Monica Jandrisits). Encouragement often comes from unexpected sources (for example Thomas Green). Chivalrous knights come to the rescue in desperate moments and share the journey onwards (Helmut Bez, Nigel Cross and Jeff Johnson). Both the positive support of those who were my friends and the unpleasant challenges posed by those who were not shaped my research and increased my horizons and interests, allowing me to explore much wider fields than I had originally anticipated. As in the mythical searches for the holy grail, if the pursuit is not a goal in its own right, then the journey is worthless. I have overall enjoyed it.

I would very much like to thank my supervisors, Dr Helmut Bez of the Department of Computer Studies at the University of Loughborough, and Dr Jeff Johnson and Professor Nigel Cross of the Department of Design and Innovation at the Open University, for their help, support and encouragement throughout the research. They have helped me significantly with getting the thesis into shape, while teaching me about academic writing. They are models for me to emulate in my later academic life. I would also like to thank Dr Ray Harwood of the Department of Fashion and Textiles at De Montfort University for signing my travel expense forms and immersing me in the culture of knitwear design and design education. I am greatly indebted to Dr Martin Stacey for his continuous support and feedback on my work, without which I could not have done the thesis.

I am greatly indebted to the knitwear designers and technicians who took the time to talk to me and allow me to observe them at work. I would like to thank specially Elaine Repper, Enid Browne and Vicki Longdon; as well as my personal friends Monica Jandrisits, Wendy Nicholson and Jane Taylor. I am very grateful for the support that Universal GmbH, and especially its technical director Dr. Wolfgang Berger, have given me, especially the opportunity to take knitting machine programming courses. Much of my PhD work was done as part of two research projects funded by the EPSRC (grant GR/J 40331) and the ESRC (grant L12730100173).

I would also like to thank Dr Simon Holland and Dr Anthony Lucas-Smith for their comments on earlier drafts of my thesis. I am very grateful to Dr Helmut Bez, Dr Martin Stacey, Monica and Mary Openshaw, Michelle Armstrong and Susan Hall for proofreading parts of the final version of my thesis.

I fondly think back to the time when my daughter Calandra sat next to my computer and watched me work, and I am grateful to her for not having obstructed my work more than one must expect from a little child. I would like to thank my mother for supporting me in many practical ways; and my late father for having taught me never to surrender when faced with academic adversities.

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Abstract

Communication between different members of a design team often poses difficulties. 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 and assemble it. This thesis reports a detailed empirical study of over twenty companies in Britain and Germany, which shows that the communication problem constitutes a major bottleneck. Designers specify their designs inaccurately, incompletely and inconsistently; the technicians interpret these specifications according to their previous experience of similar designs, and produce garments very different from the designers' original intention. Knitwear is inherently difficult to describe, as no simple and complete notation exists for knitted structures; and the relationship between visual appearance and structure and technical properties of knitted fabric is subtle and complex. At the same time the interaction between designers and technicians is badly managed in many companies.

This thesis argues that this communication bottleneck can be overcome by enabling designers to produce accurate specifications of technically correct designs, through the help of an intelligent computer support system that corrects inconsistent input and proposes design suggestions that the user can edit. In this thesis this proposal is elaborated for one aspect of knitwear design: garment shape construction. Garment shapes are modelled using Bézier curves generated using design heuristics drawn from industrial practice, to create curves that look right to a designer and can be easily edited. The development of the garment shape models presented in this thesis involved the solution of unusual problems in numerical analysis. The thesis shows how the mathematical models can be integrated into an intelligent CAD system, and discusses the benefits of such a system could have for the design process.

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Chapter 1.

Introduction

It is just a jumper, just a piece of everyday clothing. This is the attitude of most people towards knitwear. Knitting is perceived as a pastime for grandmothers. They never think about how knitwear is made, how it is designed, or why it looks the way it looks.

A knitted garment is among the most complex textile products. The design of a knitted garment involves subtle interactions between aesthetic and technical constraints under tight and complex financial pressures. Small technical modifications can change the appearance completely. A slightly different visual effect might require a total rethink about the way the fabric is created. The fabric and the shape are created at the same time from yarn. Industrial knitwear is produced on highly complex computerised machines. Industrial knitting machines can now, theoretically, produce nearly every structure possible for hand knitting, but they put unexpected restrictions on the use of certain structures for certain yarns.

Knitwear is a fashion item. Fashion changes are led by tailored fashion. Knitwear follows trends from tailored fashion closely whilst incorporating new technical possibilities. The knitwear industry operates in a tight market. Like the whole textile industry European knitwear companies are under continuous threat from low labour cost countries. The European knitwear industry can only survive by pushing the capability and productivity of the machines to their limits while producing interesting well-timed designs.

1.1 The Problem Area

Knitwear design combines artistic design with technical problem solving. In a knitted garment the fabric is created at the same time as the shape of the garment. Even when the pieces of the garments are cut rather than knitted into the required shape, the different pieces need to fit together. Not only the shape needs to be right: the decorative patterns, such as repeating motifs or cables, need to fit onto the garment piece, and they need to fit together with the pattern on the other pieces. Figure 14 - Figure 17 illustrate this problem.

This thesis addresses the knitwear design and sampling process from the time when designers begin to look at designs for a new season to the point when a sample, i.e. a prototype of a garment, is produced.

The research reported in this thesis is based on observations and interviews in twenty knitwear companies in Britain and Germany; and on domain knowledge acquired by the author of this thesis.

The knitwear design and sampling process is shared in most observed companies by three main types of workers:

- The knitwear designers, who design the visual and tactile appearance of the garment.
- The fabric technicians, who program the knitting machines, and adapt the designs to fit fabric properties and price points.
- The shape technicians, who create the cutting patterns for the shape in the given structure and yarn. They are also responsible for assembling the garments.

Most of the knitwear designers interviewed for this research have little technical training and understanding. They cannot program the knitting machines and do not know *how* visual

effects can be created with knitted fabric on a machine. However, they know *what* fabrics and shapes can be created from seeing lots of knitwear and knowing how to design it. They can visualise how the garments they design will look.

In all observed companies the technicians work out the detailed design of most garments. For them creating a garment design that is feasible at a certain price point is a problem solving task; they are seldom concerned with fashion or other aesthetic concerns. The knitwear technicians studied during this research often did not understand designing as an expression of a specific brief in the fashion context of a season.

In most companies visited during this research, garments are sampled under great time pressure, because all fashion items need to arrive in shops at precisely the right moment. Most knitted garments require many rounds of sampling before the garments correspond to the designers' initial ideas and can be produced in the specified yarns at a given price point. Many technicians interviewed complained that designers specify garments that cannot be knitted. Many designers interviewed complained that technicians did not knit what they have specified. In these companies the communication between designers and technicians was not working well.

Most knitted garments are a compromise. Refinements to a design are often abandoned because of time pressure. With the introduction of computer technology over the past twenty years, the sampling time per garment has been reduced. This has resulted in

- reductions in the design cost for equivalent designs;
- more refinements on each garment;
- more complex and innovative designs.

In knitwear the trend has been towards a constant increase in the sophistication of the design rather than a reduction in the price of the product. Designers and technicians have commented to the author that the pressures on the process have changed little over the years.

In this thesis the pattern of communication between knitwear designers and technicians is analysed. Designers do not succeed in explaining their ideas. Technicians cannot make them understand why designs cannot be realised. The communication difficulties between designers and technicians constitute a major bottleneck in the design process. The principal argument of this thesis is that:

A computer system that enables knitwear designers to create complete and consistent specifications of designs, which the technicians can understand, will help to overcome communication difficulties, thus releasing time for the design and sampling of each garment. This can be achieved by giving rapid technical feedback on tentative designs.

This argument is developed in detail for the design of garment shapes. From the designers' customary description of shapes, as a set of measurements and a short verbal description, a mathematical model can be employed to create the cutting patterns and two-dimensional outlines of the final shape of the garments. Domain heuristics are used in the mathematical model to create curves which include domain constraints and can be easily edited. The mathematical models lie at the heart of a design for an intelligent system which completes the designers' specifications and turns them into solution suggestions which can be edited.

1.2 Overview of the Chapters

Chapter 1, the introduction, presents the problem addressed by this thesis: how can the communication between designers and technicians in the knitwear design and sampling process be improved through computer support? The steps in which the research questions are posed are explained and the thesis is placed in the context of other academic and commercial work.

Chapter 2 discusses the methodology used to undertake the empirical work on the knitwear design process: ethnography has been combined with conventional knowledge acquisition

methods from artificial intelligence. The companies visited are introduced and labelled so that evidence can be attributed to specific people observed during the research.

Chapter 3 presents the results of the ethnographic study by describing the entire knitwear design process, from the beginning of the research work on a new season to the point when a garment is sold to a retail chain buyer.

Chapter 4 looks at the communication between knitwear designers and knitwear technicians. It analyses the reasons why communication often breaks down; and identifies fifteen different causes derived from intrinsic problems in knitwear, different thinking styles of the participants and the working culture.

Chapter 5 suggests ways to overcome the communication bottleneck through organisational changes and computer support. The use of computer systems to support knitwear design is placed in the context of the research literature on intelligent support systems for design.

Chapter 6 describes the mathematical construction of garment shapes. It describes the basic characteristics of knitwear shapes, and discusses the use of Bézier curves to model the curves of cutting patterns, using interpolation points and domain heuristics.

Chapter 7 suggests a design support module for garment shape calculation. The garment shapes are represented using three alternative representations: measurements, two-dimensional garment outlines, and cutting patterns (garment piece outlines). The components of such a module are explained and their interaction is described.

Chapter 8 discusses the effect of such a support module on the design process and the communication difficulties. A new model of the cutting pattern design process is shown. The causes of the communication breakdown are discussed again with reference to the proposed system. Other improvements in the design process are outlined.

Chapter 9 presents the conclusions of this thesis, looks at their validity in a wider research context and points to further work planned or in progress.

1.3 The Multidisciplinary Context of this Thesis

Like most other work in design studies this thesis is highly interdisciplinary and touches on many different areas such as the study of business processes, psychology, numerical analysis, tailoring, artificial intelligence, human computer interaction (HCI), computer aided design (CAD), and creativity research, without claiming to contribute significantly to any of them.

Design study research needs to look at design as a phenomenon in its totality within our society to understand all the factors influencing the designers and the design process. An in-depth analysis of a particular research question needs to be embedded in an understanding of this context. The research carried out for this thesis has started totally from scratch in a novel domain where research questions could not be derived from a study of the literature about the particular domain or type of domain. This would be possible in engineering design or architecture where the processes and thinking methods have been studied in depth already. The artificial intelligence for design community and to some extent the design support system community rarely look at the industrial practice of real designers. They are often driven by theoretical questions and base their understanding of design on standard literature, such as Schön (1983), Lawson (1990), Cross (1984), etc., without investigating the applicability of assertions about design in general to their particular domain. Many design support systems are built by domain experts without a theoretical interest in artificial intelligence or human computer interaction. Mathematical modelling research also does not normally begin by an analysis of the problem and the whole cultural context of the research.

1.4 Academic Research into Design in the Textile Industry

Many books are published about knitwear. As section 2.2.1 will explain in detail these books concentrate on how to produce or reproduce knitted fabric or garments. An extensive literature search in libraries (including specialist textile libraries) and on the World Wide Web, as well as communication with design educators, has revealed no references to systematic academic research into the knitwear design and sampling process. A short but typical description of the knitwear design process can be found in a booklet for school children entitled *A short history of knitwear* by Mansfield Menswear, a knitwear manufacturer visited in the course of the observation (Mansfield, no date).

On the basis of informal observations Daunt and Miller (1996) have argued that a unity (their term) between the knitwear designer and technician can be achieved through the use of CAD systems. They observed that before the introduction of CAD systems designers and technicians worked in isolation from each other, so that the communication barrier between the designer and technician led to a huge rejection rate of samples. They argue that computer technology combined with a better training in technology for the designers enables them to specify and simulate what they want. The paper describes the potential of the Stoll and Shima Seiki systems (section 1.5.1). Daunt and Miller's description of the tasks and problems of the designers is accurate though not detailed. They attribute the communication failure entirely to the lack of technical knowledge of the designers and the traditional division of labour.

Computer support for the textile industry has been studied in several academic research projects. Scaife et al. (1994) describe the process of developing guidelines for the introduction of computer technology into the textile industry. Fieldwork undertaken in three major British fashion manufacturers focused on the knowledge underlying a design activity;

both the tasks of the designers and the development of the products were studied. They found that much design occurs by modification from previous designs, yet hardly any records are kept from previous designs. They developed a prototype system to record and modify design information in a database. Industry still has 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) came to a similar conclusion about the reuse of designs when they investigated the potential for improving computer systems for fashion designers. Based on forty five structured interviews with designers and a questionnaire, they developed a theory of the fashion design process and creativity in general, based on quantum mechanics, psychoanalysis, and mother and child bonding in early infancy. They view idea generation as the 'The Great Mystery'. They did not attempt to analyse or overcome communication problems, even though they acknowledge that designers and technicians have different frames of reference. Besides hardware considerations they recommend the extensive use of general and personalisable databases, a 'virtual catwalk' presentation, which is being developed by a variety of researchers, for example Grey (1995), and a portable computer sketching environment, which is already implemented in the form of the *electronic cocktail napkin* (Gross, 1996).

Rhodes and Carter (1996) look at possible improvements to design generation and production in the light of the global changes in the textile industry. They address the new potential for computer technology in the manufacturing process in the context of a 'quick response' strategy. In particular they focus on the use of multimedia in training the people who assemble garments.

Research is also being undertaken into the three-dimensional modelling of garment shapes, see for example the special issue of the *International Journal of Clothing Science and Technology*, Volume 3 Number 3, 1996, on modelling fabric and garment drape. Modelling garment drape is a difficult problem which has not been successfully solving for most types

of garments. For example Hinds and McCartney (1990, 1992) propose a computer aided design system for three-dimensional design, where a garment is defined by the offset of the of the fabric from the underlying dummy. The three-dimensional image is mapped to a two-dimensional cutting pattern.

Winifred Aldrich discusses a CAD system for fashion design in her PhD thesis (Aldrich 1990). She is an experienced practising fashion designer and pattern cutter. She devised a system for expert pattern cutters, which converts hand-drawn lines into smooth curves and provides automatic evaluation, thus initiating the development of the commercial ORMUS system. In her thesis she shows that the system did not have an adverse effect on the creative potential of a group of students in comparison with a test group who did not use the system. The students increased their knowledge about pattern cutting and enjoyed using the system. Unlike the system proposed in this thesis, her system is not generative. As it enables designers to produce complete and consistent shape descriptions quickly, the system could also be used to mediate the communication bottleneck. Winifred Aldrich did not address the communication problem in her thesis.

1.5 Commercial CAD Systems

Since the late 1980s the commercial CAD systems have made enormous progress at the same time as the technical scope of the knitting machines they program has nearly reached that of hand knitting. The problem addressed by the knitwear CAD systems is primarily the programming of a knitting machine. The focus of technical development has been and still is the use of increasingly sophisticated schematic visual representations of knitted garments, from which knitting machine programs are created automatically. Computer systems are used in fashion design for the interactive creation of cutting patterns, the generation of

presentation material for customers, and for the support of the business processes of companies.

1.5.1 Knitwear Systems

Currently the technical potential of the knitting machines of different manufacturers is very similar and many machines are sold on the strength of their CAD systems. The systems are not compatible, and tie the expertise of the knitwear technicians to one machine builder. They are created to make programming the knitting machine easier for the technicians, and to enable the technicians to do more with the machines. Even though the most modern CAD systems are marketed as empowering the designer to define their designs in exactly the way they want, the technicians are still the primary users of the systems. In none of the companies that the author visited recently did designers make extensive use of the CAD system used to program the knitting machines.

The CAD systems are major capital investments. A complete system with the functionality described in Figure 1 costs at least £50 000. Companies have been using old CAD systems for a long time.

In the meantime, commercial knitwear CAD systems have become powerful intelligent systems. They have automated much of the thinking involved in programming a knitting machine, by turning a symbolic description of a structure into a machine program, i.e. they have developed compilers which translate a high level description into the older generation machine languages which in turn are compiled into machine code. In the process the systems can do clever conflict resolution. All systems translate what the user has specified rather than what the user might have tried to specify. There is no reasoning based on the users' intentions. The state of the art CAD systems of all manufacturers have the same basic components as illustrated in Figure 1.

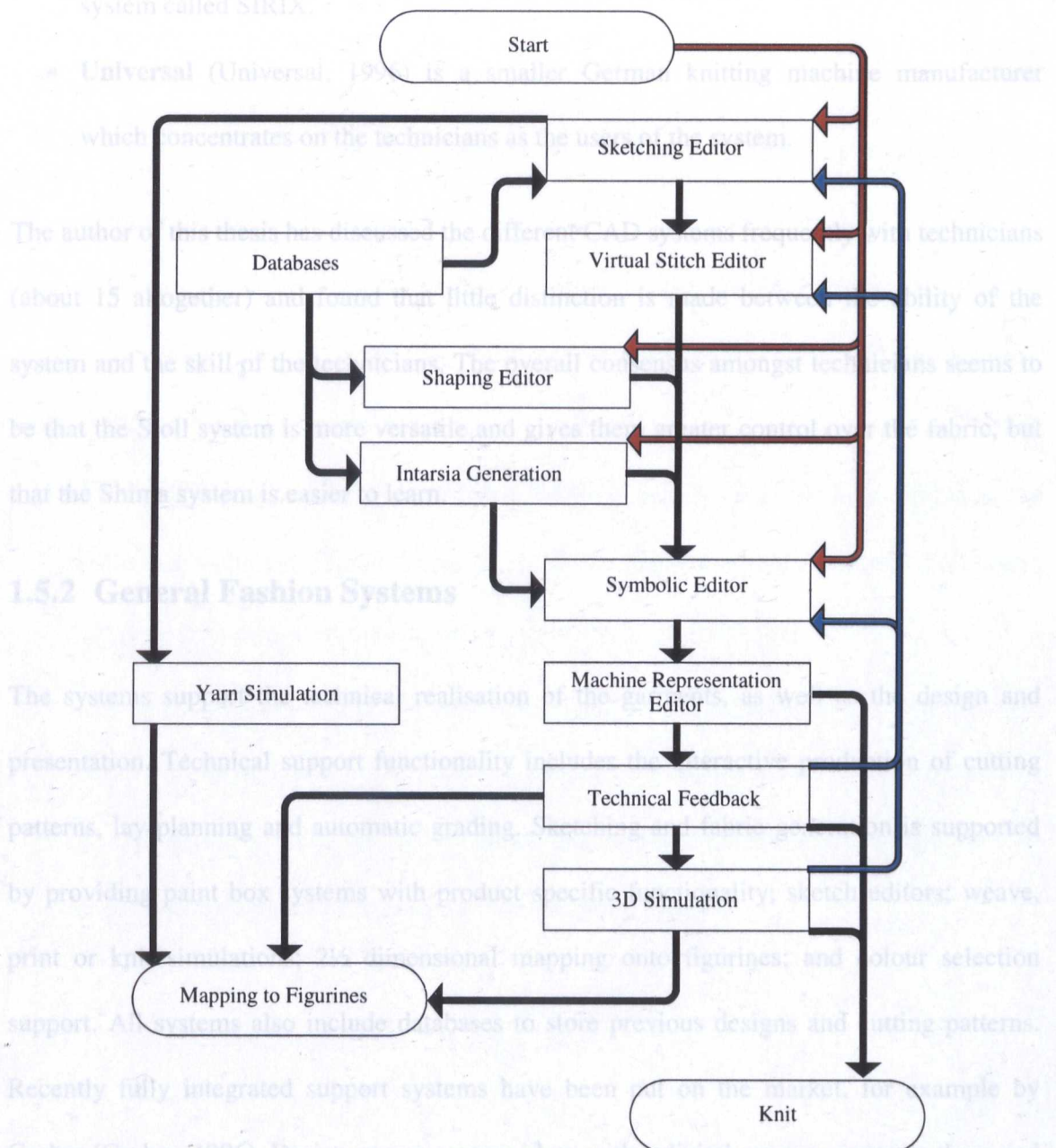


Figure 1. Components of Commercial CAD systems and their Interaction.
The red lines indicates optional starting points.

The flat bed knitting machine market is controlled by two major companies plus a few smaller ones. A summary description can be found in Daunt and Miller (1996):

- **Shima Seiki** (Shima Seiki, 1996) is a Japanese machine builder which has taken over a large part of the British market in recent years.

- **Stoll** (Stoll, 1996) is a German knitting machine builder offering a UNIX based CAD system called SIRIX.
- **Universal** (Universal, 1996) is a smaller German knitting machine manufacturer which concentrates on the technicians as the users of the system.

The author of this thesis has discussed the different CAD systems frequently with technicians (about 15 altogether) and found that little distinction is made between the ability of the system and the skill of the technicians. The overall consensus amongst technicians seems to be that the Stoll system is more versatile and gives them greater control over the fabric, but that the Shima system is easier to learn.

1.5.2 General Fashion Systems

The systems support the technical realisation of the garments, as well as the design and presentation. Technical support functionality includes the interactive production of cutting patterns, lay planning and automatic grading. Sketching and fabric generation is supported by providing paint box systems with product specific functionality; sketch editors; weave, print or knit simulations; 2½ dimensional mapping onto figurines; and colour selection support. All systems also include databases to store previous designs and cutting patterns. Recently fully integrated support systems have been put on the market, for example by Gerber (Gerber, 1996). Designers can capture ideas with a digital camera, annotate them and send them electronically to their home base. They use the two-dimensional outlines of existing garments to describe new designs and gain initial costing information from the previous design. At the same time the system provide a standard sketching environment and 2½ dimensional simulation facilities. These systems demonstrate the feasibility of the proposals made by this thesis for general textiles, which are less technically complex than knitwear. The aim of this thesis is to show that the same is possible in knitwear.

1.6 Summary

This thesis will argue that

- the knitwear design process in Britain and Germany can be characterised in the ways described in chapter 3.
- Communication between the knitwear designers, who design the garments, and the technicians, who program the knitting machines and create cutting patterns, constitutes a major bottleneck.
- CAD approaches from the fashion industry can be extended to knitwear by including technical domain knowledge. In this thesis new mathematical techniques are used to create a representation of the knitwear garment shapes.
- The proposed system will mediate the communication bottleneck by ensuring that complete and consistent information is passed between designers and technicians.
- The proposed system will allow more design iteration and release resources to create more complex designs or reduce sampling time.

Chapter 2.

Methodology for Empirical Studies

This chapter describes how the data for this analysis was gathered. The author employed an approach drawn on the practices of ethnography, together with a combination of an ethnographic approach and interviews in 20 knitwear companies in Britain and Germany, talking to and observing designers and technicians.

The study of the knitwear design and sampling process was initially undertaken as knowledge acquisition for an intelligent support system to support placing pattern elements onto the shape of a garment. The analysis of the design process and the interaction between the designers and technicians became the focus of later observations. An approach based on ethnography was chosen as a method of knowledge acquisition since it is applicable when easy and repeated access to the same domain experts is impractical.

2.1 Methods for Studying Design

Stauffer et al. (1991) point out in the conclusion of their paper on “Eliciting and analysing subjective data about engineering” that “the study of the engineering process is too complex for traditional study and analysis. Techniques from the social sciences need to be employed” and recommend that the researcher should concentrate on a small and focused problem. In a previously unstudied domain like knitwear design the latter is not an option. To identify particular problems, such as the efficiency of the communication between designers and technicians, and applications for computer support, such as pattern construction, the whole process needs to be studied.

The knitwear design process is a complex industrial process taking many months to develop a garment from design research to production: this suggests the use of a combination of knowledge acquisition techniques. This thesis looks at the potential for intelligent support of the design process, which was the original goal of the research, and so comes from an artificial intelligence starting point. The study of the design process was therefore viewed as knowledge acquisition. This was complemented by a user-centred viewpoint as taken in ethnography. In social sciences the term ethnography covers a wide range of ideological viewpoints (see Beynon-Davis, 1995, for a brief discussion of different social science approaches to ethnography). The author does not wish to become involved in this discussion. The method devised for data collection draws on the practices of ethnography, but does not belong to any particular approach. It is presented for what it is, and the quality of the data can be judged accordingly.

2.1.1 Knowledge Acquisition for Design Studies

Machine learning techniques have been applied to design studies, either after an initial analysis by a human, for example Reich (1991), or fully automatically, for example Dong and Agogino (1996) analyse design documentation to distil design concepts from it. These approaches require access to design documentation. They also assume that a reasonably complete picture of the design process can be obtained from evidence in human or machine readable forms. Large parts of the knitwear design process are undocumented, and important design decisions are not visible to anybody other than the person undertaking the design action. The author believes that it would be possible to extract procedural design knowledge, for example in pattern placing, through machine learning on records of technicians working on an existing CAD system.

Particular questions in design studies have been successfully studied using protocol analysis (Ericson and Simon, 1984). for example in architecture, (see for example Chun, 1990) or

software design (Visser, 1995). An overview of different approaches to protocol analysis in design can be seen in Cross et al. (1996). The strength of protocol analysis is giving an insight into the thinking processes of the designer doing specific design tasks. There is, however, strong evidence by Brandimonte and Gerbino (1996) that continuous verbalisation interferes with mental imagery, which is at the core of many design activities. The study described in this thesis did not address one particular aspect of the knitwear industry, but aimed to get an overall picture of the industry.

The successful application of various methods to elicit design knowledge can be seen in Magee (1987), Stauffer et al. (1991) and Tunnicliffe and Scrivener (1991). All conventional knowledge acquisition techniques, other than observation, require the undivided attention of a domain expert. This was never available. And as a design support system is used by many different people, the knowledge acquired to develop it needs to be derived from a representative sample of experts.

2.1.2 Ethnography

Meyer (1991) bridges the gap between traditional knowledge acquisition techniques and methods derived from social sciences by suggesting the use of participatory observation to gain a preliminary insight into a new domain before using more structured knowledge acquisition techniques. She quotes the following definition of participatory observation as a “field method whereby the ethnographer is immersed in the day-to-day activities of the community being studied . . . The objective of this method is to minimise the presence of the field worker as a factor affecting the responses of the people and to provide a record of observed behaviour under varying conditions” (Hunter and Whitten, 1976). The ethnographer takes a dual perspective of looking at everything from the viewpoint of the insiders while at the same time keeping an outsider’s distance (see Agar, 1980).

Meyer followed scientists and technicians around in their natural work environment. This enables the knowledge engineer to understand organisational and personality issues to provide a background for structured interviews and set tasks. Hales (1987) used participatory observation to study an engineering design process which he had been part of himself.

The special emphasis of ethnography is to observe a group from an inside viewpoint, while remaining conscious of being an outsider. Lundsteen (1987) defines ethnography as “studying and capturing of real-life processes, . . . , ways of living in that . . . context, its culture”. Speadley and McCurby (1972) define the perspective of ethnography as “instead of asking ‘What do I see these people doing?’ [the ethnographer] must ask ‘What do these people see themselves doing?’”.

Hunsaker (1992) points out the potential of ethnography in the study of creativity. Bucciarelli (1988) applies an ethnographic perspective to engineering design. He claims that representations of the design, in reports, drawings, specifications or material lists do not constitute the design as such. They are artefacts and documentation of the designs. Design for him is a social process undertaken by all participants. His study describes design activity and is not aimed at building design support systems. In the last five years ethnography has increasingly been applied to study the requirements for CSCW or HCI aspects of computer systems. In both cases the cultural factors are essential for the success of a system. In-depth understanding of the needs and thinking styles of system users, as well as their world views, is essential for the success of the system (Preece et al., 1994). These issues are exemplified in the study of air traffic controllers (Hughes et al., 1993). Their emphasis is on the importance of ethnography “to get an insight into fine grained and often ‘invisible’ aspects of work”.

The problems with an ethnographic study are as outlined by Hughes et al. (1993):

- the large amount of time invested by the ethnographer in the study;

- the diversity of the field;
- the incompleteness of the observed data.

Ethnographic studies can be highly inefficient as Stauffer et al. (1991) point out about the work of Hales (1987) “who spent 2.8 years to collect 1180 pages of field notes, 76 hours of tape recordings, 116 weekly reports, and design reports.”

The author sees ethnography as a way of developing the gut instincts of domain experts while learning about the design process and acquiring knowledge for the knowledge based modules of intelligent design support systems.

2.2 Approach Taken

The acquisition of domain knowledge for this thesis had to be opportunistic; it had to be guided by what could be learned under the circumstances of the research. The aim was to study industrial practice, to identify the needs of domain experts and gather at the same time the knowledge necessary to build an intelligent design support system meeting those needs. The author did not have access to domain experts who would participate in classical AI knowledge acquisition exercises. As noted in section 2.1., it is essential for traditional artificial intelligence knowledge acquisition to have repeated access to at least one domain expert, ideally more. However, the author found it easy to visit companies and talk to knitwear designers and technicians.

The knitwear design process had not previously been studied in detail. Technical and design knowledge in knitwear is not well described in the literature. Most of the knowledge in this thesis therefore had to be gathered from primary sources:

- Learning the skills of the trade: knitwear design, knitting on knitting machines, programming power knitting machines.

- Studies of practitioners in industry.

2.2.1 Literature on Knitting

Many books are published on knitwear. The vast majority of books are written for lay users:

- Introductions to how to knit by hand or with a domestic knitting machine, for example “The Handknitter’s Design Book” (Ellen, 1992).
- Collections of hand knitting or machine knitting pattern elements to be incorporated into the readers’ own designs, for example the pattern collection published in Burda (1988).
- Design books by hand knitting designers containing complete designs which the readers are expected to produce with few variations, for example “Glorious Knitting” by Kaffe Fasset (Fasset, 1985).

Magazines about hand or machine knitting, such as *Sandra*, mostly cover all three categories of information in all of their issues. These books and magazines contain no information about industrial practice or about the process which was used to derive the designs they present.

Specific training books for professional knitwear designers do not exist, as far as could be determined in the course of this research. Tailoring textbooks are used in the knitwear industry to teach and apply cutting pattern construction techniques. The mathematical modelling in this thesis makes use of Aldrich (1987). Textbooks on knitwear technology, for example Spencer (1989), provide an introduction to the way knitting machines work and can be programmed.

2.2.2 Learning the Domain Skills

Further sources of knowledge were knitting classes and training courses. The author attended knitwear design classes for BA and BSc students at what was then Leicester Polytechnic,

now De Montfort University, Leicester, in knitwear design, knitting on domestic knitting machines, pattern cutting for knitwear, pattern cutting for tailoring, and grading in tailoring. She further went through an intensive one-to-one training period over 52 hours with Monica Jandrisits, in pattern construction, pattern cutting, make up and finishing in knitwear. She also attended two knitting machine programming courses for professional knitwear technicians at Universal Strickautomaten GmbH in Westhausen Germany.

2.2.3 Strategy of Interaction

The knitwear industry has a tradition of students coming into companies to find out about the design process and certain design activities for BA projects. Most companies also have placement students. Like an observer these students follow the designers round and ask questions when they do not understand what the designers are doing. They already bring some knowledge to the company and have an aptitude for design. The industry considers friendly and supportive treatment of students as an integral part of its recruitment and training process. Unless not told to the contrary, everybody assumed that the author, being a young female, was a final year design student working on a BA thesis.

Most research was conducted according to the same pattern. The author worked out the issues and questions she was interested in before the beginning of the meeting. A worked out set of questions were used for the first group of company visits. These were inspired by the FOCUS methodology, which concentrates on participants and their tasks and interactions, developed at Loughborough University (Rousseau 1991). However, these questions were only used when the flow of natural conversation came to a pause. Even though the author volunteered often just to sit and watch the designers and technicians, they insisted on conducting a conversation and explaining their actions. The author tried to encourage them to speak as freely as possible about whatever they liked. At the same time she encouraged the experts to talk her through the overall process and to discuss practical examples. The

author tried to get experts to comment on issues raised by people she has previously spoken to. The interviews were steered by the author starting with very general questions and leading towards more focused questions and suggestions if necessary:

- initial warm up conversation, for example brief description of the range of designs produced in the company;
- encouragement to speak about the tasks of the expert in general terms, for example the overall design process;
- focusing on a sub-task, for example shape design;
- discussion of a particular design;
- encouragement to elaborate further about possible problems in undertaking this sub-task through a general remark, for example mentioning buyers from retail chain;
- specific questions about problems and interfaces to other sub-tasks;
- specific questions about interactions with other members of the company working in the design and sampling process;
- the author analyses the sub-task or draws on discussions with other experts and asks about specific problems, for example the definition of raglan sleeves;
- the author describes her analysis of problems and asks the designer to comment;
- the author volunteers her possible solution suggestion to draw comments from the designers and falsify her hypotheses.

In many cases detailed information was only obtained when the author asked very specific questions. From dealing with visiting placement students the experts are used to questions of the kind “I always find it difficult to do” ; or “I could imagine that I might get stuck here”. They are very happy to help and teach a novice.

2.3 Observations and Interviews

The section describes the author's contact with designers through company visits, interviews and social activities.

2.3.1 Company Visits

The visits to companies and observations of designers in practice underlying this thesis were undertaken in three phases. Unless indicated otherwise, the companies design and sample garments in house. The companies are listed in Table 1 in the chronological order of the visits.

During the early visits to design companies in German and Britain in 1991 and 1992, the author was working full-time on her PhD research. Most companies were visited for about half a day as a student studying the use of computers in the knitwear industry. The focus of the study was to understand the use and acceptance of CAD systems in industry, to establish which parts of the design process might benefit from computer support, and to gather knowledge to build support modules. The author talked primarily to knitwear technicians as the prime users of CAD systems. The visits of 1996 were undertaken as part of a research project concentrating on the early stages of the design process: design research, planning of a collection and design of garments. Mansfield Ladieswear was an industrial collaborator on a research project (Eckert and Murray 1993); and as such was the only company which had consciously entered a knowledge acquisition process.

	Name	Time	Short Description
	Germany		
C1	Canda Ulm	3/92	top and medium range supplier to C&A in Germany. The designs range from standard designs to technically demanding garments.
C2	Dino Valiano Pappenheim	3/92	manufacturer of expensive ladieswear collections of knitwear and wovens.
C3	März Munich	3/92	manufacturer of good quality expensive garments.
C4	Kimmerle	3/92	supplies the bottom end of the C&A market. The garments are designed by the technician as quick responses to fads.
C5	Holzschuh	3/92	supplies cheap German mail order companies using a freelance designer.
C6	Bogner Munich	3/92	manufactures coordinated fashion and sport ranges in knitwear and wovens.
C7	ESCADA Munich	4/92	one of the world's leading fashion companies and gives great importance to knitwear
	Great Britain		
C8	Stuart Mensley Sysby	6/92 5/96	supplies the retail chains at the lower end of the market. Many designs are simplified versions of other designs.
C9	John Smedley Matlock	6/93	produces own label fully-fashioned knitwear from their own yarns.
C10	Mansfield Menswear Loughborough	7/92 9/92	supplies menswear to Marks & Spencer.
C11	Mansfield Ladieswear Alfreton	6/93 - 10/93	supplies ladieswear to Marks & Spencer and are one of Europe's largest knitwear manufactures.
C12	Cooper & Row, Sutton in Ashfield	3/96	supplies fully-fashioned knitwear to Marks & Spencer.
C13	Jaeger London	6/96	produces high end of the market own label collections of knitwear and wovens.
C14	Charnos Ilkeston	6/96 10/96 11/96	supplies ladieswear and menswear mainly to Marks & Spencer.
C15	Turner & Jarvis Broughton Astley	6/96	samples and produces for Next and other chains. The designs are mainly supplied to them.
C16	Courtaulds Knitwear Mansfield	6/96 9/96	supplies ladieswear to Marks & Spencer.
C17	Lyle & Scott Hawick	9/96	manufactures own label golf and leisure knitwear.
C18	Pringles Hawick	9/96	manufactures own label golf and leisure knitwear.
C19	Ballantyne London	10/96	manufactures very high quality garments.
C20	Zoë Mellor London	10/96	independent hand knitting designer.

Table 1. Visited Companies

2.3.2 Data Recording and Reporting Convention

The companies are coded with a reference code, as introduced in Table 1, that is used in the footnotes. The companies are numbered C1, C2, etc. The participants in the design process also have distinct labels shown in Table 2. Head designers and head technicians are included in the count of designers and technicians. Within each company the participants are numbered within each group; e.g. C1FT2 stand for the second fabric technician in the company C1.

Abbreviation	Person
D	Designer
HD	Head designers
FT	Technicians (FT for fabric technician)
ST	Pattern Maker (ST for shape technician)
DA	Design Assistants
M	Managers

Table 2. Participants in the Design Process

The contact with practitioners was a combination of observations and interviews depending on the preference of the company. Some companies¹ did not feel comfortable with an outsider seeing their work in process, others² felt that a formal interview was a better use of the available time. These will be referred to as formal interviews (FI). During observations (O) the author has always³ been encouraged to ask questions. These informal interviews are referred to as (I).

¹ C6
² C12, C13,C16 (but allowed a subsequent visit), C18,
³ No exceptions.

Code	Name	Type of Visit	Contact Time	Number of Designers	Number of Technicians		People spoken to
					Fabric	Shape	
C1	Canda	O/I	2 ½ h	?	2	?	M1,FT1
C2	Dino Valiano	O/I FI	5 h	3	2	2	HT1, FT1,FT2, ST1,D1
C3	März	O/I	4 h	3 or 4	4	?	FT1, DA1
C4	Kimmerle	O/I I	3 ½ h	FT designs	1	1	FT1,M1
C5	Holzschuh	O/I	2 ½ h	1 freelance	1	1	FT1,M1
C6	Bogner	FI	1 ½ h	?	?	?	HT1
C7	ESCADA	O/I		?	3	?	FT1,M1
C8	Stuart Mansley	SV IF	2h 1 ¼ h	3	3	?	HD,D1
C9	John Smedley	SV	2h	?	?	?	guide
C10	Mansfield Menswear	SV O/I	2h 5 days	7	5	1	HD,D1,D2,D3, D4,HT,FT1, FT2,FT3,ST1, MU,M1,DA1-3
C11	Mansfield Ladieswear	O/I FI	2 days 4 hours	7	7	2	HD,D1,D2,D3,H T,FT1,FT2, FT3,ST1, DA1,DA2
C12	Cooper & Row	FI	1 h	?	?	?	HD
C13	Jaeger	FI	1 ¼ h	?	?	?	HD
C14	Charnos	FI, O/I	10 h	7	5	-	HD,D1,D2,D3,D 4,D5,DA1+2
C15	Turner & Jarvis	O/I	6h	3	3	-	HD,D1,FT1, MU, M
C16	Courtaulds	FI O/I	1 ½ h 5 h	5	?	?	HD,D1,D2,D3,D 4,DA1
C17	Lyle & Scott	O/I, I(pu b)	3 days	3	4	1	M,D1,D2,D3, DA1,FT1,FT2,M U, Finance
C18	Pringles	FI	1 h	5	4	?	HD
C19	Ballantyne	FI	1 h	1	?	?	HD
C20	Zoë Mellor	FI	2 h	1	-	-	D

Table 3. Overview of visited companies with reference code

Questions were asked mainly at natural breaks in the workflow or while the practitioners were not involved in problem solving tasks. For example, while waiting for the knitting machine to knit a sample⁴ or while cutting out fabric swatches⁵. Student visits are marked (SV). The main person observed is marked in bold. Participants in formal interviews are in italics.

2.3.3 Individual Designers

In the course of the research the author befriended various knitwear designers and talked to them on numerous occasions socially. The comments of these designers reflect their own experience in different companies as well as their friends' experience.

Monica Jandrisits (ID1) had her own designer label company in Canada after graduating in fashion design. She came to Britain to do a BSc in Knitwear Design and Technology while working freelance for a small knitwear company in Leicester. Subsequently she was employed as a designer for babywear and as an assistant to the sales director for a large Marks & Spencer supplier.

Annabel Duncan (ID2) worked as a fully-fashioned designer in Scotland after a degree in Fashion Design before working for Jaeger. Later she worked as a freelance designer and part-time design lecturer at De Montfort University.

Wendy Nicolson (ID3) worked as hand knitting pattern designer for a spinner before doing a BSc in Knitwear Design and Technology. She worked as a freelance hand-knitting designer and for different small textile firms. She is now a secondary school teacher.

Jane Taylor (ID4) graduated in Knitwear Design and worked as a knitwear designer before joining C15. She is now a head designer.

⁴ C10FT1

⁵ C12D1+ID2

2.4 Methodological Considerations in Data Collection

Research such as that reported in this thesis is always subject to the criticism that the researchers are influencing the people being studied, that the researchers may be selective in what they record, and that the researchers present interpretations as primary data.

2.4.1 The Problem of Selective Recording

All observation is ultimately subjective, and one assumes that scientists record what they see and hear as honestly as possible. Even so, decisions must be made as to what is relevant and what is not. Even when researchers are trying to be as inclusive and atheoretical as possible, they are influenced by their assumptions. Inevitably therefore, the observers will be selective in what they record.

The usual way to address this problem is to keep a contemporaneous record of the observations and interviews. This includes

- use of videotape,
- use of audiotape,
- keeping verbatim notes,
- keeping summary notes.

The ideal is to have all these records. The reality is that some or all may be impractical in the field. Any of these methods can be intrusive and detract more than they add. Being recorded can influence what people are saying, unless they are entirely comfortable with it. Conspicuous notetaking can be even more intrusive; it may affect people's emotional reactions to being observed or interviewed. While taking extensive verbatim notes the researcher might miss other things. Producing verbatim records of conversations is a difficult task requiring skills few people have. Summary notes may be very valuable but they are necessary selective and biased by prior expectations; most useful notes may be as much an

interpretation as subsequent reports are. Notetaking can easily distract the researcher from observing the situation in its fullness; there is always a trade-off to be made between the accuracy of concurrent record taking and the fullness of the observation itself.

2.4.2 The Problem of the Researcher Influencing the Interviewee

How people answer particular questions depends not only on the individual, but also according to their expectations of the interviewer, the context, and how the questions are phrased. In the face of this the best a study can achieve is to record the questions and how they are asked so that they may be assessed by subsequent researchers. Ways to achieve this include:

- Preparing questions before data collection, making its purpose clear.
- Avoiding making suggestive remarks or leading the interviewee.
- Recording one's impression of the meeting which may help subsequent researchers to detect bias.
- Audio or video recording the session, thereby allowing subsequent researchers to detect bias by studying the original tapes.

Although the last of these not always be feasible, the first three should always be possible. The last two strategies give information about the data being collected.

There is, however, always a trade-off between following a protocol and getting the most information out of contact with interviewees. Questions need to be phrased so that individuals can understand them, and different people respond to different phrasings, so the questions might not be comparable between subjects. An explanation of a question might already be leading the subjects towards particular answers. There is a trade-off between the strictness with which an interview protocol is adhered to and the amount of information gathered from the interviewee. In the author's experience, elicitation of knowledge and information works best by guiding a free conversation according to a previously planned

agenda, often by rephrasing a question or asking it in a different context until it elicits a response. There is also a trade-off between the time and subject contact used to work out appropriate questions, that can be understood by most subjects and be posed in a sensible order, and the time and resources available for other research.

2.4.3 The Researchers may Present their Interpretations as Data

Researchers' interpretations may distort the information conveyed to them by the interviewees. For example, a researcher may record that 'x said "such and such"'. This is data, assuming that x really said precisely "such and such". On the other hand the researcher may observe that every time a "busy" design appears, the interviewee reacts negatively. The researcher may then record that "x does not like busy designs", but this is an interpretation based on the observed facts (which may not be explicitly recorded).

To avoid this problem researchers can adopt the following strategies:

- Try to record direct quotations as far as possible with the greatest possible accuracy.
- Try to make it clear when an interpretation is being offered as opposed to a quotation.
- Keep an audio or video record of the interview to allow questions and answers to be checked and tested against any interpretation.
- Make a return visit to present the interpretation to the interviewee to see if they agree that the interpretation is correct.

2.4.4 The Generalisability of the Findings

Contact with subjects for interviews or observations is often opportunist. Researchers have to interview the people who they can access and who are willing to talk to them. During an observation researchers see particular tasks for a certain length of time. There is great danger in generalising from isolated interviews or observations. It is important to identify whether assertions derive from the personality of the interviewee, the peculiar features of the problem

under discussion, or features common to all problems of a particular type. Generality can be assessed by a variety of measures:

- Repeating observations in the same company at different times.
- Observing or interviewing other individuals and companies in a similar situation.
- Discussing the same issue and observing the same task with other parties involved who can comment on their side of the story.
- Eliciting as much background information and domain knowledge as possible to place assertions into context.

In many cases it can be impractical to repeat observations or gain access to different parties who could comment on interviewees' assertions and allow comparisons. However, assessing the generality of the findings by comparing companies, including direct competitors, was a vitally important part of author's research strategy.

2.4.5 Approach taken in this Thesis

When collecting data by interview and observation there will always be problems of objectivity and data reliability. The ideal approach does not deny that these problems exist, but attempts to mitigate their effects as far as possible. A major element in this is keeping objective contemporaneous records as far as possible. These allow the researcher's report to be checked by subsequent researchers, and thereby validated or criticised.

Unfortunately the ideal cannot always be achieved; sometimes lack of resources limit what can be done; sometimes the situation does not lend itself to the ideal. For example, interviews and observations undertaken in noisy environments⁶ may make audiotaping impractical. Also, these methods are sometimes obtrusive and frequently inappropriate on early visits before trust has been built up between interviewer and interviewee.

⁶ C1, C2, C3, C4, C7, C10 interviews were partly conducted in machine rooms.

Much of the data reported in this thesis is not supported by audiotapes and videotapes⁷, although some of it is. This data is recorded in extensive notes written up after the interviews. Every time a statement or assertion is attributed to an interviewee, it is identified by a footnote. In principle it would be possible to trace each person, and ask them the same question again. To this extent the research is replicable, although of course practical consideration may make this difficult.

Throughout this research the emphasis lay on collecting as much information as possible about a wide range of issues, with the aim of understanding the knitwear design and sampling process in its entirety while acquiring domain skills. The author aimed to make subjects comfortable about talking about their work in familiar patterns of interaction:

- Talking to the researcher as a placement student or apprentice;
- Talking to the researcher as an understanding outsider.

The subjects were encouraged to talk freely about whatever subjects they chose. For example, one technician provided a very interesting explanation about problems with production in different countries as part of a monologue about his worries about the collapse of the Soviet Union⁸.

The research in this thesis has gone beyond the collection of data from which conclusion can be drawn. The author has at least partially turned herself into a domain expert, and developed an inside understanding of the entire working culture.

⁷ See footnotes 15 and 16.

⁸ CIFT1

2.5 Scope of the Observations

The selection of companies and interaction approaches has been opportunistic. It would have been preferable to do more observations instead of interviews. Some companies⁹ did not wish to take visitors into their work environment, others felt that an interview would be a more time efficient way to explain their design process¹⁰. Observations were most successful when the designers¹¹ understood the basic idea of scientific research and understood what observations were for. Some designers¹² felt very uncomfortable being observed.

The research has covered a wide range of companies from the low end of the market to the top end¹³. As far as possible the author attempted to talk to direct competitors to compare the design process for the same market and price point¹⁴. The process described in chapter 3 follows the general pattern across the industry. At this level of description there is very little variation. The details vary in different company depending on the product and the personality of the individuals. Some of the company visits have been recorded in audio tapes¹⁵ and video recordings¹⁶.

Despite these considerations about a quarter of the major British and German knitwear companies have been visited. This is a much larger sample then exists in most of the literature, and therefore the survey is likely to be representative of the whole industry.

⁹ C6, C13, C19

¹⁰ C8, C18, C12, C16 first visit.

¹¹ C14HD, C17D1+D2. (C17D1 is very interested in psychology).

¹² C16D2+D3 expected the author to be a spy for M&S in spite of repeated assurances to the contrary.

¹³ C1, C4, C5 and C8 are supplying to mail order companies and cheaper retail chains. C3, C15 and C17, C18 are producing mainly for the medium price range. C10, C11, C12, C14, C16 mainly supply M&S.

C19, C13, C9, C7 produce very high quality knitwear under their own label and are generally considered to be among the market leaders. C20 is a hand knitting designer.

¹⁴ C14 and C16 both supply M&S ladieswear in the same price bracket, all M&S suppliers work under the same pressure. C17 and C18 supply the golf market.

¹⁵ C16, C17, C18

¹⁶ C14

Chapter 3.

The Knitwear Design Process

Section 3.1 provides statistical information and outlines some of the main pressures faced by the knitwear industry. The knitwear design and sampling process is described from the beginning of fashion research for a new season to the sale of sample garments. The efficiency of this process in current industrial practice is discussed.

3.1 Background Information about the Knitwear Industry

The knitwear industry is one of Britain's largest industries. Like the rest of the textile industry it is under pressure to produce to tight price points and delivery dates.

3.1.1 Statistics

The textile industry is the fifth largest industry in Britain. The knitting industry is a very large part of the textile industry. The term knitting industry usually includes: knitted fabrics, which are used in clothes and other applications with a production value in 1994 of £541,000,000; hosiery such as socks with a production value of £499,500,000; and knitwear with a production value of £896,900,000; and other types of knitted outerwear and underwear. In 1993 the United Kingdom had 352 establishments listed under knitwear with 30,300 employees. (All statistical figures are quoted from *Knitstats 1993-1994* (Knitting Industries Federation, 1996), which defines knitwear as comprising sweaters, jumpers,

pullovers and cardigans. Some knitwear companies also produce other knitted garments such as dresses, trousers and hats.)

3.1.2 Commercial Pressures

The knitwear industry is under constant financial pressure from:

- Imports from other countries. The average manufacturing price of a knitwear item is £9.55 in the UK compared to £4.23 in other European countries and £4.67 in the rest of the world. This is not an entirely fair comparison as many imported products are comparatively simple garments. However, there is a trend of moving production to overseas countries, especially the Far East and Turkey.
- Expensive fast-changing technology. Within the last ten years knitting machine and CAD system technology has changed completely and made a greater variety of stitch structures possible. Many companies¹⁷ have largely replaced their machine stock in this period. A knitting machine with a CAD system costs in the order of £100,000¹⁸. A machine on its own costs about £65,000.
- Labour shortage for production. In the traditional textile areas of the East Midlands and the Scottish Borders there is a shortage of skilled production staff at the rates the companies are willing to pay (£4.41 on average per hour for a female employee).
- Increasing yarn prices through tougher environmental legislation.

Fashion changes also put pressure on the industry: -

- Fashion changes require different skills and machinery. For example in the late 1980s and early 1990s embroidery was very fashionable. Designing embroidery requires

¹⁷ C2, C11, C16, C17, C18 all other companies had modern machines.

¹⁸ Prices quoted by Stoll in February 1997

textile design skills and expensive machinery¹⁹. Now the fashion emphasis is on shapes, so manufacturing knitwear requires tailoring skills.

- Fashion has a tight deadline. The new season's garments must arrive in the shop at the beginning of the season after the sales. The earliest manufacturer often gets the window space²⁰.
- Many samples are produced which are never manufactured. Producing samples is a major drain on resources, especially for the Marks & Spencer suppliers²¹ who produce about fifty samples in order to sell about four garments, at an estimated cost of over £1000 per sample. The sampling costs remain with the manufacturers.

¹⁹ For example, C17 bought an embroidery sample machine and production machines, which are now hardly used.

²⁰ C3DA1

²¹ C14HD

3.2 Overview

This description follows the development of a garment from the fashion research for the initial idea to the sale of the sample garment. Industrial practice varies enormously, but the fundamental structure described here was observed throughout the industry. This process stretches over up to 1½ years. The process is described using the terminology of the domain and does not follow any particular model of the design process. The description focuses on companies who design for retail chains, as is typical for British companies²².

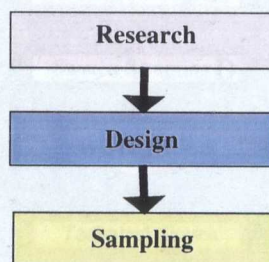


Figure 2. Basic Stages of the Knitwear Design Process

The knitwear design process has three distinct phases:

- fashion research, where information is gathered about how the garments will look and the fashion context;
- design, where the visual and tactile appearance of the garment is designed;
- sampling, where a design idea is realised as a swatch or a garment.

²² C10, C11, C12, C14, C16 supply M&S; C8 supplies Littlewoods and Burton Group; C15 supplies Next. C8, C13, C17, C18, C19 produce own label designs. They are comparatively smaller, but have been contacted because they are known as brand names.

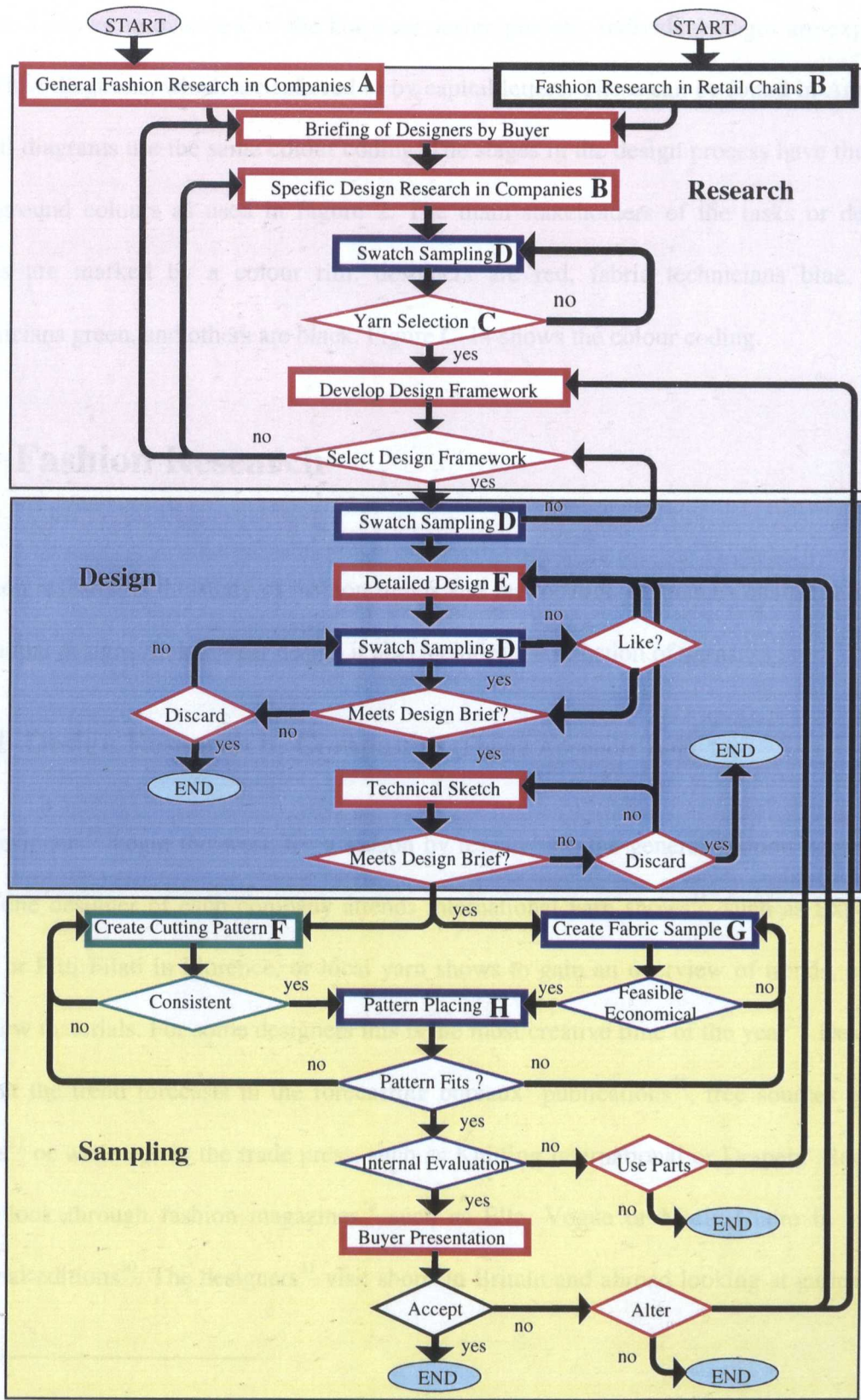


Figure 3. Overview of the Knitwear Design Process

Figure 3 shows an overview of the knitwear design process. Individual stages are expanded into flow diagrams, which are referred to by capital letters. These can be found in Appendix A. All diagrams use the same colour coding. The stages in the design process have the same background colours as used in Figure 2. The main stakeholders of the tasks or decision points are marked by a colour rim: designers are red, fabric technicians blue, shape technicians green, and others are black. Figure C-14 shows the colour coding.

3.3 Fashion Research

Fashion research is the study of fashion trends and the location of sources of inspiration for individual designs. In knitwear design it also includes the selection of yarns.

3.3.1 Design Research in Companies (Figure Appendix A-1)

All designers²³ begin the work for a season by researching the general fashion context. At least one designer of each company attends international yarn shows²⁴, such as Expofil in Paris or Pitti Filati in Florence, or local yarn shows to gain an overview of trends, colours and new materials. For some designers this is the most creative time of the year²⁵. Designers look at the trend forecasts in the forecasting bureaux' publications²⁶, free sources at yarn shows²⁷ or write ups in the trade press, such as Knitting International or Drapers' Record²⁸. They look through fashion magazines²⁹ such as Elle, Vogue or Marie Claire in various national editions³⁰. The designers³¹ visit shops in Britain and abroad looking at garments of

²³ No exceptions; even designers in C15 who don't design garments present a summary of trend and idea swatches to buyers.

²⁴ C10HD, C12HD, C13HD, C14HD, C15HD, C16HD, C17D1+D2 (C17 works one season ahead of other companies and only confirms choices), C18HD, C19HD

²⁵ C14HD

²⁶ C17, C18, C19

²⁷ C14HD

²⁸ C17D1

²⁹ No exceptions

³⁰ C16D3, C17D2, C11D1

leading companies and their own direct competitors, often in combination with yarn shows or other fashion shows³². From this the designers gain an overview of the trends for a common season. They discuss these among themselves³³.

3.3.2 Design Research in Retail Chains (Figure Appendix A-2)

A very similar research process³⁴ occurs in parallel in the retail chains when they are working out their ranges for a coming season. The retail chain needs to offer a coordinated range appealing to a cross section of their customers. The garments need to be novel while fitting into existing wardrobes. The designers and buyers employed by the retail chains attend yarn and fabric shows and fashion shows to see emerging trends and study forecasting materials. In recent years there has been an increasing trend in some retail chains to sell garments which are similar to designs that were a success under a design label. Each retail chain³⁵ produces its own fashion prediction material which sets a framework for all their suppliers, based on:

- predicted future fashion;
- successful designer label garments on sale;
- success of previous lines;
- classic themes.

For example, Marks & Spencer develops four or five fashion themes expressed by mood boards with an overall colour palette of about 40 colours³⁶. In addition the buyers develop briefs for the type of garments they would like produced. The briefs can vary from fully worked out designs to leaving the choice to the designers³⁷. In most cases the buyers give a

³¹ No exceptions

³² C10D2, C17D1, C15HD, C16HD, C11HD, C18HD, C19HD

³³ C10 observed, C11HD, C12HD, C13HD, C14HD, C15HD, C16 observed, C17D1, C18HD

³⁴ C15HD, C10D1, C14HD

³⁵ Seen in C10, C16

³⁶ Seen in C16

³⁷ C15HD receive design to sample from next, but also have other buyers saying "knit something my customers will like".

brief description of the garments³⁸ they would like to see, for example two fair isle sweaters, two intarsia sweaters etc.

3.3.3 Briefing of Designers by Buyers

The retail chains work with different suppliers. Each supplier is given the retail chains' forecasting material to place their designs into context. This is a two-way suggestion process³⁹: the buyers give briefs to companies, but also expect design suggestions from the companies. The briefs are often given to more than one company⁴⁰. Occasionally the order to produce a garment is given to a different company from the one which produced the design, if the retail chain tries to keep all its suppliers equally occupied⁴¹.

3.3.4 Specific Research for Themes

Once the companies have received specific themes from retail chains they research within these themes⁴². The themes are evaluated for their applicability to knitwear and are placed in the context of the house style and previous successful sales. The designers look again through magazines or their own previously collected clippings for suitable examples. Within themes they also look at artefacts, artwork or natural objects which could be used to set the context for designs or serve as direct inspirations for a design or part of it⁴³. For example for a "William Morris" theme⁴⁴ designers would look at books of designs and pre-Raphaelite paintings as well as flower or nature books. Some companies can also make use of their own design history and reuse features of old designs⁴⁵.

³⁸ C10M1

³⁹ C11HD, C14HD, C10HD

⁴⁰ C11, C14 and C16 directly compete for M&S ladieswear, C10 and C16 for M&S menswear

⁴¹ C14HD, C16D1 both commented on getting each others orders.

⁴² Process explained by C10D2, who showed the author M&S briefs (in confidence).

⁴³ C10D2, C17D1 and observed C17D3, C16HD+D1+D2.

⁴⁴ Theme was suggested by D13HD as a possible theme for 1997 on V&A exhibition.

⁴⁵ C18 has a complete history and uses 1930 and 1960 features in current fashion.

The designers produce sketches of garments and a scrap book of images by tearing pages out of magazines and books, and stick them up in their offices⁴⁶. Designers discuss their findings with each other. As this process happens in parallel with the selection of yarns the designers begin to have simple swatches of the type of yarns they would like to use. When the company has reached a consensus a designer produces mood boards to express the themes selected for further work using⁴⁷:

- a picture to set the context for the theme (optional);
- magazine clippings of garments that fit the theme;
- sketches of possible garments;
- swatches or little bows of yarn.

The mood boards express the mood or feel⁴⁸ of the theme and set the context for the design of individual garments.

3.3.5 Yarn Selection (Figure Appendix A-3)

The specific design research goes hand in hand with the selection of yarns for a new season. The designers⁴⁹ pick up yarn cards at the big yarn shows, Expofil and Pitti Filati, and receive others directly from the spinners. Yarn cards include yarns wound round cardboard and often little swatches, which can be very innovative, and sometimes photographs or artwork to tie colour ranges together⁵⁰. These yarn cards enable the designers to gain an overview of the coming colours, materials and structure trends. Initially designers select yarn independently of the price point or material to encapsulate a feel⁵¹. They analyse the feels and weights of yarn relevant to their themes and customers⁵². If they have decided on a type of yarn they begin looking for specific colours. They often try to find a cheaper version from their own

⁴⁶ Seen in all offices that were visited.

⁴⁷ These are often pinned up in offices, e.g. C14, C10, C11, C16, C15.

⁴⁸ The terms mood or feel are used in the domain and are extremely difficult to unpack and define.

⁴⁹ C10D1, C11HD, C12HD, C13HD, C14HD, C15HD, C16D1, C19HD

⁵⁰ For example Lister Yarns, Courtaulds Yarn.

customary suppliers⁵³. Sometimes designers develop yarns in collaboration with spinners based on expensive yarns they have seen⁵⁴. The yarn selection is narrowed down to a few different types of yarn (5 - 10) and a small range of colours (2 - 6)⁵⁵. Only companies which knit plain classical garments have large colour palettes in one quality⁵⁶.

Most companies try to maintain continuity in their yarns and only include a few new yarns every season using tested yarns in new colours for the bulk of their work⁵⁷. British designers often look at yarns from Italy and France for inspiration, but rarely buy yarn other than from their customary suppliers. Individual yarns are selected for:

- their feel and appearance, which is a subjective decision of the designer;
- their price;
- their technical properties.

Technical properties, feel and appearance are tested in swatches, see below.

3.3.6 Development of a Design Framework

From the beginning of their design research, designers are thinking in terms of completed garments, which they can visualise⁵⁸. As the research process progresses the mental images and sketches created while looking at sources of inspiration become more specifically geared towards a target. They still represent placeholder garments. With the themes set and the yarns selected the designers work out a framework for the specific designs in a season⁵⁹. They decide on:

⁵¹ C14HD, C10D1, C17D1

⁵² Observed in C14

⁵³ C14HD, C11HD, C10D1; only top range company such as C13 or C19 can buy yarns when they like the look of them and pass the cost on to the end product.

⁵⁴ C17D1

⁵⁵ Seen in C10, C11, C14, C16

⁵⁶ C17, C18

⁵⁷ C10HD, C11HD, C14HD

⁵⁸ C17D1+D2, C16D2, C14HD+D4

⁵⁹ C6, C7, C8, C10, C11, C12, C14, C16

- the style of garments
- yarns for each style
- the type of patterns.

For example within a menswear collection for the summer a company might decide to produce two polo shirts in cotton/tactel with small cable patterns⁶⁰.

The selection of garment styles produced by a company varies little from season to season, but new styles are included for fashion features⁶¹. Continuity in the design framework assures reasonably stable use of production resources. The design framework is worked out by the designers in each specific area, such as menswear, and the head designer, in discussion with other designers. Technicians or production staff are not included in the decision making process⁶².

The design framework is expressed in mood boards with swatches in the right yarn with a plausible structure. These are presented officially to buyers together with a verbal explanation. The designers receive initial feedback on possible designs and buyer preferences from the buyers' comments on the prototypical designs⁶³.

3.4 Design

The distinction between the design and sampling stages in the process is not clear cut. When designers research a new season they think in terms of designs; when they are designing specific garments they do more research.

⁶⁰ Seen in C14

⁶¹ C17D1, C11HD

⁶² Never mentioned in context of design research at all other than swatch sampling for yarn selection.

⁶³ All M&S suppliers

3.4.1 Swatch Design (Figure Appendix A-4)

Swatch design begins with the selection of yarn and continues until a season is finished. Most of the swatch development occurs once the design framework has been established. Often designers create fabric swatches independently of specific garments they are used in later⁶⁴. The design process and the specification of swatches depend on the type of fabric created:

- Colour patterns are typically designed by the designer in some detail on graph paper or directly on a CAD system. Colour patterns are mostly designed specifically for a garment. Figurative or ornamental patterns are often based very closely on a source of inspiration⁶⁵. Designs with colour blocks are often designed *ab initio* by the designers based on general styles from magazines⁶⁶.
- Structure patterns are often selected from a pattern book or adapted from other garments. As section 4.3.1 will show, structure patterns are hard to describe and designers often understand the visual effects but not the technical realisations. A new design is often described as a variation of an existing design. Cable designs are often sketched⁶⁷. Fabric effect patterns achieve an overall effect for a piece of fabric. Designers either work them out in great detail⁶⁸ and specify the effect accurately; or only give very brief specifications, such as “crochet effect”⁶⁹.

The designers select as a starting point for the design of a swatch either an image or another piece of fabric; and specify it as a knitted fabric. Designers comment that the transformation process is often instantaneous⁷⁰. Ideally designers would like an opportunity to explore

⁶⁴ C10, C14, C10. Whether designers design fabric separate from the shape also seems to depend on their background. According to C11HD and C14HD designers with a background in fabric design work on swatches initially. Trained fashion designers think about the garment as a whole.

⁶⁵ All designers comment on this. Observed in C10, C17

⁶⁶ All comment, especially C3DA1, observed in C10

⁶⁷ Observed in C11, C17, commented on by most designer and technicians.

⁶⁸ D1

⁶⁹ C10T1

⁷⁰ C16HD+D1+D2, C14HD+D1, C17D1+D2

design ideas as fabrics, try out many fabrics and evolve ideas until they are happy with them. In practice they rarely have the time to do so. Some companies have placement students working with domestic knitting to design swatches, in particular to work out colour combinations and balances⁷¹.

Swatches are selected and evaluated internally⁷², and sometimes also shown to buyers.

3.4.2 Garment Design (Figure Appendix A-7)

In garment design the designers work out the visual and tactile appearance of an individual garment. It is closely linked with swatch design. Garment design can be driven by swatches, by specific shapes or by the desired overall appearance of the garment. Overall designs need to be worked out as complete garments and have no distinct swatch sampling stage. Some garments are only designed when the technical sketch (see section 3.4.3) is worked out⁷³. Current fashion places importance on the shape of the garment with relatively plain fabric. Structural features are often used to enhance the shape. These garments are mainly designed during the garment design stage.

Designers need to work out the balance of the patterns, shapes and colours on a person. The most modern computer programs allow the creation of knitting simulations from fabric specifications and map these onto figurines. However, this is not yet used much in the design of garments, but rather in their presentation to outsiders.

Often designers do their creative designing at home or after hours⁷⁴. Some designers design all their garments in one big burst of creative energy⁷⁵. Some designers produce sketches as part of the idea generation process. Others only sketch to communicate ideas.

⁷¹ C10, C16

⁷² C3, C6, C7 have formal selections, C10, C1, C14, C16 have informal meetings.

⁷³ C10

⁷⁴ C16HD+D1+D2, C17C1+C2, C14HD, D1, D2

⁷⁵ D2

3.4.3 Technical Sketches

A technical sketch is the formal specification of an individual garment. At this point the design enters the formal system and is recorded and accountable for⁷⁶. No previous design efforts are recorded⁷⁷ other than through mood boards. Figure 4 shows a typical industrial example of a technical sketch⁷⁸. The technical sketch typically includes:

- a brief verbal description, such as *Ladies A line Tunic*, describing the overall garment, and a description of the neckline, such as *small blanket edge neck*, and the sleeve shape, such as *shaped*. On this level the descriptions are accurate. Missing information is implicitly filled in by default values. For example, it is assumed that the neck is a round neck.
- technical specifications for yarn, gauge and make up.
- a set of measurements to describe the broad dimensions of the garment. Designers take these measurements from previous garments or guess them. The measurements are often incomplete, inconsistent and inaccurate⁷⁹.
- a two-dimensional outline sketch of the garment. It shows the garment spread out flat unlike sketches on mood boards, which have the arms hanging down. The main purpose of this sketch is to indicate the relative positions of pattern elements on the garment shape. As can be seen from Figure 4, the sketches are rough and often not even symmetrical.

In addition the technical sketch can include:

- sketches of shape details, such as necklines or pockets⁸⁰.

⁷⁶ Explained in detail by C10. Only then a garment has an official number and finance is informed. Records are kept for two years (C10, C14). Only sample garments are kept longer (C10, C11, C14, C17, C18).

⁷⁷ No company mentioned any records of sketches. C14HD commented records are in designer's head.

⁷⁸ C11, the author has seen the same form in other companies: C14, C10

⁷⁹ See example. Also C11D1+ST1, C10ST1, C2ST1

⁸⁰ Seen in C11

- information to communicate the fabric (see above and section 4.3.1).

Often the technical sketch is the first description of the shape. The fabric or at least its main parts have already been designed and sampled as swatches, so that information about it has been already been provided to the fabric technician, and is never explicitly shown in the technical specification.

Producing technical sketches is a time-consuming job, which designers consider fairly mindless. Some companies have a formal decision making meeting to decide which garments to pursue on the basis of garment design sketches⁸¹, and others on the technical sketches⁸². In many cases⁸³ the selection of garments for sampling is a continuous process, and the designers might discuss the designs with their head designer and give them to the technicians as they go along.

⁸¹ C10, C11, C14

⁸² C2

⁸³ All companies issue technical sketches when required. Companies with a few designers, such as C17, rarely have formal meetings.

REQUESTED BY: Helen	DATE ISSUED: 6/14/74	F/F GAUGE: 7/24	PURPOSE: TWD	SAMPLE No.: 784
	REQ. COMPLETE	N/F GAUGE: 7/24		AMOUNT: 2/10
FULL DESCRIPTION: Ladies Viscose. Charlie A line Tunic		NECK STYLE & METHOD OF ATTACHMENT: Small blanket edged neck		SLEEVE SHAPE: Shaped
RIBS:		BASED ON: 7768		
YARNS: 5.5 Viscose Charlie ex. Bolderini				

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

FINISHING INST.: Team 7/10/72	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/ARM BAND 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	3			BUTTONS No./TYPE		
	BACK NECK SEAM-SEAM	16			FINISHED WEIGHT		

SKETCH:

Figure 4. Industrial Example of Technical Sketch⁸⁴

3.5 Sampling

Sampling is the creation of a prototype garment. A significant part of sampling occurs at the same time as design. The designers need swatches to feel in order to select yarns and try out their fabric ideas.

3.5.1 Programming of a Knitting Machine (Figure Appendix A-11 - A-13)

Some swatches are created on domestic knitting machines. Most sampling, however, requires the use of power knitting machines. The bigger companies have dedicated sampling machines, others use the production machines.

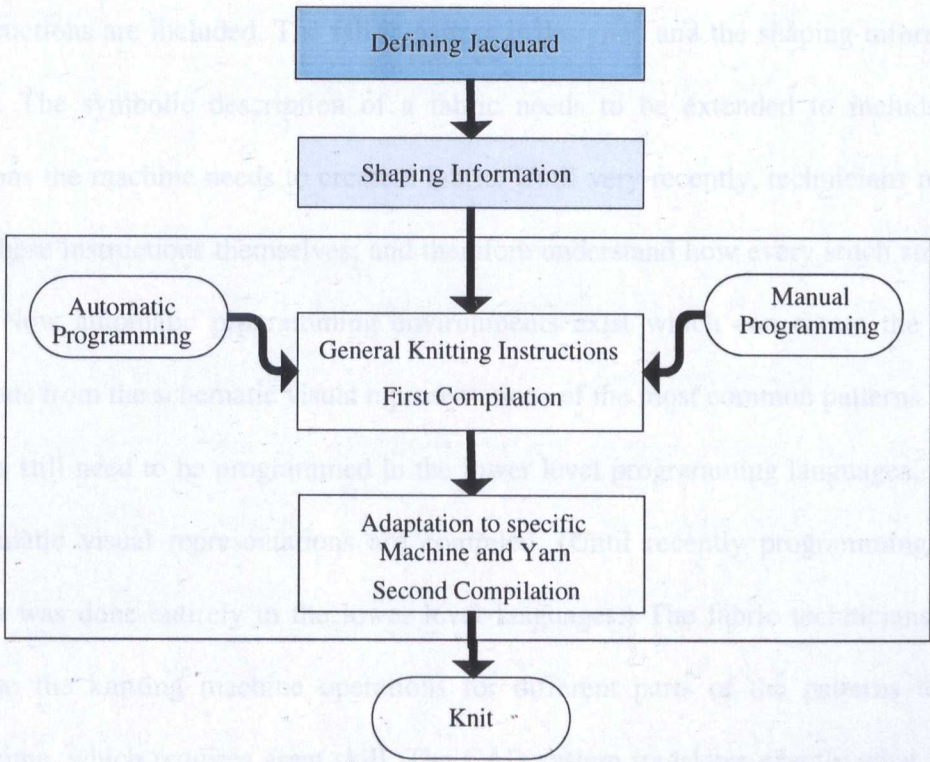


Figure 5. Overview of Knitting Machine Programming

Programming⁸⁵ begins by describing the pattern in the symbolic notation of the CAD system. The visible stitch types are encoded by symbols. It needs to be decided which stitch type is required to achieve a certain effect. This symbolic specification tends to be the detailed design of the fabric (see below). The technicians work out the fabric from the designers' specifications and additional materials, by expressing what they think is required directly in machine notation. Designers are also increasingly designing directly on the CAD systems⁸⁶. Sometimes designers create the adaptation of their inspiration materials to machine representation themselves. Some companies employ specific people for this task⁸⁷.

Initially a straight piece of fabric of the appropriate size is specified and the waist band or cuff instructions are included. The fabric pattern is designed and the shaping information is included. The symbolic description of a fabric needs to be extended to include all the instructions the machine needs to create a fabric. Until very recently, technicians needed to include these instructions themselves; and therefore understand how every stitch structure is created. Now automatic programming environments exist which can create the machine instructions from the schematic visual representations of the most common patterns. Unusual structures still need to be programmed in the lower level programming languages, in which the schematic visual representations are compiled. (Until recently programming knitting machines was done entirely in the lower level languages.) The fabric technicians have to coordinate the knitting machine operations for different parts of the patterns to reduce knitting time, which requires great skill. The CAD system translates exactly what has been

⁸⁵ Author has attended knitting machine programming classes run by a machine builder. Programming process also observed or discussed in C1, C2, C3, C4, C5, C6, C7, C10, C11, C17

⁸⁶ C11, C14, C15, C16 designers are now using the CAD system for some specifications. Use has increased over observation period.

⁸⁷ C3, C7

specified in the visual representations, so the technicians have to arrange patterns in a sensible way⁸⁸.

The machine-generated knitting instructions are independent of the yarn used. The fabric technicians need to include specific parameters for each yarn, such as tension, knitting time or pulling weight. Knowing the properties of each fabric requires great experience and a feeling for yarn. A simple cable pattern⁸⁹ can knit easily in acrylic yarn, which is robust but stretches. The same program knitted in mohair could break the yarn, and knitted in cotton might cause the machine to jam, because the yarn does not stretch.

3.5.2 Swatch Sampling (Figure Appendix A-4)

Swatch sampling begins with the selection of the yarns for a new season, smoothly changes into garment sampling and ends when the garments of a season are sold.

Section 4.3.3 discusses typical descriptions of swatches and explains that none of these descriptions are unambiguous besides an actual swatch. The technicians need to interpret them and translate them into knitted structures. Technicians need to work out which effect the designer has in mind⁹⁰, which machine operations are required for it and how it can be achieved on a particular knitting machine in a particular yarn. This interpretation process is the detailed design. To produce a swatch the technician needs to gain access to a CAD system and program the knitting machine (see above), gain access to the knitting machine, set up the machine, knit the fabric, wash it in finishing lotion and tumble dry it. The whole process can take three hours for a simple alteration⁹¹. The programming time for the fabric depends on the structure.

⁸⁸ Only by programming a CAD system did it become obvious to the author how much in-depth knowledge was required in the simple programming of a stripe pattern.

⁸⁹ Example used by C2FT1

⁹⁰ "can read designers, mind" C14HD

⁹¹ Observed with C10FT1

3.5.3 Fabric Sampling (Figure Appendix A-9)

Fabric samples are panel-sized pieces of fabric from which the garment part could be cut out. Pattern elements that might have been sampled separately are put together⁹². The fabric technicians need to create the specified balance between different elements of the pattern. Conflict in knitting operations can increase the knitting time of a piece significantly; for example if two cables (see Figure 18) are crossed in different rows instead of the same row, the number of empty traverses doubles. The fabric technicians simplify the fabric and move pattern elements in order to create the fabric closest to the specification at the lowest cost. Finding this balance requires subtle judgement⁹³. Often fabric sampling is indistinguishable from swatch sampling. The emphasis shifts from creating what the designer would like to creating an economically viable design.

3.5.4 Construction of Cutting Patterns (Figure Appendix A-8)

Knitwear is either cut into shape (steamed fabric does not unravel) or knitted into shape. Shaped knitwear has the shape information included in the knitting instructions of the fabric. Shape creation occurs therefore during garment sampling. The so-called cut-and-sew knitwear uses cutting patterns created by shape technicians⁹⁴ just as in tailoring to cut the shape out of the fabric panels. While the fabric technicians produce fabric panels the shape technicians create cutting patterns from the designers' specifications.

In both cases the technicians need to interpret the measurements from the designers. The designers specify the final measurements of the garment after finishing and steaming. The measurements required for the cutting pattern are the measurements adapted to the fabric

⁹² Note in C10 garments are assembled from swatches designed for other garments.

⁹³ Explained in detail by C10FT1+HT

⁹⁴ The industry normally uses the terms "pattern cutter" or "make up" person to refer to the person creating the cutting pattern. These terms are ambiguous as they also refer to the people cutting out shapes in production and assembling garments; the term "shape technician" is used in this thesis.

properties⁹⁵. The measurements also need to be adapted to the specific measurement chart of the retail chain; each retail chain sets a measurement for the cuff in each size⁹⁶ for example.

The shape technicians create the shape as they go along and immediately include adjustments for the fabric properties based on a swatch; for example in the industrial example (Figure 4), the width of the back neck was reduced by 2cm to allow for the stretch of the fabric. For most shape technicians this is an intuitive process. They have a feeling for the properties of the fabric which they cannot express⁹⁷.

The shape technicians are mainly guided by the verbal descriptions of the garments. They use the specified measurements for reference, but rarely look at the two-dimensional sketches for reference⁹⁸. See section 4.2 for a detailed example.

3.5.5 Pattern Placing (Figure Appendix A-10)

In many respects pattern placing and garment sampling are the same operations. A distinction has been made here to indicate that garment sampling is concerned with creating a fabric which knits smoothly and economically. Pattern placing is concerned with placing the elements of a pattern onto an exact shape, as section 4.3.2.1 illustrates.

The technicians need to find a balance between the technical requirements and the aesthetic appearance of the garment. In practice the technicians seem to fiddle with difficult garments until they run out of time⁹⁹. The compromises required for a technically viable solution are often a long way away from the designers' specifications. Technicians have commented that

⁹⁵ Explained in detail by C11ST1 and C10ST1.

⁹⁶ C11ST1

⁹⁷ Author has queried C11ST1 and C10ST1

⁹⁸ Complaints from D1, D2, C11D1

⁹⁹ C10HT, C3FT1, C1FT1,

only 30% of the designs specified by designers are technically feasible (see section 3.7).

Pattern placing accounts for a large part of this¹⁰⁰.

3.5.6 Physical Production of the Sample

When the pattern placing is correct, the garment is knitted¹⁰¹. A cut-and-sew garment is cut out and overlocked (the seams are finished by cutting excess fabric and covering them with stitches as the pieces are stitched together). A shaped garment is either overlocked or linked (each stitch is connected to another) and the neckline is cut out. The trims are attached. The garment is washed in finishing solution, dried, and steamed into shape.

3.5.7 Selection and Production

Sample garments are produced over months. Each garment is evaluated by the technicians and the designers, and changes are made if time allows. Often the buyers like a design, but require changes¹⁰². Designers also need to make changes to designs to make them cheaper or give the fabric a different handle¹⁰³. This can be an iterative trial and error process stretching over many days.

During the garment sampling process the companies critically evaluate their designs so far with reference to the design framework¹⁰⁴. If some of the places in the design framework are not filled to everybody's satisfaction, new garments are designed to fill these slots¹⁰⁵. Designs are also evaluated on how they fit into the context of the fashion of a season, so that changes can be made to accommodate new trends that have emerged since design research.

¹⁰⁰ C11HT, C1FT1

¹⁰¹ Same stages in all companies

¹⁰² C14HD

¹⁰³ Negotiations between designer and technician observed in C14D3, C10FT1, commented on by C16HD.

¹⁰⁴ C2HT, C7FT1, C10HD, C11HD, C13HD, C16HD, C17D1

¹⁰⁵ Explained in detail in C10.

Buyers might also approach companies to request specific garments if they have become aware of new trends¹⁰⁶.

3.6 Sale and Production

Garments are sold by presentations to buyers. Only once they are sold are the garments graded and production set up.

3.6.1 Buyer Presentations

Companies internally evaluate all garments to select a range to show to buyers. All designers look at their own final sample garments and those of their colleagues¹⁰⁷. They look at the quality of the designs against the brief, the company style and the target customer. These decisions are subjective, but designers in a company understand the house style¹⁰⁸; even though they might not be able to define it, they recognise when a design is inappropriate. The garment is also evaluated in terms of the production cost per garment and the company's production resources¹⁰⁹. Companies which sell complete collections decide on the range.

After this internal selection process the garments are shown to the buyers of the retail chains¹¹⁰. In the case of Marks & Spencer this involves a formal presentation at the Marks & Spencer headquarters. The companies bring all their garments and hire models or use their designers to model the garments¹¹¹. The garments are put in the context of fashion by mood boards showing other magazine cuttings of garments and inspiration material to set the context for a collection.

¹⁰⁶ C8, C10, C11, C14

¹⁰⁷ C14HD, C11HD

¹⁰⁸ C17D1 on the subject of training new designers to work in house style.

¹⁰⁹ All companies, most dominant in C4FT1 which designs features with knitting cost in mind.

¹¹⁰ Explained by C10HD, C11D1, C14HD, C16HD

¹¹¹ C14HD

3.6.2 Grading

The garments are sold in the sample size (12 for ladies). Grading is done by the shape technicians¹¹² or production make up¹¹³. In some companies the designers who make the cutting patterns in the first place also grade¹¹⁴. In knitwear garments are graded by reconstructing the cutting pattern with new measurements, unlike tailoring where the sample size cutting pattern is modified for a new size¹¹⁵. The pattern placing process needs to be repeated. Many designers include plain areas around panels to ease grading¹¹⁶. In most cases compromises need to be made in the pattern placing for bigger sizes¹¹⁷.

3.6.3 Production

A detailed description of the production process¹¹⁸ is beyond the scope of this thesis. If the production machines are different from the sample machines, which is not common, the program for the fabric needs to be rewritten¹¹⁹. Production capacity is planned with machines and make up resources allocated to the garments. For typical cut-and-sew garments the pieces are knitted, steamed, cut out and overlocked at the sides. The neck trim is attached. The label is sewn in. The garment is checked for faults. It is finished, dried and steamed to shape. Then it goes through quality control again and is packed into bags and boxes and shipped.

¹¹² C17,C10

¹¹³ C11

¹¹⁴ C15

¹¹⁵ De Montfort University Pattern Cutting course, C10HD

¹¹⁶ D1FT1, seen on panels of other companies.

¹¹⁷ C11HD

¹¹⁸ Explained in C8, C9, C10, C17

¹¹⁹ Normally occurs when production is outsourced: C7, C6. C17 bought new sample machines to give production overload to C16.

3.7 Efficiency of the Process

Practitioners do not normally comment on the efficiency of the process as such. However, on the advice of business consultants one company¹²⁰ has recently reorganised its business process from a typical process as described in this chapter to a new structure according to concurrent engineering principles . The company now has a far closer collaboration than previously between the designers and technicians. The technicians are accountable to the head designer and join the designers in their design research. The company develops new design features all year round. By working to a tight timetable they overcome much of the time pressures. The head designer commented that the new process is far more efficient and the job satisfaction of all participants has increased.

The inefficiency manifests itself in comments made by different participants:

- Ratio of design ideas to samples: Ideas are cheap. Designers produce design ideas as part of their normal life¹²¹ whenever they see suitable sources of inspiration. Each designer¹²² produces hundreds or even thousands of design ideas in each season, which they visualise mentally as garments. 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 fewer than 10 are bought by the retail chain.
- Technical feasibility of designs: Almost all technicians complain about the designers' lack of technical knowledge¹²³. Only about 30% of all specified designs, i.e. those that have reached technical specification stage, can be turned into samples at the intended price point¹²⁴. This leads to mutual dissatisfaction. The designers complain that

¹²⁰ C18, explanation by C18HD

¹²¹ C16HD+D1+D2, C17D1+D2, C10D1

¹²² Explained by C14HD. Similar ratio discussed in other M&S suppliers and D1, D2.

¹²³ Most technicians have commented that they would like designers to have greater technical knowledge, e.g. C1FT1, C2FT1, C3FT1, C7FT1, C10FT1

¹²⁴ C11HT, C1FT, similar ratios implied by other technicians.

technicians often say that a design is technically infeasible and later return with a good suggestion; and imply laziness in the technicians¹²⁵. The technicians complain that they have to prove to the designer that a design is infeasible and know that this is logically impossible¹²⁶. They view it as a disregard for their professional expertise¹²⁷.

- Time pressure during sampling: All participants in the knitwear design process complain about running out of time during the design process¹²⁸. Before deadlines when collections need to be presented to the general public or shown to retail chains all participants need to work overtime and weekends¹²⁹. Compromises are often made in the later stages of sampling because the technicians are running out of time¹³⁰. Designers might also not have the time to design new garments if they feel that slots in the design framework are not satisfactorily filled¹³¹. The time pressure increases especially towards the end of the work on a new season before Christmas and midsummer. With four seasons being designed in many companies¹³², designers complain that they don't get any rest¹³³.
- Formal sampling rounds: Companies that produce their own collections have internal selection meetings where the management, the designers and to a lesser degree the technicians decide which designs to carry forward. Much time is lost by formal presentations for these selection meetings; and the time pressure for deadlines is artificially increased¹³⁴.

Knitwear companies don't keep many records of previous designs¹³⁵. Some companies keep all finished sample garments¹³⁶, others only all sold garments or selected designs¹³⁷. The

¹²⁵ D1, C10D1

¹²⁶ C11HT. C11HD considers this good practice to push the technician to the limit.

¹²⁷ C11HT

¹²⁸ No exceptions

¹²⁹ C3FT1+DA1, C5FT1, C7FT1, C7HD+D1, C10D1+D2+FT1, C11HD, C14HD+D4, C17D1+D2, D1, D2 Issue is treated as a well known fact about the industry.

¹³⁰ Explained in detail by C10HT.

¹³¹ C11HD

¹³² D1, trend in M&S.

¹³³ C14HD+D4

¹³⁴ Explained in detail by C2FT1.

¹³⁵ Discussed in detail with C14HD.

¹³⁶ C18 has complete archive, C19.

technical specifications are kept for one or two years and are then thrown out¹³⁸. Theme and mood board are recycled after the end of the season¹³⁹. The records are kept in the memory of the participants¹⁴⁰. Yet designers and technicians frequently use old designs to describe new ones in terms of changes from them, and copy measurements from old designs or technical sketches¹⁴¹. New designers have to put significant effort into learning the house style¹⁴². 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 jobs¹⁴³.

¹³⁷ C10, C11, C14, in C17 C17ST1 has sold a complete archive of old garments, C17D2+D3 think this is "criminal".

¹³⁸ C14, C17, C18

¹³⁹ C17HD

¹⁴⁰ C14HD, C17D1

¹⁴¹ observed in C14, where C14HD defended keeping no records beyond one year.

¹⁴² Discussed in detail with C17D1 who needed to train C17D3.

¹⁴³ Personal communication with D1, D2, D3, D4 on the careers of their friends. Many designers in their twenties talk about previous jobs when the opportunity arises.

Chapter 4.

The Communication Bottleneck

The knitwear design process is inefficient: of hundreds of original designs only a small number are carried through to a sample and often only a few are sold. Resources are wasted on these unsuccessful designs. The design and sampling process is a close collaboration between the designers and technicians. The task of the designers is to design the visual and tactile appearance of a garment. The task of technicians is to realise designers' ideas. Designers and technicians are different types of people with a different standing in the company, and a different way of thinking. The structure of the industry is not conducive to efficient communication. The knowledge is also inherently difficult to communicate. This chapter will show that this collaboration does not work very well, because there is a communication bottleneck between designers and technicians.

4.1 Overlap of Tasks

Designers and technicians share many of the tasks in the knitwear design process. The levels of involvement in the different tasks are illustrated in Table 4.

Participant:	Designer	Fabric Technician	Shape Technician
Tasks:			
Fashion Research	with Buyer		
Yarn Selection			
Development of Design Framework			
Designing of Fabric Swatches			
Sampling Idea Swatches			
Conceptual Design of Whole Garments			
Swatch Sampling			
Detailed Design of Garments			
Design of Shape			
Technical Sketch			
Construction of Cutting Pattern			
Evaluation of Cutting Pattern			
Modification of Cutting Pattern			
Creation of Fabric Sample			
Evaluation of Fabric Sample			
Modification of Fabric Sample			
Pattern Placing			
Evaluation of Pattern Placing			
Modification of Pattern Placing			
Make Up of Sample Garment			
Evaluation of Make Up			
Evaluation of Design	with Buyers, Management		

Tasks in bold are shared. Grey levels indicate level of involvement.

Table 4. Overlap of Tasks

4.2 Example of Interaction between Designers and Technicians

Figure 4 shows an industrial example of a technical sketch¹⁴⁴. Figure 22 (p.105) and Figure 23 (p. 106) show the location of the measurements on the garment. It will be helpful to refer to them to understand the jargon. The shape technician¹⁴⁵ constructed a cutting pattern for this shape to illustrate her way of working to the author. She had previously constructed the

¹⁴⁴ C11

cutting pattern as part of the sampling process. She went straight from the measurements, which the designer had specified, to the construction of the cutting pattern. She began by constructing the front piece. She took the length measurements from the specification and drew a straight line. She used the specified chest measurement for the underarm width and drew a straight line parallel to the centre line as an auxiliary line to indicate the chest width. She reduced the across front measurement slightly “to allow for the fabric”. She narrowed the neck measurement significantly, because she always does so, used the front neck depth and drew in the front and back neck curve. She used a standard shoulder drop and drew in the shoulder line, ignoring the specified shoulder measurement. She took the armhole depth measurement and marked the chest width line at this point. She then drew a free hand curve to the shoulder point. In the end she drew in the welt width and joined this line to the underarm point.

To construct the sleeve cutting pattern she started by drawing a line for the width of the sleeve under the sleeve crown and draw a line up the side of this line. Then she measured the indicated sleeve widest measurement on the horizontal line. She measured the diagonal from the underarm point to the shoulder point and drew a line of this length from the shoulder widest point to the vertical line. She drew the sleeve crown curve freehand. When the author asked her to measure the length of the curve to compare it with the armhole length the difference was only a few millimetres. She normally never measures the length of her curves, because she gets it right. To construct the rest of the sleeve she took the underarm measurement and continued the sleeve centre line by this amount and took the wrist measurement for the width of the sleeve. She finished by connecting the wrist point and the underarm point. She had ignored the elbow width

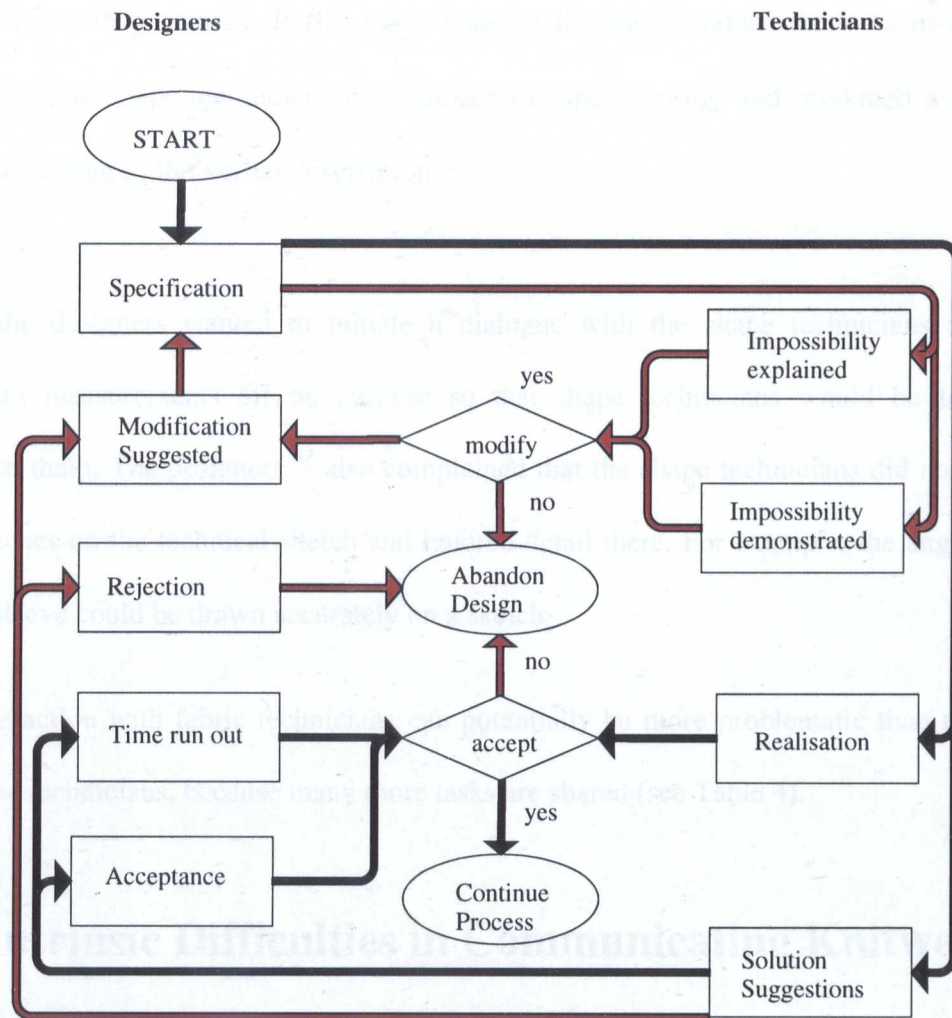


Figure 6. Modes of Feedback between Designers and Technicians

measurement, which is 1 cm less than the wrist measurement (see Figure 4). When asked, she explained that the sleeve would flair anyway. The underarm measurement is intended as the length of the line between the sleeve widest point and the wrist point, but the technician took it as the measurement of the sleeve centre point to the wrist centre point. The designers¹⁴⁷ in the same company made several comments about the working of the shape technicians. They praised the overall skill of their shape technicians and did not assume that dissatisfactory results are caused by the inability of particular individuals. The shape technicians did not question their specifications often enough or discuss specifications adequately. For example, the designers could specify whatever shape of

¹⁴⁷ C11D1, these comments were discussed with D2, who said this corresponded to her own experience.

raglan sleeve they wanted. It still came back as the same raglan sleeve as in all other garments. The shape technicians had ignored the specification and produced a standard shape according to the verbal description.

When the designers wanted to initiate a dialogue with the shape technicians they left important measurements off on purpose so that shape technicians would be forced to approach them. The designers¹⁴⁷ also complained that the shape technicians did not look at the sketches on the technical sketch and ignored detail there. For example, the angle of the raglan sleeve could be drawn accurately on a sketch.

The interaction with fabric technicians can potentially be more problematic than that with the shape technicians, because many more tasks are shared (see Table 4).

4.3 Intrinsic Difficulties in Communicating Knitwear

Knitwear design does not have a model to communicate a knitted structure short of a knitted structure. Technical and design considerations are closely linked in the appearance of garments. This section argues that information about knitted structures is inherently difficult to communicate.

4.3.1 Traditional Ways to Represent Knitted Structures

A theoretically infinite number of different knitted structures can be created. All look different according to material and context. To create a design these structures need to be represented and communicated to another person to whom this representation is meaningful.

¹⁴⁷ D2 was particularly aggravated by this point and showed the author several examples of pockets and side splits.

The only accurate model of a knitted structure is a knitted structure. Knitwear information is intrinsically difficult to communicate. The existing symbolic descriptions are either incomplete or very complicated to use. Verbal descriptions are patchy and prone to different interpretations. Knitwear is difficult to sketch. The following text will briefly explain the different types of specifications, their use in industry and the difficulties associated with them.

4.3.1.1 Photographs

If designers cannot get hold of a swatch or garment, they often use a photograph of a



garment¹⁴⁹. The photographs normally come from fashion magazines such as Vogue, or photographs that designers have taken on shopping trips. Fashion photographs communicate the mood of a garment and the overall impression¹⁵⁰. It is often difficult to see details in a fashion photograph. The technicians recreate the overall effect or a specific detail¹⁵¹. Most of the designers' own photographs that the author¹⁵² has encountered were very bad quality and did not show much detail.

Figure 7. Photograph of a Garment with Lace Pattern
(taken from Vogue 1996, 12; garment by Karl Lagerfeld)

4.3.1.2 Swatches

Existing swatches or garments are often used to specify a new fabric¹⁵³. Designers search through stocks of swatches, use the knitting machine manufacturers' swatches¹⁵⁴ (for

¹⁴⁹ C10D1, C11HD, C14HD+D3, C16HD+D1+D2, C17D1+D2, C18HD, C19HD,

¹⁵⁰ Explained by D1, who hired models to communicate moods.

¹⁵¹ C10HT

¹⁵² Seen in C14, C16, C17

¹⁵³ Used in all companies, observed in C10.

¹⁵⁴ Marketed by Stoll, C10HT. Problematic, because the designers want fabrics that cannot be done in certain yarns or are time consuming to knit. Explained by technician at De Montfort.

which the programs are supplied), look at old sample garments¹⁵⁴ and buy garments on shopping trips¹⁵⁵. The technicians have to rethink how the fabric can be created. Technicians sometimes unravel a swatch to copy the fabric¹⁵⁶. If the garment needs to remain intact the technicians need to study the structure of the fabric from its appearance. A real piece has the advantage that one can study the back of the fabric and pull it. Changes are often specified verbally with reference to an old swatch or garment. A swatch that can be copied is the most precise way to define a knitted structure.

4.3.1.3 Sketches and Drawings

Pictorial images stress the emergent properties of the fabric, rather than its structure. For example, some lace patterns cause a wave effect if the holes are arranged suitably on top of each other. This emergent appearance is hard to predict exactly from a defined structure. It is also difficult to work out the required structure from the desired emergent properties.

Colour patterns are often represented by accurate, detailed drawing of the image on a CAD system or on paper. The designers put all the required detail into the design. Sometimes these designs are worked out by the designer on a grid. Ambiguities arise when an image with continuous lines is turned into a grid pattern, because of the low resolution of knitwear (see also Eckert, 1990 for details). For example, the author observed a design assistant¹⁵⁷ turning a drawing of a seascape with swirls into a grid pattern. When the drawing was scanned in, the circular lines had blurred and needed manual correction.

¹⁵⁴ C18HD

¹⁵⁵ C10, C11, C14, C16, C17.

¹⁵⁶ Explained by technician at De Montfort University and C11HT.

¹⁵⁷ C3DA1

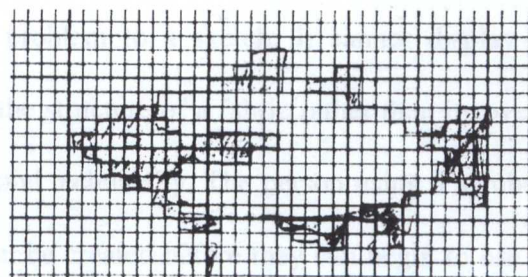


Figure 8. Example of the conversion of a Drawing into a Grid Pattern
blue fish taken from Glassborow (1986)

Some but not all designers create sketches during the idea development phase¹⁵⁹. Almost all designers create sketches as part of the technical sketch¹⁶⁰. Sketches give a good indication of the intended proportions of a structure or the whole garment. They are however notoriously vague. Some structures are hard to sketch, for example if the designer wants to achieve a “crochet effect”¹⁶¹. The quality of the sketches obviously depends on the individuals’ ability to sketch. Sketches can lead designers into the temptation to forget the technical properties of knitwear and treat it like fabric or fashion design. For example, many designers communicate complex Arran patterns by sketches¹⁶². In a sketch they can have all possible angles, however real Arran pattern can only have 60°, 45° or 30° angles (crossing over two stitches over one, one over one, one over two). For example, a designer sketched three Arran diamonds on top of each other over the whole length of the garment. The angle, and with it the whole pattern, could not be knitted and did not fit over the specified lengths¹⁶³. This problem was caused by the lack of technical knowledge of the designers and the freedom of sketches (see also section 4.3.3.2).

¹⁵⁹ C17D1+D2, C16HD+D1+D2 commented on sketches during idea generation, observed in C16D3. However, also don’t have time to make sketch books like students, C16HD+D1+D2, C11HD.

¹⁶⁰ The author heard rumours from D2 about a designer who never sketched, also designer in Richard Roberts, Leicester, commented that she never produces technical sketches, but explains designs verbally to technician.

¹⁶¹ C11FT1 has given only verbal description for design.

¹⁶² C17D1, C16D4, C3FT1

¹⁶³ Problem explained by C3FT1 for Arran, similar problem observed for intarsia diamond in C14D4

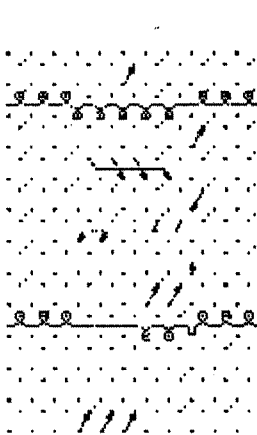
4.3.1.4 Symbolic Representations

A symbolic representation has the opposite problem to a sketch: it cannot display the emergent properties of the fabric. It describes the structure of a fabric rather than its overall appearance. The structure needs to be understood technically. The person using a symbolic notation needs to think about how an effect can be created before they can begin to use the notation.

Symbolic descriptions divide into two fundamental groups:

Loop descriptions

A loop descriptions shows the position of the needles on the needle beds and the way the yarn loops between them. This description is accurate, but it requires the user to have all knitting operations fully planned. It does not resemble the visual appearance of the fabric and



does not describe one stitch type by one symbol. With this notation all knitted structures can be described, but the descriptions are extremely lengthy and give no visual help. The loop notation is used in education. The Universal CAD system uses it to show stitch details in an automatically created structure instead of a knitting simulation¹⁶³.

Figure 9. Loop Description of Part of a Cable Crossover taken from Universal (1996). See for example Spencer (1989) for an introduction to loop descriptions.

Specific symbols

Specific symbols for each stitch type are used in schematic visual representations of garments, either with colour codes for stitches, or iconic symbols vaguely resembling the appearance of the structure. The CAD systems use symbols to specify a pattern by using a different symbol for each type of stitch (see section 1.5.1); these symbols are mainly in

colour. The Universal system also uses black and white symbols for simple standard patterns which create a three-dimensional visual effect; and enables the user to switch between the colour coding, black and white symbols and the loop description. The CAD systems have roughly 50 different colour symbols. Berlin et al. (1969) argue that at most 12 - 20 colours can be named and distinguished by an average person. The users can be misled by similar colours. The real colour of the stitch is lost entirely in colour coding of the stitch type. The colour combinations are often visually unappealing and bother the colour-sensitive designers.

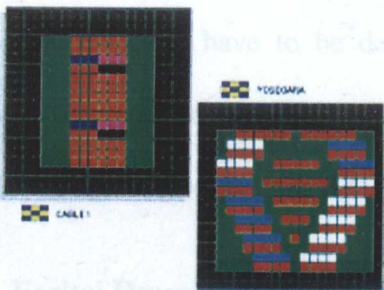


Figure 10. Colour Coded Structure (Cable Pattern on the Right)
taken from Shima (1996)

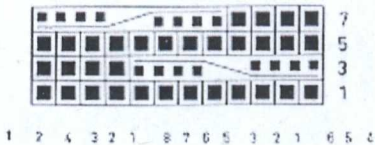


Figure 11. Symbolic Notation of a Cable Pattern
taken from Burda (1988)

Some hand knitting books such as those by the German Burda publisher (for example Burda, 1988, see Figure 11) use a set of black and white symbols that vaguely represent the visual appearance of the structure. These symbols are efficient and accurate, but do not necessarily cover all possible knitting operations. It is also difficult and tedious to use these notations to note down a structure. It requires a considerable degree of experience to read a symbolic notation easily and visualise what structure emerges from it. The notations vary from publisher to publisher. Hand knitting notations are not used in industry, even though the pattern books are popular with industrial designers¹⁶⁵.

¹⁶⁴ The author does not know how much this feature is used industry, not having encountered a Universal user since the introduction of the new system.
¹⁶⁵ C17D2 had imported them from Germany, similar books used in C10, C16 and by C20.

Some patterns and types of knitted shapes can be described accurately by a standard name such as moss stitch. This however only applies to a small fraction of the possible patterns. Designers often describe modifications to a swatch verbally. Some companies depend almost entirely on verbal descriptions during the design process¹⁶⁹. These verbal descriptions depend very strongly on the thinking style of the person describing them (see section 4.4).

4.3.2 Intrinsic Problems in Knitwear

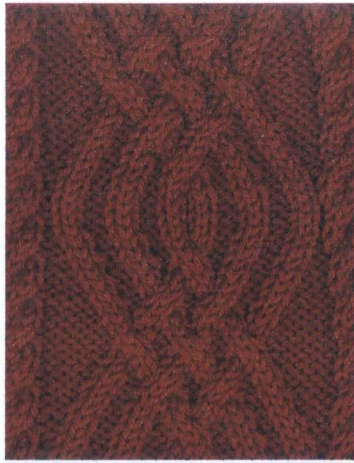
In knitwear the fabric and the shape are created at the same time and yarns often have unpredictable properties. It is also not possible to create a mock up of a knitted garment without creating a knitted fabric. There is no universally applicable easy way to specify knitted fabric.

4.3.2.1 The Intertwining of Design and Technical Realisation

Technical and aesthetic design issues can never be completely separated in knitwear. It is the only textile product where the fabric is created at the same time as the shape. Section 3.5 discusses the stage in the design process when the pattern and shape are brought together.

A detailed analysis of the influence of the technical properties of knitwear on design is far beyond the scope of this thesis. The complexity of knitted structure can be seen from textbooks on knitwear technology, for example Spencer (1989). The capabilities of each individual machine limit the space of possible designs. Only people who work regularly with a machine know its capability.

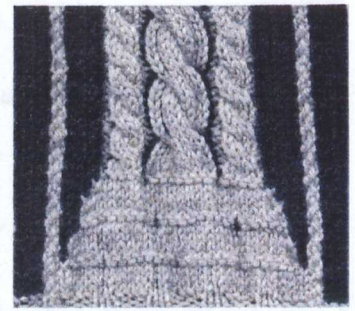
¹⁶⁹ Richard Robert see footnote. 159



(i)



(ii)



(iii)

Figure 13. 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

It is often hard for a designer to see how difficult it is to realise a design idea on a specific machine. Figure 13 shows three examples of cables that the author has hand knitted. Figure 13 (i) shows a standard Arran pattern from a pattern collection, which could equally easily have been knitted on a power knitting machine. Considerable effort was put into modifying the different cables in the pattern book so that all had the same repeat height. Figure 13 (ii) is a complex cable pattern where three groups of stitches are crossed. The two strands of knit stitches are crossed while the purl stitches remained in place, i.e. the crossover of the knit stitches occurred over the purl stitches. This structure could be created on a power knitting machine, but would be very slow to knit. The strain on the stitches during the crossover is high and there is a danger of the yarn snapping during the formation of the cable. Every technician would strongly advise a designer not to use this structure. Figure 13 (iii) is the foundation of a column in a garment based on Canterbury Cathedral and designed by the author. The blue shadowing emphasise the three-dimensional structure of the columns. This effect could not be created on a power knitting machine.

The influence of technical problems on design can be illustrated by a simple example, which has been discussed in detail in Eckert (1990). Imagine a fair isle overall pattern with a small motif, say ducks of 10 by 25 stitches, which needs to be placed onto a simple set-in sleeve

shape. Ideally the ducks should not be cut. The width of the garment is however specified to be 110 stitches. The options are:

- to ignore the problem and accept cut ducks(see Figure 14).
- to alter the distance between the individual ducks (see Figure 15 and Figure 16).
- to modify the width of the garment (see Figure 17).
- to change the design of the ducks.

All of these options are potentially unsatisfactory. Pattern placing is a compromise to reach the best possible solution. Even at this late stage of the detailed design the pattern and the shape can be altered. In a similar way as this colour pattern, the structure of patterns can become unstable when a certain part of the pattern is cut, or the visual appearance can change very strongly when a part of a pattern is missing; think for example of a cable pattern when half of the cable is missing, so that no cross-over can take place.

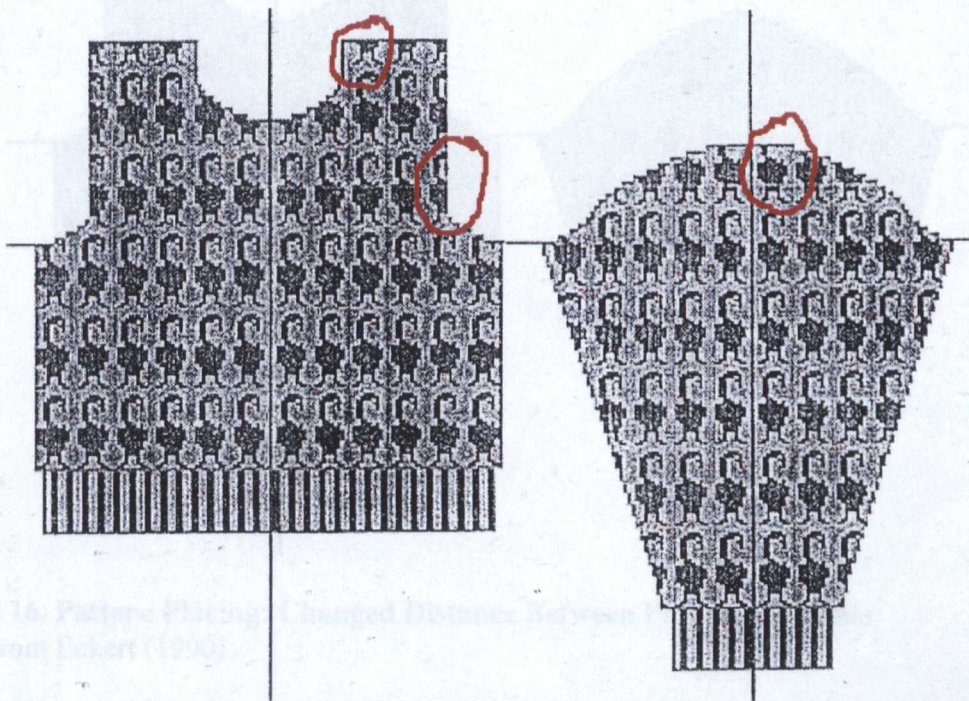


Figure 14. Pattern Placing: No Conflict Resolution
taken from Eckert (1990)

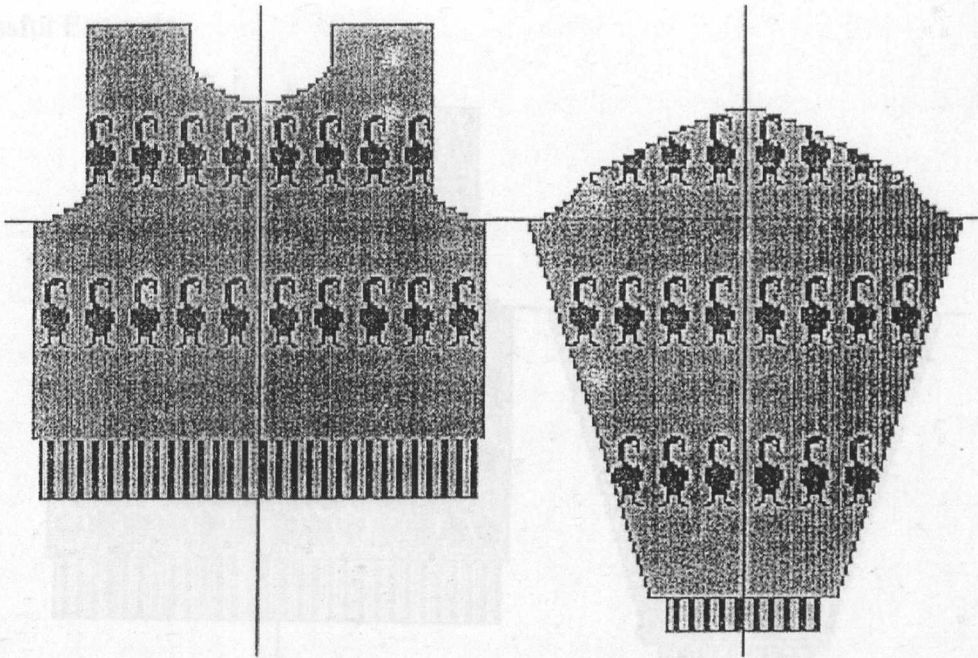


Figure 15. Pattern Placing: Changed Distance Between Pattern Elements
taken from Eckert (1990)

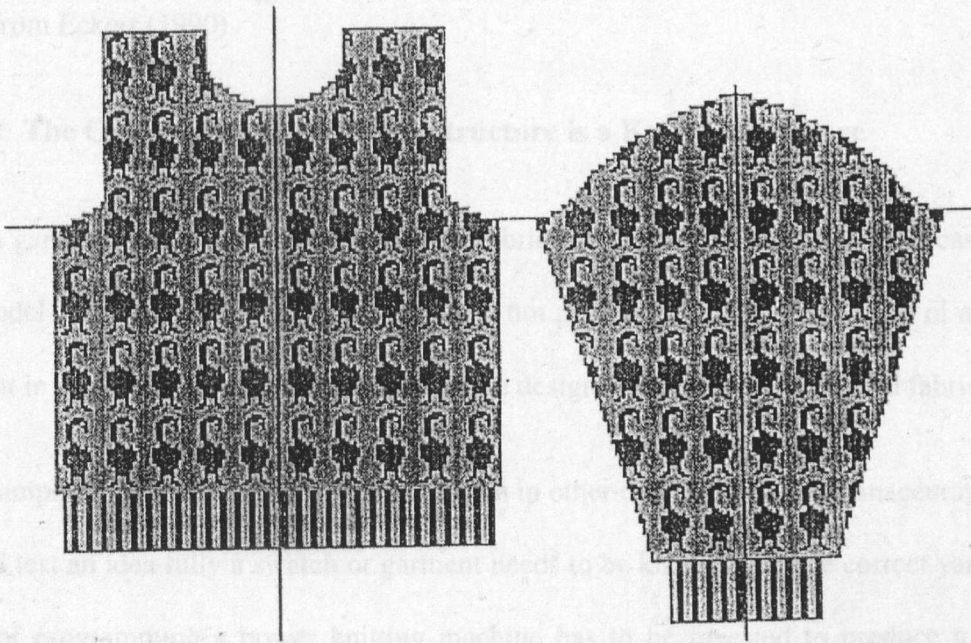


Figure 16. Pattern Placing: Changed Distance Between Pattern Elements
taken from Eckert (1990)

Successful Example

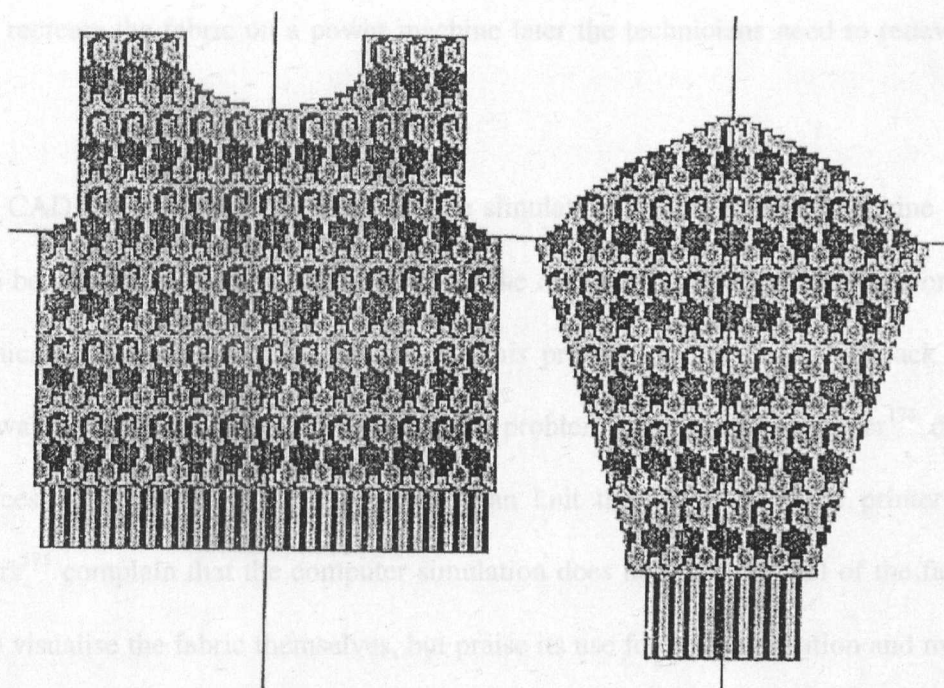


Figure 17. Pattern Placing: Modified Width of Garment
taken from Eckert (1990)

4.3.2.2 The Only Model of a Knitted Structure is a Knitted Structure

Woven garments are often made up in toile fabric, model houses are built from cardboard, and model cars are made in reusable clay. It is not possible to create a mock up of a knitted garment in another material to communicate the design without creating knitted fabric.

Even samples in different types of yarns or even in other colours of yarn are inaccurate¹⁷¹. To see and test an idea fully a swatch or garment needs to be knitted with the correct yarns. The effort of programming a power knitting machine has to be invested to produce a sample swatch. Some companies¹⁷² create swatches on domestic hand knitting machines to develop design ideas, without the time investment of programming a power machine. On hand knitting machines the users create the fabric by setting or executing themselves the knitting

¹⁷¹ C1FT1. He showed two panels knitted under identical conditions which varied in length by two centimetres. He explained the problem is much greater for different coloured yarns.

¹⁷² C10, C16, C17 mainly for the development of colour ways. C10 also used hand flats to create intarsia samples.

operations that create a particular fabric. These operations are not recorded and are therefore lost. To recreate the fabric on a power machine later the technicians need to redevelop the fabric¹⁷².

Modern CAD systems allow knitted structure simulation¹⁷³. The knitting machine program needs to be created to run a simulation. Either the designers create it themselves or have to communicate the design to the technicians. This provides much faster feedback than do fabric swatches, but the initial communication problem remains. A designer¹⁷⁴ described this process as: "The Shima [CAD system] can knit the fabric onto the printer paper." Designers¹⁷⁵ complain that the computer simulation does not give the feel of the fabric and they can visualise the fabric themselves, but praise its use for communication and marketing purposes.

4.3.2.3 No Complete and Unambiguous Representation of Knitted Structures

As section 4.3.1 shows, no simple way exists to specify a knitted structure. The only really unambiguous way to communicate a knitted structure is through a swatch of the same structure. This is often infeasible. A loop notation describes a swatch exactly. As it requires complete technical understanding it does not support sharing the development work. It is so tedious to note down that producing a swatch would not take longer.

The symbolic notations of the CAD systems also require considerable technical knowledge and familiarity with the symbols. The symbolic notations describe the structure of the fabric rather than the visual appearance of a structure. Makeshift symbols are ambiguous and the number of symbols which are easy to draw is limited. Sketches and other images are prone to ambiguity as the next points show.

¹⁷² Explained by technician at De Montfort University. C10HT on the subject of copying structures from bought garments.

¹⁷³ Stoll since 1991, Shima Seiki since 1995.

¹⁷⁴ C14D1

4.3.3 Knowledge Representation Reasons

In most notations an accurate description requires a high degree of design commitment. From a sketch it is often hard to interpret what aspects are specified accurately, and what is deliberately left vague.

4.3.3.1 Higher Design Commitment through Higher Accuracy

The description of a knitted structure becomes clearer the more technical it becomes (see above). In most cases a detailed description requires technical knowledge that many designers do not have. It is very time consuming to work out the technical details of a design. It is faster and easier for the designers to describe the pattern verbally.

Swatches and samples are already required during the conceptual design part of the knitwear design process (the planning of a collection). It lies in the very nature of conceptual design that it is floating and unspecific. Designers do not want to commit themselves to detail¹⁷⁶, even though they like to see examples of a type of design. The time commitment to specify a swatch in detail cuts off potential paths in the design solution space and can damage the overall design output. The interpretations of a technician can be a valuable input to the design development¹⁷⁷.

4.3.3.2 Conflict in the Intended Degree of Detail in a Sketch.

As the example in section 4.3.2.1 shows, technicians don't trust sketches and lose vital information. This is due to a mismatch of the accuracy of the sketch and the information communicated by it. It is impossible to indicate which aspect of the sketch is intended to communicate information that otherwise cannot be expressed and which part contains redundant information. The two-dimensional outline sketches are used to indicate the

¹⁷⁵ C14HD+D1, C15HD

proportions of the pattern elements on a garment. When the garment has plain fabric the two-dimensional outline is a formality and does not communicate more information than the short verbal description.

4.4 Different Thinking Styles between Designers and Technicians

Comments made by designers and technicians indicate that they have very different ways of thinking about knitwear designs and structures. The author has questioned members of both groups about their mental representations. As neither group considered their mental abilities very noteworthy¹⁷⁸, they rarely volunteered information and had to be asked very direct questions.

Both groups have commented on very vivid imagination skills¹⁷⁹. They can visualise garments¹⁸⁰ during the design and sample process and can mentally manipulate and rotate them. Designers can see garments on different people, and imagine the drape of a garment. Large parts of the creative design process of a design can occur through visualisation. Designers¹⁸¹ have commented that this visualisation ability is one of the most important skills of a knitwear designer. Some companies¹⁸² hire trained fashion designers, who are trained to visualise whole garments and their drape on people, in preference to trained textile designers, who are trained to create flat pieces of fabric. It seems to be easier to train a fashion designer in knitwear technology than a textile designer in garment visualisation.

¹⁷⁶ C14HD, C17D1

¹⁷⁷ C17D1

¹⁷⁸ The author has commented that some people have bad visualisation skills and memory for images. Both designers and technicians, for example D2, C14HD, C14D1, C11FT1 were quite surprised by this assertion and began to describe their mental processes in detail.

¹⁷⁹ D1, D2, D3, C14HD, C14D1, C17D1+D2, C16D3, C10FT1, C11FT1+FT2. Example quote: "The movies that come out of Radio 4 are much better than the movies on television" (D3).

¹⁸⁰ Discussed in particular with D1, D3, C14HD+D1. The author shares the visualisation skills and has therefore an intuitive understanding.

¹⁸¹ C14HD+D1, C11HD

¹⁸² C11, C14

4.4.1 Different Mental Representations of the Design

Designers think primarily in terms of the visual and tactile appearance of the fabric or the garment. They see a design primarily as an overall concept within the context of fashion which expresses a pre-decided mood. Designers think in terms of completed garments or swatches from the time they start looking at yarns and forecasting material. They cannot see a design feature independently of the yarn type and colour a potential garment will have, unless they force themselves to, because they think in concrete examples rather than abstract representations. Designers design to achieve an effect. They talk to each other about the effect they are trying to create¹⁸³, for example a crochet effect¹⁸⁴. These effects come from the emergent properties of the structure of the fabric. The designers can force themselves to think about structural properties of a fabric that achieves the desired effect.

The task of the technicians is to realise technically the designs suggested by the designers. Shape technicians think about how to achieve a shape in a certain fabric in terms of measurements. Technicians think about and describe knitwear in terms of the structure of the pattern¹⁸⁵. For example, the crochet effect has been explained in terms of a tack and racking pattern¹⁸⁶. When technicians are suggesting alterations to fabric they sometimes try to maintain the structural quality of the fabric and not the visual appearance. For example¹⁸⁷ the author has observed a technician changing the cable pattern in Figure 18 (a) to that in Figure 18 (b), because in the specified design, Figure 18 (a), the yarn broke as a result of crossing two adjacent cables in the opposite direction. The visual effect of the cables is very different. For the technicians the emergent properties are the goal of the reasoning process, not the beginning.

¹⁸³ Also observed in C10, C14, C17, discussion with D1 and D3

¹⁸⁴ C11

¹⁸⁵ All technicians explain patterns in terms of their technical structures, when they want to convince the author of their triumphs over the machine.

¹⁸⁶ C11FT1

¹⁸⁷ C11FT1

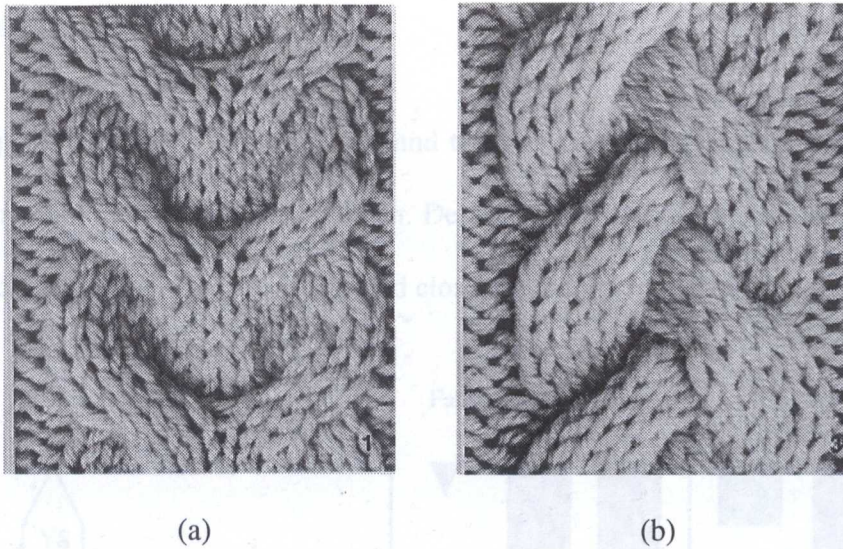


Figure 18. Different Appearance of Cable Patterns with Similar Structural Properties
Taken from Burda (1975)

4.4.2 General Difficulties in Describing Mental Images

It is difficult enough to describe a garment or painting when it is in front of the viewer. Our language is ambiguous. Sketches or drawings include considerable abstraction which leads to many possible interpretations. Even when the explanation is long and detailed, a listener who does not see a picture still only has a partial understanding of how it might look. It is possible to recognise a picture from descriptions, but unlikely that a picture can be recreated from a description, no matter how detailed. However this is exactly what needs to happen in the design process: the mental model that the designer has of a garment needs to be transferred into a garment. As a designer¹⁸⁸ has phrased it the technicians need to knit what the designers think.

4.5 Organisational Reasons

Many of the problems of the design process derive from its organisation. Some have practical causes, while others are deeply embedded in the work culture.

4.5.1 Practical Reasons

The overlap in the seasons that designers and technicians are working on is determined by the order in which tasks can be undertaken. Designers often work in quiet conditions away from the technicians, who tend to be located close to production machinery.

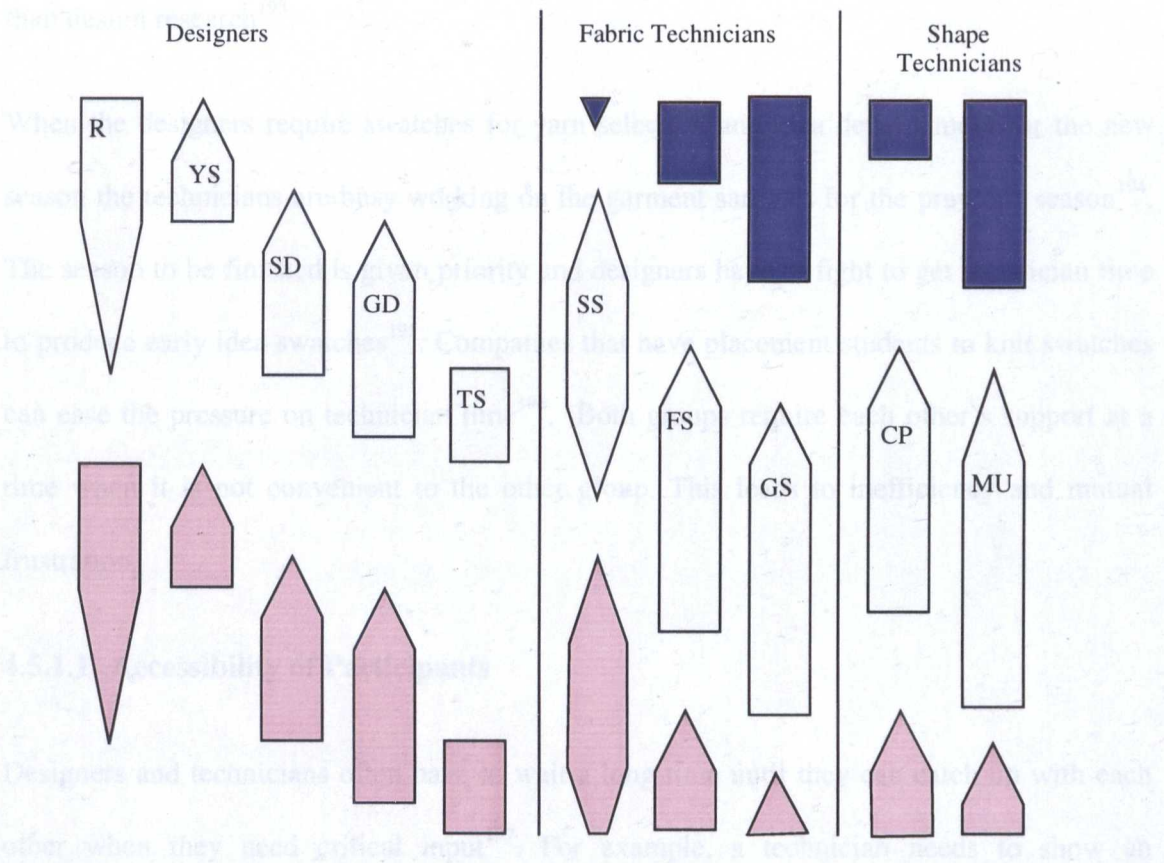


Figure 19. Time Overlap in Tasks of Designers and Technicians

Figure 19 shows the overlap of tasks and seasons¹⁹⁰. While technicians are sampling the previous season, designers are doing research for the next season. Technicians¹⁹¹ work their way through the incoming technical sketches and try to produce garment samples as soon as they can. Sometimes it is possible to produce swatches immediately, but often it takes a long

¹⁸⁹ C14HD

¹⁹⁰ All companies have similar overlap, special discussions with C1FT1, C2HT+FT1, C10HT, C11HD, C14HD

time¹⁹¹. If the time delay is long and the technicians require comments and suggestions for changes to the swatches, the designers have moved to a different stage in the process and might not remember the design in detail. This especially applies to late technical changes incorporating buyers' feedback, when the company is committed to pushing a design through to the sampling stage¹⁹². Late changes to design ideas take up more of the designers' time than design research¹⁹³.

When the designers require swatches for yarn selection and idea development for the new season the technicians are busy working on the garment samples for the previous season¹⁹⁴. The season to be finished is given priority and designers have to fight to get technician time to produce early idea swatches¹⁹⁵. Companies that have placement students to knit swatches can ease the pressure on technician time¹⁹⁶. Both groups require each other's support at a time when it is not convenient to the other group. This leads to inefficiency and mutual frustration.

4.5.1.1 Accessibility of Participants

Designers and technicians often have to wait a long time until they can catch up with each other when they need critical input¹⁹⁷. 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 of 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 problem¹⁹⁸.

¹⁹⁰ Detailed explanation by C1FT1 and C3FT1 about planning the sampling load. Doing difficult designs first to clear the way and risking not finishing routine designs, or doing easy designs first and risking not getting interesting ones done. Both use a compromise approach and muddle through.

¹⁹¹ Delay between technical sketch and swatch can be two or three months, e.g. C1.

¹⁹² Observed in particular in C14D3 trying to reduce fabric weight with technician.

¹⁹³ C14HD. Also observed in C17.

¹⁹⁴ Most designers, observed in C10.

¹⁹⁵ Observed in C10 meeting between C10HD+HT+others.

¹⁹⁶ C10, C16. In both companies the designers still complain about lack of technician time.

¹⁹⁷ Complaint from designers and technicians, for example in C10, C11 and C17. The author sympathises, having attempted to ring designers at work.

¹⁹⁸ Observed in C10FT1.

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 offices¹⁹⁹. Technicians rarely travel unless they attend training courses for extended periods²⁰⁰. In most companies there are fewer technicians than designers (see Table 3) so that designers have to wait until the technicians have finished a task for a colleague, and fit into the overall company deadlines²⁰¹.

In many companies the offices of the designers and technicians are quite a long way apart²⁰². The technicians' offices are close to the sample machines, which are noisy and therefore kept away from the designers²⁰³. Seeing each other takes effort. When designers and technicians are moved close together designers notice it as a relief²⁰⁴.

4.5.2 Work Culture Reasons

Knitwear designers and technicians have very little expertise in common, and have a very different outlook on life.

4.5.2.1 No Overlapping Expertise

Designers don't receive much technical training in the construction of knitted structures or programming CAD systems during knitwear design courses at college²⁰⁵. Many designers are trained in fashion or textile design and are not taught knitwear in depth²⁰⁶. Universities cannot afford the hardware to give each student adequate access to a CAD system or a power

¹⁹⁹ Comments from all designers, observed in C10, C17.

²⁰⁰ All technicians comment on this, only C18 technicians travel to shows.

²⁰¹ C11HD, C17D1

²⁰² Only C18 and C10 had offices close together. For example in C17 or C3 it takes a five minute walk to get from the designers to the technicians.

²⁰³ C6FT1 explained about noise proofing machine rooms. The technicians have well insulated offices, but are still in a different building from the designers.

²⁰⁴ C18HD

²⁰⁵ The emphasis in the designers' training is placed on the creative work.

²⁰⁶ The author does not have detailed figures, for example C14 hires knitwear designers, fashion designers and textile designers. D1 and D2 are trained fashion designers.

knitting machine²⁰⁷. This might change, however, with free university software licences for CAD systems²⁰⁸. Both in universities and industry the view is held by some people that excessive technical knowledge restricts the designers' creativity. There is some justification to 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 (see Eckert and Stacey, 1994, for details). However, there is no evidence that the creativity as such is restricted, rather that designers have found ways to design feasible designs fast. Knitwear companies rarely send designers on technical training courses. Only very few designers are trained to program power machines²⁰⁹, rather than just enter the Jacquards. Designers acquire technical knowledge through practical experience by seeing how their designs are realised. This knowledge is not systematically passed on to younger colleagues²¹⁰. Technicians²¹¹ repeatedly comment that they would like their designers to have greater technical knowledge, and 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 in knitwear when they are translating the designers' rough specification into fabric or shapes (see section 3.5). Technicians don't have design training. They rarely have an interest in fashion and don't follow design developments²¹². Only one company that the author has seen takes technicians along to fashion and yarn shows; it has proved beneficial to them²¹³. With practice technicians learn

²⁰⁷ In 1992 one modern Stoll system would have cost more than the whole equipment budget of the department, comment by Ray Harwood, head of Textiles department at De Montfort University.

²⁰⁸ Lectra, a tailoring system manufacturer, gives educational institutions free licences, when they buy the hardware through Lectra

²⁰⁹ Only D17D1+D2 commented that they have attended a Shima Seiki training course and could program the machine. When the author attended a Universal training course, the training course had only ever been attended by one designer by 1992.

²¹⁰ C14HD, no remarks on in house technical training.

²¹¹ C1FT1, C2FT1+FT2, C3FT1, C7FT1, C10FT1, C11HT

²¹² Author has met one technician with a personal interest in fashion during the Universal CAD programming course. C7FT1 studied women's magazines, but he designed the garments as well. C1FT1, C2FT1, C10FT1 have explicitly commented on not being interested in fashion.

²¹³ C18

design principles, such as balance of pattern elements or colours. They adapt to company house styles and learn to fit into the design style of individual designers.

4.5.2.2 Different social groups

The knitwear design process is shared by three main participants: the designers, the fabric technicians and the shape technicians, who have specific tasks²¹⁴ and skills²¹⁵. They are very different people in most respects, who do not naturally interact. Designers are young²¹⁶, university or polytechnic educated^{217, 218} women²¹⁹ with artistic aspirations²²⁰ in a job that is not highly paid²²¹. Almost all technicians are men, who see themselves as working class²²², have little interest in fashion²²³ or other artistic occupations. They are better paid, which contributes to the generally much higher job satisfaction²²⁴ of the technicians. The technicians are hard to replace²²⁵ and stay for a long time in the same company²²⁶. Table 5

²¹⁴ see chapter 3

²¹⁵ see chapter 3

²¹⁶ The author reckons that C18HD was the oldest practising designer she met who appeared to be mid to late forties (the author did not ask), but references were made to 1960 garments. Most designers have not yet had children. "Designers leave to have babies" according to C10HT. The interviewed technicians were between early twenties, e.g. C7T1, and close to retirement age, e.g. C10HT. Being a shape technician is a career goal for production make up people.

²¹⁷ Typically with degrees in knitwear design, fashion design or textile design in C8 - C20. One designer in C11 was hired without a degree. This was mentioned by C11HD as a great exception. C10FT1+FT3 explained background of technicians. The German technicians had all done a knitting apprenticeship after GCSE equivalent.

²¹⁸ All designers. C10FT1, started as sampling technician, most others had been knitters. C17FT1 was a knitting machine mechanic. C10ST1+ST2 had worked on all different machines in production.

²¹⁹ C16D3 is male. The author has not met any other male designers. C10FT3 is female. The author has not met or heard of any other female technicians. No male shape technician was ever mentioned

²²⁰ ID1, ID3, ID4, C16HD+D1 mentioned interests in painting and craft and regretted not having time to pursue them. Technicians: no mention of interest in art or artistic work in long discussion about personal interests, leisure occupations and hobbies with C1FT1, C2FT1+FT2, C3FT1, C4FT1+M1, C5FT1, C7FT1, C10FT1+FT2, C11FT3, C17D1, D1.

²²¹ C15HD had to apply for a pay rise, before she got promoted to head designer, to get a mortgage for a £31 000 house in 1993. Her company pays badly, but not exceptionally so. Figures quoted by C14HD. C17 does not pay higher salaries to technicians than designers and loses them continually.

²²² Long explanation by C10FT3 about the social implication of technicians being paid monthly, also discussed with C1FT1, C2FT1+FT2, C10FT1+ST1, C17D1.

²²³ All companies have fashion magazines, discussed with ID1, ID2, ID3, ID4, C17D1. Technicians: author encountered one technician at training course who was interested in fashion. C10FT1 clubwear. Nobody mentioned interest.

²²⁴ Private conversations with ID1, ID2, ID4. C17D1, previous C15HD explicitly contemplated career change. All shape and fabric technicians said they enjoy the job as such.

²²⁵ Colleges produce more designers than industry needs. Technicians are hard to replace (C14HD, C17HT)

Person	Designer	Fabric Technicians	Shape Technicians
Issue			
Main Tasks	design visual appearance of garments	realise designs on knitting machine	construct shape make up garment
Typical Number²²⁷ in Companies	head designer 1 - 2 designers	1 - 2 sampling technicians	1 shape technician, several make up people
Age	< 30	all ages, often older	> 30
Gender	female	male	female
Income	£10 000 - 23 000	£13 000 - 25 000	£15 000 - 20 000
Social Self -Perception	middle class	working class	working class
Education	degree from ex-polytechnic	GCSEs, trained on job	GCSEs, practical experience from production
Career Background	hired from college	hired after school from shop floor	successful in production
Average Duration in Job	2 - 4 years	life	life
Job Satisfaction	low	high	very high
Career Expectations²²⁸	low, head designer, leave designing	fight to keep up with technology	goal achieved remain in job
Artistic Aspirations	high, frustrated	none	none
Interest in Fashion	high, personal	very rare, personal	very rare
Technical Aptitude²²⁹	low	high	competent machine users
Main Skills²³⁰	Selection of design ideas, feel for market, sense for colour and proportion	programming of knitting machine, feel for yarn properties	pattern construction, make up, spatial reasoning, fabric properties
Thinking Style	visual appearance of whole garment	machine representation, fabric	garments, two-dimensional patterns
Replaceability	high	hard to find competent technicians	skilled, but desired job

Table 5 Participants in the Design Process

²²⁶ See also 216. Technicians can be head hunted (C17). No technician mentioned a previous company unless they were moved within the same group (C11HT).

²²⁷ See Table 3.

²²⁸ Only C10 and C11 had design directors, C1FT1, C2FT1, C3FT, C5FT mentioned fight to keep up with technology, also discussed with C11HT. Shape technician or production manager are the career goals of production make up people.

²²⁹ See section 4.5.2.1.

²³⁰ See section 4.4.

gives an overview of the differences between the participants in the design process. This description is inevitably a generalisation²³¹; a few individuals are badly misrepresented. A detailed analysis of the gender and other differences between designers and technicians and their differences in aptitude and access to computer technology can be found in Eckert and Stacey (1994).

The social self-perception reflects the groups' own views which have been volunteered to the author unprompted as part of general discussions on such topics as career prospects or the interaction of participants in the design process. Designers and technicians rarely socialise²³². They do not discuss problems in casual chat and generally do not know each other well enough to understand how the other group thinks.

4.5.2.3 Organisational Structure.

Only in the last few years have knitwear companies included designers in the management of a company by creating the job of design manager²³³. The other managers tend to be male²³⁴ and have degrees in textile technology or business studies, or have neither a degree nor any training in textiles. Designers often complain about having to work with people who have little understanding of design or knitting technology. For example, one designer²³⁵ is in principle not allowed to design garments with patterned fronts and backs, because this is believed to be more expensive. However, this does not need to be the case. Six cables at the front and six cables at the back can cost exactly as much as twelve cables at the front. She is not given the ultimate judgement over the visual appearance of the garment.

²³¹ C10 is a very typical company, even though it has a larger number of designers and technicians.

²³² C3DA1 explained her efforts to get designers and technicians to socialise. C17D1+D2 socialise with technicians, but generally feel socially isolated in Hawick. Designers in C10, C14, and ID1, ID2, ID3, ID4 discussed their friends with the authors and did not mention technicians.

²³³ C10, C11, C14 have promoted their head designers to directors in the last five years.

²³⁴ No female directors mentioned besides design directors.

²³⁵ C17D1

The organisational structure varies from company to company. Only in a few companies are technicians and designers in the same department under the control of the head designer²³⁶. In other companies design and sampling are on the same formal level²³⁷. Designers cannot plan the technical resources and sampling time according to their needs. They often don't have control over budgets and have to ask for money to go to shows or buy inspiration materials²³⁸.

4.5.2.4 Power Struggles between the Designers and the Technicians

Most companies declare that they are committed to realising the designers' garments as closely as possible, because the design ultimately sells the garments²³⁹. However they rarely give the designer formal power over the design process (see section 4.5.2.3). It is difficult to recruit skilled technicians²⁴⁰ (see Table 5). Colleges and universities produce a surplus of designers, and designers find it difficult to get a job²⁴¹. Companies don't have problems recruiting skilled designers²⁴², but sometimes find it difficult to find designers with management skills²⁴³. 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. This attitude was exemplified when a technician²⁴⁴ commented that he once encountered a designer having a temper tantrum because the technician did not attempt to create a fabric. The designer had to leave.

²³⁶ C11, C18

²³⁷ C10, C14, C17

²³⁸ C17D1, C16HD+D1+D2 commented that they spend their own money on inspiration books.

²³⁹ Explicitly stated by C10M1, C17M1, no contradiction.

²⁴⁰ C14HD, C17D1+MU, C7FT1

²⁴¹ D4 was the only graduate of the De Montfort University Knitwear Design BSc course in 1992, who had found a job as a knitwear designer by 1994 as far as she and D3 knew.

²⁴² Discussed with C14HD, C17D1.

²⁴³ C11HD

²⁴⁴ C7FT1

4.5.2.5 Neither Group Trusts the Other's Assertions

This issue is indivisible from the knowledge representation issues (section 4.3.3). As explained in section 3.7, many designers complain that if they are specifying a new structure, the technicians' initial reaction is: "that cannot be done". Later the technicians come back with an entirely satisfactory solution. On the other hand the technicians do not trust the designers' specifications (see section 3.7). From experience they know that the designers often define impossible designs.

The result is that both groups don't trust each other's assertions or specifications. Designers respect the technical knowledge of their technicians²⁴⁵, even though technicians do not always perceive it this way²⁴⁶. However, technicians²⁴⁷ don't always take the designers' expertise seriously.

4.6 The Communication Problem is Not Recognised

Designers often complain that technicians don't produce what they are told and the technicians complain that the designers specify garments that cannot be produced. Neither group however views this as a communication problem²⁴⁸. When asked why technicians don't produce what is specified, no designer has given a coherent explanation of the problem in general terms; they referred to the difficulties with particular designs. For example one designer²⁴⁹ had problems with a technician over the weight of a swatch, where the negotiation with the technician was clearly inefficient. But she explained the problem with a long explanation about the fussiness of Marks & Spencer buyers. Both designers and

²⁴⁵ All designers encountered spoke favourably of technicians' skills.

²⁴⁶ C11HT

²⁴⁷ C1FT1, C2FT1, C3FT1, C7FT1, C10FT1 spoke quite patronisingly about designers' skills and complained about lack of technical knowledge.

²⁴⁸ The problem has never been explained in those terms.

²⁴⁹ C14D3

technicians consider the inefficient communication an awkward feature of the job. With some justification technicians attribute the fact that designers specify impossible designs to their lack of technical aptitude. The technicians would ideally like the designers to produce the initial Jacquards to remove ambiguity, and force the designers to work out the technical problems themselves²⁵⁰. The designers complain that the technicians often offer something other than what they have asked for. Often the technicians offer old solutions to the designers (see section 4.2).

Some companies work very hard at achieving successful communication between designers and technicians. Some German companies²⁵¹ employ specific people who create the Jacquards on the CAD systems. They²⁵² need to interpret the designers' specifications and know the technical capabilities of the knitting machine to some extent. They can have an intermediary role between the designers and the technicians, organise some of the resources of the sampling process and broker negotiations over changes. Some aspects of this job are taken over by placement students in some British firms²⁵³, who do not have the long experience and respect of the German design assistants. In one company²⁵⁴ the designers made a specific effort to communicate with the technicians by using a special company language; however they still believed that the communication with technicians was difficult. Only one company²⁵⁵ has completely reorganised its design process according to concurrent engineering principles and systematically addressed the problem. The head designer remarked that communication and the efficiency of the process have greatly improved.

²⁵⁰ C1FT1, C2FT1, C10FT1, C11HT

²⁵¹ C3, C7

²⁵² Explanation by C3DA1. She is the daughter of the company owner and holds this position because she knows what is happening in design and sampling; she also enjoys her job.

²⁵³ C10DA1+DA2+DA3, C16 has placement students. Author watched the interview for a new placement student with her task description.

²⁵⁴ C17

²⁵⁵ C18. Neither the author nor C18HD has heard of other companies working in this way.

Computer technology has already revolutionised the design process in many ways and brought many improvements over the last few years. Technicians have to spend much less time on the programming of simple designs. However, the basic work pattern has remained the same. Some companies have cut the number of technicians. Technicians²⁵⁶ have commented that the work load 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.

The main contribution so far by commercial CAD to facilitating the design communication has been to make the creation of Jacquards significantly easier, so that designers could define their own Jacquards. Designs that took a matter of weeks twenty years ago such as the creation of intarsia patterns from pictures, now take a matter of hours,.

4.7 Problems in the Shape Construction Process

The example in section 4.2 illustrates general problems. The effects of the communication difficulties on the shape construction process can be summarised in the following way:

- Designers cannot evaluate their shape specifications before they see a fully made up sample garment, because there is no model of a garment before it is made up (see section 4.3.2.2).
- Designers will have moved on to a different task by the time a sample garment reaches them.
- The designers often don't know the precise measurements for the garments that they have visualised.

²⁵⁶ C1FT1, C2FT2. C5FT1 did not want the technology to change any more, because now he knew it.

- Some features of a shape are inherently difficult to define.
- Even if the designers have specified the shape they want correctly, the shape technicians normally *interpret* the specifications in the light of their previous experience when they are adapting the specification to the fabric, so altering the shape into a standard form.
- It is very hard for the designer to unpack appropriateness of their own definitions of the fabric and other factors.

Chapter 5.

Overcoming the Bottleneck

As chapter 4 has shown, the communication between knitwear designers and technicians is a significant bottleneck in the design and sampling process. This chapter outlines some possible organisational changes to the design process; and proposes a CAD system which would help to overcome the problem by supporting designers in creating complete and consistent representations of their designs. The system is placed in the context of other research on intelligent design support systems.

It will be argued that the automatic creation of solution suggestions from tentative design definitions can give the designer early feedback at the same time as providing a technically correct design specification.

5.1 Organisational Changes

A detailed analysis of possible organisational changes, to improve the efficiency of the knitwear design process in general and to overcome the communication problems, is beyond the scope of this thesis. Some general basic points, should however be noted:

- Recognising the problem: As section 4.6 argues, the communication problem is not recognised as such. A conscious effort by all parties could alleviate the situation.
- Keeping records: The records of a knitwear company are the heads of the designers and technicians. Technical sketches are only kept one season back. However, as section 4.3.1 shows, designs are often specified as modifications of past designs. Valuable data is lost and design operations need to be repeated.

- **Sharing references to other designs:** Designers discuss designs among themselves by reference to other designs, often ones they have seen in magazines. If the technicians participated in design research they would know the reference designs, and understand the overall context for the designs they are sampling.
- **Sharing expertise:** Designers have little technical knowledge and technicians don't understand about design.
- **Concurrent engineering:** A radical restructuring of the process, so that knitwear designs are developed by designers and technicians together, taking technical and aesthetic considerations into account could lead to a higher success rate for specified designs. Continuous development of new design features would alleviate time pressure and allow work on innovations, as these would not be sacrificed due to short-term pressure.

Eckert (1997) and Eckert and Demaid (1997) discuss the benefits of these changes in more detail. This thesis, however, is concerned with overcoming communication difficulties and changing the work culture through intelligent CAD support.

5.2 Intelligent Support Systems for Design

Research into artificial intelligence for design has taken two different approaches: systems that design or take over part of the design task; and systems that support the user doing design tasks. Most intelligent design support systems employ a combination of both approaches, as does the system proposed in this research.

5.2.1 Critiquing Systems

Critiquing systems are concerned with evaluating a design or part of it within an intelligent design environment; see Hägglund (1993) for an introduction, and Silverman (1992) for an extensive review. Most critiquing systems employ passive critiquing which evaluates a

design when it is completed or has come to a natural breakpoint, for example Kumar et al. (1994). Active critiquing involves monitoring the designers' actions and interrupting the design process to point out errors and give guidance. The ability of a system to critique actively is ultimately limited by its knowledge of the users' goals. Miller (1986) distinguishes between critiquing by reacting, critiquing by local risk analysis and critiquing by global plan. Critiquing by reacting occurs when (1) specific rules can be written for each type of wrong answer, (2) the rules for reviewing the user solution optimality are objective and few, (3) only one or two possible correct outcomes exist for the task, (4) each sub-task can be critiqued independently of the others. Fischer and his group have analysed what information could or should be presented to users during a design episode by an active critic; and how this should be presented (see Fischer et al. (1993), for a good overview of their concerns and approaches). Lemke and Fischer (1990) conclude from a protocol analysis study that active critiquing is preferable, even though it interrupts the thought process of the designer, because designers only request passive critiques at the end of an operation - once costly mistakes have been made. The research of the Fischer group has so far mainly concentrated on relatively simple design tasks, such as their canonical example kitchen design (see for example Fisher et al., 1991), which are not undertaken by trained design experts.

In Eckert (1995) the author has argued that knitwear designers and technicians are best supported through a combination of active critiquing, interrupting the designers, and making feedback information continuously available to them. In the case of garment shape design we can assume that much of the design has been completed in the designer's mind before they use a computer to specify a shape. Active critiquing could be used when specified measurements are clearly outside certain parameters, for example less than the underlying body measurement. The automatic creation of a shape from the measurements can be seen as

passive critiquing, as it poses an evaluation of the specification and communicates the feedback as a visualisation of the design.

5.2.2 Automatic Creation of Designs

Automatic designs aim to create a design solution from a problem specification, however vague, without the interference of the user. Some problems can be modelled through accurate mathematical models. Algorithms can only be applied when:

- the problem is well understood;
- the problem specification is sufficiently complete;
- the goal is clearly understood, i.e. the major characteristics of the finished design can be described a priori.

In most design tasks this is not the case. It lies in the nature of design that the problem specification changes in the light of possible solutions, until a satisfactory solution is found to a satisfactory problem. However, many design tasks have sub-tasks which are clear problem solving tasks. For example, to design an aeroplane engine to a certain specification an optimal shape for the rotor blades needs to be found. To design a knitted garment it is necessary to define the shape of garment. Constructing a shape using a mathematical model does not need to follow the traditional methods of the industry. Mathematical models can only be applied when the input data is complete and correct.

Otherwise different strategies need to be employed: in the simplest case default values can be used for missing input. Case based reasoning is concerned with the analysis or solution of problems based on previous cases (see Kolodner, 1993, for an introduction). It consists of the following steps: (1) assess situation, (2) index target problem, (3) retrieve similar case, (4) assess similarity, (5) adapt case to target problem, (6) assess solution, (7) store solution. Steps (3) and (5) are the core operations of case based reasoning. Case based reasoning systems either adapt a single case or multiple cases. The adaptation can occur through the

use of problem solvers or heuristics. See 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. It will be argued in section 7.3.3 that case based reasoning could be employed to provide starting measurements for cutting pattern construction.

Other AI techniques are concerned with creating designs from scratch. Shape grammars (Stiny, 1980) have been introduced as a formal way to create descriptions of designs. A shape grammar consists of an alphabet of shapes, a starting shape and rules that define the spatial relations between different shapes. Shape grammars are a systematic mechanism to create the space of possible designs. Shape grammars were initially developed for architecture and have been applied to a variety of architectural problems, for example the creation of Frank Lloyd Wright houses (Koning and Eizenberg, 1981), and mechanical design (see Schmidt and Cogan (1996) for a review and concrete example). The possible solutions need to be evaluated either by a human, as in Todd and Latham (1992) in the generation of creative art forms; or tested by a machine against pre-defined constraints. Most grammars also use a hierarchy of generation levels. Suitable solutions are located within the space of possible solutions through search algorithms such as simulated annealing. However, shape grammars require careful manual coding of the generative rules. They can be combined with genetic algorithms to increase the search space or reduce the initial start-up cost of finding the generation rules. Rosenman (1996) shows how building forms can evolve in combination with shape grammars. Schnier and Gero (1996) show how genetic algorithms can learn suitable representations and thereby gather domain knowledge. The problem with genetic algorithms, however, is the definition of a suitable fitness function for the specific problem.

5.2.3 Architecture Systems with a Similar Approach

Much research has been put into the development of intelligent design support systems for engineering and architecture. The following describes briefly an architecture system with a similar approach to the proposed knitwear support system.

Papamicheal et al. (1996) describe the Building Design Advisor (BDA) developed at the Lawrence Berkeley National Laboratory to incorporate climate and site considerations into the design of a building. The system has grown out of research into technical aspects of building design such as lighting or heating considerations and was devised to provide an integrated design environment. BDA has simulation tools, analysis tools and databases. The system can use 'smart' default values to produce multiple initial solution suggestions from a very minimal building description plus keywords and a specification of the site. BDA uses databases of previous cases and has databases containing building regulations, as well as access to geographical information for a specific site. Rooms and buildings can be edited in a specific editor and for each change automatic evaluation can be provided in multiple representations - for example an analysis of the lighting in the room through the day over the whole year. Changes to one room are automatically carried through to other rooms. The default values can be overwritten with detailed technical specifications whenever the user wants. The system uses a generic object oriented representation and has been implemented in C++ on PCs.

The IDIOM system (Smith et al., 1996) is a system for composing layout designs for buildings using cases. The layout can also be viewed in a modeller. The system supports designers by reducing the constraint complexity and managing design preferences. The layouts are created interactively either by modification from previous cases or by being built up from components. Changes to rooms in the building are carried through to other rooms automatically while maintaining conformity to regulations and following rules within a

specified class of designs. The system manages some of the conflict resolution involved in making modifications to designs through case based reasoning on multiple cases. Mistakes are picked up through active critiquing as soon as they have violated a built-in rule. Smith et al. (1996) also reviews other case based architecture systems.

5.3 Intelligent Support through Solution Suggestions

Current CAD systems support the automatic generation of knitting machine programs from a symbolic representation and give efficient feedback through design simulation (section 1.5.1). They do not support the evaluation of tentative designs. To receive feedback the users need to commit their ideas and invest time into working designs out in detail.

As section 4.2 shows, however, many design specifications are incomplete, inaccurate and inconsistent, because designers do not have the time or technical knowledge to express their ideas accurately. Designers need technical feedback during the idea generation process. A CAD system should allow designers to specify tentative designs quickly and receive fast initial feedback, so that they can then explore the design space and hand over a design which is technically plausible. This approach has been introduced in fashion information systems, such as the Gerber system (Gerber, 1996), where designers can specify a design through modification to older designs and receive initial costing feedback. A knitted garment is far more complex than a woven garment, because in knitwear the shape and fabric are created at the same time. Feedback entirely based on descriptions of modifications to a previous design would not be enough, considering the idiosyncrasies of the material and the decisions required for each design (see example in section 4.3.2.1 and Figure 14 to Figure 17).

The communication problem can partially be overcome by a computer system that can turn a tentative and potentially incompletely specified design into a technically correct version which could be understood by a technician, as illustrated in Figure 20. This thesis proposes a

system to create solution suggestions automatically from designers’ customary specifications. These suggestions can be evaluated visually and edited by the designers while maintaining internal consistency. The communicated design corresponds to the designers’ intentions. It is technically correct and complete; and can be presented in multiple representations.

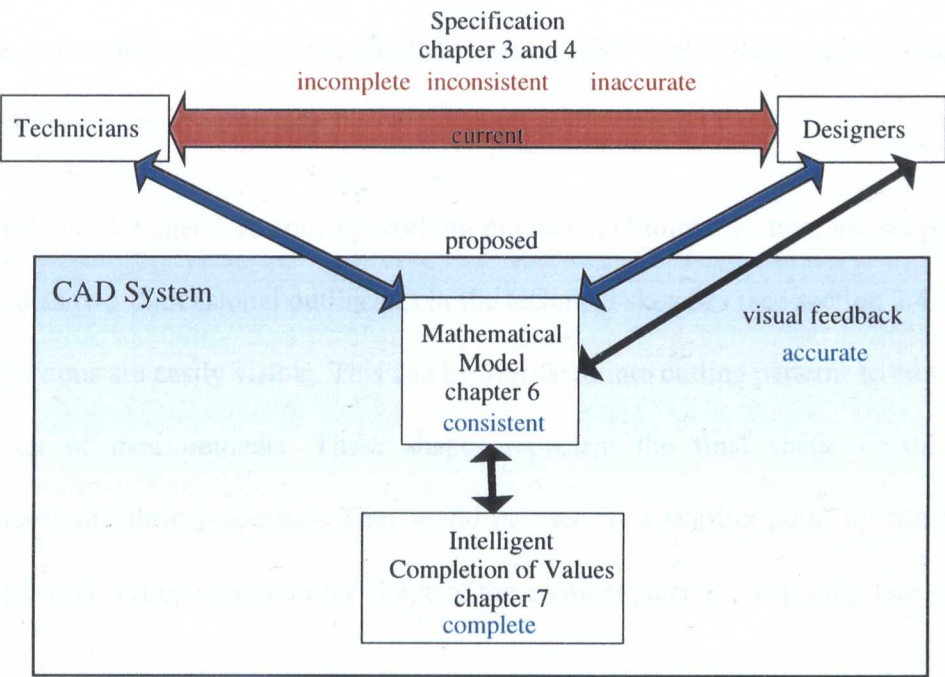


Figure 20. Overcoming the Communication Problems for Garment Shapes through a Mathematical Model as part of an Intelligent CAD System

The following chapters discuss the application of this approach to garment shapes. Traditionally garment shapes are constructed in industry using a manual craft approach (see section 4.2 for a description of a practical example). To create automatic solution suggestions the construction of garment shapes needs to be modelled mathematically. The model needs to enable the design support system to meet the following requirements:

- design starts from the designers’ customary notations;
- designs are easy to edit, so that users can modify the solution suggestion;
- the system maintains domain constraints;
- the system is adaptable to individual company styles;
- the system allows easy use of the intelligent completion of values;

- the system highlights and modifies inconsistent input measurements.

The thesis uses a co-ordinate system with lines and Bézier curves to create a mathematical model of garment shapes (see chapter 6). A similar approach has been successfully employed by Papamicheal et al. (1996) in the BDA system. It uses default values, with a possible extension to case based reasoning, to complete input data; and displays the data instantly in multiple representations. As in the IDIOM system (Smith et al., 1996), active critiquing and user preferences could be included.

To fit into the designers' customary working practice and thinking style, the shapes need to be presented as two-dimensional outlines as in the technical sketches (see section 3.4.3), so that the proportions are easily visible. This can be translated into cutting patterns to edit details or into a set of measurements. These shapes represent the final shape of the garment independent of fabric properties. They could be used as a starting point by technicians to create the final cutting pattern or the shape of the garment piece for a specific fabric.

Designers are used to solution suggestions, because technicians present them with completed suggestions after a considerable time delay (see section 4.5.1). This approach exploits the designers' skills in the perceptual evaluation of designs, because they are able to recognise good or technically correct solution suggestions, even if they could not specify them.

Chapter 6.

Mathematical Models of Garment Shapes

This chapter discusses the construction of cutting patterns based on correct input measurements. Knitted fabric has specific characteristics which influence the construction of cutting patterns. These are discussed at the beginning of this chapter. The cutting patterns comprise coordinates and lines between them. The coordinates are calculated from the input measurements. The curves on the cutting patterns can be modelled mathematically. This chapter discusses an approach using Bézier curves and domain heuristics. As the difficulties of the modelling process lie in the shape of the sleeve, these are discussed under separate headings. The last section of the chapter looks at the applicability of the approach to knitwear design.

6.1 Basic Characteristics of Cutting Patterns

Most garments are constructed using two cutting patterns: a cutting pattern for the body and a cutting pattern for the sleeve. The cutting patterns are also called blocks. The body block shows half of the piece, because most garments are symmetrical. Apart from the neckline, most knitted garments have the same shape at the front and the back, so one cutting pattern has both the front and back neckline drawn in.

In knitwear the seam allowances are directly drawn onto the cutting patterns. They are excluded in this implementation, because they do not concern the designers directly, who wish to do initial visual evaluations of the shape of the garment.

6.1.1 Specific Constraints on Knitwear

A small number of very basic properties of knitted fabric affect the shape of knitted garments enormously:

- The single most important fact about knitwear shape is that knitted fabric stretches. The fabric is not stable. It can be pulled or pushed together without showing much effect. Two pieces of woven fabric pucker unless they are exactly the same length. It is not a problem to stitch two pieces of knitted fabric together when one piece is 10% longer than the other. Ideally knitted fabric is not pulled or pushed, because it can lead to distortions in the decorative pattern. Many shape technicians aim to stitch seams of the same length together. Often the fabric slackens more across rows than across columns. This affects sleeve heads, because the sleeve is cut across the width of the fabric and the arm hole curve along the length of the fabric. Therefore some shape technicians construct sleeve curves that are shorter than the relevant armhole curves.
- Knitted fabric unravels easily. In cut-and-sew knitwear, square pieces of fabric are knitted on a power knitting machine. They are steamed to fix the fabric and then cut to shape. A stitch that is cut across at a wrong angle can unravel before it is overlocked. The risk can be decreased by minimising the length of the cut. This leads to important constraints on the shapes:
 - The fabric is cut as long as possible straight between stitches. The beginning or end of a curve is cut along a row or along a column, because pointed corners are hard to overlock. This leads to the constraint of vertical and horizontal end tangent vectors of curves. This is most relevant at the shoulder end point and the under arm point.
 - When it is necessarily to cut across stitches then the shape technicians cut as shallow as possible. Very steep angles are cut as a straight piece and a shallower piece (see Figure 21)

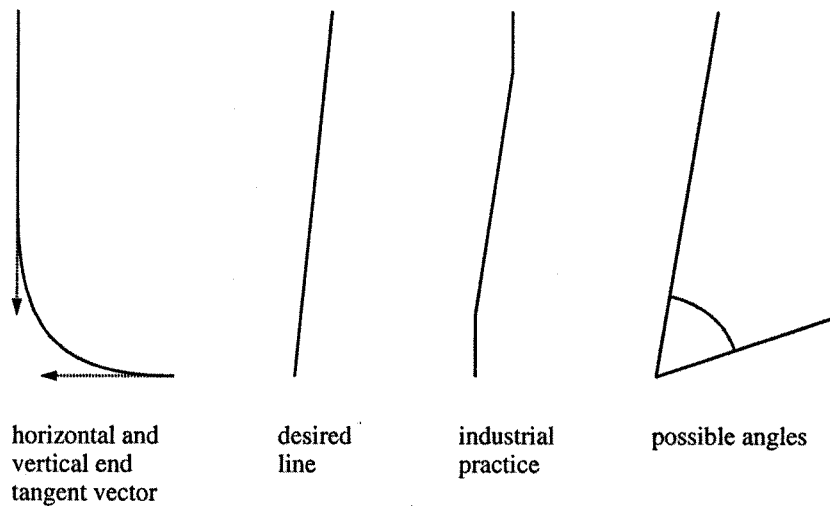


Figure 21. Cutting Angles for Cut-and-sew Knitwear

The stretch properties of each fabric are different. Each cutting pattern needs to be adapted to each new fabric. Not only has every stitch structure its own stretch properties, but also the same fabric can behave differently when knitted under slightly different conditions. In the current industrial practice shape technicians interpret the designers' input measurements at the same time as adapting a cutting pattern to a particular fabric. Cutting patterns are therefore often mathematically inconsistent. For example the sleeve head curve of a cardigan stitch garment is at least 10% shorter than the arm hole curve, because the fabric is so stretchable horizontally. It is very hard to unpack mathematical construction mistakes from adaptations to stretch properties. The stretch behaviour of fabric is not yet understood well enough to be mathematically modelled sufficiently to include it into shape considerations. The Shima Seiki CAD system (see section 1.5.1) requires the users to put in the specific measurements of a fabric piece to do a rudimentary adaptation.

6.1.2 Construction of Cutting Patterns

Figure 22 and Figure 23 show the outline of cutting pattern pieces. Names in black indicate the input measurements and names in blue refer to the construction coordinates of the cutting pattern. The coordinates are placed in a Cartesian coordinate system. The

construction of the coordinate location is based on basic geometry and is explained in detail in Appendix C.

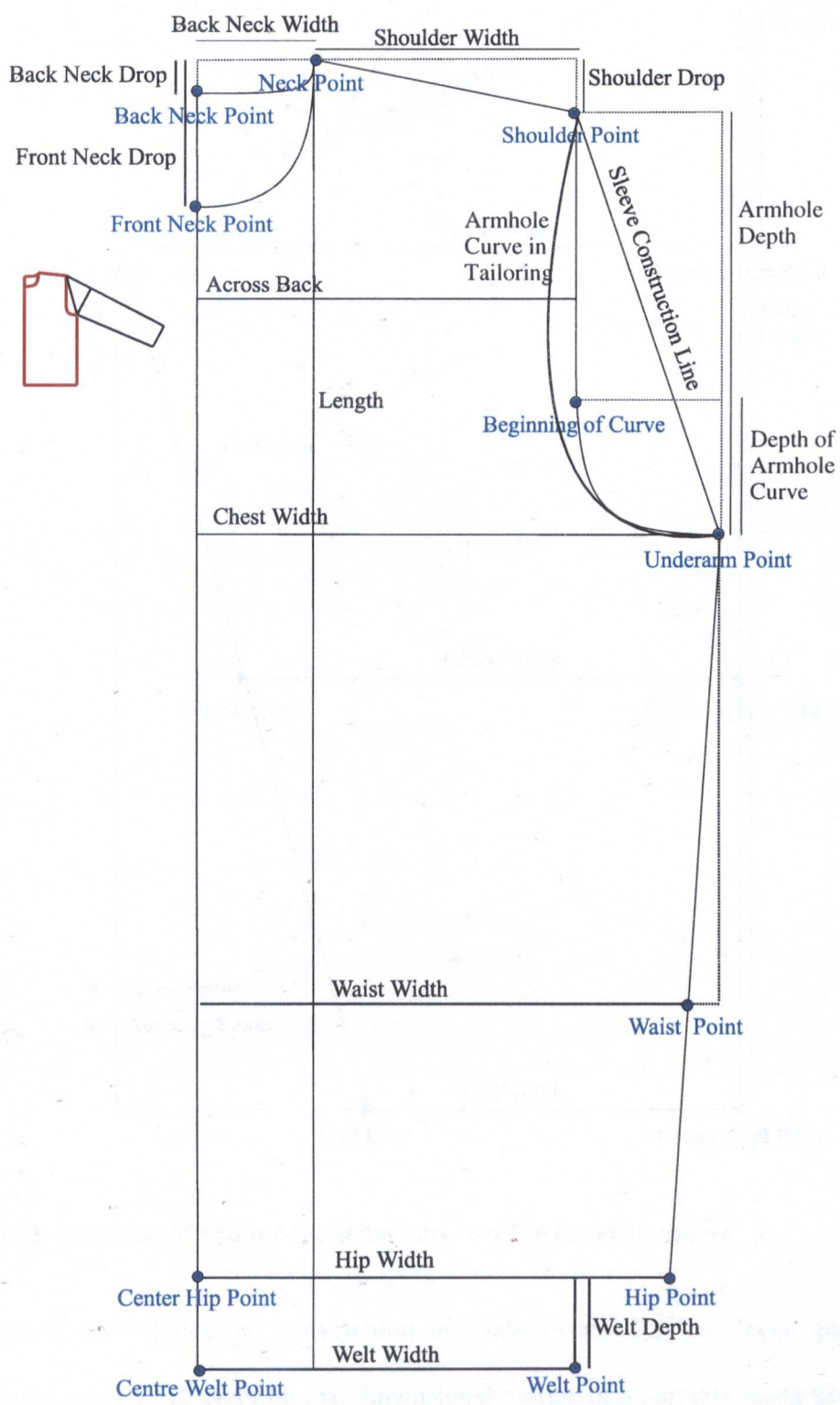


Figure 22. Location of Input Measurements on a Basic Body

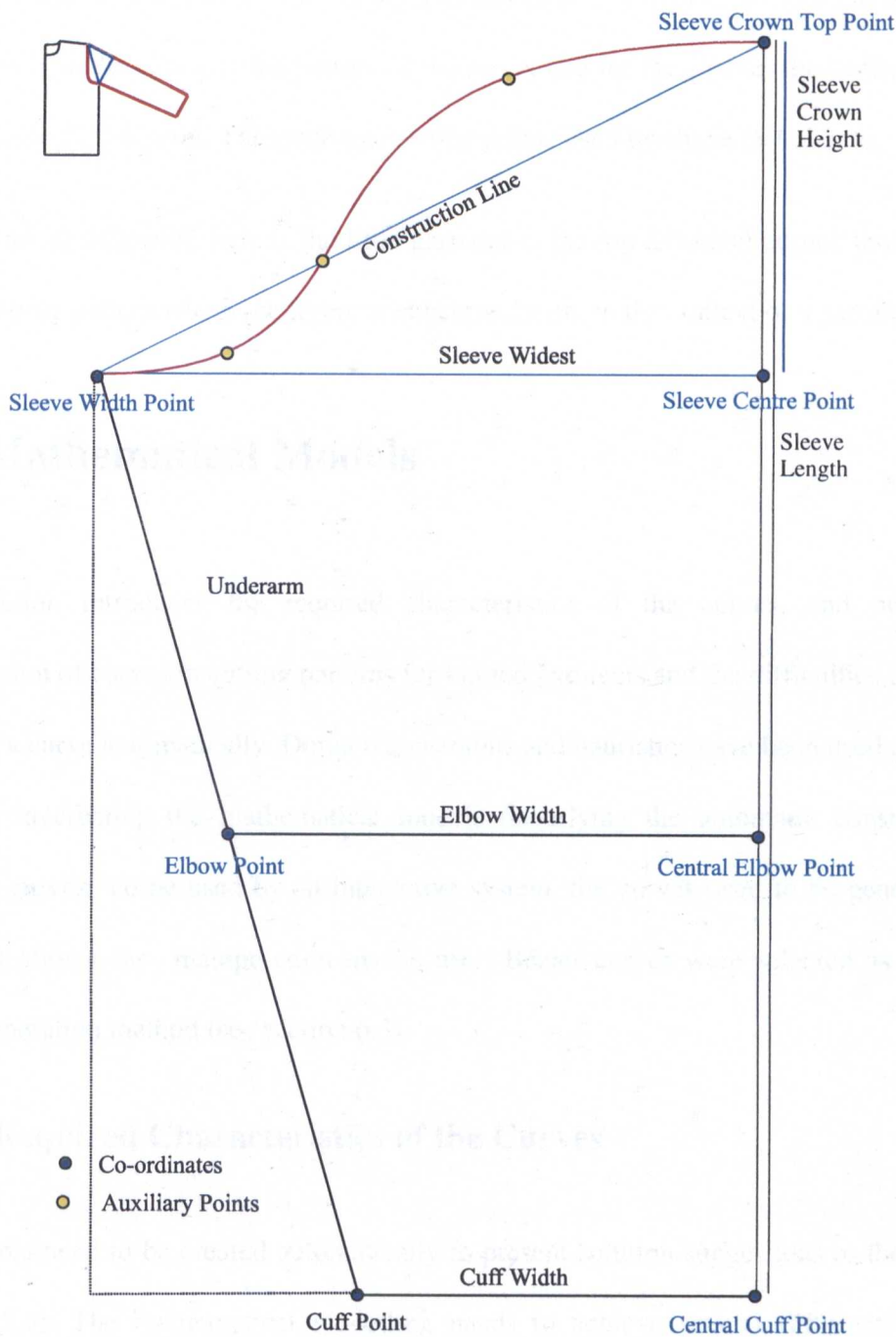


Figure 23. Location of Input Measurements in a Basic Set-in Sleeve

Appendix C also shows the construction of T-sleeve and Raglan sleeve garments. The cutting patterns are mapped to a two-dimensional outline of a garment using geometry, also explained in Appendix C.

The construction of the coordinates of the garment is closely modelled on the manual construction process in the industry. It is similar to the way shape technicians use the input

measurements to construct the beginning and end points of their lines. For the body pieces the origin is in the centre at the bottom of the piece, and for the sleeves the centre is located at the sleeve centre point. These are the starting points used by shape technicians.

In this and all following figures the little garment in the top left hand corner shows the part of the cutting pattern which the figure is concerned with, in the context of a garment outline.

6.2 Mathematical Models

This section introduces the required characteristics of the curves, and outlines the construction of curves in cutting patterns for knitted garments and the difficulties involved in creating a curve automatically. Domain constraints and heuristics have been used as much as possible in creating the mathematical models underlying the automatic construction of garment curves. To be used by an interactive system, the curves need to be generated in a way that allows easy manipulation by the user. Bézier curves were selected as a suitable curve generation method (see section 6.3).

6.2.1 Required Characteristics of the Curves

The curves need to be created automatically to present solution suggestions to the user (see section 5.3). The mathematical modelling needs to achieve several different objectives simultaneously. It should:

- Create curves that follow the domain constraints and customs.
- Create visually appealing curves, that look right to the user.
- Create curves that are mathematically consistent between different pieces of the garment, especially a sleeve crown curve with the appropriate length so that it fits into the specified armhole.
- Be simple to use, so that a mathematically inexperienced user can modify the curves.

- Use the minimum possible number of assumptions that are not derived directly from the users' input.
- Be flexible enough to incorporate individual styles and company default values into the automatic solution suggestions.

6.2.2 Solution Overview

Domain heuristics provide points that the curve must pass through (see section 6.4), as well as constraints to which the curve must conform (section 6.6 and 6.7). The heuristics were derived by the author from the design teaching given to undergraduate knitwear designers and from a standard textbook on the construction of cutting patterns (Aldrich, 1987).

These heuristics provide interpolation points as constraints, so generating curves requires a way to calculate the control points of Bézier curves from the interpolation points. Doing this requires a method to approximate the value of the parameter t of the curve $p(t)$ at the interpolation points (see section 6.5). A simple geometric algorithm for calculating t values has been developed. The same algorithm has also been applied iteratively to higher order curves.

Armhole curves and neckline curves can be modelled using cubic Bézier curves (see section 6.6).

Modelling the sleeve curves of set-in sleeves, the most common form of knitted sleeves, proved to be a harder problem; it will be discussed in detail in section 6.7. Initially the maximum number of domain constraints were gathered to describe the curve as accurately as possible. One of the most stringent domain constraints is that the end tangent vectors need to be parallel. Therefore they are linearly dependent. This means that the length of these vectors cannot be calculated. After many unsuccessful modelling attempts as described in Appendix B, two different types of successful methods for constructing curves were found. One uses

composite cubic Bézier curves (see section 6.7.4), which incorporate most of the domain constraints but give very little freedom to manipulate the curve and still have a legal solution. The other uses curves for which the length of the end tangent vector is set by heuristics (see section 6.7.4). These solutions are visually satisfactory, and easy to calculate and manipulate, but don't use all the domain constraints that could be imposed on the curves.

Solution suggestions for the sleeve crown curve not only have to look right, but also must have the right length. All the curve solutions are constructed in a way that allows a curve with the correct length to be obtained by moving the end points of the curves iteratively. It is not possible to use the length of the curve as the only input constraint to the construction of the curve, because infinitely many curves of equal length can be found between two points. The locations of the end points are likely to be specified inaccurately in the input from the user. As the locations of the interpolation points are calculated from the endpoints they will also be wrong.

6.3 Bézier Curves

A number of numerical techniques have been looked at to select an appropriate modelling approach. Bézier curves were selected because they allow the incorporation of constraints on end tangent vectors and always produce smooth curves. Both criteria are very important to a knitwear designer.

Bézier curves are typically used in two different applications:

- Interactive ab initio design of curves to model an existing object. For example the original application of Bézier curves was in the modelling of car bodies (Bézier, 1968). This approach is explained and illustrated in detail in Forrest (1990). The shapes tend to be modelled by cubic curves, which are joined to give a continuous appearance. The joining of the curve segments is problematic and attracts great discussion in the

literature (for example Farin, 1982; Filipe, 1993; Shetty & White, 1991 and Harada et al., 1984). Even though it is in many cases problematic to create curves to model an object such as a car modelled in clay or depicted by a sketch, the curves can easily be modified to achieve a more accurate model of the original object. Unlike this application to knitwear design the curve is not the starting point for the creation of a shape.

- Interactive creation of design objects. Slater (1988) proposes Bézier curves to create the cutting patterns in fashion design interactively. In this case the designers are responsible for the shape of the curve. Curve segments are combined as the users see fit.

Not all the curves in a knitted garment can be described by a single analytical function of a single variable in a given coordinate system; see, for example, the 'sweetheart' neckline in Figure 24 . The armhole, sleeve and neckline curves, as they are discussed here, could however be modelled as a function of one variable; but for design reasons it might be necessary to change these curves to ones that could not be described as a simple function; see Figure 24. Therefore the curves need to be modelled as parametric curves.

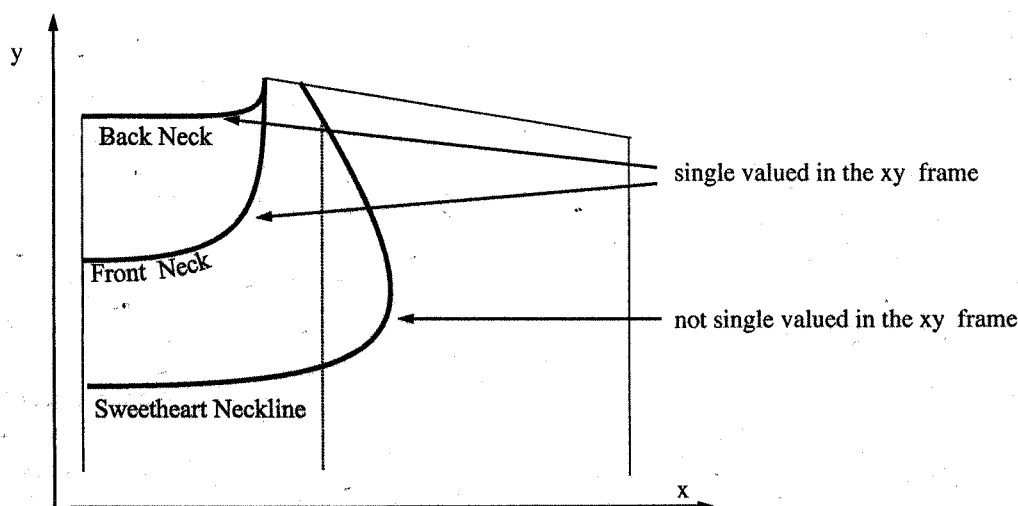


Figure 24 Problematic Necklines

Example of a neckline (the 'sweetheart' neckline) that cannot be represented as a single-valued function in the given coordinate system.

The aim was to model each curve on the garment with a single curve type to fit in with the thinking patterns of the users. Many interpolation approaches' such as different types of splines' use parametric polynomials to interpolate between different points and to make differentiation easy (see Faux and Pratt (1979) for a detailed account). The overall curve is represented by a piecewise polynomial curve. These were first introduced by Ferguson (1964) in the early 1960s. Bézier curves were selected as the modelling technique. A Bézier curve is defined by a polygon of control points. As Figure 25 shows the curve is a smooth approximation of the defining polygon, and this is important for design applications.

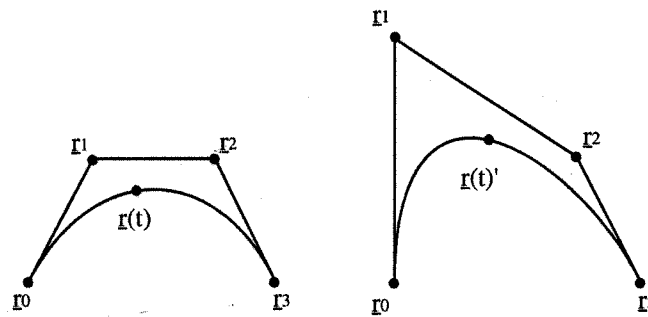


Figure 25. The Relation of Bézier Points and the Bézier Curve

A Bézier Curve $(t, \underline{r}(t))$; $0 \leq t \leq 1$ has the general form:

$$\underline{r}(t) = (t, \sum_{k=0}^N \begin{bmatrix} N \\ k \end{bmatrix} t^k (1-t)^{N-k} \underline{r}_k) \quad , \quad 0 \leq t \leq 1, \quad \text{with} \quad \begin{bmatrix} N \\ k \end{bmatrix} = \frac{N!}{k!(N-k)!}$$

Equation 1. Bézier Curves

$\underline{r}_0, \underline{r}_1, \dots, \underline{r}_N$ are the control points of the curve, called Bézier points.

$\underline{r}(t_i)$ is the curve at a specific point, $0 \leq t_i \leq 1$.

A cubic Bézier curve has the form:

$$\underline{r}(t) = (1-t)^3 \underline{r}_0 + 3(1-t)^2 t \underline{r}_1 + 3(1-t) t^2 \underline{r}_2 + t^3 \underline{r}_3$$

Equation 2. Cubic Bézier Curves

where $\underline{r}(t)$ is a parametric function of t and \underline{r}_i are the Bézier points. In the case of knitted garments the curves are two-dimensional, so that $\underline{r}_i = (x_i, y_i)$.

A Bézier curve of order N has $(N + 1)$ Bézier points. A cubic curve has four Bézier points.

The two end points of the curve are also the first and the last Bézier points:

$$\underline{r}(0) = \underline{r}_0,$$

$$\underline{r}(1) = \underline{r}_N.$$

The control points adjacent to the first and last control points are the end points of the tangent vectors of the Bézier curve at its end points:

$$\underline{r}_1 = \underline{r}_0 + \mu \underline{r}'(0)$$

$$\underline{r}_{N-1} = \underline{r}_N + \lambda \underline{r}'(1)$$

In the case of cubic Bézier curves this gives:

$$r_0 = r(0), \quad r_3 = r(1), \quad r_1 = r_0 + \mu r'(0), \quad r_2 = r_3 + \lambda r'(1)$$

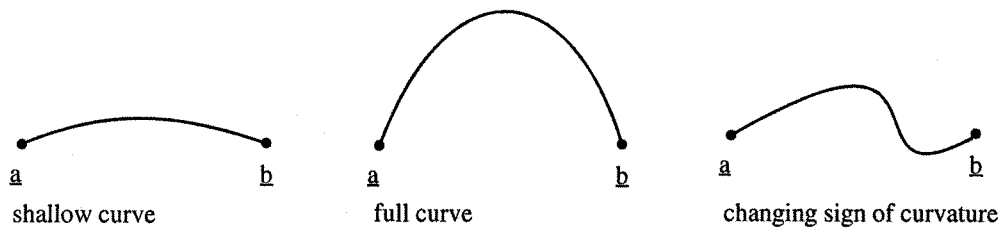
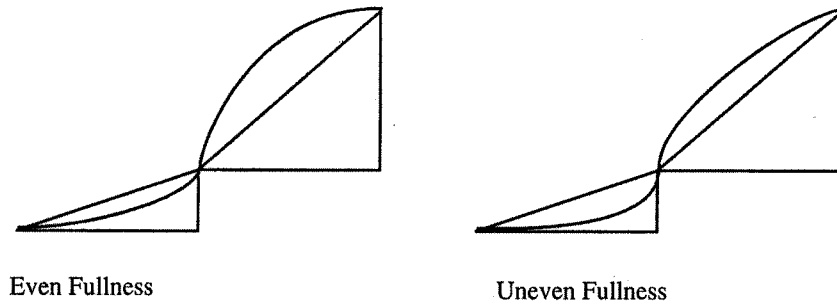
Equation 3. End Vector Tangents

$\underline{r}'(0)$ is the tangent vector of the curve at \underline{r}_0 . It is generally true that the vector $\underline{r}'(t)$ is tangential to the curve at the point $\underline{r}(t)$.

Bézier curves were chosen for the following reasons:

- The manipulation of Bézier curves is fairly intuitive, see Figure 25. By moving a Bézier point the curve is moved in the same direction.
- The representation as a polynomial and the mathematical manipulation via the control points $\underline{r}_0, \underline{r}_1, \dots, \underline{r}_N, \underline{r}_{N+1}$ is fairly simple.
- Bézier curves give easy control over the end tangent vectors.

The easy and intuitive manipulation of the end tangent vectors is most important in knitwear design as a domain where end tangent vector constraints need to be built into the automatic solution suggestions.

**Figure 26. Fullness****Figure 27. Even Fullness**

The term fullness is used in the context of this research as an intuitive term to indicate how “rounded” the curve is between two different points. As Figure 26 illustrates the fullness of the curve between two points is given by the length of the curve without a change in the sign of the curvature (see Equation 9). In this application it is very important that the fullness of the curve is distributed evenly over the curve segment (see Figure 27).

The traditional shape construction methods of the industry provide domain heuristics to calculate interpolation points. These could be used to calculate the curves for the cutting patterns. The neckline and armhole curves could be modelled using cubic Bézier curves.

Various solution strategies were tried for the sleeve curves:

- Composite cubic Bézier curves (section 6.7.4), where curves are modelled by different cubic curves with curvature continuity at the joints: These curves look satisfactory, but are over-constrained so that the user has no freedom to edit the curves.
- Quintic Bézier curves, where four Bézier points need to be calculated. As the sleeve curve requires parallel horizontal end tangent vectors at the beginning and end of the

curve, the problem had four unknowns in one coordinate and two unknowns in the other coordinate and was therefore over-constrained.

- Application of domain heuristics to calculate the location of the two Bézier points for a quintic Bézier curve adjacent to the curve's end points. This worked satisfactorily. The same approach could be applied to curves of order four and six. Cubic curves did not allow any flexibility to edit the curve.

6.4 Construction of Interpolation points

Interpolation points within the range of a Bézier curve, of the type $p_{aux1} = r(t_1)$, are not customarily used. The interpolation points are constructed using only the end points and domain heuristics. When the locations of the end points are moved, for example to create a curve with a different length, the location of the interpolation points are recalculated. The heuristics used here are derived from *Metric Pattern Cutting* (Aldrich, 1987).

6.4.1 Armhole and Neckline Curves

The cubic curves used in this modelling of garment shapes have known end tangent vector directions, therefore it is sufficient to use one interpolation point to calculate the two remaining Bézier points. Figure 28 shows the construction of this interpolation point p_{aux1} . As any curve must cross a vector at a 45° angle from the corner of the construction triangle, the intersection point with this line is used as the interpolation point. (The term construction triangle is used for the right-angled triangle whose hypotenuse is the straight line between the end points, and whose short sides are parallel to the horizontal and vertical axes.) The distance of this point to the corner point, denoted *dis*, is given as a domain constraint. In this implementation *dis* is set to a default value. This default value could be set by the user; in the example shown in Figure 34 $dis = 2cm$.

In the following diagrams the bold lines on the small garment show where this curve occurs in the design.

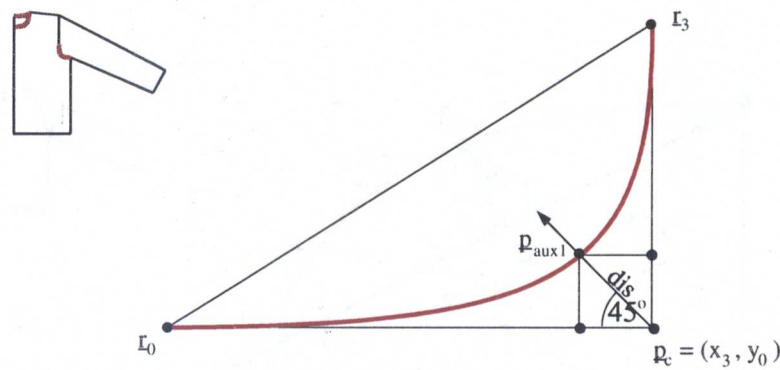


Figure 28. Construction of Interpolation Points for Cubic Bézier Curves

The interpolation point p_{aux1} is at a 45° angle from the corner point p_c .

$$x_c = x_3$$

$$y_c = y_0$$

applying Pythagoras' theorem

$$x_{aux1} = x_c - \frac{1}{\sqrt{2}} \text{dis}$$

$$y_{aux1} = y_c + \frac{1}{\sqrt{2}} \text{dis}$$

6.4.2 Sleeve Crown Curves

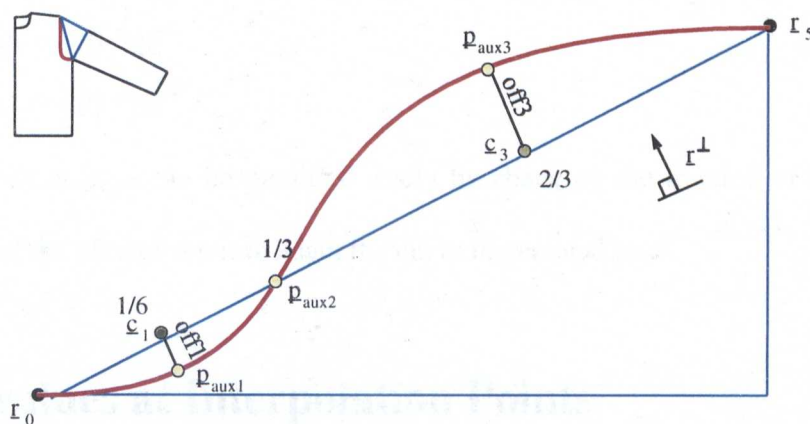


Figure 29. Calculation of Interpolation Points for Quintic Bézier Curves

The following describes the calculation of the three interpolation points $p_{aux1}, \dots, p_{aux3}$ as input to the calculation of sleeve curves. Most of the attempts to use quintic Bézier curves for sleeve crown curves make use of three interpolation points; see Appendix B. The location of the interpolation points is based on heuristics given to guide novices in Metric Pattern Cutting (Aldrich, 1987). The offset values are also derived from Metric Pattern Cutting. They could be set by the user to assure individual solution suggestions.

The interpolation points are calculated as offsets from fractions of the construction line

$$p_{aux2} = r_0 + 1/3 * (r_5 - r_0)$$

$$c_1 = r_0 + 1/6 * (r_5 - r_0)$$

$$c_3 = r_0 + 2/3 * (r_5 - r_0)$$

The offset is a specified length on the normalised orthogonal vector $r^\perp(t)$ to the construction diagonal, $r_5 - r_0$. The orthogonal vector has the coordinates:

$$x^\perp = y_0 - y_5 \quad y^\perp = x_0 - x_5$$

We have

$$\|r^\perp\| = \sqrt{(x_5 - x_0)^2 + (y_5 - y_0)^2}$$

and therefore the normalised orthogonal vector \underline{nr}^\perp

$$\underline{nr}^\perp = \underline{r}^\perp / \|\underline{r}^\perp\|$$

The location of the points is:

$$\underline{p}_{aux1} = \underline{c}_1 + off_1 * \underline{nr}^\perp$$

$$\underline{p}_{aux3} = \underline{c}_3 + off_3 * \underline{nr}^\perp$$

The locations of \underline{p}_{aux3} can be modified easily by changing the fraction of the construction diagonal and the offset from it to adapt the curve to personal taste.

6.5 T-values at Interpolation Points

The construction of a curve through interpolation points proved to be a difficult problem, because the calculation of the appropriate t-value poses a novel problem. A simple geometric algorithm, using both the distance and the angle between the connection line between two points and the horizontal is introduced to assure aesthetically pleasing curves. This algorithm has been applied successfully to cubic Bézier curves and iteratively also to higher order curves.

6.5.1 Cubic Bézier Curves

If $\underline{r}(t_1)$ and $\underline{r}(t_2)$, $t_2 > t_1$, are two points on the Bézier curves, then $t_2 - t_1$ is related to the length of the curve between the two points. When interpolation points are used to construct the Bézier curves, their relevant t values need to be known to achieve a “satisfactory” curve. This is not a standard problem and interpolation points are not normally used to construct Bézier curves.

Initially the author attempted a linear approximation of the t-value in proportion to the distance between \underline{r}_0 and \underline{p}_1 and \underline{p}_1 and \underline{r}_3 (see section 6.5.2 for location of points), with t_1 such that $\underline{r}(t_1) = \underline{p}_{aux}$.

$$d_1 = \sqrt{(x_{aux1} - x_0)^2 + (y_{aux1} - y_0)^2}$$

$$d_2 = \sqrt{(x_{aux1} - x_3)^2 + (y_{aux1} - y_3)^2}$$

$$t_1 = d_1 / (d_1 + d_2)$$

The results were unsatisfactory and the curve produced a loop at the end to accommodate the additional curve length.

For the smooth single-valued curves of the this application domain it is intuitively obvious that if two pairs of points are the same distance apart, then the length of the curve segment is greater if the angle between the vector connecting the points and the horizontal is greater, and if the curve maintains the same relative fullness, see Figure 30.

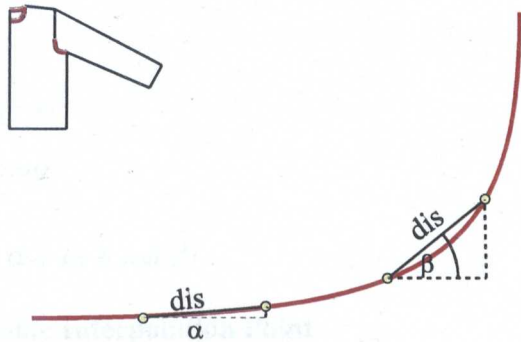


Figure 30. The Relation Between the Distance Between Points and the Curvature

Based on this intuition an algorithm was developed that takes both the angle between points and the distance between them into consideration. Section 6.5 illustrates this process. All the Bézier curve construction methods that produce successful curves use this algorithm; see section 6.7.

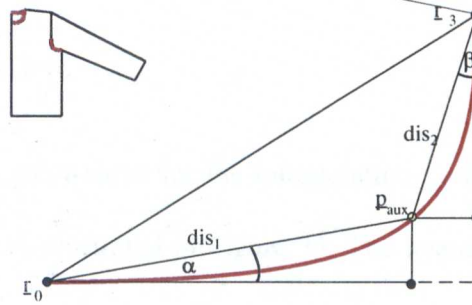


Figure 31. Calculation of t-value at the Interpolation Point

$$dis_1 = \sqrt{(x_{aux} - x_0)^2 + (y_{aux} - y_0)^2}$$

$$dis_2 = \sqrt{(x_3 - x_{aux})^2 + (y_3 - y_{aux})^2}$$

$$t_{l1} = dis_1 / (dis_1 + dis_2)$$

$$t_{l2} = 1 - t_{l1}$$

$$\tan \alpha = (y_{aux} - y_0) / (x_{aux} - x_0)$$

$$\tan \beta = (x_3 - x_{aux}) / (y_3 - y_{aux})$$

$$t_l = (t_{l1} + \alpha) / (t_{l1} + \tan \alpha + t_{l2} + \tan \beta)$$

Equation 4. t-value for Cubic Interpolation Point

6.5.2 Quintic Bézier Curves

The problem of correct t-values at the interpolation points proved even more significant for quintic Bézier curves. The domain heuristics suggest the use of up to three interpolation points for the construction of the sleeve curve, which leads to the use of quintic curves. The construction of the interpolation points is explained in 6.4.2. We have three equations (see Equation 8):

$$r(t_1) = p_{aux1}$$

$$r(t_2) = p_{aux2}$$

$$r(t_3) = p_{aux3}$$

The interpolation point p_{aux2} is most important, because its tangent vector can be defined and the curvature is known to be zero.

The method for calculating the t-value for the interpolation point of cubic curves has been extended to quintic curves as illustrated in Figure 32. The overall interval between the end points is used for the first iteration, as in the cubic case with one interpolation point p_{aux2} and r_0 and r_5 as end points. The resulting t-value at p_{aux2} is used as the value of t_2 . In the next step the whole interval is split up into two subintervals between r_0 and p_{aux2} and between p_{aux2} and r_5 . These intervals are again treated as in the cubic case. Using r_0 and p_{aux2} as endpoints and p_{aux1} as the one interpolation point, and p_{aux2} and r_5 as end points and p_{aux3} as the interpolation point. This operation provides intermediate t-values t_{1int} and t_{3int} . These values provide a proportion for t at the interpolation point for their subinterval and are multiplied by the proportion from the previous iteration. The formulae for the final values are:

$$t_1 = t_2 * t_{1int}$$

$$t_3 = t_2 + (1 - t_2) * t_{3int}$$

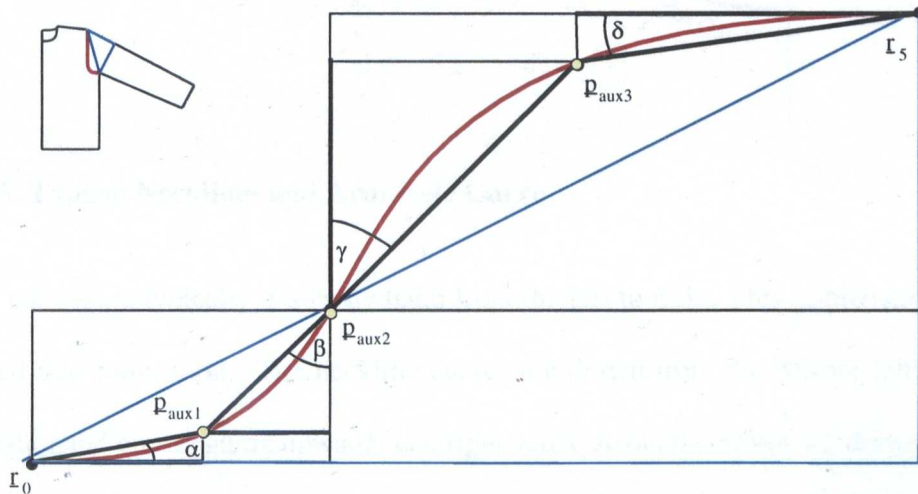


Figure 32. t-Values for Quintic Bézier Curves using Iterative Splitting of the Interval

6.6 Armhole and Neckline Curves

The armhole curves and the neckline curves both can be modelled using the same technique. Both curves are smooth and single-valued (see section 6.7.6.1 for a definition of single-valued in the context of parametric curves). Both curves have one horizontal and one vertical end tangent vector. Armhole curves vary relatively little, but a wide variety of different neckline curves need to be modelled. Figure 33 shows a small variety of typical necklines and a typical armhole curve.

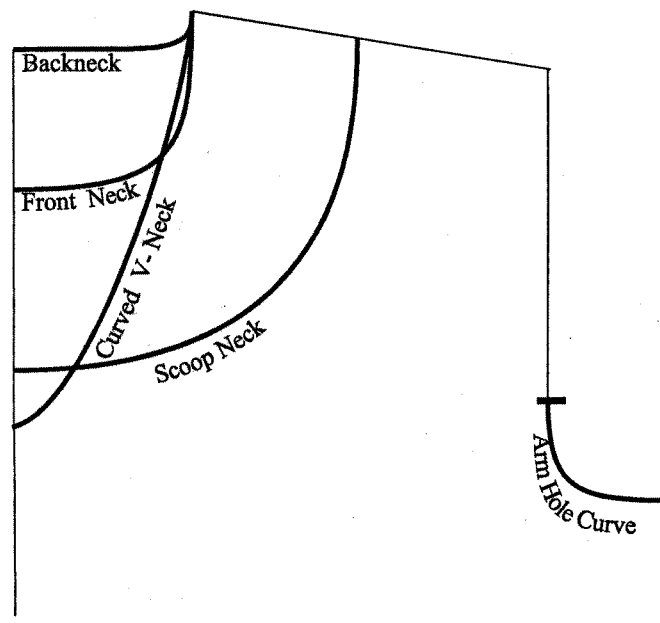


Figure 33. Typical Necklines and Arm Hole Curve

Neckline curves are typically drawn by hand from the left to right. This implementation has maintained this convention. The neckline curves are drawn from the bottom left corner to the top right hand corner going upwards and rightwards. Armhole curves are drawn from the top left corner to the bottom right end point. They are mirror images of the neckline curves and the constraints need to be changed accordingly.

Neckline and armhole curves are modelled as cubic Bézier curves (see Equation 2).

Constraints:

- The end points, \underline{r}_0 and \underline{r}_3 of the curve are known
- The directions of the end tangent vectors are known. The end tangent vector at \underline{r}_0 is horizontal and at \underline{r}_3 it is vertical.

Substitution into Equation 3. gives:

$$\underline{r}_1 = \underline{r}_0 + \mu (1, 0)$$

$$\underline{r}_2 = \underline{r}_3 - \lambda (0, 1)$$

Equation 5. End Tangent Constraints on Cubic Curves

The curve has one interpolation point $\underline{p}_{aux1} = \underline{r}(t_1)$ using Equation 4. for calculation of t_1 .

Substituting Equation 5. into Equation 2.:

$$x_{aux1} = (1 - t_1)^3 x_0 + 3 (1 - t_1)^2 t_1 (x_0 + \mu) + 3 (1 - t_1) t_1^2 x_3 + t_1^3 x_3$$

$$y_{aux1} = (1 - t_1)^3 y_0 + 3 (1 - t_1)^2 t_1 y_0 + 3 (1 - t_1) t_1^2 (y_3 - \lambda) + t_1^3 y_3$$

Equation 6. Cubic Interpolation Point

Equation 6 can be solved for μ and λ .

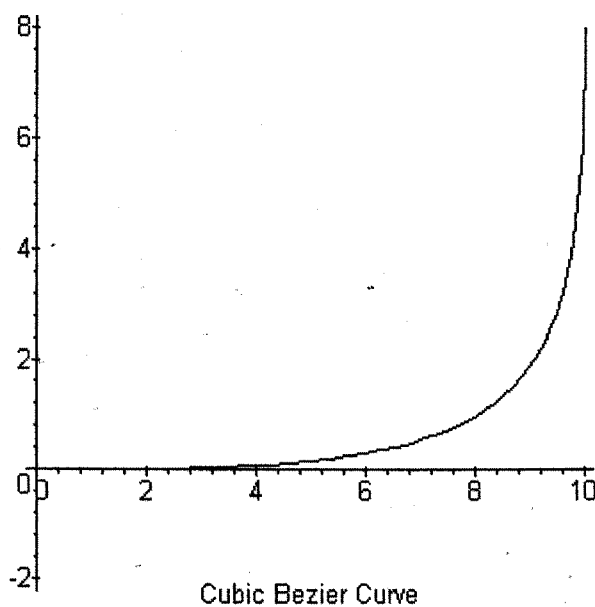


Figure 34. Neckline or Armhole Curve

The curve in Figure 34. shows an example of a neckline curve with the end points

$$r_0 = (0,0) \text{ and } r_3 = (10,8).$$

6.7 Sleeve Crown Curves

Set-in sleeves are the most common form of sleeves. The sleeve curve must be stitched into the armhole. The creation a second curve with a given length and specific characteristics poses a rare mathematical problem, because it only occurs when flexible materials such as fabric is used. A quintic Bézier curve appeared to be the lowest odd order curve that could include the required characteristics. Initially the author attempted to calculate all the Bézier points from constraints on the curve, but a satisfactory curve could only be found when heuristics were used to calculate the location of the two Bézier points adjacent to the endpoints. Composite Bézier curves also fulfil the requirements, but allow the user little freedom to manipulate the curve.

The input data to all the curves displayed in the following discussion is $x_0 = (-20,0)$ and $x_5 = (15,0)$. The interpolation points in all examples are constructed as explained in section 6.4 and the t-values were calculated based on the algorithm presented in section 6.5.

6.7.1 Constraints for the Construction of Mathematical Models

A number of constraints for sleeve crown curves can be derived from the customary construction of sleeve crown curves in the industry. These conditions are mainly heuristics. They are sufficient to assure a reasonable curve for the majority of problems. These are not necessary conditions. As long as the end points are met and the length constraints are maintained the choice of the exact shape of the curve is subjective. The interpolation points are derived from Metric Pattern Cutting (Aldrich, 1987). The end tangent vector directions

are normally maintained, because they increase the structural stability of the fabric. Some companies, however have been observed breaking the end tangent vector constraints.

The following constraints are described for quintic Bézier curves.

Constraints

The end points, \underline{r}_0 and \underline{r}_5 of the curve are known.

Strong Heuristics

The end tangent vectors of the curve are horizontal and facing towards the other end point:

$$\underline{r}_1 = \underline{r}_0 + \mu (1, 0)$$

$$\underline{r}_4 = \underline{r}_5 - \lambda (0, 1)$$

Equation 7. End Tangent Vectors for Sleeve Crown Curves

Useful Heuristics

Interpolation points

Section 6.4.2 explains the construction of the three interpolation points \underline{p}_{aux1} , \underline{p}_{aux2} , \underline{p}_{aux3} , and section 6.5 discussed the importance and location of the t-values, t_1 , t_2 , t_3 , at interpolation points.

$$\underline{r}(t_1) = \underline{p}_{aux1}$$

$$\underline{r}(t_2) = \underline{p}_{aux2}$$

$$\underline{r}(t_3) = \underline{p}_{aux3}$$

Equation 8. Interpolation Points

Curvature

In the construction suggested in Aldrich (1987) the interpolation point \underline{p}_{aux2} is also a point of inflexion. This means for a parametric curve zero curvature at this point.

The curvature of a parametric curve is defined as (see Faux and Pratt, 1979)

$$\kappa(t) = \frac{\|\underline{r}'(t) \wedge \underline{r}''(t)\|}{\|\underline{r}'(t)\|^3} \quad \text{therefore} \quad \kappa(t_2) = \frac{\|\underline{r}'(t_2) \wedge \underline{r}''(t_2)\|}{\|\underline{r}'(t_2)\|^3}$$

If $\kappa(t_2) = 0$ then $\| \underline{r}'(t_2) \wedge \underline{r}''(t_2) \| = 0$

or equivalently

$$x'(t_2)y''(t_2) - x''(t_2)y'(t_2) = 0$$

Sometimes the curve is constructed so that the curve has a vertical tangent vector at the point of inflexion.

$$\underline{r}'(t_2) = \beta(0,1)$$

$$x'(t_2) = 0$$

$$y'(t_2) = \beta$$

Equation 9. Curvature

Vertical Tangent Vector at second interpolation point p_{aux2}

$$\underline{r}'(t_2) = (0,1)$$

Equation 10. Vertical Tangent Vector

Overall Properties of the Sleeve Crown Curve

Single-Valuedness

As with all cutting pattern curves, the sleeve crown curve needs to be smooth. It needs to be a continuous and single-valued curve. Single-valuedness in a given interval of a parametric curve is achieved when the derivatives of the x and y coordinates are greater than or equal to zero.

$$x'(t) \geq 0$$

$$y'(t) \geq 0 \quad \text{for } 0 \leq t \leq 1$$

Equation 11. Single-Valuedness

Single Point of Inflexion

The curve has only one point of inflexion. Fullness is taken out of the curve under the arm, i.e. the curve is concave. Fullness is required on the upper part of the arm to give freedom of movement. There the curve is convex. This shape has historically evolved and proved sensible. The condition is essential that the curve is perceived to be smooth and can be expressed as,

$$\kappa(t_i) = 0 \text{ and } \kappa(t) \neq 0 \text{ elsewhere in } 0 \leq t \leq l$$

$$\text{and } \kappa(t) < 0 \text{ when } t < t_i$$

$$\text{and } \kappa(t) > 0 \text{ when } t > t_i$$

Equation 12. Single Point of Inflexion

Length Constraints

A three-dimensional garment is achieved by joining two-dimensional shapes together. The garment becomes three-dimensional by joining curves of the same length but different shape. Only when the garment is gathered or pleated do the curves not need to have the same length, otherwise the shape is distorted. Unlike most woven fabrics knitwear can be stretched or pushed together to fit two curves together. Stretching the fabric can lead to a distortion of the pattern. The fabric pieces need to be joined with great care. Knitted fabric stretches much more horizontally then vertically. Some companies prefer to stretch the fabric horizontally before joining pieces and therefore create their sleeve crown curves slightly shorter than the armhole curves. Even though knitwear does not always require exactly the same length for the two curves, the lengths still need to be expressed as a ratio of each other. The sleeve curve is always fitted to the armhole, never vice versa.

It will be assumed in the following that the curves have the same lengths.

In mathematical terms the length of a parametric curve $p(t)$ with the x coordinate $x(t)$ and the y coordinate $y(t)$ between the points $p(t_1)$ and $p(t_2)$ can be expressed as:

$$l = \int_{t_1}^{t_2} \sqrt{((x'(t))^2 + (y'(t))^2)} dt$$

The armhole consists of the armhole curve and a straight line of length len . The armhole curve and the sleeve crown curve are expressed in the interval $0 \leq t \leq l$. The equal length condition can be expressed mathematically as

$$\int_0^1 \sqrt{((x'_{armhole}(t))^2 + (y'_{armhole}(t))^2)} dt + len = \int_0^1 \sqrt{((x'_{sleevecrown}(t))^2 + (y'_{sleevecrown}(t))^2)} dt$$

Equation 13. Same Length of Armhole and Sleeve Crown

6.7.2 Quintic Bézier Curves

A quintic Bézier curve has the form:

$$\underline{r}(t) = (1-t)^5 \underline{r}_0 + 5(1-t)^4 t \underline{r}_1 + 10(1-t)^3 t^2 \underline{r}_2 + 10(1-t)^2 t^3 \underline{r}_3 + 5(1-t)t^4 \underline{r}_4 + t^5 \underline{r}_5$$

To fully describe a quintic Bézier curve under the conditions stated above the following unknowns needed to be solved:

- μ and λ the length of the end tangent vectors.
- t_1, t_2, t_3 the t-values of the Bézier Curve at the interpolation points.
- \underline{r}_2 and \underline{r}_3 the two remaining Bézier Points, with the coordinates x_2, y_2 and x_3, y_3 .

Equation 14. Quintic Unknowns

6.7.3 Unsuccessful Strategies and their causes

This section introduces a number of different approaches to modelling a sleeve crown curve. Some strategies have clearly failed while others are only partially successful. The reasons for the success and failure of each particular solution strategy are discussed. The failed solution attempts are reported in detail in Appendix B. Initial solution attempts concentrated on trying to solve the problem by fulfilling the maximum number of constraints with the lowest order of curve. They concentrated on solutions using a quintic Bézier curve.

Theoretically it might be possible to solve all the unknowns $\mu, \lambda, t_1, t_2, t_3, x_2, y_2, x_3, y_3$, for a fixed length of the tangent vector at $\underline{r}(t_2) = \underline{p}_{aux2}$, using

Equation 14, Equation 9, Equation 10 and Equation 13. This proved impossible in practice, because the equation solver did not reach a solution to the set of equations in a reasonable

time. If an exact solution had been reached it could have been problematic to ensure the monotonicity of the curve, because the length of the tangent vector would have been the only free variable left.

Initially the three interpolation points (Equation 8.) and the curvature condition (Equation 9.) and the end tangent vectors (Equation 7.) were used. The next attempt used the tangent condition on the second interpolation point and the point of inflexion (Equation 10.). The author also tried to calculate t_2 from the heuristic constraints, but the value could not be guaranteed to create a legal curves. Successful curves were only achieved once heuristics were used to define the values for μ and λ , and the constraints on derivatives were dropped.

A number of problems occurred in the process of trying to create a quintic Bézier curve. These problem are not specific to quintic Bézier curves. They apply to the problem of modelling garment curves or more generally to using interpolation points to calculate Bézier curves:

- Parallel end tangent vectors

The end tangent vectors are linearly dependent, because they are parallel. An attempt to solve the problem by exploiting the rotation invariance of Bézier curves (Faux and Pratt, 1979) and rotating the input points was bound to fail, because of the linear dependence of the end tangent vectors. Therefore it was concluded that an exact solution based on parallel end tangent vectors as an input condition was impossible and only a combination of heuristics and iteration could produce a legal result.

- Finding exact t-values at interpolation points

As Bézier curves are normally used to create curves interactively, there is little need for a theoretical understanding of the behaviour of the parameter t of a curve $r(t)$. However when the curve is constructed using interpolation points, the exact t -value at the interpolation point is essential. This issue is badly covered in the literature. The author used geometric heuristics based on the relative location of the interpolation

points (see section 6.5.2). The problem became aggravated when more than one condition was placed on one interpolation point, because it increased the relative importance of this t-value.

- Single-valuedness

Single-valuedness is an important domain constraint. Equation 9. states that the curve has only one point of inflexion at p_{aux2} . The problem was posed by the negative condition that zero curvature may not occur anywhere else. Inequalities cannot be used to solve equations. Instead of leading to one accurate solution, they map out a space of legal solutions.

Assuring the single-valuedness was further problematic because the suggested curve was based on the heuristic values $\mu, \lambda, t_1, t_2, t_3$, which could fail under extreme conditions. These values could also be seen as degrees of freedom: parameters to be altered until a solution is reached interactively. The conditions stated in Equation 11 can therefore be used as test criteria for a solution suggestion, rather than a constraint that can be included in initial calculations.

6.7.4 Composite Bézier Curve

Let $\underline{r}^{(1)}$ and $\underline{r}^{(2)}$ be the cubic Bézier segments defined by

$$\underline{r}^{(1)}(t) = (1-t)^3 \underline{r}_0^{(1)} + 3(1-t)^2 t \underline{r}_1^{(1)} + 3(1-t) t^2 \underline{r}_2^{(1)} + t^3 \underline{r}_3^{(1)}, \quad 0 \leq t \leq 1$$

and

$$\underline{r}^{(2)}(u) = (1-u)^3 \underline{r}_0^{(2)} + 3(1-u)^2 u \underline{r}_1^{(2)} + 3(1-u) u^2 \underline{r}_2^{(2)} + u^3 \underline{r}_3^{(2)}, \quad 0 \leq u \leq 1$$

For a continuous curve we must have

$$\underline{r}_0^{(2)} = \underline{r}_3^{(1)}$$

The two curves are joined at the p_{aux2} , the point of inflexion.

The general conditions of the curve apply to composite cubic curves as follows:

The end points $r_0^{(1)}$ and $r_3^{(2)}$ are known

The end tangent vectors

$$r_1^{(1)} = r_0^{(1)} + \mu(1, 0) \quad (\text{cc.1})$$

$$r_2^{(2)} = r_3^{(2)} - \lambda(1, 0) \quad (\text{cc.2})$$

Interpolation points

$$r^{(1)}(t_1) = p_{aux1}$$

$$r_0^{(2)}(1) = r_3^{(1)}(0) = p_{aux2}$$

$$r^{(2)}(t_3) = p_{aux3} \quad (\text{cc.3})$$

Derivatives

$$\kappa^{(1)}(1) = \frac{\|r^{(1)'}(1) \wedge r^{(1)''}(1)\|}{\|r^{(1)'}(1)\|^3}$$

some standard transformations, see Faux and Pratt (1979) give

$$\kappa^{(1)}(1) = \frac{2\|(r_2^{(1)} - r_3^{(1)}) \wedge (r_3^{(1)} - r_2^{(1)})\|}{3\|(r_3^{(1)} - r_2^{(1)})\|^3}$$

We know that $\kappa(1) = 0$, therefore

$$0 = \frac{2((x_2^{(1)} - x_1^{(1)})(y_3^{(1)} - y_2^{(1)}) - (y_2^{(1)} - y_1^{(1)})(x_3^{(1)} - x_2^{(1)}))}{3((x_3^{(1)} - x_2^{(1)})^2 + (y_3^{(1)} - y_2^{(1)})^2)^{\frac{3}{2}}}$$

substituting (cc.1) and (cc.2) into the above equation gives

$$0 = \frac{2((x_2^{(1)} - x_0^{(1)} + \mu)(y_3^{(1)} - y_2^{(1)}) - (y_2^{(1)} - y_0^{(1)})(x_3^{(1)} - x_2^{(1)}))}{3\sqrt{((x_3^{(1)} - x_2^{(1)})^2 + (y_3^{(1)} - y_2^{(1)})^2)}} \quad (\text{cc.4})$$

tangent vector at the point of inflexion.

$$r_3^{(1)} = \beta(0, 1) \quad x^{(1)}(1) = 0 \quad y^{(1)}(1) = \beta$$

Two suggestions for the second part of the curve are presented, using $r^{(2)}(t_3) = p_{aux3}$ and

assuming continuity of the tangent at the joining point and either using the known end tangent vector direction or assuming continuity of the curvature at the joining point.

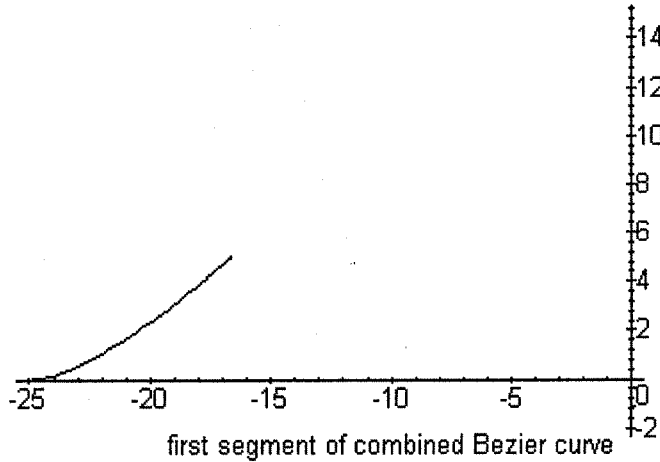


Figure 35. First Segment of Composite Bézier Curve

The equations (cc.1) and (cc.4) can be solved to obtain the three unknowns: μ , x , y

Conditions for the construction of the second segment of the curve

Tangential continuity gives the following conditions:

$$\begin{aligned} r_1^{(2)} &= r_3^{(1)} + \alpha(r_3^{(1)} - r_2^{(1)}) & x_1^{(2)} &= x_3^{(1)} + \alpha(x_3^{(1)} - x_2^{(1)}) \\ y_1^{(2)} &= y_3^{(1)} + \alpha(y_3^{(1)} - y_2^{(1)}) \end{aligned}$$

To assure continuity of the curvature the following condition must be fulfilled,

$$r_2^{(2)} = \beta^2 r_1^{(1)} - (2\beta^2 + 2\beta + \alpha/2) r_2^{(1)} + (2\beta^2 + 2\beta + 1 + \alpha/2) r_3^{(1)}$$

which leads to the conditions:

$$x_2^{(2)} = \beta^2 x_1^{(1)} - (2\beta^2 + 2\beta + \alpha/2) x_2^{(1)} + (2\beta^2 + 2\beta + 1 + \alpha/2) x_3^{(1)} \quad (\text{cc.5})$$

$$y_2^{(2)} = \beta^2 y_1^{(1)} - (2\beta^2 + 2\beta + \alpha/2) y_2^{(1)} + (2\beta^2 + 2\beta + 1 + \alpha/2) y_3^{(1)} \quad (\text{cc.6})$$

Condition (cc.2) and conditions (cc.8) and (cc.9) both define the location of point $r_2^{(2)}$.

Continuous curvature is therefore mutually exclusive with the fixed direction of the end tangent vector. Both are important constraints from a domain point of view. The continuous curvature could be seen as a mathematical expression of the criterion of “smoothness”, as

defined by the practitioners in the domain. The end tangent vector constraints are important from the fabric technical viewpoint. Figure 36 shows a curve with continuous curvature. The Bézier points are calculated using the interpolation point equations (cc.3) to solve the unknowns α and β , and (cc.5) and (cc.6) to define $r_2^{(2)}$.

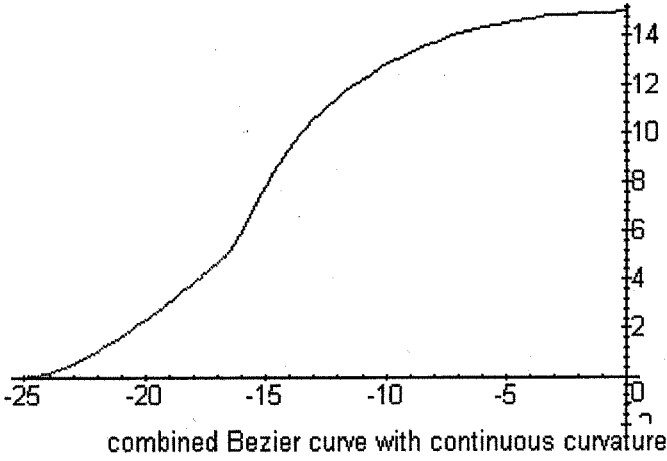


Figure 36. Composite Bézier Curve with Continuous Curvature

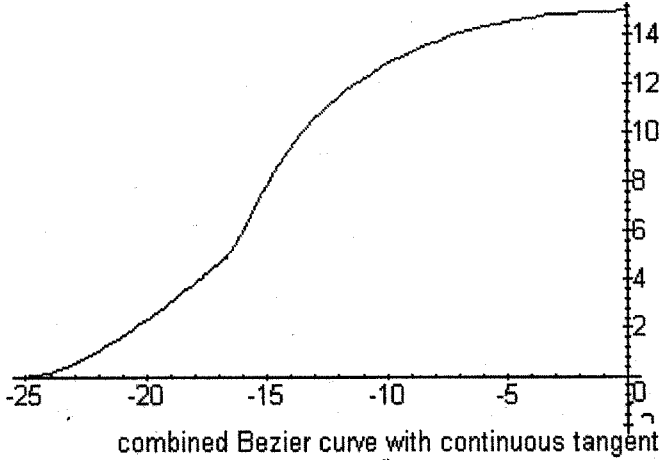


Figure 37. Composite Bézier Curve with Continuous Tangent

Figure 37 shows a curve with a continuous tangent vector and guaranteed horizontal end tangent vectors. The Bézier points are calculated using the interpolation point equations (cc.3) to solve the unknowns α and λ , but using (cc.2) to define $r_2^{(2)}$.

Both curves present legal and acceptable solutions on a visual evaluation and could serve as cutting pattern curve suggestions. In both cases there is no degree of freedom left, with which the curve could be manipulated, but the constraints are fulfilled. This reduces the ability of an inexperienced user to make modifications to the curve.

A further solution attempt was made using t_3 as a further unknown to impose the continuous curvature condition and the end tangent vector condition on $r_2^{(2)}$. This took over ten minutes to calculate (using Maple) and did not provide a legal t_3 value.

The author also attempted to solve the equation system by setting $\lambda = 5$ and using the then exact definition of $r_2^{(2)}$ to solve α and β . The values for α and β were extremely high and indicated that theoretically a solution with these values would have been impossible, but rounding errors led to extreme suggestions from the equation solver.

6.7.5 Heuristics for Length of End Tangent Vectors of Quintic Curves

The following section introduces alternative methods for creating successful curves, which are based on heuristics to determine the values of μ and λ . These heuristics were obtained through trial and error to suit the type of input data.

The quintic curves are discussed in detail to compare them with previous unsuccessful solution attempts. Modelling folklore claims that curves of an odd order look better than even order curves. Curves of order 3, 4 and 6 were also constructed, see Appendix B.3. The cubic curves do not give enough scope for user alterations; and the order six curves are a higher order than necessary. The quartic curves look fine.

The beginning and end points of the curves are referred to as r_b , r_e respectively, if the argument is made independently of the order of the curve.

In this calculation all the constraints on the derivatives are dropped and the length of the end tangent vectors is determined by heuristics, so that r_1, r_2, r_4, r_5 , are known. The two unknown Bézier points can be calculated using two interpolation points.

The values of μ and λ depend on the ratio of the sleeve width to the sleeve height, which form the two short sides of the construction triangle. The construction triangle is marked in blue on previous diagrams, for example Figure 32.

Satisfactory curves have been reached with the following values of μ and λ :

$$\tan \alpha = (y_e - y_b) / (x_e - x_b)$$

Equation 15. Tangent Ratio

$$\mu = 2/3 * (x_e - x_b) * \tan \alpha$$

$$\lambda = (x_e - x_b) * \tan \alpha$$

With μ and λ set the interpolation points are required as the only other constraints, as specified in Equation 8. Only two interpolation points are required. p_{aux2} and p_{aux3} were chosen.

Figure 38 to Figure 40 show this curve with various input data. All the curves are monotonic, tested by condition Equation 11. If the curve does not appear entirely smooth then this is due to distortions in the equation solver's plot.

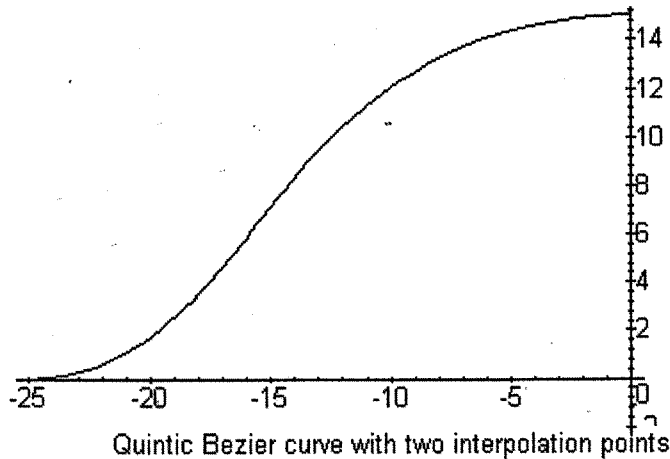


Figure 38. Quintic Bézier Curve with Typical Sleeve Width to Crown Height Ratio

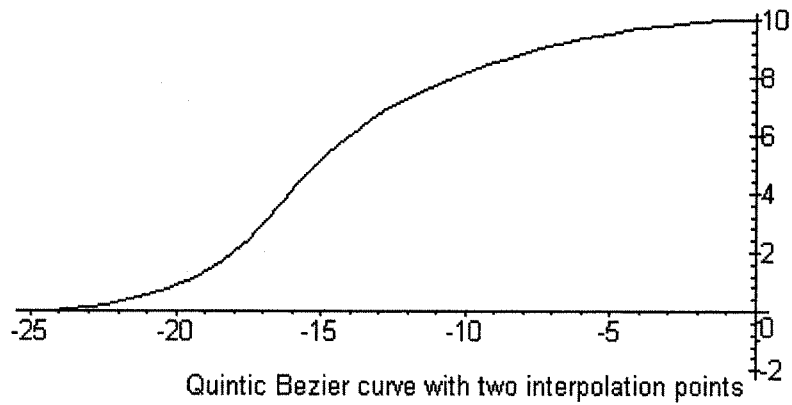


Figure 39. Shallow Quintic Bézier

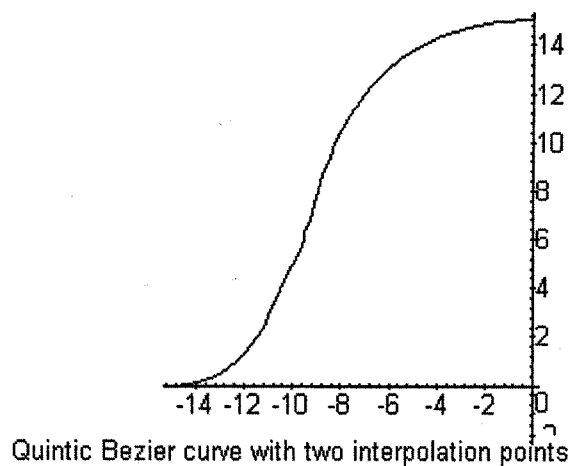


Figure 40. Quintic Bézier curve same sleeve width as height

The curve in Figure 40 has an isosceles construction triangle. It is used to construct a curve for extremely high sleeve crowns by inserting straight pieces into this curve.

The construction diagonal of the isosceles triangle is used to calculate $\tan \gamma$. It is used at the beginning of the program to determine whether the specified construction triangle lies within the customary range for set-in sleeves. These heuristics have been developed based on the typical range of sleeves. If the specified triangle lies outside this range then the curve contains straight lines, see for example Figure 41 and Figure 43. The author has defined the customary range of sleeve shapes, so that the construction triangle can lie in a range of $0.25 \leq \tan \gamma \leq 1$. I.e. the sleeve crown height is between a quarter of the half sleeve width and the

full half sleeve width. If the sleeve crown is higher then it is wide (see Figure 41) the sleeve curve is constructed for an isosceles triangle and a straight piece is inserted at the first interpolation point p_{aux2} :

$$\begin{aligned} \tan \gamma \geq 1 \quad x_e' &= x_e \\ y_e' &= x_b * -1 \end{aligned}$$

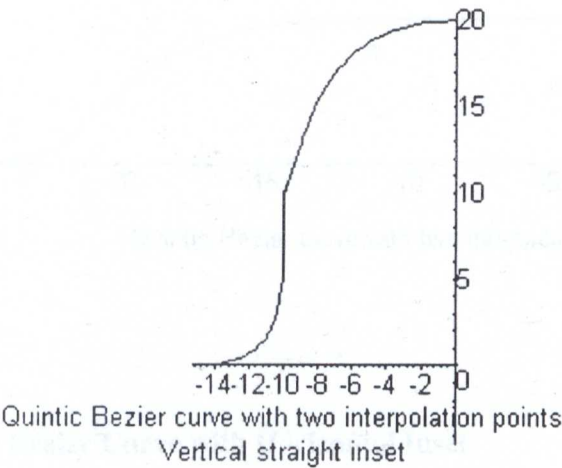


Figure 41. Quintic Bézier Curve with Vertical Inset

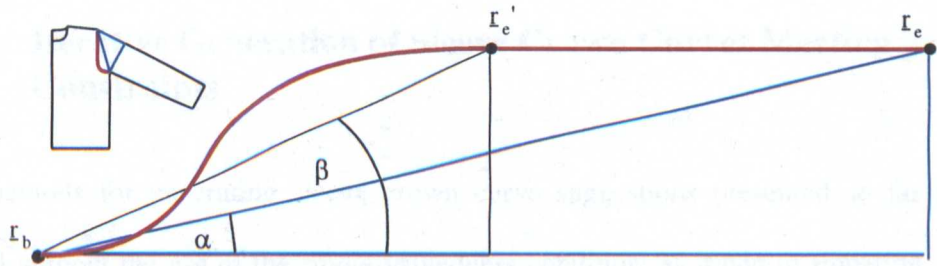


Figure 42. Shift of End Point for Shallow curves

If the curve is very shallow, then often only the beginning of the curve is shaped and the end is a long straight piece, as illustrated in Figure 42 A shallow curve has been defined to mean that the height of the sleeve crown is less then one quarter of the half sleeve width. In this case the curve is only curved a width of four times the crown height and a straight piece is inserted. Figure 43 shows this curve:

$$\begin{aligned} \tan \gamma \geq 1 \quad x_e' &= x_e \\ y_e' &= x_b * -1 \\ \tan \gamma < 1. \quad x_e' &= x_b + y_e \\ y_e' &= y_e \end{aligned}$$

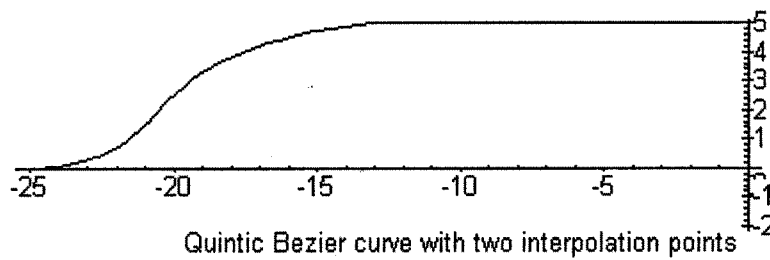


Figure 43. Quintic Bézier Curve with Horizontal Inset

This construction produces a visually satisfactory curve.

6.7.6 Iterative Generation of Sleeve Crown Curves Meeting Constraints

The methods for generating sleeve crown curve suggestions presented so far have been created without the use of the single-valuedness condition, as stated in Equation 11 and the length constraint, Equation 13. Both are vital conditions for the correctness of the curve. These two conditions are more significant for the mathematical correctness of the curve than most of the conditions that have been used to create the curve suggestions. The single-valuedness condition defines a range of legal solutions and does not provide exact equations to be used to find unknowns; it is however easy to test whether the condition is fulfilled. It was used to determine suitable domain heuristics. The length condition provides a single equation.

6.7.6.1 Single-valuedness

The single-valuedness condition can be most easily tested in the form stated in Equation 11. The derivatives of both coordinates need to have the same sign. As the sleeve crown curve is increasing, they can be expressed as

$$x'(t) \geq 0 \text{ and } y'(t) \geq 0.$$

The solution presented in section 6.7.5 uses heuristics to calculate the values of λ and μ . The location of the y-unknowns is independent of these heuristics, as it is calculated entirely from the y-coordinates of the interpolation points. As long as the interpolation points are reasonably spaced-out the y-component of the curve is single-valued.

In the x-component the heuristic values of λ and μ can be adjusted to reach a monotonic solution. The values of λ and μ were chosen so the solution is always monotonic in all the cases that have been tested so far. If we assume a fixed value of λ to maintain the fullness of the sleeve crown, then the monotonicity depends on the value of μ . If too large a value of μ is chosen the curve could fold under the point of the inflexion. The value of μ can iteratively be shortened, say by 0.1 cm until a correct solution is achieved.

6.7.6.2 Length Constraints

When the sleeve crown curve has been calculated, the length of the armhole curve is a given value, so that Equation 13 can be rewritten as

$$const = \int_0^1 \sqrt{((x_{sleevecrown}'(t))^2 + (y_{sleevecrown}'(t))^2) dt}$$

The order of the length integral function is the same as the order of the original function. For equations of order 5 it is impossible to reach accurate solutions using exact equation solution strategies. It is possible to calculate a solution to such an equation using standard complex and iterative numerical algorithms. In this particular application it is easier to calculate the shape of the curve iteratively and use the length condition as a stopping condition. The

whole calculation depends on the location of the end points; using the proposed heuristics a new solution can be calculated very simply.

The length of a single-valued curve in a given interval has an obvious upper and lower limit. Figure 44 shows the curve with the upper and lower limits. The lower limit of the length of the curve is the length of the hypotenuse of the construction triangle, as it is the minimum distance between the two end points. The upper limit is the sum of the lengths of the other two sides of the construction triangle.

$$length_{min} = \sqrt{(x_e - x_b)^2 + (y_e - y_b)^2}$$

$$length_{max} = (x_e - x_b) + (y_e - y_b)$$

The curve is single-valued and continuous. It can be approximated by a step function, as shown in the example of Figure 44.

The construction of the sleeve curve depends entirely on the location of the end points of the curve. By moving the location of the end points the length can be altered. Three very simple strategies are available for altering the length of curve:

- moving the beginning of the curve, i.e. changing the width of the sleeve
- moving the end point of the curve, i.e. changing the height of the sleeve crown
- combining both approaches and moving both points.

A simple iteration of the curve calculation by moving one of the end points by 0.1 cm reaches a solution very quickly. There is no need for a more sophisticated approximation strategy.

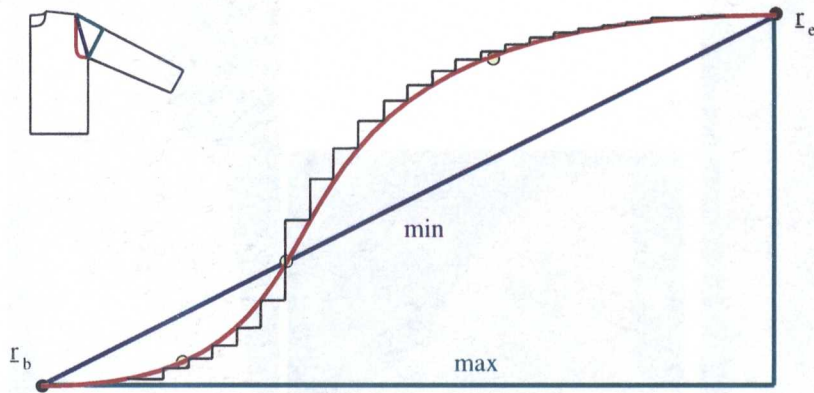


Figure 44. Length Limits of the Sleeve Crown Curve

6.8 Validity of the Approach in Knitwear

This section discusses how well the mathematical model discussed in sections 6.2 to 6.7 applies to the construction of garment shapes for knitwear.

6.8.1 Empirical Foundation for Garment Shape Construction

The mathematical models, as discussed in sections 6.2 to 6.7, and the shape construction, as discussed in Appendix C, are based on pattern construction techniques that the author learned over 52 hours of one-to-one tutoring sessions with Monica Jandrisits (D1) in the summer of 1993. In this period the author learned to construct cutting patterns, cut out the fabric and make up the garments. Metric pattern cutting (Aldrich, 1987) was used as a starting point. Almost all commonly used garment shapes were covered systematically. Over 20 different types of sleeve forms, over 20 necklines and about 10 different sidelines for sweaters were constructed, as well as other types of garments. Various alteration methods for modifications from existing shapes were addressed. For each feature a cutting pattern was constructed, and at least a partial garment made up. All were photographed. Figure 45 and Figure 46 show a classical set-in sleeve garment.

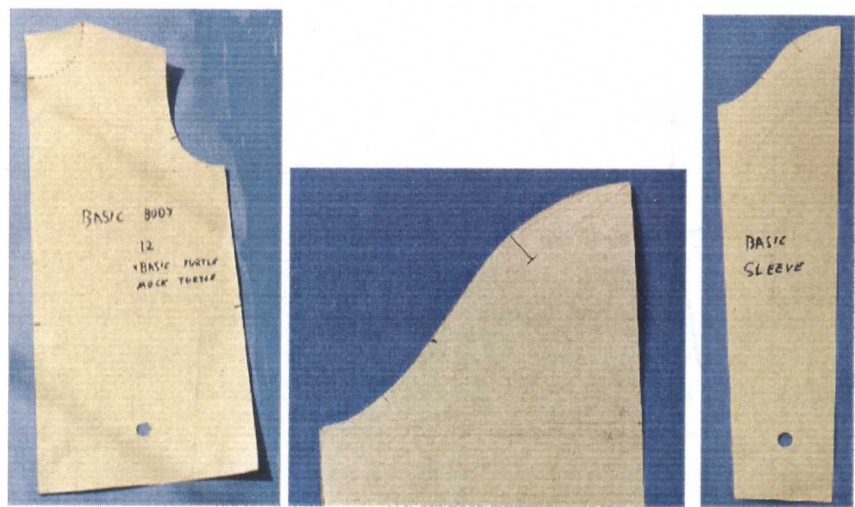


Figure 45. Set-in Sleeve Cutting Pattern, Body and Sleeve and Sleeve Crown Detail



Figure 46. Set-in Sleeve Garment

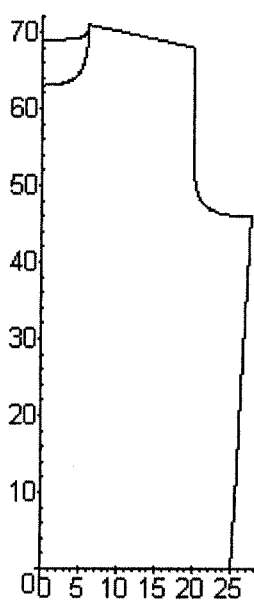


Figure 47. Body Block

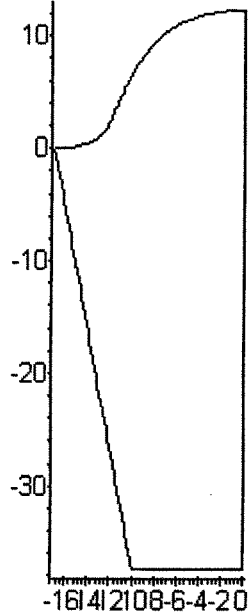


Figure 48. Sleeve Block

Set-in Sleeve Garment

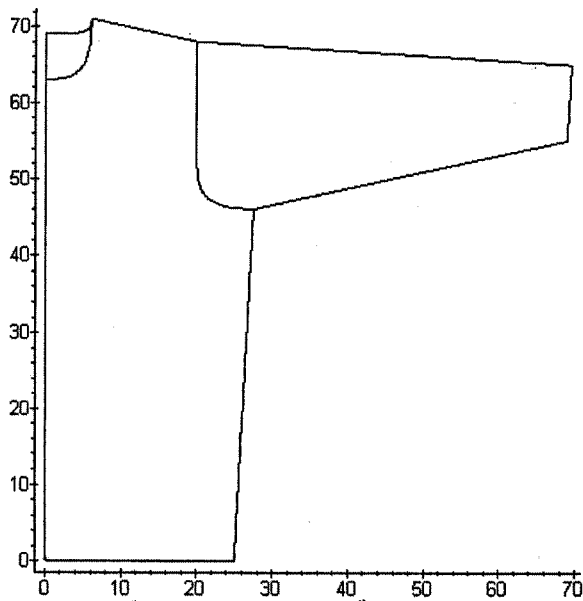


Figure 49. Outline of a Garment with Set-in Sleeves Created by Maple™ Application

Figure 47 and Figure 51 are blocks created by the Maple™ application using the mathematics explained in section 6.2 and the sleeve curve creation algorithm discussed in section 6.7. Figure 49 shows the outline of a set-in sleeve garment created from the body and sleeve block described in Appendix C.

6.8.2 Range of Garments Shapes

Type	Neck	Sleeve	Sideline
Tunic	Round	Set-in	Straight/Tunic
Standard	Square	Raglan	Fitted
Crop-top	V-neck	Saddle Shoulder	A-line
Cardigan	Polo	T-sleeve	Increasing
Vest	Turtle	Kimono	Wrap-over
Slip-over	Wrap-over	Dolman	Flared
Skirt	Boat		
Dress	Sweetheart		
Trousers			
Leggings			
Shorts			

Table 6 Garment Specifications

Table 6 shows the range of verbal descriptions of garment features that are typically used in the knitwear industry. The mathematical models can in principle support all the features shown in bold face, by supporting:

- set-in sleeves, see Appendix C.3.1.; raglan sleeves, see Appendix C.3.2.; and T-sleeves, see Appendix C.3.3.
- round necklines, square necklines and V-necklines, see Appendix C.2.1, especially Figure C-1. Most other necklines are based on these constructions, besides boat necks which are straight lines.
- Straight, increasing, decreasing and fitted side lines, see Appendix C.2.2.

At present the mathematical models do not support the construction of kimono and dolman sleeves. Both could be modelled using one cubic Bézier curve creating a continuous curve under the arm. Wrap-over sweaters or cardigans are also not supported, but their curved front line could be modelled by a cubic Bézier curve.

The cutting patterns created by a design support system using these mathematical models would be flat. Any garments with knitted-in flair are not supported at present. Such garments

have only become possible in the last few years and are becoming increasingly popular. As they are expensive to knit they only constitute a small fraction of the market.

Garments with shape curves that cannot be supported by these mathematical models currently take less than 5% of the market at a generous estimate.

6.9 Conclusion

Garment shapes can be described by coordinates, which are calculated from input measurements, and lines between them. The shape curves of a knitted garment can be modelled by using Bézier curves in combination with domain heuristics. All two-dimensional garment shapes can be modelled using these curves; this thesis presents methods for modelling the curves commonly used in the knitwear industry.

Chapter 7.

Automatic Construction of Garment Shapes

This chapter shows how a design support system to support the construction of garment shapes could look. It discusses how the mathematical models introduced in chapter 6 could be employed; and how the user would interact with them.

7.1 Overview

The aim of this module is to construct automatic solution suggestions for garment shapes based on the input data from the user. The module takes the input measurements provided by the user, which are as section 4.2 argues often incomplete, inaccurate and inconsistent; and converts them into design suggestions based as closely as possible on the input measurements, by completing missing measurements and using heuristics to resolve inconsistencies. These design suggestions provide the user with immediate feedback on their specifications. The user can edit the shapes until they are satisfied with them. The shape specification is then complete and consistent and corresponds to the designer's intentions. The garment shape information is presented in three different notations: measurements, two-dimensional outlines and cutting patterns. Each notation has its own editor. Changes to each notation are automatically carried through to the other two notations. The shape information is displayed in three different ways:

- to allow different degrees of detail in the specification;
- to communicate features that cannot be expressed well in other notations;

- to suit the working practice of different participants in the design and sampling process.

The representations reflect the practices of the domain. Designers define a garment shape by a brief verbal description and a set of measurements (see section 3.4.3 and Figure 4, which shows an industrial example of a technical sketch). The designers draw two-dimensional outline sketches of the garment to express features which are hard to describe in numbers and to show the relative location of motifs on a garment. Section 4.2 argues that the drawings are often ignored. The shape technicians turn the measurements into cutting patterns for a specific fabric.

7.2 Editing Environment

Figure 50 and Figure 51 are screen dumps of mock-up interfaces created in MacDraw. The displayed garment pieces are not the results of the accurate modelling process.

Designers must be able to annotate certain parts of the design to indicate how much they care about this particular design feature, for example by highlighting certain measurements or parts of a shape. All editors need to be adaptable to the requirements of a particular company or designer.

7.2.1 Measurement editor

Figure 51 shows the measurement editor. The input to this editor is verbal and numerical. The system provides a set of slots for writing in information, which are similar to the spaces on existing technical sketch forms (see section 3.4.3). Table 6 shows the range of likely input for the verbal description. The list of measurements changes with reference to the verbal description. By clicking red headings the user can access further windows to define details.

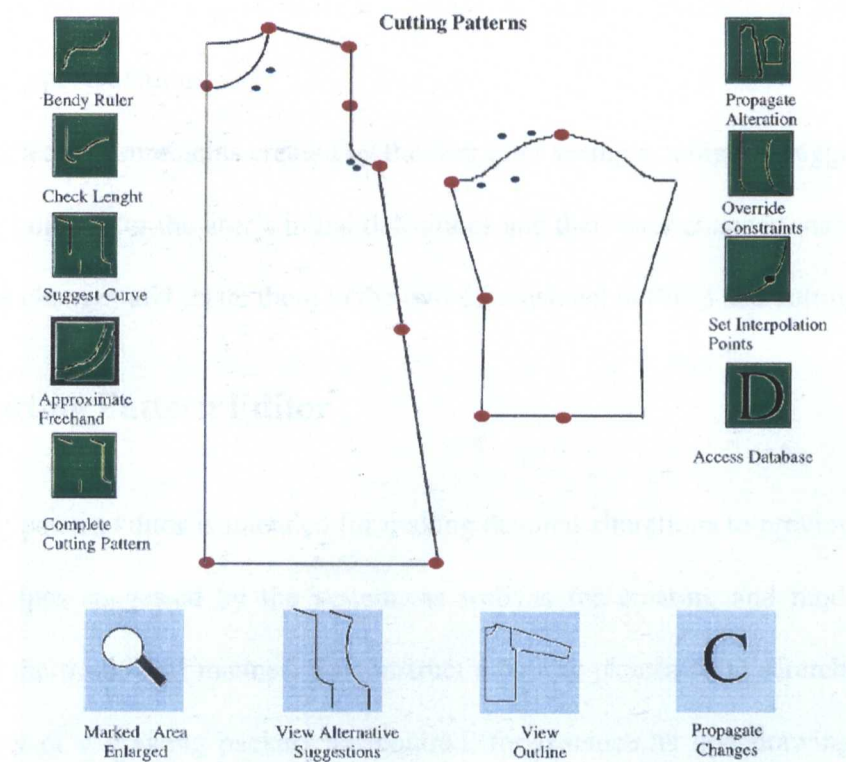


Figure 50. Cutting Pattern Window

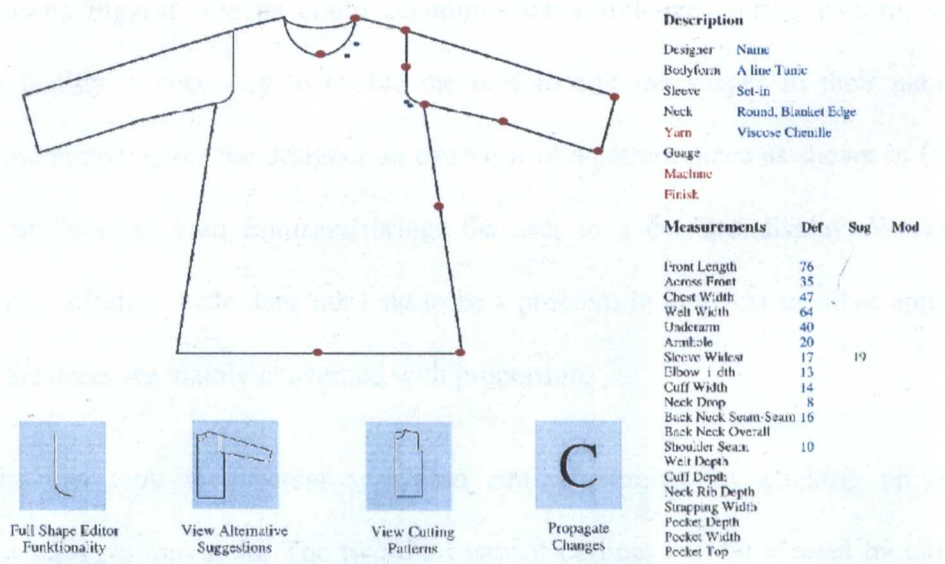


Figure 51. Outline Window and Measurement Window

The measurements are likely to be modified during the shape creation process. Different sets of measurements can be shown in different columns:

- the original measurements defined by the user;

- the measurements suggested by the system or carried through from modifications in other representations;
- modified measurements created by the user after seeing a computer suggestion.

A different column for the user's initial definitions and their later changes enables the user to monitor the changes and relate them to the two-dimensional outlines and cutting patterns.

7.2.2 Cutting Pattern Editor

The cutting pattern editor is intended for making detailed alterations to previous designs and garment shapes suggested by the system, as well as for creating and modifying cutting patterns in the traditional manner. To construct a cutting pattern from scratch, much of the functionality of a drawing package is required, for instance as line drawing, scaling and rotation.

Not even the biggest screens could accommodate a full-size cutting pattern, so that a zooming facility is necessary to enable the user to edit the shapes in their natural size. Initially the system gives the designer an overview of a pattern piece as shown in Figure 50; clicking on *Marked Area Enlarged* brings the user to a detailed display. Working with images on a different scale does not tend to be a problem in knitwear or other applications, because the users are mainly concerned with proportions.

The users can look at different suggested cutting patterns, by clicking on *the View Alternative Suggestions* field. The two-dimensional outlines can be viewed by clicking on *View Outline* and changes are carried through to the outline and the measurements by clicking on the *C* field.

The left-hand row of buttons provides the extra functionality required for a cutting pattern editor. Not all of these features can be supported by the existing implementation of the mathematical models.

- *Bendy Ruler*: Novices in industry use flexible rulers to draw curves in manual cutting pattern construction. They mark the length of the curve on the ruler and then bend it to shape. This could be supported automatically by a curve that can be modified by control points and always maintains a fixed length. This could be based on quintic Bézier curves.
- *Check Length*: Calculates the length of a curve or line that the user has selected. This is a standard feature of tailoring CAD systems. (See section 6.7.6.2 for the mathematics of length calculation.)
- *Approximate Freehand*: To give the user maximum flexibility a free hand drawing option is required. Other CAD systems for pattern construction, such as the ORMUS system (see section 1.4) use free hand drawing as the main feature. To incorporate this into the automatic reasoning and to smooth out the curve, the hand-drawn lines and curves need to be approximated by Bézier curves and lines represented by their end points.
- *Complete Cutting Pattern*: Translates the cutting pattern information available into measurements and creates an automatic solution suggestion.
- *Propagate Alterations*: Carries alterations through to other pieces of the cutting pattern. For example, when a sleeve is widened the armhole needs to be increased to fit the sleeve. Various traditional pattern cutting methods exist for propagating changes. They are not implemented, but could easily be, as they involve mainly coordinate manipulation and implemented algorithms for curve creation.
- *Override Constraints*: The two end tangent vectors are fixed in their direction by traditional knitwear constraints (see section 6.1.1). The pink lines indicate the directions in which the control points can be moved. Clicking on this icon changes the system mode so that the points can be moved freely.

- *Interpolation Points*: The Bézier curves are created using interpolation points. With this feature the users can set these interpolation points themselves and receive automatic solution suggestions.
- *Database*: Calls out to a database of existing cutting patterns, in case the users want to modify old designs. By using *Propagate Changes* a new design specification can be created very quickly from an existing one.

7.2.3 Two-Dimensional Outline Editor

The two-dimensional outline editor needs to provide the same functionality as the cutting pattern editor, which is discussed above. Figure 51 shows a two-dimensional outline editor, minus the control buttons shown in Figure 50. The garment is displayed in its full width, rather than the customary half garments in cutting patterns. The default behaviour of the system is that modifications made to one half of the garment are carried through to the other half automatically, as most knitwear is symmetrical. The shape can be modified by picking up control points. The red points correspond to the underlying construction coordinates, which are derived from the customary locations for specified measurements. The two-dimensional outline can be modified easily and quickly by moving the control points. The blue points are the control points of the Bézier curves.

When playing with the shape, the users do not necessarily want the original measurements overridden. In this suggested interface the users therefore need to click on the *propagation* field to carry the changes through to the cutting pattern or measurement displays. Alternatively the users might find it useful to see the measurements displayed for each modification. By clicking on the *View Cutting Pattern* field the user reaches the cutting pattern window. *View Alternative Suggestions* shows different suggestions based on the same input measurements.

The full cutting pattern functionality can be started by clicking on the *Full Shape Editor Functionality* field.

7.3 Architecture of a Garment Shape Construction Module

The proposed editing environment is envisaged as part of an intelligent design support system. This section explains how such a system might look.

7.3.1 The Components

Figure 52 gives an overview of the control flow of the garment shape construction module.

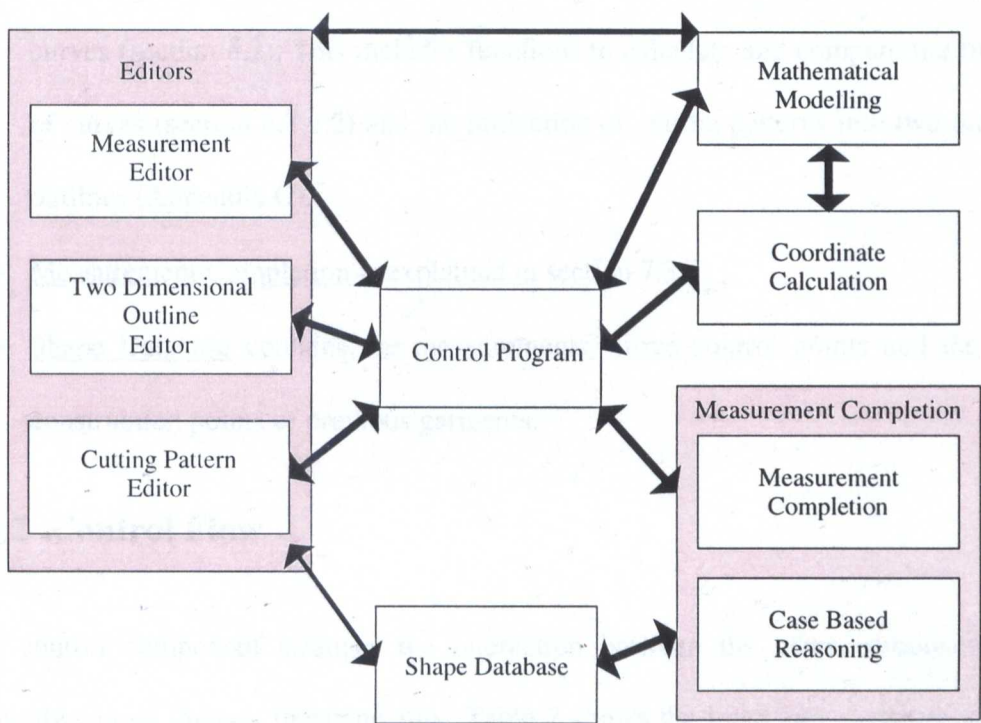


Figure 52. Overview of the Control Flow of the Garment Shape Design Module

The module is built up from the following components:

- Control Component: This component controls the interaction of the other components and decides which action needs to be taken next. Most components interact with each other through the control component, unless there is no reasoning involved. For example, database items can be recalled directly from other components or mathematical functions can be accessed directly.
- Shape Editors: The editors are discussed in section 7.2.
- Coordinate Calculation: The measurements for each garment are converted into coordinates in a Cartesian coordinate system (see section 6.1.2). Cutting patterns created by the user need to be re-translated into measurements which can be displayed to the user and used in further automatic reasoning.
- Mathematical Models: The models are used to create the exact shape of the suggested curves (section 6.2). This includes functions to calculate and compare the final length of curves (section 6.7.6.2) and the projection of cutting patterns into two-dimensional outlines (Appendix C).
- Measurement Completion is explained in section 7.3.4.
- Shape Database contains the measurements, curve control points and the auxiliary construction points of previous garments.

7.3.2 Control Flow

The control component arranges the interaction between the other components, which normally cannot interact independently. Table 7 shows the input and output to each of the components. Only the database can be accessed directly at different stages of the shape construction. The editors can call the mathematical models directly when a simple evaluation is required.

Component	Input	Output
Measurement Editor	Measurements	Measurements
Two-Dimensional Editor	Coordinates	Coordinates
Cutting Pattern Editor	Control points	Control points
	Coordinates	Coordinates
	Control points	Control points
Control Program	Measurements	Measurements
	Coordinates	Coordinates
	Control points	Control points
	Error messages	
Coordinate Calculation	Measurements Verbal Description	Coordinates
	Coordinates	Measurements
Case Based Reasoning	Measurements Verbal Description	Measurements
	Verbal Description	Measurements
	Coordinates	Control Points
Mathematical Model	Control Points	Coordinates
	Verbal Description	Measurements Cutting Patterns Two-dimensional Outline

Table 7 Input and Output of Modules

7.3.3 Automatic Shape Construction from Correct Input Data

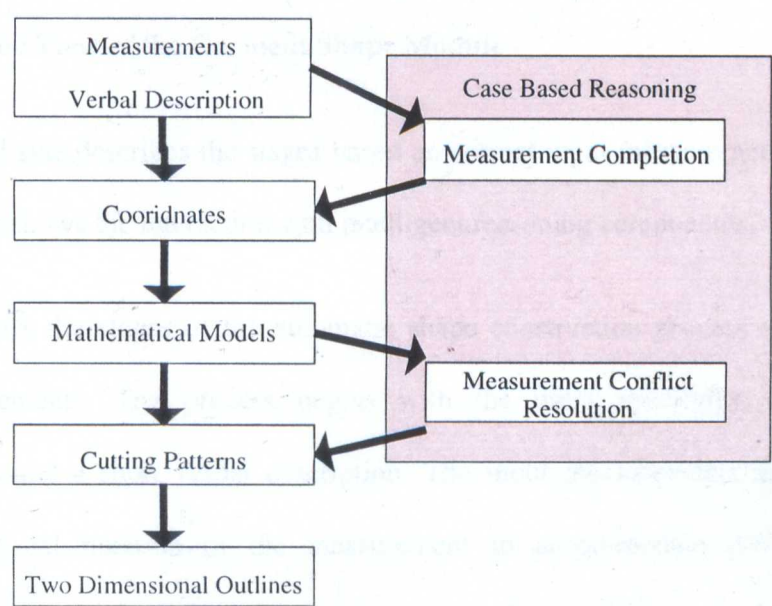


Figure 53. Stages of Automatic Shape Calculation

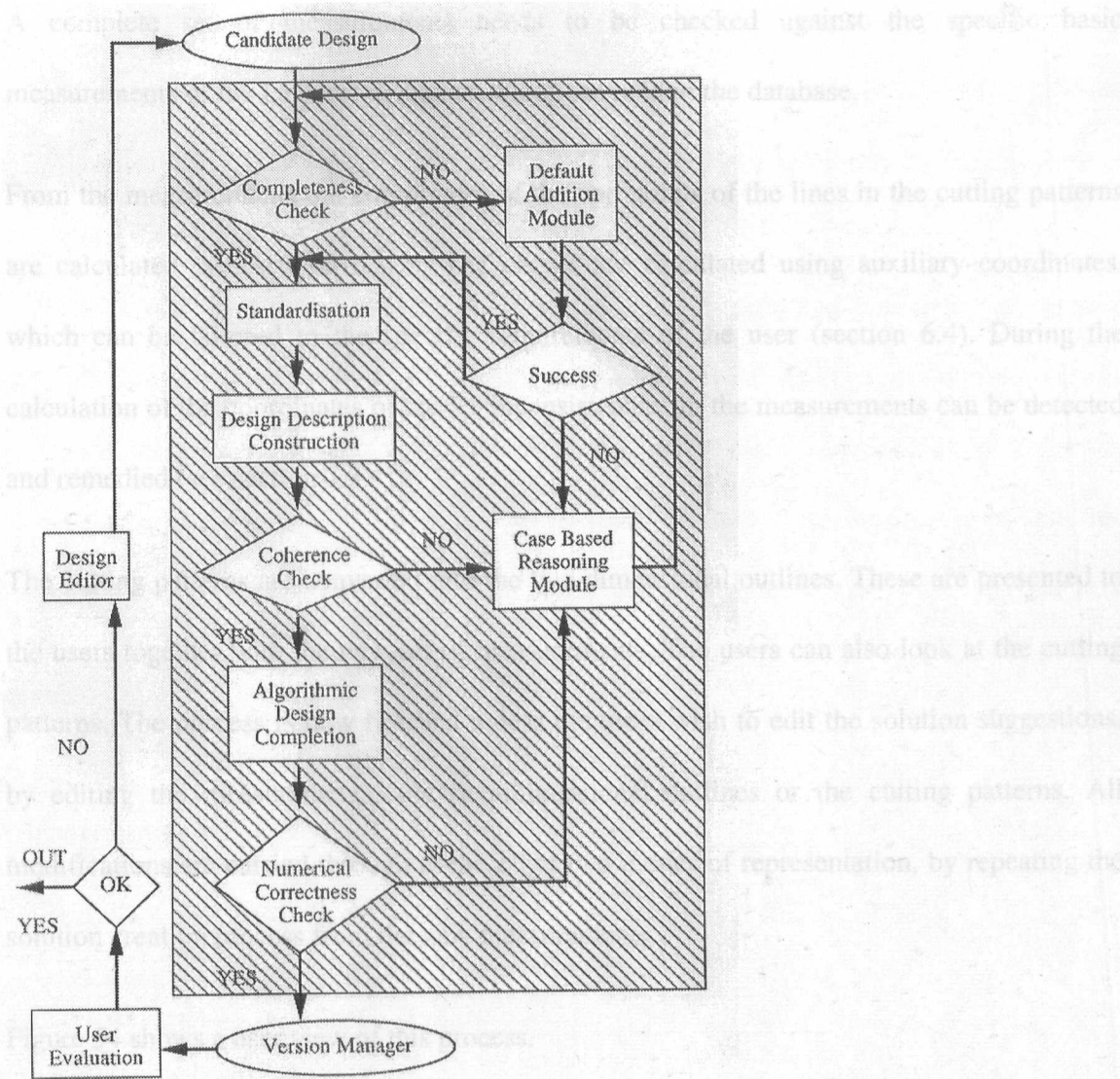


Figure 54. User View of the Garment Shape Module

The right-hand side describes the stages based on correct input measurements. The left side of the diagram shows the interaction with intelligent reasoning components.

Figure 53 shows the stages of the automatic shape construction process starting with the input measurements. The process begins with the users specifying a set of input measurements and a short verbal description. The input measurements are mapped to a consistent internal notation of the measurement to accommodate different industrial practices. The system checks whether a complete set of measurements has been provided. If this is not the case measurements are completed (see section 7.3.4).

A complete set of measurements needs to be checked against the specific basic measurements of the large retail chains, which are held in the database.

From the measurements the coordinates of the end points of the lines in the cutting patterns are calculated (see section 6.1.2). The curves are calculated using auxiliary coordinates, which can be tailored to the specific requirements of the user (section 6.4). During the calculation of the coordinates or curves inconsistencies in the measurements can be detected and remedied (see section 7.3.4).

The cutting patterns are converted into the two-dimensional outlines. These are presented to the users together with the new set of measurements. The users can also look at the cutting patterns. The process is now finished unless the users wish to edit the solution suggestions, by editing the measurements, the two-dimensional outlines or the cutting patterns. All modifications are carried through to the other two modes of representation, by repeating the solution creation process from the new measurements.

Figure 54 shows a user view of this process.

7.3.4 Potential for Intelligent Reasoning with Incomplete and Inconsistent Data

The issues of incomplete and inconsistent data are closely linked. By users' setting priorities or likelihood factors on input measurements, conflicting values of a lower priority can be treated as missing.

Measurements can be completed by applying techniques of different complexity:

- In the first instance missing values can be filled in using default values, based on the short verbal description of the garment. As Table 6 shows, the number of different descriptions are very limited.
- A closer match to the designer's intention might be created by incorporating the offsets between the specified measurements of the design (see Table 8) to the underlying body

measurements, for example the chest width of the garment compared to the chest body measurement. Heuristic rules can be used to estimate the ratio of offset for different measurements. A similar approach has been applied to architecture by Papamicheal et al. (1996) (see section 5.2.3).

- It would also be possible to employ a case-based reasoning approach (see section 5.2.2). One starting garment with the same verbal description as the missing measurements could be selected and shown to the user for approval as a starting garment. Alternatively the system could reason from various existing garments. See section 9.4 for further ideas. A case based reasoning approach has been employed for architecture by Smith et al. (1996) (see section 5.2.3).

Size Measurement in cm	10	12	14	16	18
Front-Shoulder to Waist	39.5	40	40.5	41.3	42.1
Hips	87	92	97	102	107
Bust	82	87	92	97	102
Across Back	33	34.2	35.4	36.6	37.8
Armhole Depth	26.4	28	29.6	31.2	32.8
Shoulder	11.9	12.2	12.5	12.8	13.1

Table 8. Measurements for Standard Body Shape, from Aldrich, 1987

Inconsistencies in the measurements can occur in different ways:

- specified measurements and the verbal description do not concur: for example a garment is described as a trapeze shape, but has straight side lines defined. In this case it is reasonable to assume that the verbal description is correct and treat the problematic values as missing, because even fleeting designs can be placed verbally in the right class by designers, at this level of abstraction.
- The specified measurements are internally inconsistent: for example an armhole depth that is wider than the width of the sleeve or sleeve curve longer than the armhole curve; or the resulting shape does not fit human anatomy, for example a resulting sleeve length that is far too long. In both cases problems can only be detected in the

Chapter 8.

The Benefits of the Design Support System

This chapter explains the effect we expect the proposed garment shape construction module to have on the creation of garment shapes. This would constitute an improvement to the knitwear design process through a system facilitating the communication between designers and technicians through technical feedback to the designer on tentative solutions. Following the analysis of the factors leading to a breakdown in communication in chapter 4, this chapter shows how some of the contributing factors can be alleviated. Additional benefits to the design process will be explained briefly.

8.1 Summary of the Benefits

In summary, the benefits of the proposed design support system are:

- The shape is described unambiguously by the designer, so that complete and correct information can be communicated to the technician.
- Designers can iterate round the generate-evaluate cycle without the need for technicians to be involved. This will improve the design by allowing the designer to explore much more of the whole space of possible designs. It will reduce frustration on both sides: designers will not be delayed by waiting for technicians to respond; technicians will not waste time by trying to create designs that will be rejected by the designers because they do not like the outcome.

8.2 The New Garment Shape Construction Process

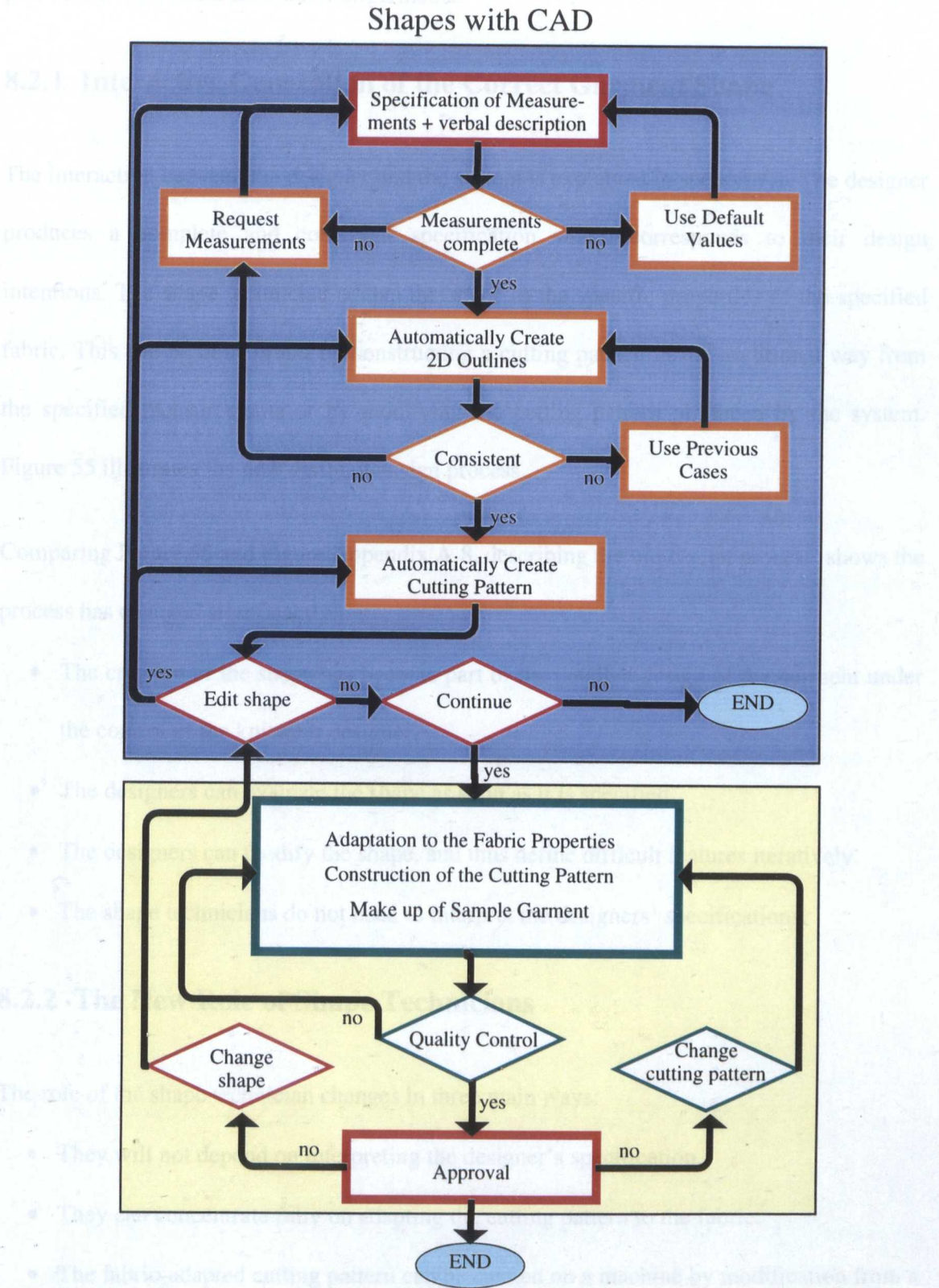


Figure 55. Constructing Garment Shapes with the CAD System

With the introduction of an intelligent design support system the design process changes: designers can provide correct design specifications, for technicians to use as the starting point for the technical realisation of garments.

8.2.1 Interactive Generation of the Correct Garment Shape

The interaction between the designer and the system is explained in section 7.1. The designer produces a complete and consistent specification which corresponds to their design intentions. The shape technician adapts the shape to the specific properties of the specified fabric. This can be done either by constructing a cutting pattern in the traditional way from the specified measurements or by modifying the cutting pattern produced by the system. Figure 55 illustrates the new garment design process.

Comparing Figure 55 and Figure Appendix A-8, describing the old design process, shows the process has changed significantly:

- The creation of the shape has become part of the detailed design of the garment under the control of the knitwear designer.
- The designers can evaluate the shape as soon as it is specified.
- The designers can modify the shape, and thus define difficult features iteratively.
- The shape technicians do not need to interpret the designers' specifications.

8.2.2 The New Role of Shape Technicians

The role of the shape technician changes in three main ways:

- They will not depend on interpreting the designer's specification.
- They can concentrate fully on adapting the cutting pattern to the fabric.
- The fabric-adapted cutting pattern can be created on a machine by modification from a final shape pattern.

This shape construction module does not replace the shape technicians. Their expertise in fabric handling is as valuable as ever and constitutes the focal point of their work. This knowledge cannot be encoded at present, because much of it is not yet understood theoretically.

Given the changes in fashion and the heuristic nature of computer systems, the creation of only about 95% of all shapes can be supported (section 6.8.2). The shape technicians are still required to help the designers in specifying novel shapes.

The role of the shape technician is currently affected by two trends in the knitwear industry:

- The increased use of shaped knitwear. These garments are knitted rather than cut to shape. No paper pattern is required. The shape technicians are less and less involved in the construction of the shape and concentrate on make up. However, at the lower end of the market cut-and-sew knitwear will remain important for as long as the increased knitting time and higher make up costs for shaped garments outweigh the additional yarn costs.
- The increased complexity of the make up and trims. Currently knitwear has complex neck trims, collars, belts and pockets. Many styles from tailoring are adapted into knitwear. The make up of these garments requires considerable skill. Shape technicians in the future will be more valued for their make up skills than for their cutting pattern skills.

8.3 Overcoming the Communication Bottleneck

The following explanation follows the structure of the analysis in chapter 4, from which the headings are derived.

8.3.1 Intrinsic Difficulties in the Communication of the Knitwear

(section 4.3)

- The intertwining of design and technical realisation

The purpose of the system is to give designers access to technical knowledge, and enable them to modify their designs based on technical feedback on designs.

- The only model of a knitted structure is a knitted structure.

The system creates technically correct models of knitwear. In the case of the garment construction model the two-dimensional outline of the garment is an accurate model.

- No complete and unambiguous representation of knitted structures

Even though no single notation in knitwear expresses all features, automatic mapping between different representations can make it possible to express certain features.

8.3.2 Knowledge Representation Reasons (section 4.3.3)

- Higher design commitment through higher degree of accuracy

The system allows fast exploration of the design space. The designers can input tentative specifications and see design suggestions quickly. A high degree of accuracy is therefore not a high commitment of design time. As an accurately defined solution always appears more finished than a tentative description, there is however a danger that designers commit themselves to the first plausible solution.

- Conflict in intended degree of detail in sketch

All parts of a representation created by the system are equally reliable.

8.3.3 Different Thinking Styles of the Designers and Technicians (section 4.4)

- Different mental representations of the design

The automatic translation between the different representations and the use of an accurate model can alleviate this problem, by providing notations closer to the mental models of the participants.

- General difficulties in describing mental images.

Suitable knowledge representation can help in describing a design more efficiently, but it cannot overcome the fundamental difficulties of describing rich mental images.

8.3.4 Organisational Reasons (section 4.5)

A CAD system can only have an indirect effect on the working culture by easing the pressures on participants and supporting communication.

- Time overlap between seasons

Immediate technical feedback from a CAD system enables designers to improve their design specifications, so that technicians will require fewer clarifications. It will also reduce the overall number of samples required. There will always be a certain overlap between the seasons the designers and technicians are working on as the designers' work concentrates on the beginning of a new season and the technicians' tasks towards the end.

- Accessibility to participants

The proposed system does not make the participants of the design process more accessible, but reduces the need to cross-check information. A commercial system could include a messaging system or shared workspaces.

- No overlapping expertise

The system is set up to overcome this barrier by making technical knowledge available to designers; through use of the system the designers are likely to pick up technical skills. It does not make design knowledge available to technicians.

- Different social groups

Unless a CAD system attracts different people into a career they cannot easily overcome these social divisions.

- Organisational structure

A CAD system on its own cannot directly change the organisational structure, unless it leads to the recruitment of different people or empowers one group to change the structure.

- Power struggle between designers and technicians

The power struggle between designers and technicians exists because technicians are highly skilled experts who are hard to replace while designers are easy to replace. The systems will, however, reduce the work-related frustration of both groups.

- Neither group trusts the others' assertions and specifications.

The system can provide feedback to designers, which they perceive as neutral. The suspicion of laziness does not apply to a computer program. Technicians can trust specifications generated using the system.

- Problems are not recognised and not counteracted.

A CAD system cannot directly address this problem.

8.4 Efficiency of the Design and Sampling Process

The design support module addresses the points raised by practitioners in section 3.7 directly:

- Close mapping to designers' initial ideas: The designers receive technical feedback and can modify the designs until they are satisfied.
- Reduction of modification cycles: Many garments are currently compromises, because the time for changes has run out. Initial modification cycles due to an inadequate specification of the design are cut out.
- Technically feasible designs: The design support system gives the designers technical feedback on their designs and will try to alert them to infeasible designs.

It is however debatable whether an increase in the technical correctness of garments is an undivided blessing. Domain experts hold the view that the creativity of a designer is decreased by technical knowledge, because they hesitate to explore the frontiers of the design space and stay within the range of already existing designs. There is anecdotal

evidence that these prejudices are not unjustified; see Eckert and Stacey (1994). The other point of view is that the limitation of the scope of the designs has arisen from an incomplete understanding of the technology and could be overcome by the designers having better technical knowledge. However, many designers²⁵⁷ comment that the stitch structures created by the technicians accidentally by misinterpreting their specifications are either as acceptable as the original design; or at least inspire the designers to produce other designs.

8.5 Additional Advantages of this Approach

So far the analysis of the effects that a design support system would have on the communication process has concentrated on the communication between designers and technicians. The proposed design support system would however have further significant benefits.

- Record keeping

A design created on a CAD system can easily be recorded. The space occupied by the recorded designs is not a consideration.

- Accurate sketches for conceptual design development

Designers²⁵⁸ currently often use a standard figure consisting of a sketch of a person and the outline of a garment to sketch in colours, decorative and structural patterns. Even when they plan to have a variety of shapes later, they often use the same outline for all garments when they begin to sketch. This CAD system can very easily create a two-dimensional outline which is close to the shape designers want.

²⁵⁷ Discussed in detail with C17D1.

²⁵⁸ Observed in C17D2.

- Reduction of Duplication

Designers put effort into designs that they can visualise but not communicate. The technicians have to redesign from the partial information, which is available. The effort is duplicated.

- Learning for Designers and Technicians

Through immediate technical feedback designers can explore the design space and acquire technical knowledge. Fabric technicians are increasingly responsible for the creation of the shapes of garments in fully-fashioned and shaped knitwear. Fabric technicians can learn about shape construction in exactly the same way as the designers.

Chapter 9.

Conclusions

A jumper is far from being a simple product. It is the result of a complex industrial process produced under significant time pressure to a price point for exactly one time period in the development of fashion. The thesis has examined this process of designing and sampling knitted garments, and how it could be made more efficient.

The findings of this thesis are based on observations and interviews in 20 different companies in Britain and Germany, covering the whole spectrum of the industry from market leaders to the suppliers to cheap retail chains. A communication bottleneck between designers and technicians was identified and a possible CAD-based system to overcome the bottleneck was proposed. New mathematical modelling procedures were developed for such a system.

9.1 Main Conclusions

- The knitwear design process follows a similar pattern of research, design and sampling in all the observed companies (chapter 3).
- The knitwear design process is inefficient. This can be attributed to a failure in the communication between designers and technicians (sections 3.7 and 4.2). The participants recognise the process as inefficient.
- The communication bottleneck cannot be attributed to one single cause, but is caused by difficulties inherent in the structure of knitwear and by factors deriving from the traditional work culture of the knitwear industry (chapter 4).

- An intelligent CAD system, which uses knowledge involved in the technical realisation of garments, would enable designers to create complete and exact descriptions of their designs and thus ease the communication difficulties (chapter 8).
- Relevant aspects of garment shapes can be represented through mathematical models using Bézier curves and incorporating domain heuristics (chapter 6).
- Garment shape construction can be used in combination with automatic reasoning from partial information, to increase the scope of existing textile CAD systems (chapter 7).

9.2 Generality of the Findings

This thesis is concerned with the knitwear design and sampling process and its possible improvement. Not all of the 20 companies visited face all the problems mentioned, because the tasks and abilities of individuals are different; for example in some companies²⁵⁹ designers and technicians have worked out their own language for stitch structures. However, the same pattern of problems applies to all the observed companies. One company²⁶⁰ has overcome some of the problems associated with the working culture by taking a concurrent engineering approach.

Some results of the empirical work apply to other areas of textile and fashion design, because knitwear includes the tasks of these domains. It subsumes the creating of fabric in textile design, the design of the shape of the garment in fashion design and the granularity problems associated with carpet design:

- The initial design research process is the same throughout the textile industry with different emphases on individual products; see section 3.3.

²⁵⁹ C17

²⁶⁰ C18

- The mathematical models can also be applied to fashion design. The cutting patterns in fashion design have fewer constraints than in knitwear design, because there is no need to worry about the fabric unravelling. The mathematical models can be applied to fashion design after changing the end tangent vector constraints. The shape construction module described in chapter 6 could be applied in exactly the same way to fashion design. The significance of the shape construction module would be even greater in fashion than in knitwear design, because the shapes are more complex and more important.

The mathematical modelling approach, using Bézier curves with interpolation points that can be edited by a user, would also apply to other craft domains, such as furniture design. In these domains solid modellers or surface modellers can be used to create three-dimensional objects. Creating mathematically correct outlines could serve as a halfway step between sketching and using the three-dimensional modeller functionality. Designs could be annotated, communicated and initially checked using this much simpler representation. Two-dimensional outline designs suggested by a CAD system could provide the input measurements for solid modellers.

9.3 Limitations of the Research

The mathematical models of garment shapes have been implemented using a mathematical equation solving package, Maple, but have not been included in any other computer program. The iteration required to achieve the correct length has not been implemented in the mathematical equation solver, but was programmed in a previous version implemented in Prolog and C. The garment shape module has not been implemented and could therefore not be evaluated by real users.

9.4 Further Work

This research has been the first academic study of the design and sampling process in the knitwear industry, and one of the first systematic studies of any part of the textile industry. Communication between designers and technicians has been the focal point of the thesis, but much more analysis could have come out of the empirical work. This study of an artistic design domain has opened up many questions for design studies and for research on computer support systems. The main issue arising from this research is, however, the implementation of an intelligent design support system.

9.4.1.1 Intelligent Design Support

Implementation

A direct manipulation interface for garment shapes could be implemented to test the idea, as suggested in chapter 7.

Traditional tailoring methods for shape manipulation

Currently all garment shapes are created from measurements. Such a system could be extended for practical knitwear applications to incorporate traditional tailoring methods to create cutting patterns by modification from existing shapes. This would be simple to implement, because it only involves the manipulation of coordinates.

Incomplete measurement

So far the system can also only handle complete input measurements. Incomplete measurements could initially be supplemented by default values. Alternatively the system could reason from previous cases with the same verbal description regarding the feature which causes difficulty. Mismatches in the specification of sleeve crowns and armholes can be altered by moving the position of the end points of the sleeve curve. Case-based reasoning

could be applied from cases with similar descriptions. Similar systems have been developed for architecture in the last few years (see section 5.2.3). They are concerned with floor plans for buildings, which have a simpler geometry than knitted shapes. Applying case-based reasoning to the generation of garment shapes from partial information could be an interesting way to test the applicability of case-based reasoning to an artistic domain.

An intelligent support system for knitwear design

The architecture of a complete knitwear design support system has been presented in Eckert and Stacey (1995). However, further implementation decisions would have to be made. The author has identified two other main areas for design support for knitwear designers: the sizing of structure patterns and the placing of motif and structure patterns onto garment shapes. These modules were proposed by a project to develop a full-scale design support system for knitwear design, funded by the ACME initiative of the SERC in 1993.

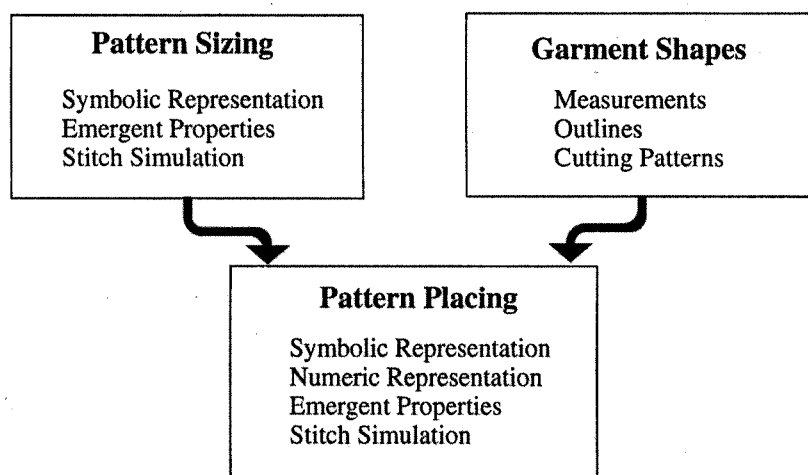


Figure 56. Module of Knitwear Design Support System

Automatic design

Cutting patterns of knitted garments would pose an interesting and challenging application domain for automatic shape generation. Possible interesting new shapes for garments could be discovered. It is however hard to see how it would be possible to test the automatically created shapes against the current context of fashion. It might be possible to use the input

measurements as evaluation constraints and ask the user to select appropriate shapes. However, this would be computationally expensive.

9.4.1.2 Design Studies

Comparisons with other parts of the textile industry.

Based on this analysis of the knitwear industry, it would be interesting to compare and contrast other domains within the textile industry. Practitioners refer to similarities. The author suspects that the practitioners do not value the importance of the domain knowledge suitably, such the lack of technical training shows and might underestimate its importance in the design process.

Design Cognition

This thesis makes two assumptions about design cognition based on anecdotal evidence:

- Designers are extremely good at visualising knitted garments and think in terms of the visual appearance of the fabric, i.e. the emergent properties.
- Designers can perform fast visual evaluations of design solution suggestions.

These hypotheses merit further testing. There will doubtlessly be individual differences between designers, but fashion designers and knitwear designers are a self-selected group who seem to have good visual memories and strong visual imaginations, and knitwear design training seems to favour people with good mental imagery. The author hypothesises that designers in other visual or artistic design domains, such as architecture or industrial design, can also visualise their designs early in the design process. Many researchers, for example Darke (1979), hint at the mental images of architects but a systematic study has yet to be done.

9.4.1.3 Mathematics

The t-values at interpolation points of Bézier curves

The mathematical models currently produce satisfactory results, but depend strongly on domain heuristics. The problem of t-values at interpolation points (see section 6.5.2) has been solved by an iterative approach and justified from domain intuition. A general mathematical proof would give this approach relevance beyond the generation of smooth monotonic curves in shape calculation in knitwear.

Individual Characteristics

This system uses the location of interpolation values to encode the individual characteristics of curves. Using this representation it would be possible to learn individual characteristics of designers or pattern makers from scanned-in or modified patterns. In the next few years made-to-measure clothes will become part of high-street fashion. Using individual characteristics of curves would enable CAD systems to combine the style of the designer or pattern maker with the measurements of the user.

References

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

Aldrich, W. (1987) *Metric Pattern Cutting* (4th Edition), Unwin Hyman, London, UK.

Aldrich, W. (1990) *New Technology and Clothing Design*, PhD Thesis, Nottingham Polytechnic, Nottingham, UK.

Berlin, Brent and Kay (1969), *Basic Color Terms*, University of California, Berkeley, CA.

Beynon-Davis, P. (1995), 'Ethnography and Information System Development: Ethnography of, for and within IS development', *Symposium on Ethnography and Software*, Open University, UK.

Bézier, P. (1968) 'How Renault uses numerical control for car body design and tooling' *Paper SAE 6800010*, Society for Automotive Engineers.

Bucciarelli, L. (1988) 'An ethnographic perspective on engineering design', *Design Studies*, Vol 9 No 3.

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

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

- Brandimonte, M. and Gerbino, W. (1996)**, 'When Imagery Fails: Effects of Verbal Recording on Accessibility of Visual Memories' In: Cornoldi, C. et al (Eds.) *Stretching the Imagination*, Oxford University Press, New York, NY, pp. 31-76.
- Chun, C. (1990)** 'Cognitive Processes in Architectural Design Problem Solving', *Design Studies*, Vol 11 No 2, pp. 60-80.
- Concept II (1996)**, *Concept Pattern Studio* and *Concept Design Studio*, Concept II Research Limited, Old Stevenage, UK.
- Cross, N. (Ed.) (1984)** *Developments in Design Methodology*, John Wiley, Chichester, UK.
- Cross, N. (1989)**, *Engineering Design Methods*, John Wiley, Chichester, UK.
- Cross, N., Christiaans, H., Dorst, K. (1996)**, *Analysing Design Activity*, John Wiley, Chichester, UK.
- Darke, J (1979)** 'The Primary Generator and the Design Process', *Design Studies*, Vol 1 No 1, also in: Cross, N. (Ed.) *Developments in Design Methodology*, John Wiley, Chichester, UK, pp 175 - 188.
- Daunt, M. and Miller, D. (1996)** 'Integrating the Designer & the Technologist, Diversification Towards 2000', In: Proceedings of *Textile Institute's 77th World Conference*, pp. 361 - 375.
- Dong, A. and Agogino, A. (1996)** 'Text analysis for constructing design representations' *Proceedings of Artificial Intelligence in Design '96*, Kluwer Academic Publishers, Dordrecht, Holland.
- Eckert, C. (1990)** *Prototype of an Intelligent CAD System for Knitwear Design*, MSc Thesis, Department of Computing Science, University of Aberdeen, Aberdeen, UK.

- Eckert, C.** (1995) 'Intervention Strategies for Critiquing Professional Designers', *Research Report 9504*, Centre for the Design of Intelligent Systems, Design Discipline, The Open University, Milton Keynes, UK.
- Eckert, C.** (1997), 'Design Inspiration and Design Performance', *Proceedings of the 78th World Conference of the Textile Institute*, Thessaloniki, Greece.
- Eckert, C. and Demaid, A.** (1997), 'Concurrent Design', *Proceedings of the 78th World Conference of the Textile Institute*, Thessaloniki, Greece.
- Eckert, C. and Murray, B.** (1993) *User Study*, CAD/CAM for knitwear design and development, Deliverable for ACME project GR/J40331, Loughborough University of Technology Department of Computer Studies .
- Eckert, C. and Stacey, M.** (1994) 'CAD systems and the division of labour in knitwear design', in Adam, A., Emms, J., Green, E. and Owen, J. (eds.) *Woman, Work and Computerisation: Breaking Old Boundaries - Building New Forms*, North-Holland, Amsterdam, Holland, pp. 409-422.
- Eckert, C. and Stacey, M.** (1995) 'An Architecture for an Intelligent Support of Knitwear Design' in Sharpe, J. and Oh, V. (eds.) *AI System Support for Conceptual Design*, Springer-Verlag, Berlin, Germany.
- Ellen, A.** (1992) *The Handknitter's Design Book*, David & Charles, Newton Abbot, UK.
- Ericson, K. and Simon, H.** (1984) *Protocol analysis: verbal reports as data*, MIT Press, Cambridge, MA, UK.
- Farin, G.** (1982) 'Visually C2 cubic splines', *Computer-Aided Design*, Vol 14 No 3, pp. 137 - 139.
- Fasset, K.** (1985), *Glorious Knitting*, Ebury Press, London, UK.

Faux, I. And Pratt, M. (1979) *Computational Geometry for Design and Manufacture*, Ellis Horwood.

Ferguson, J.C. (1964) 'Multivariate Curve Interpolation' *Journal ACM*, Vol 11 No 2, pp. 221 - 228.

Filipe, A. (1993) 'Methods of Local Adjustment of Composite Curves', *Combined proceedings of EDUGRAPHIC'93 and COMPUGRAPHICS'93*, pp. 374 - 379.

Fischer, G., Nakakoji, K. Ostwald, J., Stahl, G. and Sumner, T. (1993) 'Embedding critics in design environments', *Knowledge Engineering Review*, Vol 8 No 4, pp. 285 - 307

Fischer, G., Lemke, A, McCall, R. and Morch, A. (1991) 'Making argumentation serve design', *Human Computer Interaction*, Vol 6 No 3-4, pp. 393-419

Forrest, A. (1990) 'Interactive interpolation and approximation of Bézier polynomials' , *Computer-Aided Design*, Vol 22 No 9, pp. 527 - 537.

Gerber Garment Technology (1996), *Design and Merchandising*, Sales Brochure, Gerber Garment Technology, Inc., Tolland, CT.

Glassborow, J. (Ed.) (1986), *The Complete Book of Nature*, Dragon, London, p.49.

Gross, M. (1996) 'The Electronic Cocktail Napkin', *Design Studies*, Vol. 17.

Hales, C. (1987), *Analysis of the Engineering Design Process in an Industrial Context*, *PhD Thesis*, Gants Hill Publication, Hampshire.

Harada, K., Kaneda, K. and Nakamae, E. (1984) 'A further investigation of segmented Bézier interpolants', *Computer-Aided Design*, Vol 16 No 4, pp. 186 - 190.

Hägglund, S. (1993), 'Introducing Expert Critiquing Systems', *Knowledge Engineering Review*, Vol 8 No 4, pp. 281-284.

Hill, C., Crampton-Smith, G., Curtis, E. , Kamlish, S., and Scaife, M. (1993),

'Designing a visual database for fashion designers' Proceedings of *CHI 93*, ACM Press.

Hinds, B., and McCartney, J. (1990) Interactive Garment Design, in *The Visual Computer*,

Vol 6 pp. 53 - 61.

Hughes, J., Somerville, I., Bentley, R. and Randall, D. (1993) 'Designing with

ethnography: making work visible', *Interacting with Computers*, Vol 5 No 2.

Hunsaker, S. (1992), 'Towards an Ethnographic Perspective on Creativity Research',

Journal of Creative Behaviour, Vol 26 No 4, pp. 235 - 241.

Hunter, D. and Whitten, P. (Eds.) (1976) *Encyclopaedia of Anthropology*, Harper and

Row, New York, NY, p. 294.

International Journal of Clothing Science and Technology, Vol 8 No 3, 1996, special issue

on modelling fabric and garment drape.

Knitting Industries Federation (1996) *Knitstats 1993-1994*, Knitting Industries Federation,

53 Oxford Street, Leicester, LE1 5XY.

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

Koning, H. and Eizenberg, J. (1981) 'The language of the prairie: Frank Lloyd Wright's

prairie houses, *Environment and Planning B*, Vol 8, pp. 97-114.

Kumar, S., Suresh, S., Krishnamoorthy, C., Fenves, S. and Rajev, S. (1994) 'GENCRIT:

A tool for knowledge-based critiquing in engineering design' *Artificial Intelligence for*

Engineering Design, Analysis and Manufacturing, Vol 8, pp. 239 - 259.

Lawson, B. (1990), *How Designers Think*, Academic Press, London, UK.

Lemke, A. and Fischer, G. (1990) 'A co-operative problem solving system for user interface design' in *Proceedings of AAAI*.

Lundsteen, S. (1987), 'Qualitative assessment of gifted education', *Gifted Child Quarterly*, Vol 31, pp. 25 - 29.

Magee, K. (1987), 'The elicitation of knowledge from designers' *Design Studies*, Vol 8 No 2, pp. 62 - 69.

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

Mansfield Knitwear Menswear, *A short history of knitwear*, Mansfield Knitwear, Trinity Street, Loughborough, Leicestershire, LE11 1BY.

McCartney, J. and Hinds, B. (1992), 'Computer aided design of garments using digitized three-dimensional surfaces' *IMechE*, Vol 206 pp. 199 - 206

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.

Miller, P. (1986) *Expert Critiquing Systems: Practise-Based Medical Consultation by Computer*, Springer-Verlag, New York, USA.

Papamicheal, K., LaPorta, J., Chauvet, H., Trzcinski, T., Thorpe, J. and Selkowitz, S. (1996) 'The Building Design Advisor', *Proceedings of ACADIA '96*.

Preece, J., Rogers, Y., Sharp, H., Benyon, D., Holland, S. and Carey, T. (1994) *Human-Computer Interaction*, Addison-Wesley, Wokingham, UK.

Reich, Y. (1991) 'Design knowledge acquisition: task analysis and a partial implementation' *Knowledge Acquisition*, Vol 3, pp 237 - 254.

Rhodes, E. and Carter, R. (1996) 'Bridging the gap between concept and reality: strategy and implementation for textile and apparel SME'S' *Proceedings of Investing in Design by Computer*, Textile Institute, Manchester, UK

Rosenman, M. (1996) 'The generation of form using an evolutionary approach', *Proceedings of Artificial Intelligence in Design '96*, Kluwer Academic Publishers, Dordrecht, Holland.

Rousseau, N. (1991) *Human issues in the design of software development tools LUTCHI* Research Centre Report No. LUTCHI/0100, LUTCHI Research Centre, Loughborough University, Loughborough, UK.

Sandra Sandra Fashion Knits, Gruner + Jahr AG & Co, Germany.

Scaife, M., Curtis, E., and Hill, C. (1994). 'Interdisciplinary collaboration: a case study of software development for fashion designers', *Interacting with Computers*, Vol 6 No 2, pp. 395 - 410.

Schmidt, L. and Cagan, J. (1996) 'Grammars for Machine Design' *Proceedings of Artificial Intelligence in Design '96*, Kluwer Academic Publishers, Dordrecht, Holland.

Schnier, T. and Gero, J. (1996), 'Learning Genetic Representations', *Proceedings of Artificial Intelligence in Design '96*, Kluwer Academic Publishers, Dordrecht, Holland.

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

Shetty, S. and White, P. (1991) 'Curvature-continuous extensions for rational B-spline curves and surfaces', *Computer-Aided Design*, Vol 23 No 7, pp. 484 - 491.

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

Silverman, B.G. (1992) 'Survey of Expert Critiquing Systems: Practical and Theoretical Frontiers', *Communications of the ACM*, Vol 35 No 4, pp 106 - 127.

Slater, M. (1988), 'A top down method for interactive drawing' *Computer Graphics Forum*, Vol 7, 323-329.

Smith, I., Stalker, R. and Lottaz, C. (1996) 'Creating Design Objects from Cases for Interactive Spatial Composition', *Proceedings of Artificial Intelligence in Design '96*, Kluwer Academic Publishers, Dordrecht, Holland

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

Staufer, L., Diteman, M., and Hyde, R. (1991) 'Eliciting and Analysing Subjective Data about Engineering Design' *Journal of Engineering Design*, Vol 2 No 4, pp. 351 - 366.

Stiny, G (1980) Introduction to shape and shape grammars, *Environment and Planning B: Planning and Design*, Vol 7, pp. 343-351.

Stoll (1996) *The whole world of flat knitting technology*, Sales Brochure, H. Stoll GmbH & Co., Reutlingen, Germany.

Todd, S and Latham, W. (1992), *Evolutionary Art and Computers*, Academic Press, London.

Tunnickliff, A. and Scrivener, S. (1991) 'Knowledge Elicitation for Design', *Design Studies*, Vol 12 No 2, pp. 73 - 80.

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

Visser, W. (1995) 'Use of episodic knowledge and information in design problem solving', *Design Studies*, Vol 16 No 2.

Vogue, 1996, August, Nast Publication, London, p. 73

Vogue, 1996, December, Nast Publication, London, p. 143

Voss, A. (1996) 'Towards a methodology for case adaptation', *Proceedings of 12th European Conference on Artificial Intelligence*, John Wilney, Chicester, UK.

Voss, A., Bartsch-Spörl, B. and Oxman, R.(1996) 'A study of case adaptation systems' *Proceedings of Artificial Intelligence in Design '96*, Kluwer Academic Publishers, Dordrecht, Holland.

Appendix A Flow Diagrams of the Knitwear Design Process

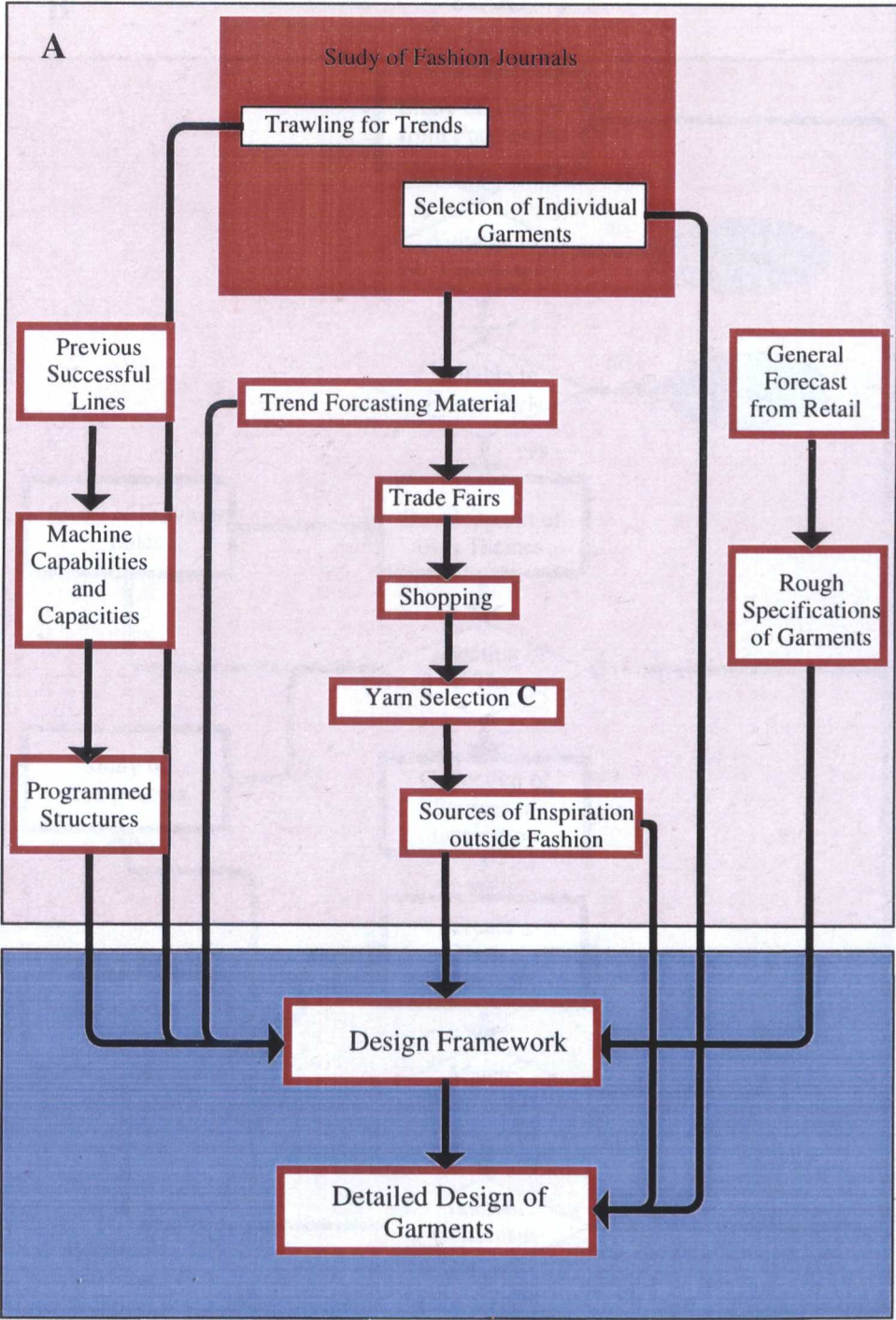


Figure A-1. Fashion Research in Design Companies

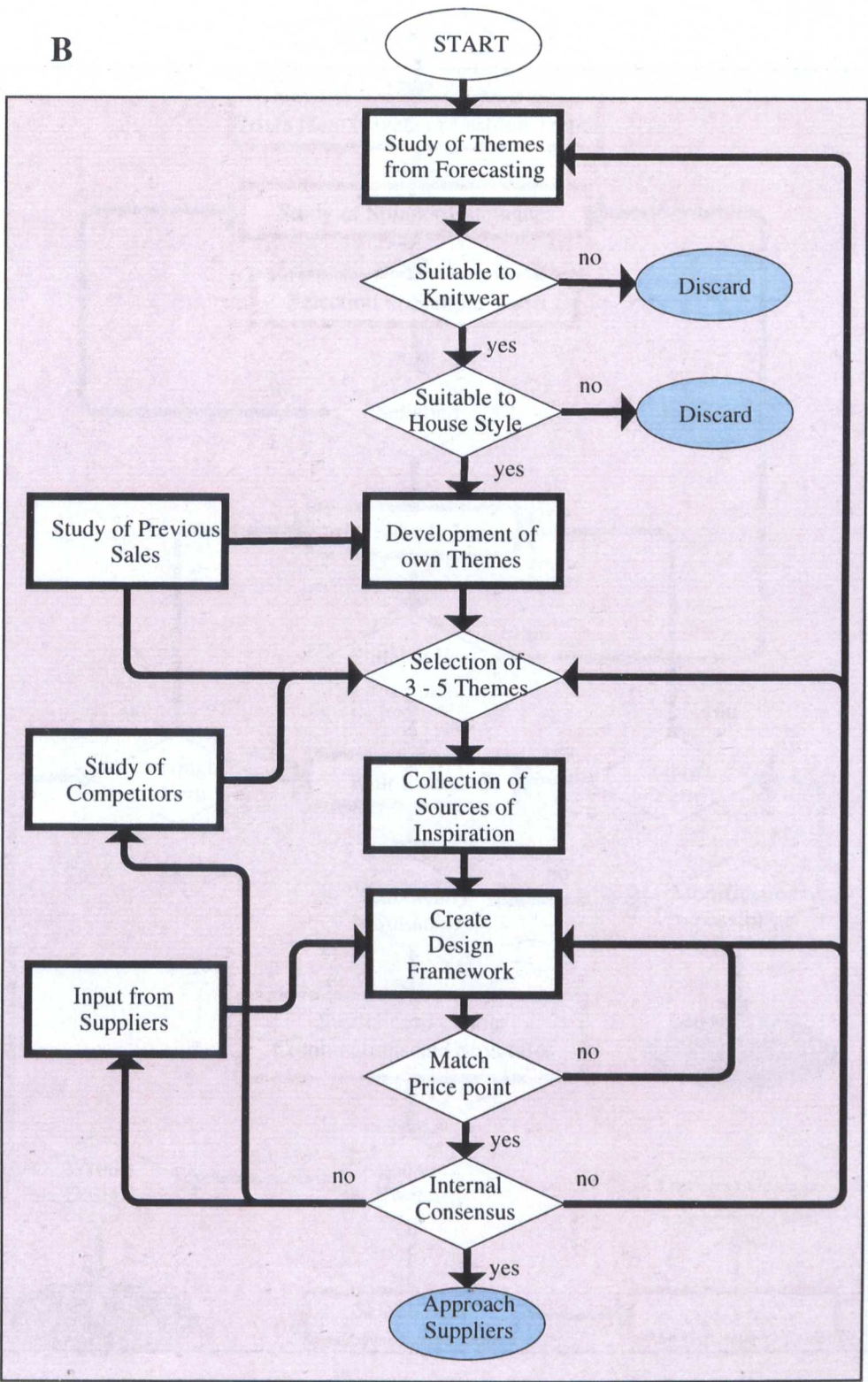


Figure A-2. Fashion Research in Retail Chains

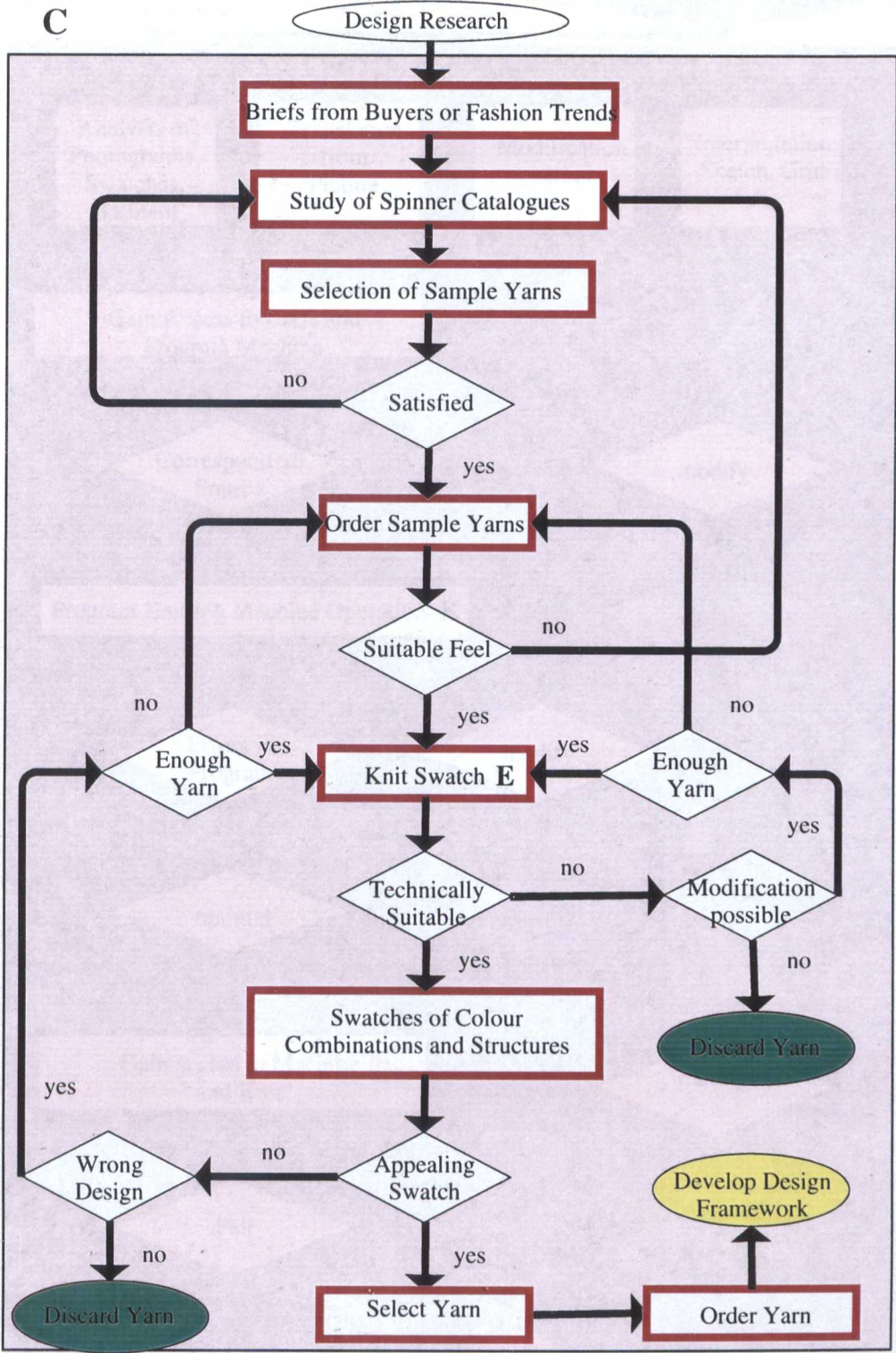


Figure A-3. Yarn Selection

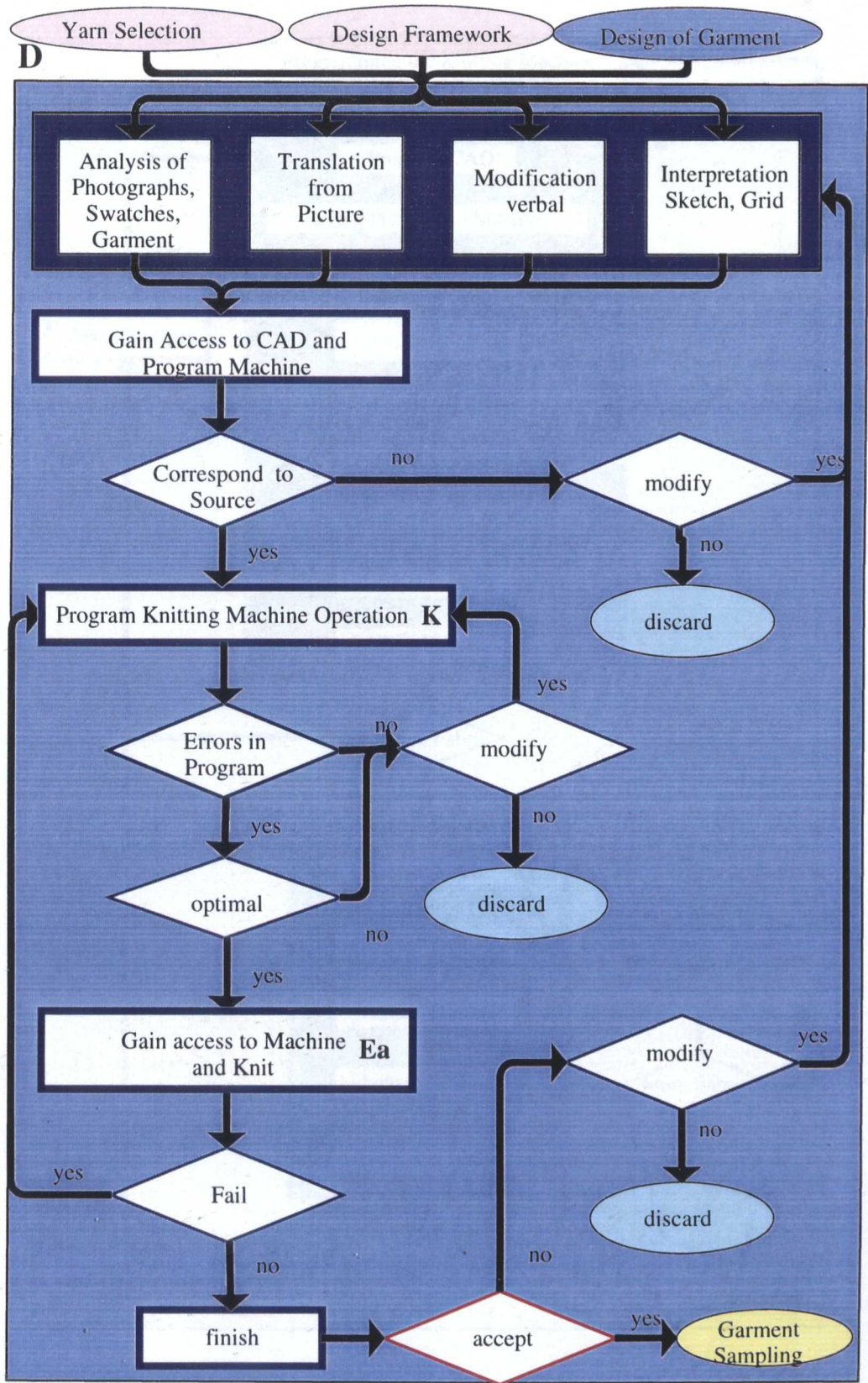


Figure A-4. Swatch Sampling

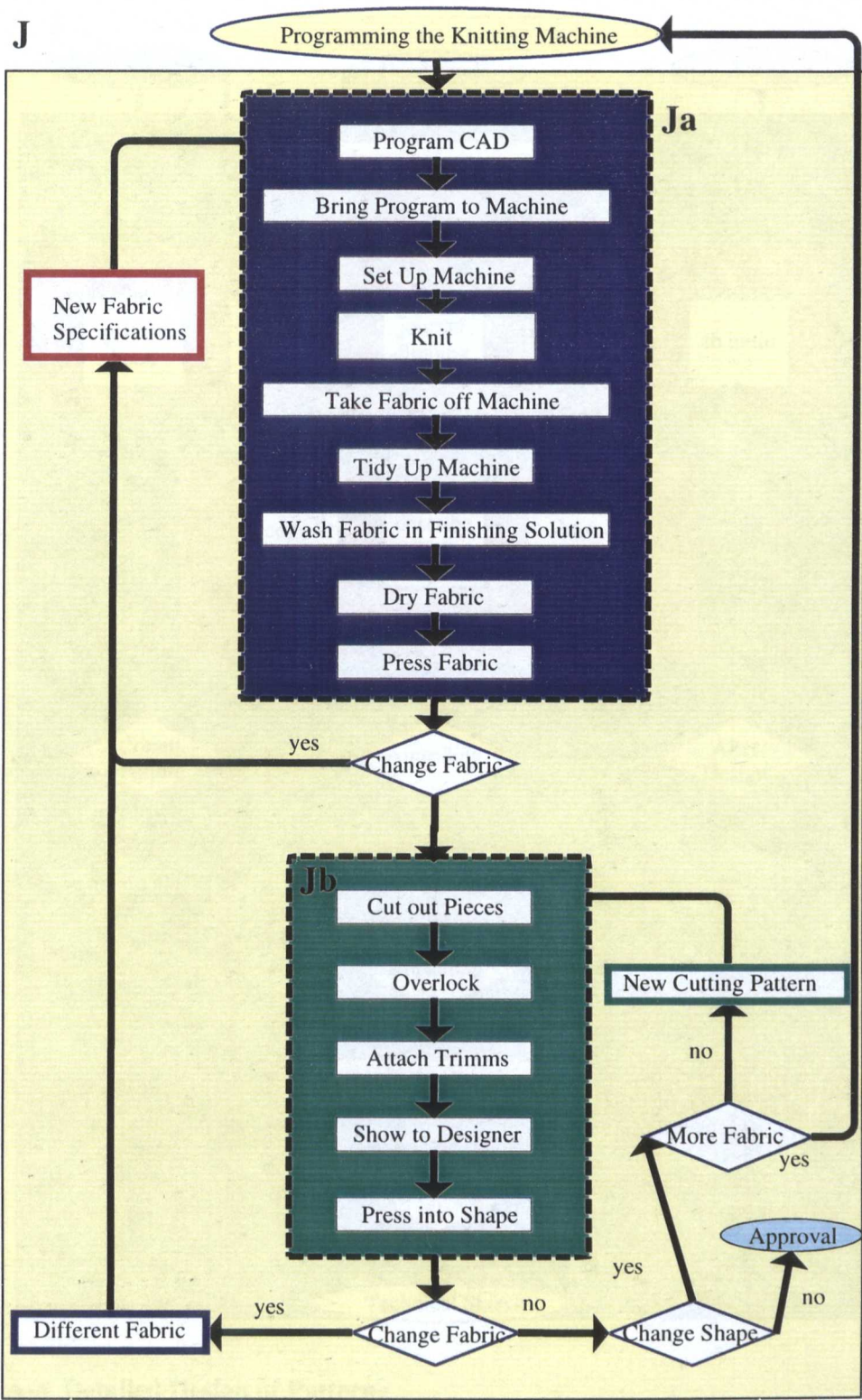


Figure A-5. Knitting and Finishing

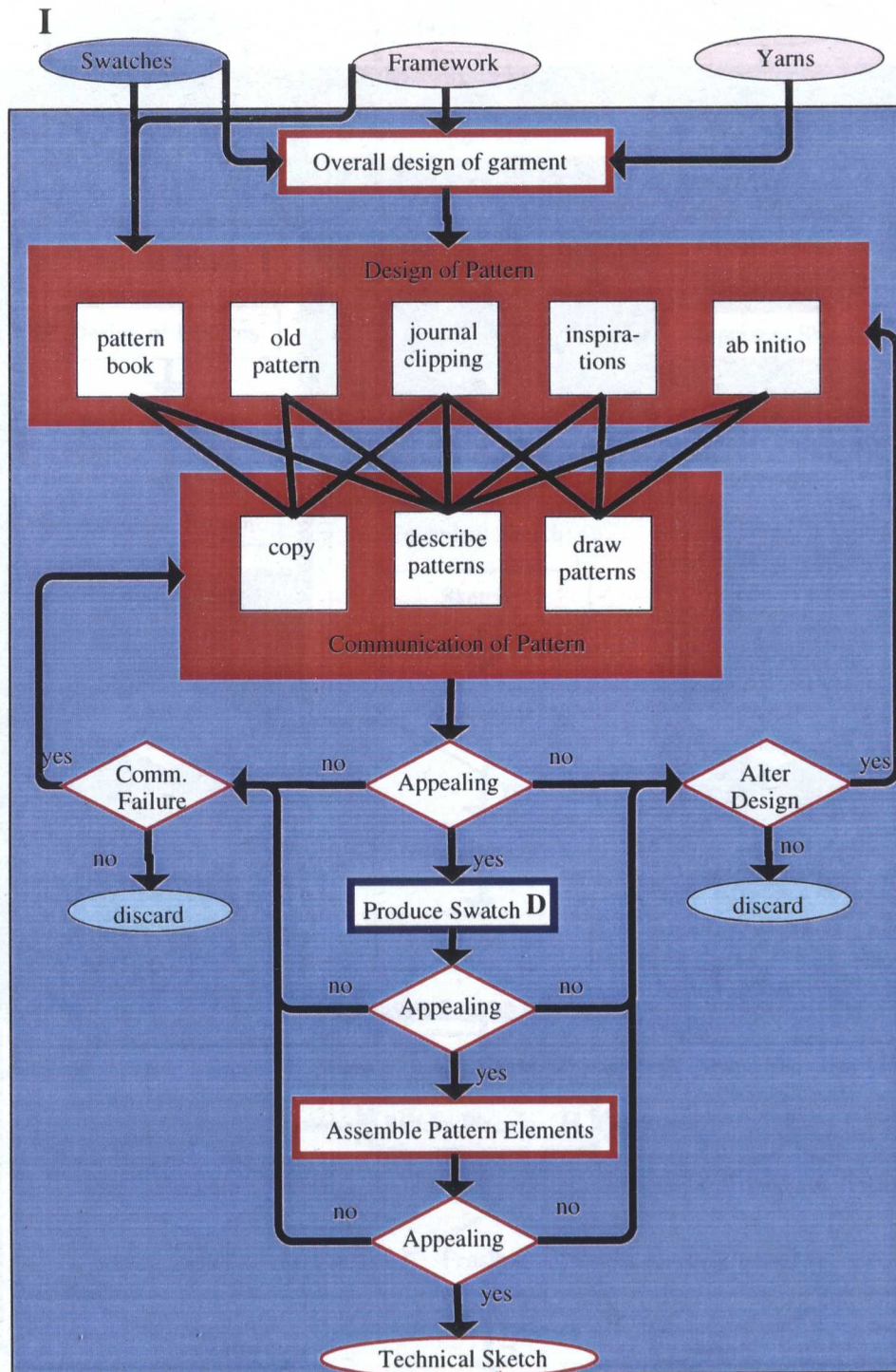


Figure A-6. Detailed Design of Patterns

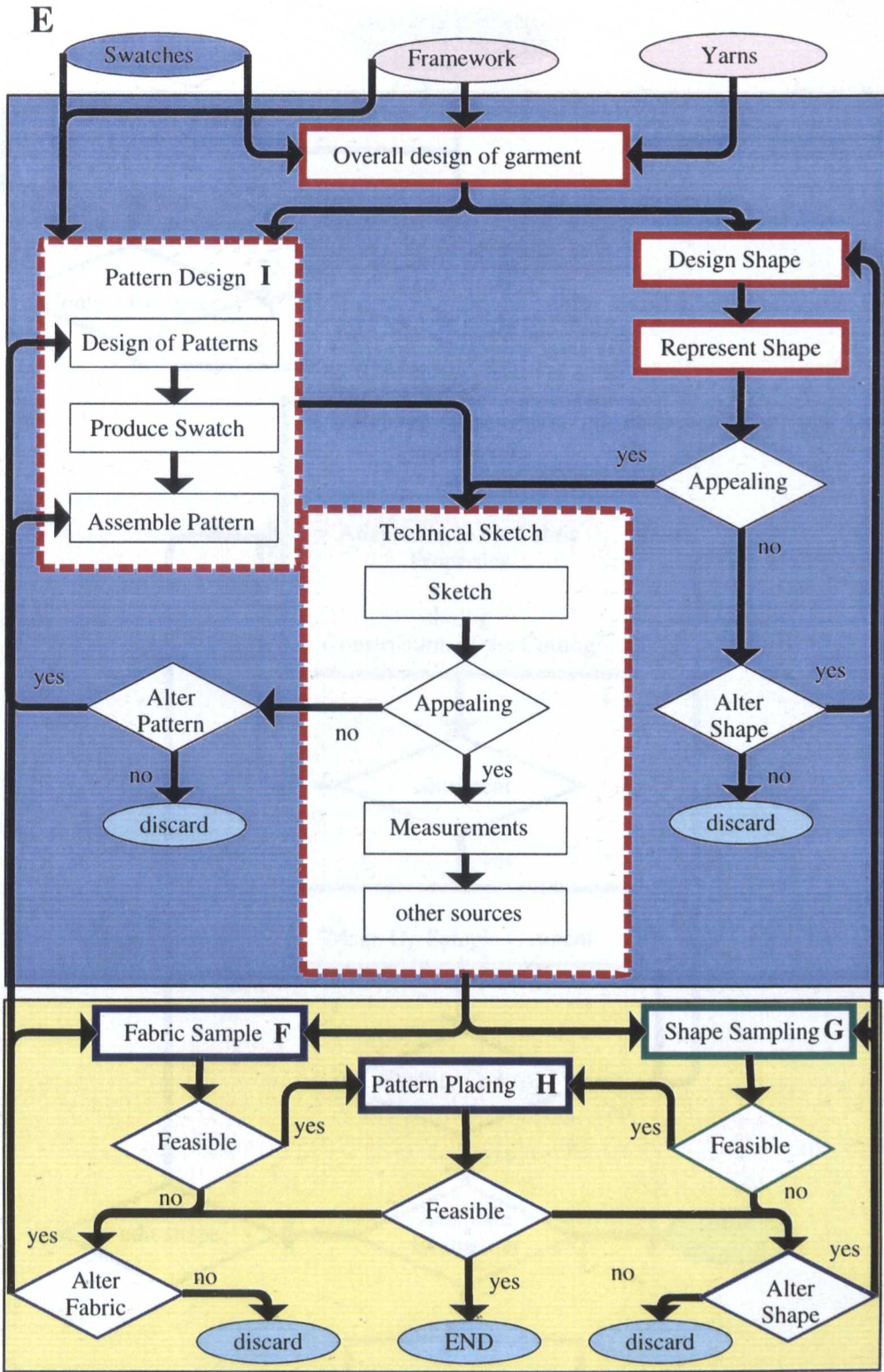


Figure A-7. Detailed Design of Garments

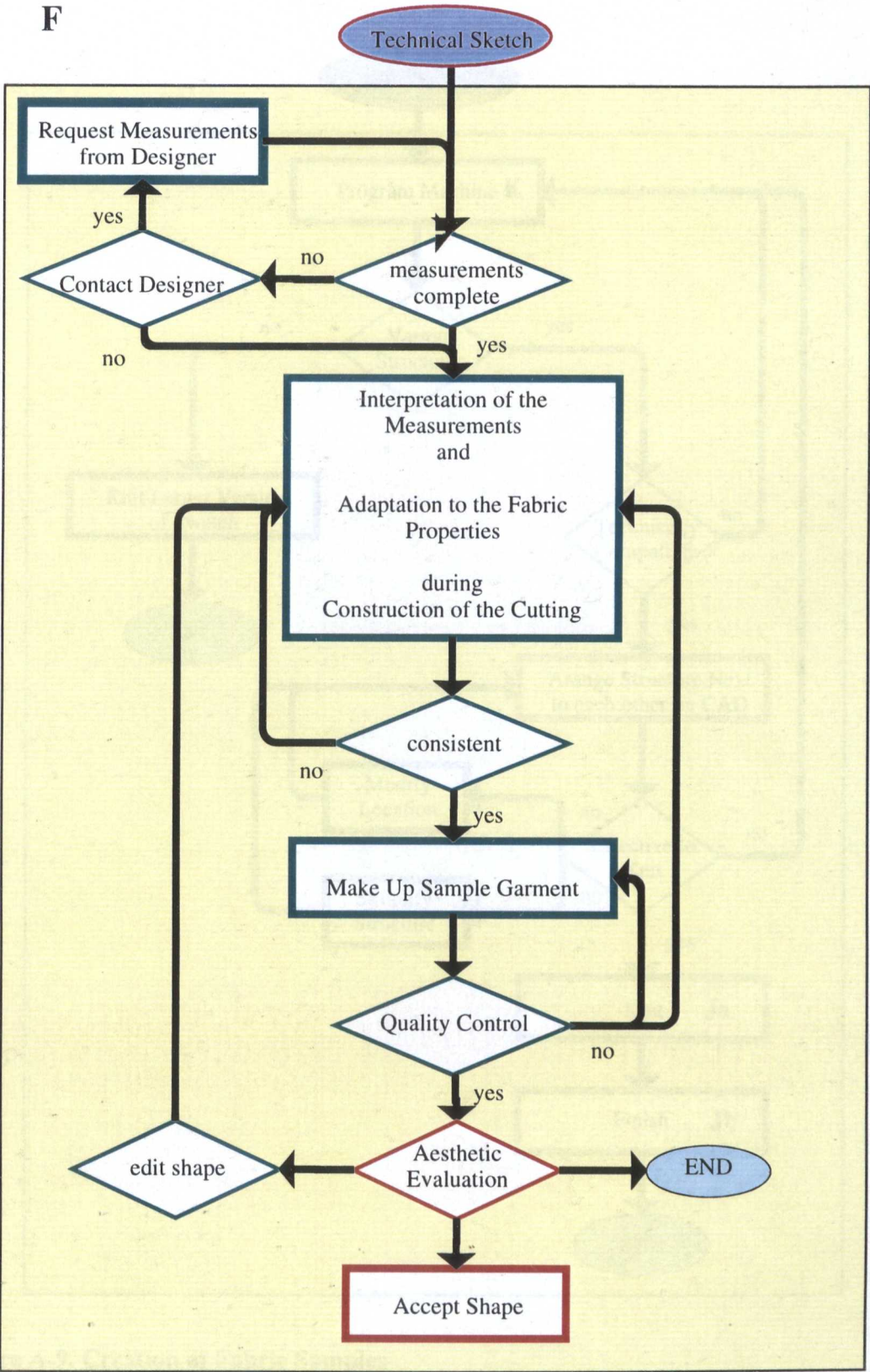


Figure A-8. Creation of Cutting Patterns

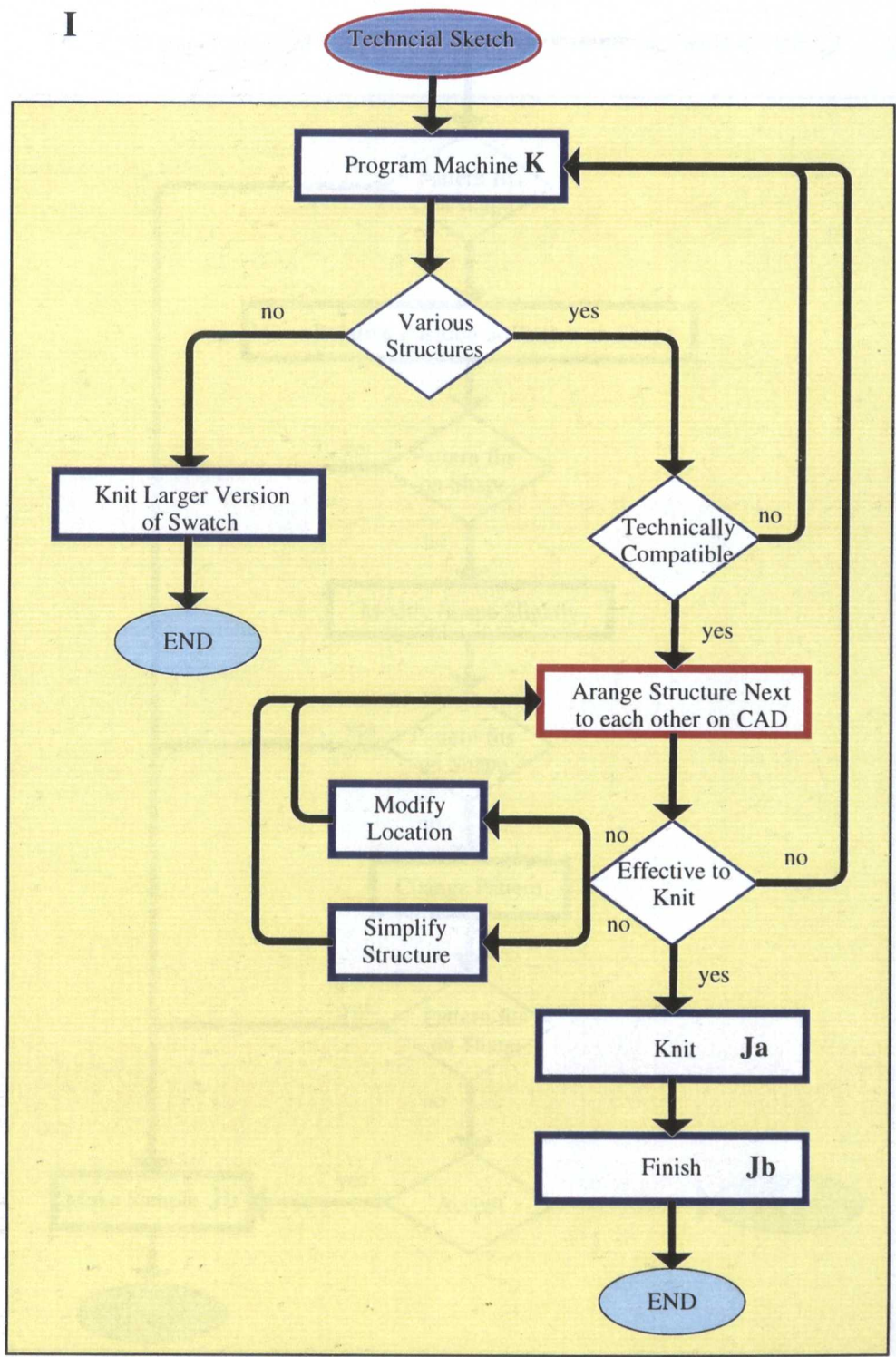


Figure A-9. Creation of Fabric Samples

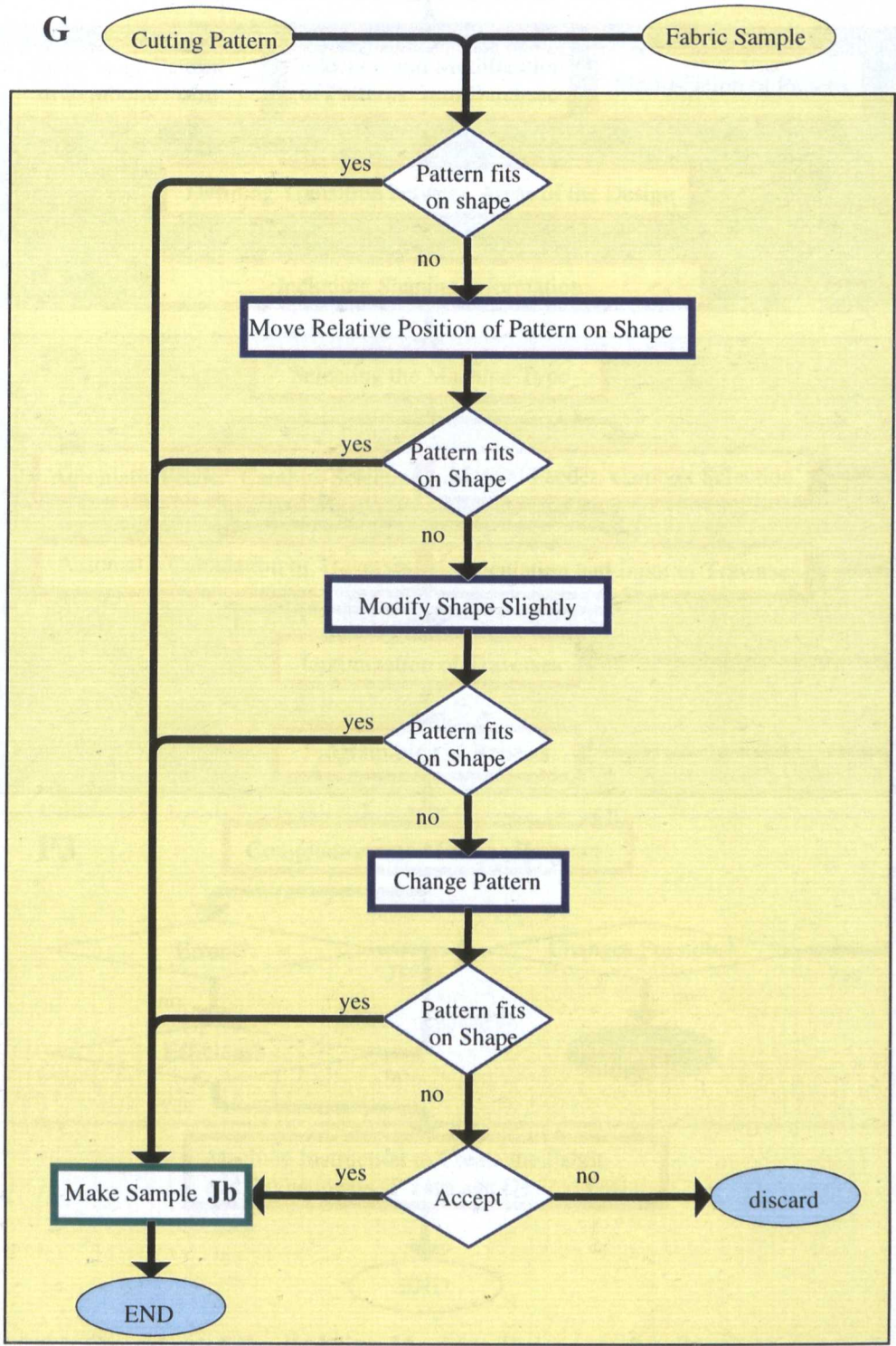


Figure A-10. Pattern Placing

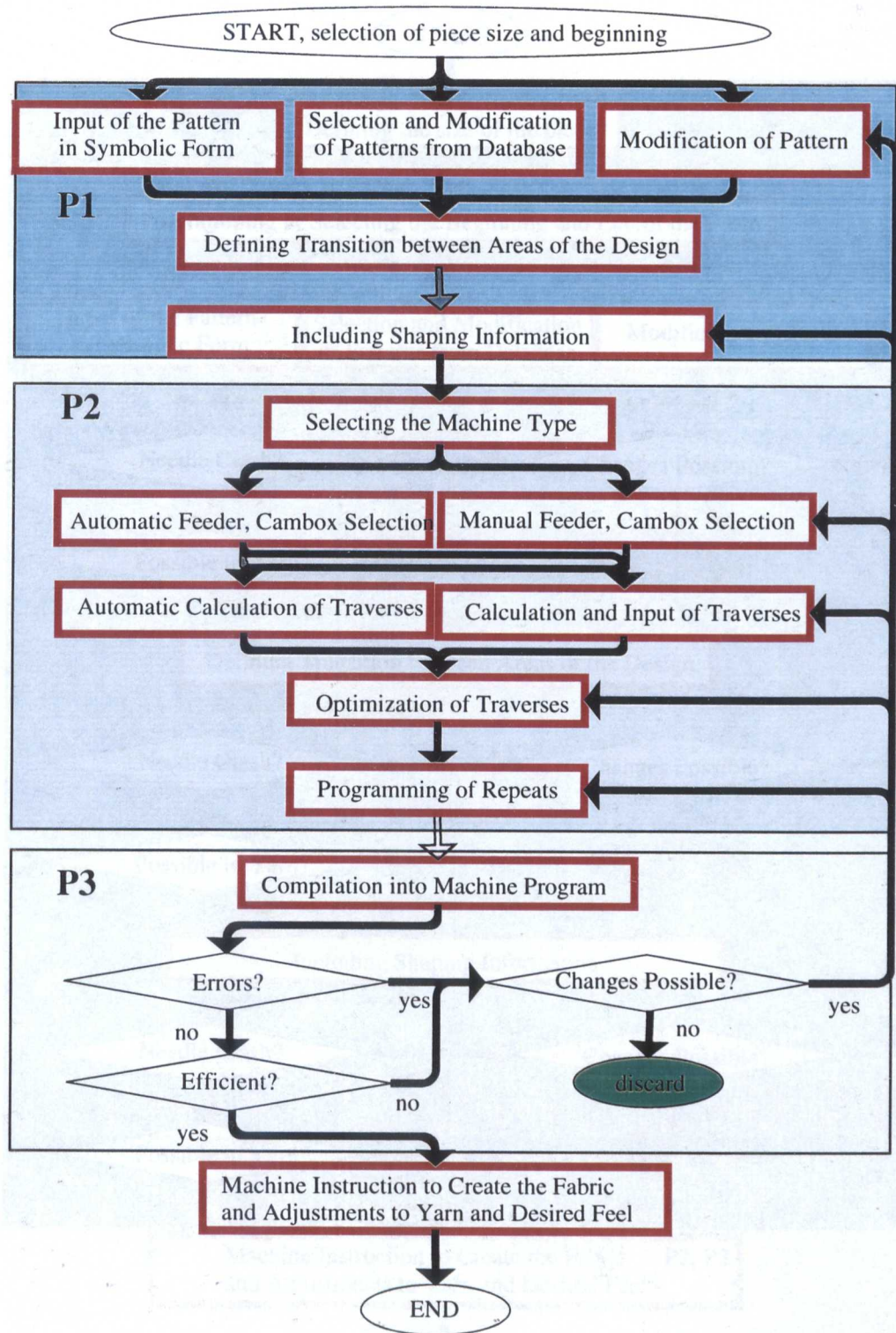


Figure A-11. Overview of the Knitting Machine Programming Process

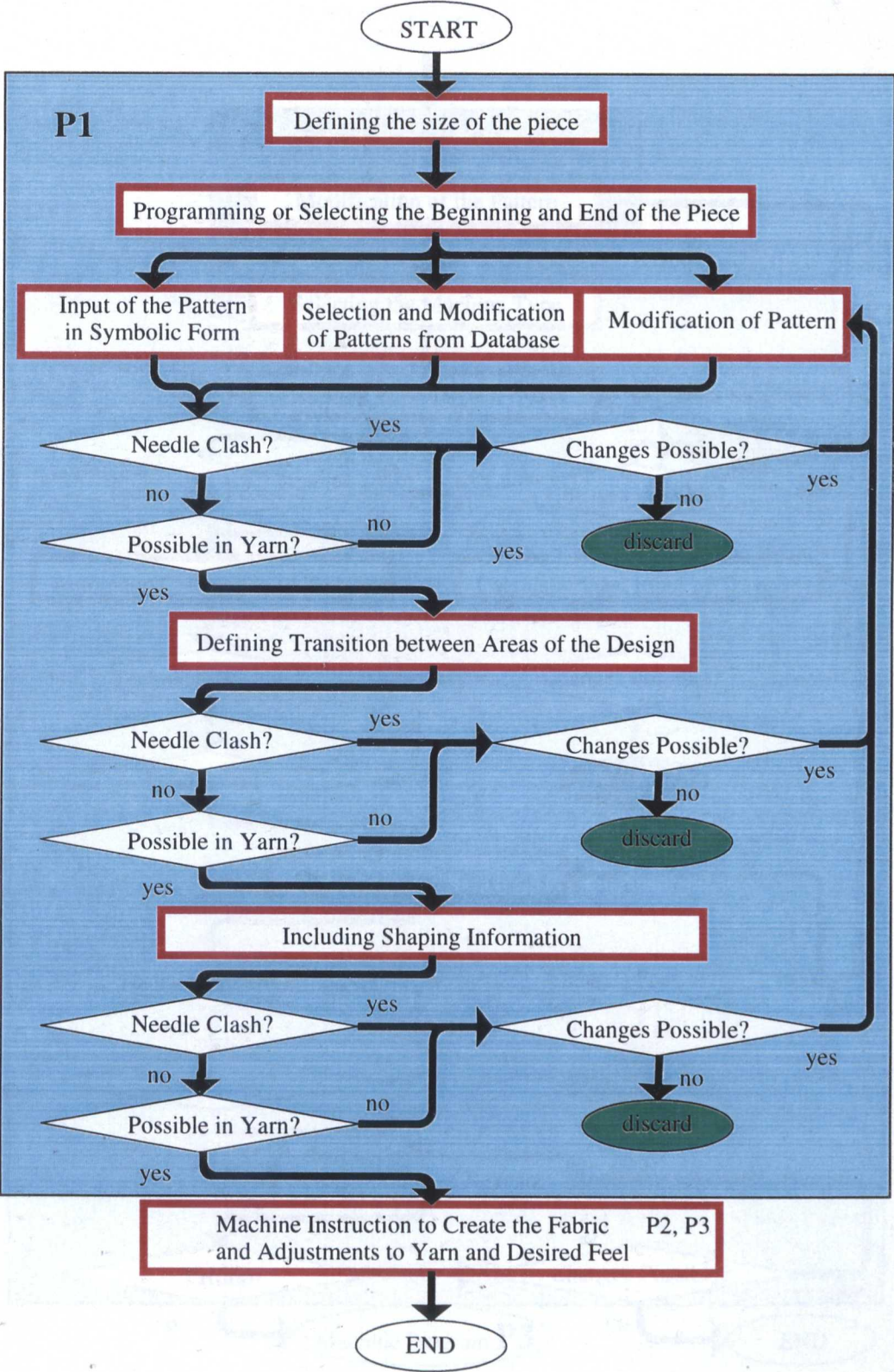


Figure A-12. Programming the Jacquard

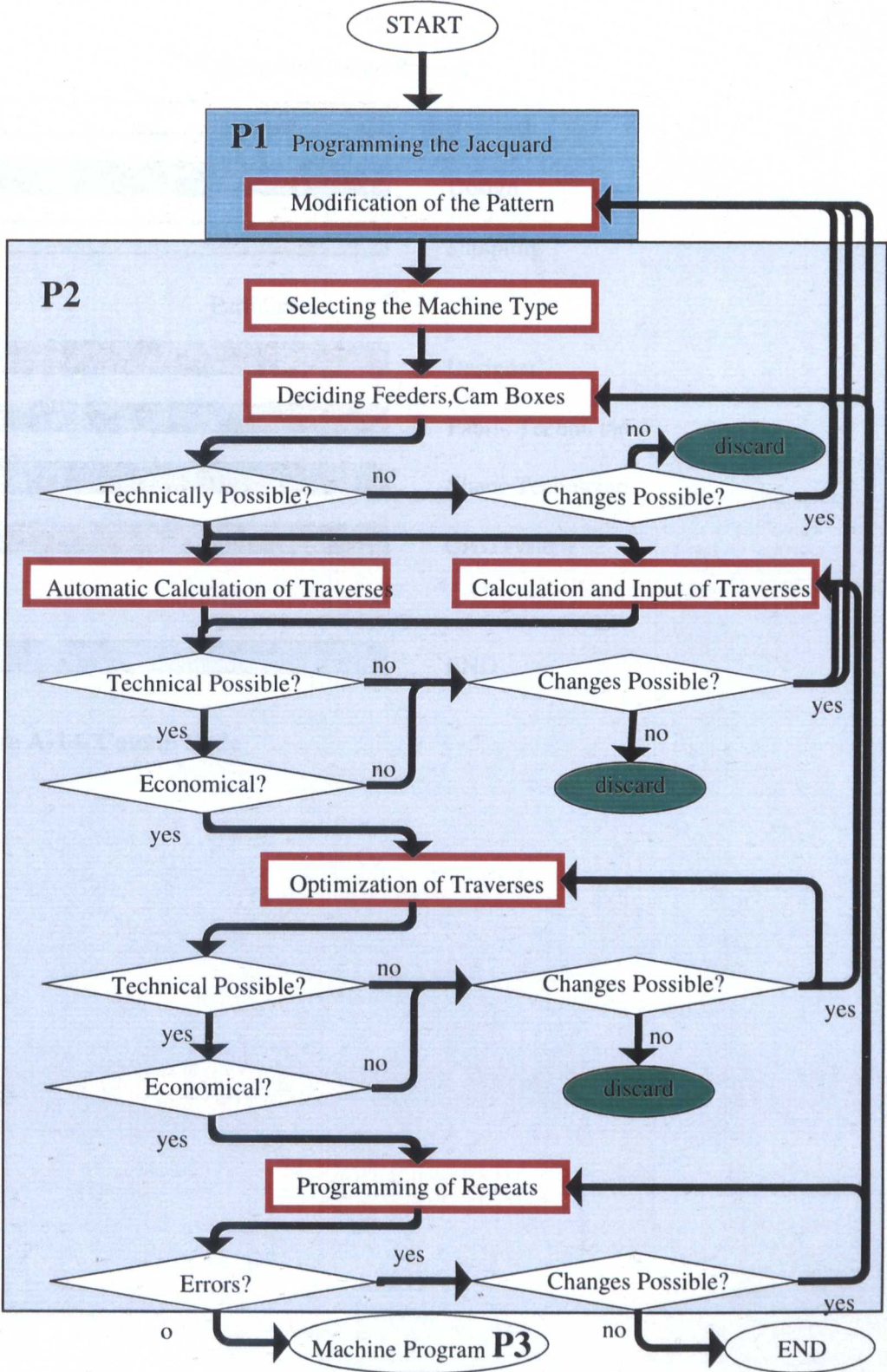


Figure A-13. Machine Specific Instructions

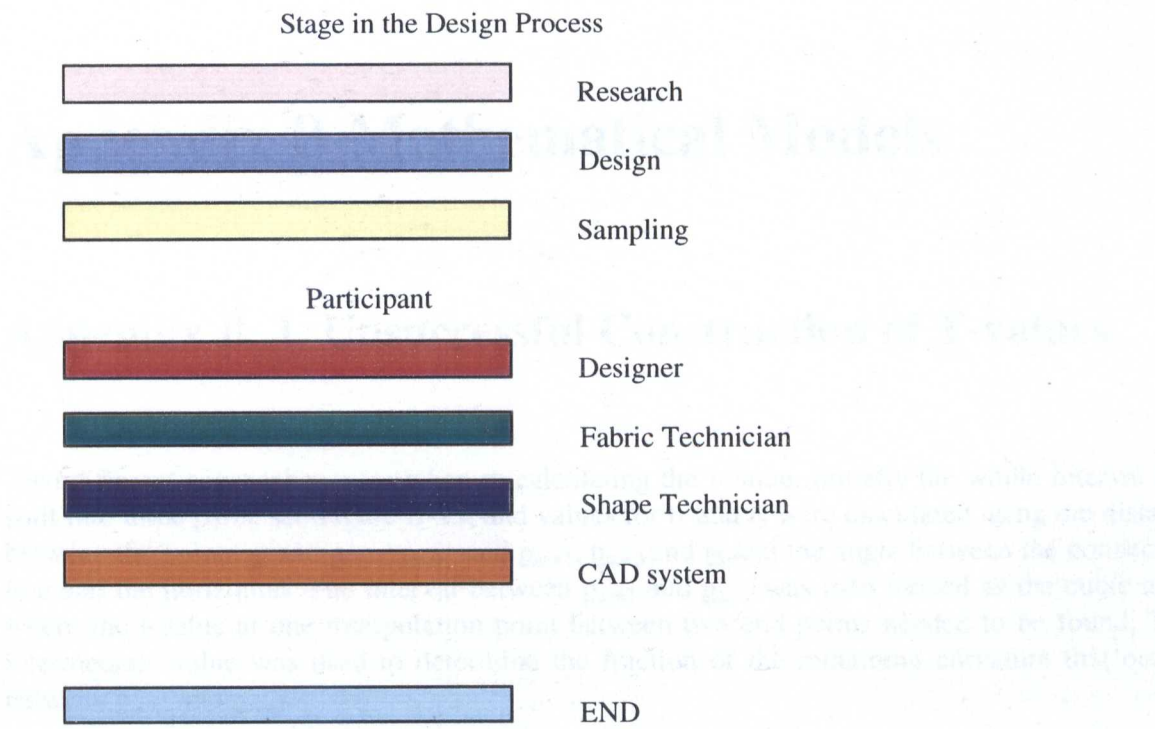


Figure A-14. Colour Code

Appendix B Mathematical Models

Appendix B .1. Unsuccessful Construction of T-values

Two different approaches were taken to calculating the t-value. Initially the whole interval was split into three parts, see Figure B-15, and values for t_1 and t_3 were calculated using the distance between the points r_0 and p_{aux1} , p_{aux1} and p_{aux3} , p_{aux3} and r_5 and the angle between the connection line and the horizontal. The interval between p_{aux1} and p_{aux3} was then treated as the cubic case, where the t-value at one interpolation point between two end points needed to be found. This intermediate value was used to determine the fraction of the remaining curvature that occurs between p_{aux1} and p_{aux2} .

In the second attempt, as illustrated in Figure B-15, treats the interval iteratively as the cubic with one interpolation point. The remaining sub-intervals are again treated as in the cubic case and the t-values are distributed proportionally.

Three Intervals

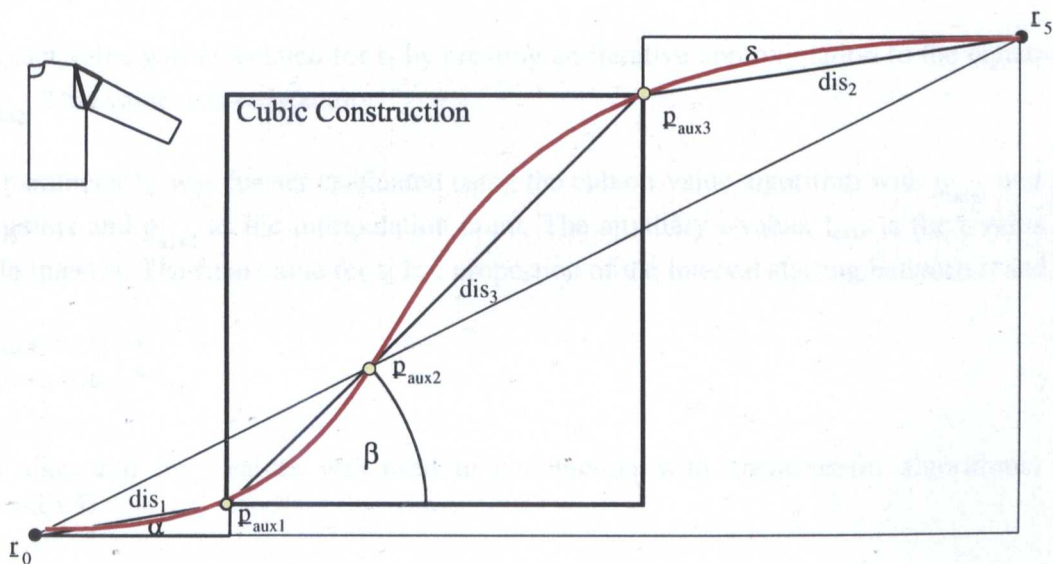


Figure B-15. Initial Construction of t-values for Quintic Bézier Curves

The proportions of the distances between the auxiliary points, p_{aux1} , p_{aux2} , p_{aux3} are calculated using Pythagoras' theorem:

The distances:

$$\begin{aligned} \text{dis}_1 &= \sqrt{(x_{\text{aux1}} - x_0)^2 + (y_{\text{aux1}} - y_0)^2} \\ \text{dis}_2 &= \sqrt{(x_{\text{aux1}} - x_3)^2 + (y_{\text{aux1}} - y_3)^2} \\ \text{dis}_3 &= \sqrt{(x_5 - x_{\text{aux3}})^2 + (y_5 - y_{\text{aux3}})^2} \end{aligned}$$

The proportions:

$$\text{dis} = \text{dis}_1 + \text{dis}_2 + \text{dis}_3$$

$$\text{disf}_1 = \text{dis}_1 / \text{dis}$$

$$\text{disf}_2 = \text{dis}_2 / \text{dis}$$

$$\text{disf}_3 = \text{dis}_3 / \text{dis}$$

$$\text{disf}_1 + \text{disf}_2 + \text{disf}_3 = 1$$

The tangent vectors:

$$\tan \alpha = (y_{\text{aux1}} - y_0) / (x_{\text{aux1}} - x_0)$$

$$\tan \beta = (y_{\text{aux3}} - y_{\text{aux1}}) / (x_{\text{aux3}} - x_{\text{aux1}})$$

$$\tan \delta = (y_5 - y_{\text{aux3}}) / (x_5 - x_{\text{aux3}})$$

The tangents and proportional lengths

$$\text{base} = \tan \alpha + \tan \beta + \tan \delta + 1$$

The t-values

$$t_1 = (\text{disf}_1 + \tan \alpha) / \text{base}$$

$$t_3 = (\text{base} - \text{disf}_3 - \tan \delta) / \text{base}$$

An exact value was calculated for t_2 by creating an iterative approximation to the equation, $r(t_2) = p_{\text{aux2}}$. This value was satisfactory.

The parameter t_2 was further calculated using the cubic t-value algorithm with p_{aux1} and p_{aux3} as end points and p_{aux2} as the interpolation point. The auxiliary t-value, t_{aux} , is the t-value for the whole interval. The final value for t_2 is a proportion of the interval starting between t_1 and t_3 .

$$t_{\text{rest}} = 1 - t_1 - t_3$$

$$t_2 = t_1 + t_{\text{rest}} * t_{\text{aux}}$$

This algorithm for t-values was used in conjunction with unsuccessful algorithms; see Appendix B.

Appendix B .2. Failed Attempts of Quintic Curves

A quintic Bézier Curve has the form:

$$r(t) = (1-t)^5 \underline{r}_0 + 5(1-t)^4 t \underline{r}_1 + 10(1-t)^3 t^2 \underline{r}_2 + 10(1-t)^2 t^3 \underline{r}_3 + 5(1-t)t^4 \underline{r}_4 + t^5 \underline{r}_5$$

To fully describe a quintic Bézier Curve under the conditions stated above the following unknowns needed to be solved:

- μ and λ the length of the end tangent vectors
- t_1, t_2, t_3 the t-values of the Bézier Curve at the interpolation points
- r_2 and r_3 the two remaining Bézier Points, with the coordinates x_2, y_2, x_3, y_3 ,

For a quintic curve Equation 14 can be expanded to:

$$\begin{aligned} x_{aux1} = & (1-t_1)^5 x_0 + 5(1-t_1)^4 t_1 (x_0 + \mu) + 10(1-t_1)^3 t_1^2 x_2 + \\ & 10(1-t_1)^2 t_1^3 x_3 + 5(1-t_1)t_1^4 (x_5 - \lambda) + t_1^5 x_5 \end{aligned} \quad (e 14.1)$$

$$\begin{aligned} y_{aux1} = & (1-t_1)^5 y_0 + 5(1-t_1)^4 t_1 y_0 + 10(1-t_1)^3 t_1^2 y_2 + \\ & 10(1-t_1)^2 t_1^3 y_3 + 5(1-t_1)t_1^4 y_5 + t_1^5 y_5 \end{aligned} \quad (e 14.2)$$

$$\begin{aligned} x_{aux2} = & (1-t_2)^5 x_0 + 5(1-t_2)^4 t_2 (x_0 + \mu) + 10(1-t_2)^3 t_2^2 x_2 + \\ & 10(1-t_2)^2 t_2^3 x_3 + 5(1-t_2)t_2^4 (x_5 - \lambda) + t_2^5 x_5 \end{aligned} \quad (e 14.3)$$

$$\begin{aligned} y_{aux2} = & (1-t_2)^5 y_0 + 5(1-t_2)^4 t_2 y_0 + 10(1-t_2)^3 t_2^2 y_2 + \\ & 10(1-t_2)^2 t_2^3 y_3 + 5(1-t_2)t_2^4 y_5 + t_2^5 y_5 \end{aligned} \quad (e 14.4)$$

$$\begin{aligned} x_{aux3} = & (1-t_3)^5 x_0 + 5(1-t_3)^4 t_3 (x_0 + \mu) + 10(1-t_3)^3 t_3^2 x_2 + \\ & 10(1-t_3)^2 t_3^3 x_3 + 5(1-t_3)t_3^4 (x_5 - \lambda) + t_3^5 x_5 \end{aligned} \quad (e 14.5)$$

$$\begin{aligned} y_{aux3} = & (1-t_3)^5 y_0 + 5(1-t_3)^4 t_3 y_0 + 10(1-t_3)^3 t_3^2 y_2 + \\ & 10(1-t_3)^2 t_3^3 y_3 + 5(1-t_3)t_3^4 y_5 + t_3^5 y_5 \end{aligned} \quad (e 14.6)$$

Equation B-14. Quintic Conditions

Appendix B .2.1. Calculation of $\mu, \lambda, t_2, r_2, r_3$ using Curvature

Appendix B .2.1.1.Exact solution of t_2

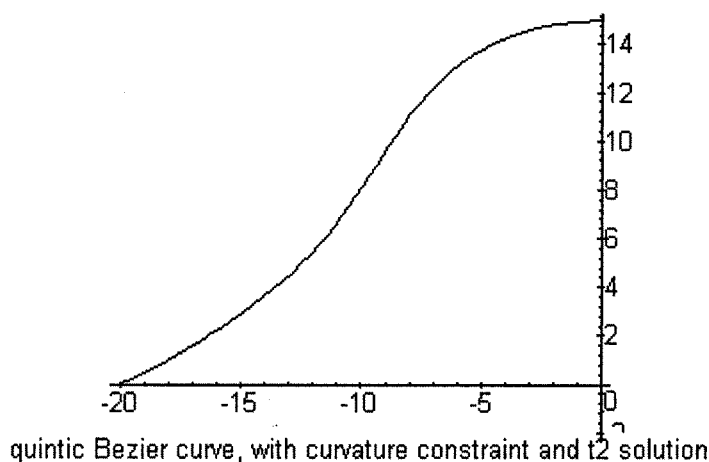


Figure B-16. quintic Bézier curve, with curvature constraint and t_2 solution

The values of t_1 and t_3 have been calculated by geometric approximation, as described in section B.1. The three interpolation points and the curvature condition were used to calculate μ , λ , t_2 , r_2 , r_3 . Equation (e 14.2) and (e 14.6) have been solved to gain y_2 , y_3 . These values have been substituted into (e 14.4) to calculate an exact value of t_2 . Equations (e 14.1), (e 14.3), (e 14.5) for the x- coordinate of the interpolation points and the curvature condition Equation 9 has been used to calculate the remaining unknowns.

Figure B-16 shows this curve with a value of $t_2 = -0.22$ as a solution to equation (e 14.4), which is outside the interval $t \in [0,1]$ for $r(t)$. For this particular input data the resulting curve would have constituted a legal solution, but the beginning of the curve appears very steep and would lead to fabric gathering under the arms

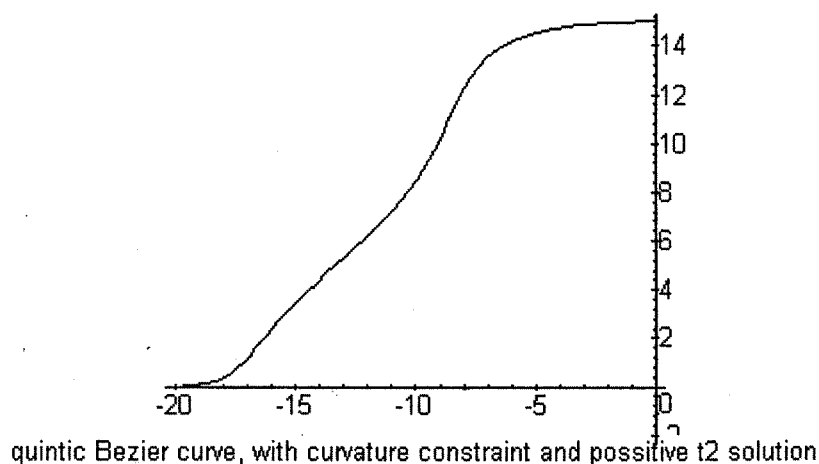


Figure B-17. quintic Bézier curve with curvature constraint and positive t_2 solution

Figure B-4 shows the next solution attempt when a solution to equation (e 14.4) was sought within in the legal interval. This curve does clearly not fulfil condition 12, as it has more than one point of inflexion.

Exact solution of t_2 with geometric approximation over whole over split interval for t_1 and t_3 expressed in terms of t_2

In the next attempt the initial values of t_{1aux} and t_{3aux} have been calculation by geometric approximation with the split interval algorithm, as described in section 6.5.2. The values of t_1 and t_3 were defined as:

$$t_1 = t_{1aux} * t_2$$

$$t_3 = t_2 + t_{3aux} * (1 - t_2)$$

Equations (e 14.2), (e 14.2) and (e 14.6) have been solved to gain t_2, y_2, y_3 . For the given end point no set of values satisfied the equation in the legal range of value:

$$t_2 \in [0,1], y_2 > 0 \text{ and } y_3 > 0$$

Geometric approximation of t_1, t_2 and t_3 in sub- interval

The values of t_2, t_{1aux} and t_{3aux} have been calculation by geometric approximation with the split interval algorithm, as described in section 6.2.3.2. As a solution for the variable t_2 was no longer required. Condition (e 14.4), the y value of the interpolation point p_{aux2} has been dropped. All other conditions remained the same as in the previous solution attempts.

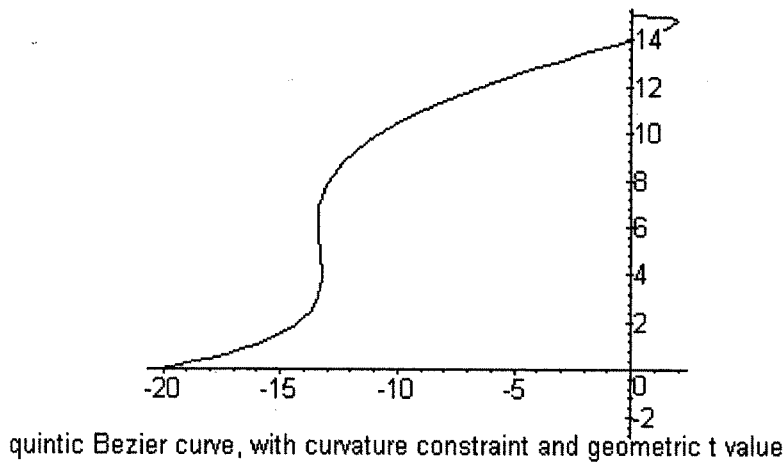


Figure B-18. Quintic Bézier curve with curvature constraint and geometric t value

Figure B-5 shows that the curve is not monotonic and exceeded the boundary of regular solutions of the curve, given by the end points. If the input data defined an overall shallower curve, then this solution produced many more oscillations.

Appendix B .2.1.2.Calculation of μ, λ, r_2, r_3 using tangent constraints

Geometric approximation of t_1 and t_2 , calculation of β using tangent constraints and curvature, using p_{aux1} and p_{aux2} :

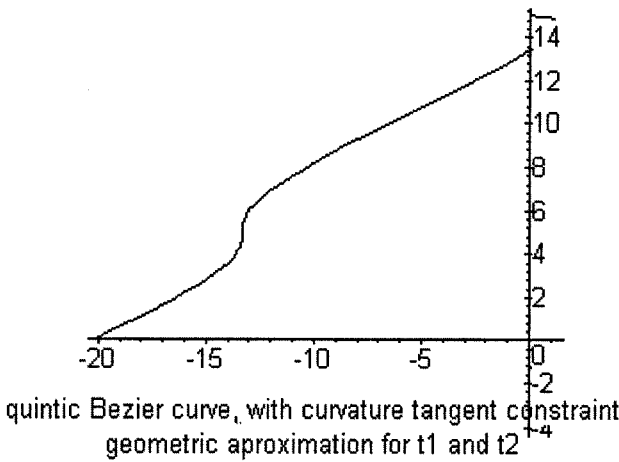


Figure B-19. quintic Bézier curve, with curvature tangent constraint and geometric approximation for t_1 and t_2

The tangent constraints on the curve at $r(t_2) = p_{aux2}$ were used to replace the third interpolation point $r(t_3) = p_{aux3}$. By solving equations (e 14.1), (e 14.3) and (e 14.5) μ , x_2 , x_3 were gained. Solving (e 14.2), (e 14.4) and (e 14.6) give values for β , y_2 , y_3 . The curvature condition, section 6.3.6.1. was used to solve λ .

Figure B-6 shows clearly that this curve is not monotonic. The solution of the system of equations provided negative values for λ and μ . With the present set of constraints it is not possible to ensure that p_{aux2} is the only point of inflexion.

Geometric approximation of t_1 and t_2 , calculation of β using tangent constraints and curvature, using p_{aux2} and p_{aux3} :

The attempt is exactly the same but using p_{aux3} in state of p_{aux1} .

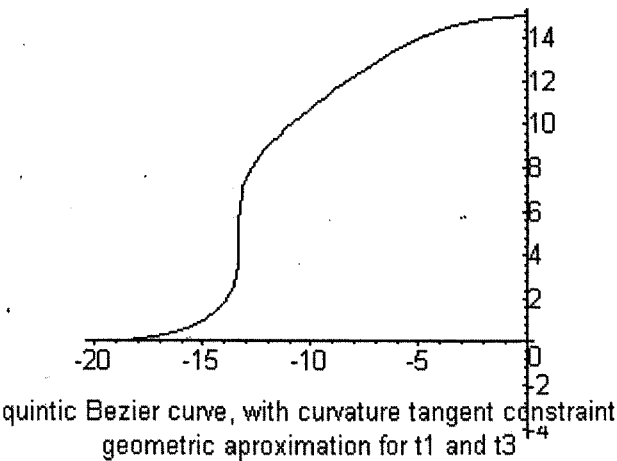


Figure B-20. quintic Bézier curve with curvature and tangent constraints and geometric approximation for t_3 and t_2

Appendix B .2.1.3. Solutions for $t_2, t_3, x_2, x_3, y_2, y_3,$

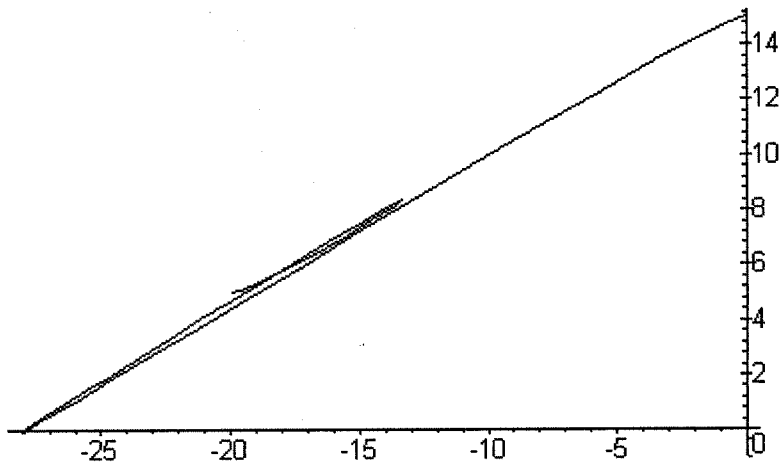


Figure B-21. Quintic Bézier Curve with set tangent vectors and calculated t value

In this solution attempt μ, λ, β were set of default values: $\mu = \lambda = 3.0$ and $\beta = 1$, was solved for $t_2, t_3, x_2, x_3, y_2, y_3$. The only solution of the equation system in $t_2, t_3 \in [0,1]$ had $t_2 > t_3$.

Figure B-21. shows this curve.

Appendix B .3.Sleeve Crown Curves of Different Orders

Appendix B .3.1.Quartic Curves

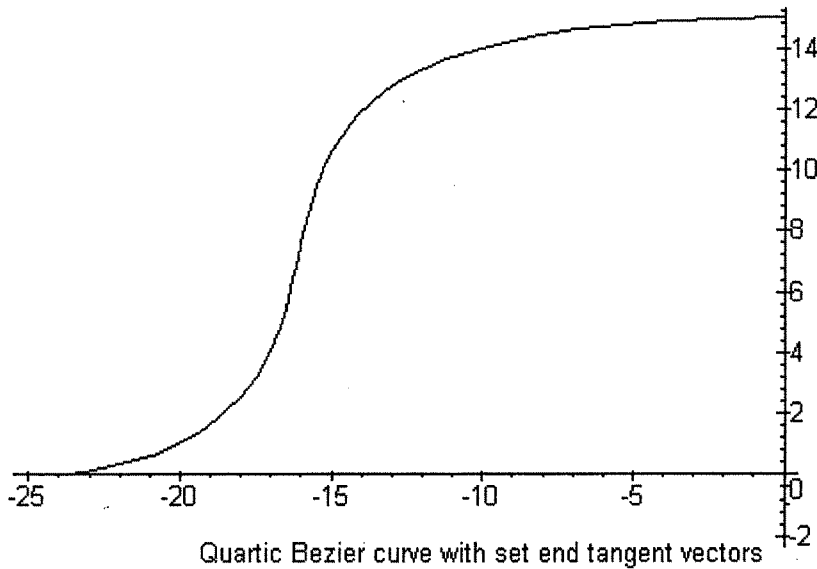


Figure B-22. Quartic Bézier Curve with Set End Tangents

A quartic Bézier has the form by writing equation 1 with $N = 4$:

$$\mathbf{r}(t) = (1-t)^4 \mathbf{r}_0 + 4(1-t)^3 t \mathbf{r}_1 + 6(1-t)^2 t^2 \mathbf{r}_2 + 4(1-t)t^3 \mathbf{r}_3 + t^4 \mathbf{r}_4 \quad (\text{qr.1})$$

This curve uses one interpolation point and set end tangent vectors. $\tan \alpha$ is calculated using Equation 15. Satisfactory curves have been reached with the following values of μ and λ :

$$\mu = 1/2 * (x_4 - x_0) * \tan \alpha$$

$$\lambda = (x_4 - x_0)$$

\mathbf{p}_{aux2} is used as the interpolation point.

$$\mathbf{p}_{\text{aux2}} = \mathbf{r}(t_2)$$

\mathbf{r}_2 is calculated by substituting the values for μ and λ Equation 15 and solving (qr.1) at the interpolation point.

Appendix B .3.2.Cubic Curve

For the general form of a cubic Bézier curve see Equation 2.

All the curves in the construction diagrams, for example Figure 28, are drawn using cubic Bézier curves as they are offered by *Professional Draw*TM. The curves in the diagrams are manually edited to go through the interpolation points, especially p_{aux2} . As the two end tangent vectors are parallel it is not possible to calculate the exact length of μ and λ to go through the control point. No interpolation point is required for cubic curves.

In this suggestions μ and λ are set to:

$$\mu = \frac{1}{2} * (x_3 - x_0)$$

$$\lambda = (x_3 - x_0)$$

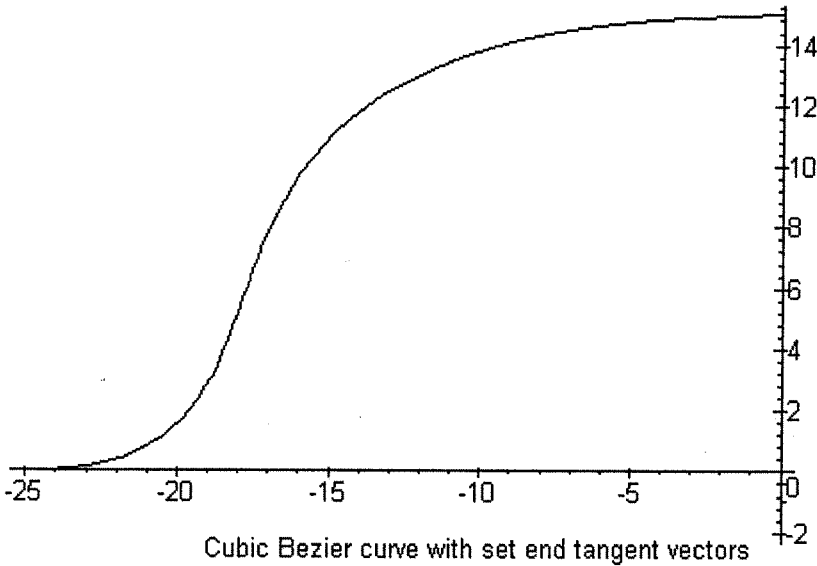


Figure B-23. Cubic Bézier curve with set end tangents

This curve is a satisfactory solution and easy to create. However the only degree of freedom is the length of the end tangent vectors. It is impossible to control the fullness of the curve purely by the length of the end tangent vectors. Therefore a simple cubic curve is not sufficient to model the sleeve crown curve and edit it.

Appendix B .3.3. Order 6 Curve

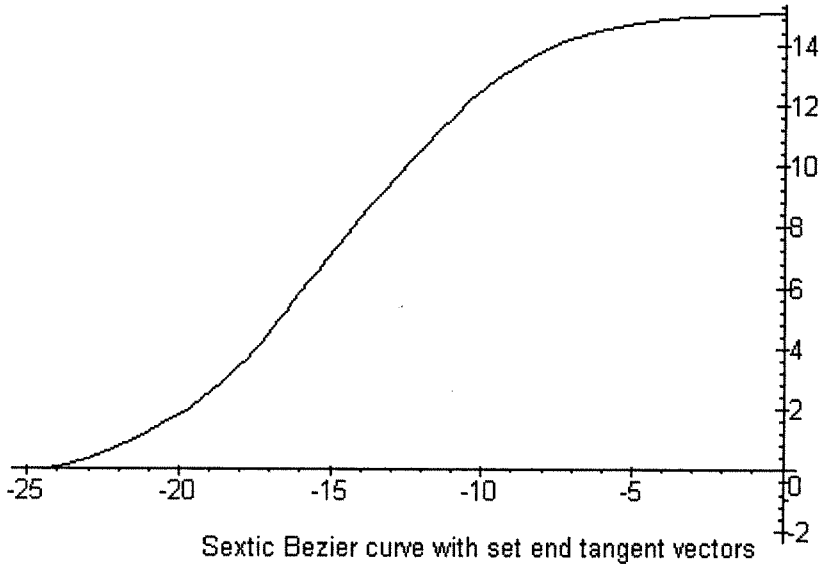


Figure B-24 Order 6 Bézier Curve with set end tangent vectors

An order 6 Bézier curve has the general form by expanding Equation 1 for $n = 6$

$$\mathbf{r}(t) = (1-t)^6 \mathbf{r}_0 + 6(1-t)^5 t \mathbf{r}_1 + 15(1-t)^4 t^2 \mathbf{r}_2 + 20(1-t)^3 t^3 \mathbf{r}_3 + 15(1-t)^2 t^4 \mathbf{r}_4 + 6(1-t)t^5 \mathbf{r}_5 + t^6 \mathbf{r}_6$$

The values of λ and μ are set

$$\tan \alpha = (y_6 - y_0)/(x_6 - x_0). \quad (\text{sss.1})$$

Satisfactory curves have been reached with these values of μ and λ :

$$\mu = 1/3 * (x_6 - x_0) * \tan \alpha \quad (\text{sss.2})$$

$$\lambda = (x_6 - x_0) * \tan \alpha \quad (\text{sss.3})$$

When the value λ and μ are known $\mathbf{r}_2, \mathbf{r}_3, \mathbf{r}_4$ are the only unknowns. They can be solved using three interpolation points. The t -values are calculated using the iterative partition of the whole interval into subintervals with one interpolation point, as explained in section 6.5.2. The solution appeared more visually appealing when the interpolation point \mathbf{p}_{aux3} was shifted slightly. Using the interpolation points $\mathbf{p}_{\text{aux1}}, \mathbf{p}_{\text{aux2}},$ and $\mathbf{p}_{\text{aux3}}, \mathbf{r}_2, \mathbf{r}_3, \mathbf{r}_4,$ can be obtained by solving the order 6 form of Equation B-1.

Appendix C Garment Shapes

A general introduction to the construction of garment shapes is given in section 6.1.

In the following description the different garments are divided by the type of sleeve they have. Different side lines and neck lines are discussed in the general section.

Most sleeves are also constructed from half cutting patterns. Traditionally the left half of the sleeve is represented in the cutting pattern. Raglan sleeves are always asymmetrical and have full size cutting patterns.

Appendix C .1. Input Measurements

The designers provide the system with a set of input measurements. The following set is a very basic list, used in a variety of companies (see Figure 4) shows the input measurements on a basic body of a set in sleeve garment. There are no standard names for the different measurements. Alternative names are given, but the description of the coordinate location uses the name in bold which are introduced here. *Metric Pattern Cutting* (Alrich 1987) has a table on page 28, explaining how the measurements are taken.

Length, Front Length: The length of the garment from the shoulder to the bottom of the waist band. For clarity the waist band has been omitted in the example shapes. It could easily be added. The length measurement includes the waist band, unless specified otherwise. Normally the length is measured from the middle of the shoulder seam over the bust to the bottom of the waist band. As a simplification the length is taken here from the Neck Point

Chest Width, Bust: Width of the garment round the chest under the arms. This measurement is normally taken round the whole chest and needs to be quartered for a normal cutting pattern.

Hip Width, Bottom Width, Welt Width: Measurement taken round the whole garment at the bottom. If the garment has a welt, then the hip measurement is above the welt and the welt measurement gives the width of the garment at the bottom. This and needs to be quartered for a normal cutting pattern.

Waist Width: The measurement round the garment at the waist. This measurement is missing, unless the garment is shaped at the waist. This and needs to be quartered for a normal cutting pattern.

Across Back, Across Front: The measurement above the bust between the end points of the shoulders taken about 10 cm below the shoulder. This and needs to be halved for a normal cutting pattern.

Back Neck Width, Back Neck Seam to Seam: Straight measurement between the right and left neck points. This needs to be halved for a cutting pattern.

Shoulder Width: Shoulder: The horizontal distance between the Neck Point and the Shoulder Point.

Shoulder Drop: The depth of the shoulder slope. The vertical measurement between the Neck Point and the Shoulder Point.

Back Neck Drop, Back Neck Depth: The depth of the neck line curve at the back.

Front Neck Drop, Front Neck Depth, Neck Depth: The depth of the neckline at the front.

Armhole Depth: The vertical distance between the Shoulder Point and the Underarm Point.

Depth of the Armhole Curve: Normally a default value or a fraction of the Armhole Depth.

Sleeve Construction Line: The diagonal connection line between the Underarm Point and the Shoulder Point.

Shoulder to Waist: A standard value measured from the shoulder over the bust to the waist. Values can be found in British Standard Table. Occasionally this value is defined by the designer, if the garment gathers and falls over the welt.

Sleeve length: The whole length of the garment from the top of the sleeve crown to the bottom of the sleeve from the Sleeve Crown Top Point to the Central Cuff Point.

Sleeve Crown Height: The measurement from the Sleeve Centre Point to the Sleeve Crown Top Point.

Sleeve Widest: The widest measurement of the sleeve. Ordinarily this is the measurement before the beginning of the sleeve crown. This measurement needs to be halved for a normal sleeve.

Underarm Measurement: The measurement from the Sleeve Widest Point to the Cuff Point. Normally this is taken as the diagonal measurement between those two points, but in some companies it can also be just the vertical measurement.

Cuff Width: The measurement round the cuff, which needs to be halved for a normal sleeve.

Elbow Width: The measurement round the sleeve at the height of the elbow. This measurement is optional. This measurement needs to be halved for a normal sleeve.

Appendix C .2.General Co-ordinates

Figure 51. shows the cutting pattern for a basic body shape. Refer to this figure to see an overview of the cutting pattern. The cutting patterns of a round neck garment with set in sleeves are used in tailoring as the foundation for all other constructions and is used here also as an illustration for the construction of side and neck co-ordinates. Input measurements are in bold, point names are underlined.

Appendix C .2.1.Neck Points

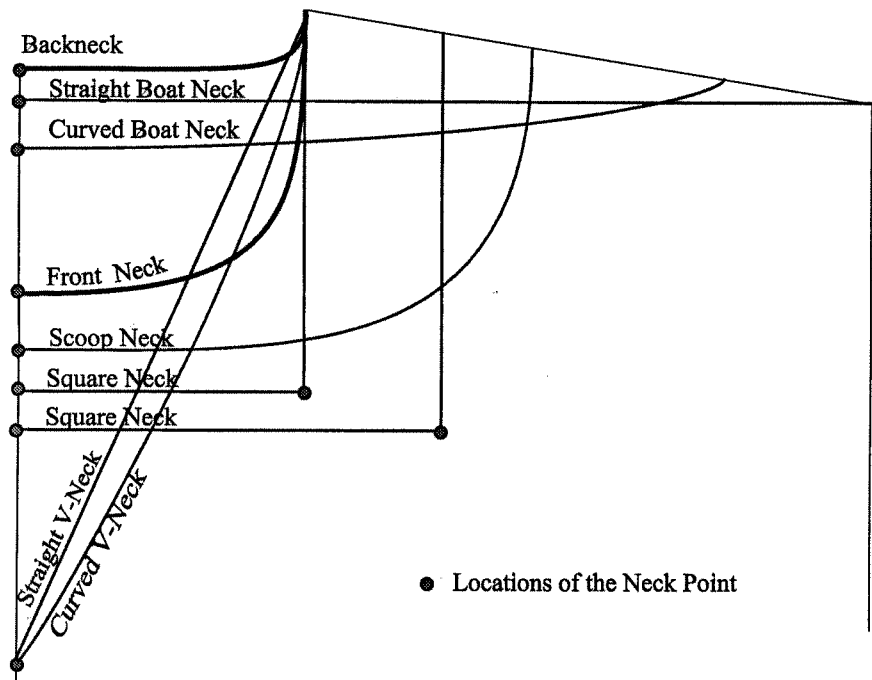


Figure C-1. Locations of the Neck Point

The construction of most garments begins from the neck down wards:

At the Neck Point , P_{neck} , the shoulder seam and the necklines meet. It is the end of the front and the back neck line curve. The location of this point is moved along the shoulder seam for wider neck lines.

$$x_{neck} = 1/2 \text{ Back Neck Width}$$

$$y_{neck} = \text{Length}$$

Back Neck Point $P_{backneck}$ is the deepest point of the back neck line in the middle of the garment. This value is often a default value used for most garments in the company and not defined by the user.

$$x_{backneck} = 0$$

$$y_{neckpoint} = y_{neckpoint} - \text{Back Neck Drop}$$

Front Neck Point $P_{frontneck}$ is the deepest point of the front neck line in the middle of the garment. The location of this point does not only define the traditional round neck, which is close to the neck, but also all other curved necklines, such as scoop necks or polo necks. The point also defines the tip V-necks. For square neckline this point can be moved inwards from the centre line of the garment. Figure C-1 shows the location of the Neck Point in various types of neck lines.

$$x_{frontneck} = 0$$

$$y_{frontneck} = y_{neckpoint} - \text{Front Neck Drop}$$

The construction of the auxiliary point for the neck lines is in section 6.2.3.1. The default values used in this implementation is 2.0 cm and 0.6 cm inwards on the construction

diagonal for the Front Neck Interpolation Point and the Back Neck Interpolation Point respectively.

Appendix C .2.2. Shoulder Point

The Shoulder Point P_{shoulder} marks the end of the shoulder seam where the two body pieces meet with the sleeve. The length of the defined shoulder measurement is not given as the length of the actual shoulder seam line, but the length of the connection line between the Neck Point and the Shoulder Point, see Figure C-2. The Shoulder Point is either defined as a shoulder drop and the across back measurement, or as the shoulder width measurement and the shoulder drop. In knitwear it is generally true, that:

Across Back = $\frac{1}{2}$ Back Neck Width + Shoulder Width

In tailoring however the armhole can be curved inwards and the two measurements indicate how much this curve bends.

$x_{\text{shoulder}} = \text{across back} / 2$

$y_{\text{shoulder}} = y_{\text{neckpoint}} - \text{shoulder drop}$

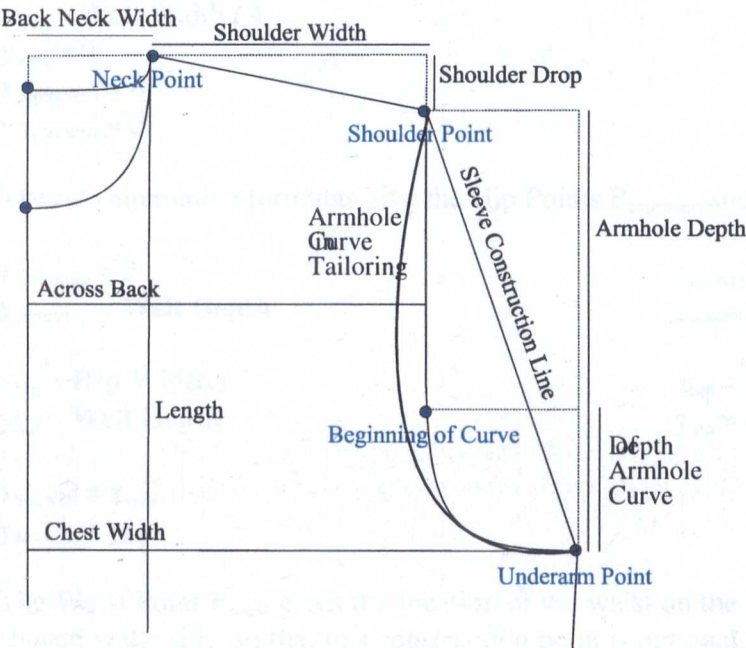


Figure C-2. Shoulder Point and Armhole Construction

Appendix C .2.3. Side Points

Not all garments have waist bands. Currently tunics are fashionable without welts. In this case the Hip Point P_{hip} and the Welt Point P_{welt} coincide and are referred to as the Hip Point; and similarly for the central points. The length is the length of the garment including the welt. For clarity the welts are omitted in all further examples.

Figure C-3 shows a part of a typical cutting pattern with a welt. The welt is normally made from rip fabric which stretches. The welts are knitted onto the main fabric and are stretched

out to the width of the hip point for cutting. The welt width on the cutting pattern indicates the stretchability of the rip fabric. The welt is drawn onto a cutting pattern to show its overall length and give a guideline where to start cutting the rip in the unstretched state.

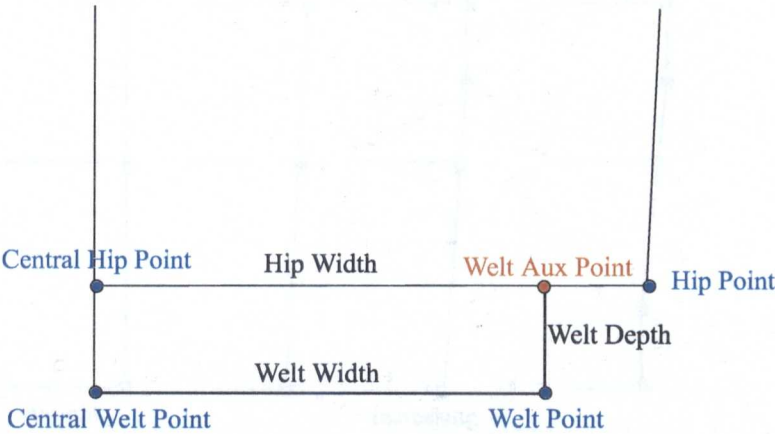


Figure C-3. Cutting Pattern Representation of a Welt

Welt Points

$$\begin{aligned}x_{\text{welt}} &= \text{Welt Width} / 4 \\y_{\text{welt}} &= 0 \\x_{\text{centrewelt}} &= 0 \\y_{\text{centrewelt}} &= 0\end{aligned}$$

The two alternative formulas give the Hip Points $P_{\text{centrehip}}$ and P_{hip} with and without welt.

$$\begin{aligned}x_{\text{centrehip}} &= 0 \\y_{\text{centrehip}} &= \text{Welt Depth} \\x_{\text{hip}} &= \text{Hip Width} / 4 \\y_{\text{hip}} &= \text{Welt Depth} \\x_{\text{auxwelt}} &= x_{\text{welt}} \\y_{\text{auxwelt}} &= y_{\text{hip}}\end{aligned}$$

$$\begin{aligned}x_{\text{centrehip}} &= 0 \\y_{\text{centrehip}} &= 0 \\x_{\text{hip}} &= \text{Hip Width} / 4 \\y_{\text{hip}} &= 0\end{aligned}$$

The Waist Point P_{waist} gives the location of the waist on the garment. Many garments are not shaped at the side, so that this construction point is optional. The industrial example Figure 4 do not have a slot to define this values.

$$\begin{aligned}x_{\text{waist}} &= \text{Waist Width} / 4 \\x_{\text{waist}} &= \text{Front Length} - \text{Shoulder to Waist}\end{aligned}$$

The Underarm Point P_{underarm} defines the beginning of the armhole for all types of sleeves.

$$\begin{aligned}x_{\text{underarm}} &= \text{Chest Width} / 4 \\y_{\text{underarm}} &= y_{\text{shoulder}} - \text{Armhole Depth}\end{aligned}$$

Figure C-4 and Figure C-5 show the most common sidelines that are currently used in knitwear design. Section 6.1.1. explains the need to avoid cutting across stitches at a very steep angle. So many garments have a straight piece before stitches are cut diagonally. The change of angle needs to be defined. In industrial practice the shape technicians work out the side lines when the cutting pattern in constructed without much input from the designers.

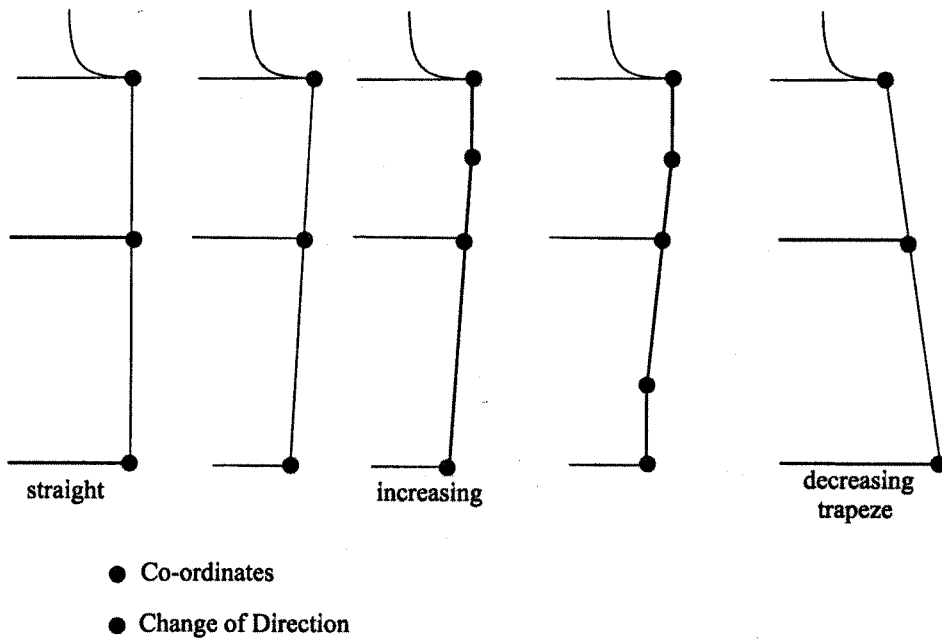


Figure C-4. Straight, Increasing and Decreasing Side Line

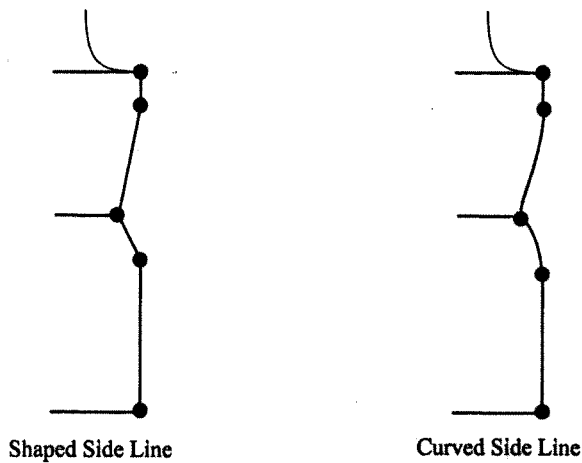


Figure C-5. Curved and Shaped Side Line

Two points P_{side1} and P_{side2} are required to mark the change of the angle of side line. The users can define the length of the straight pieces, **straightside1** and **straightside2**.

$$x_{side1} = x_{underarm}$$

$$y_{side1} = y_{underarm} - \text{straightside1}$$

$$x_{side2} = x_{hip}$$

$$y_{side2} = y_{hip} + \text{straightside2}$$

Appendix C .2.4. Lower Part of the Sleeves

The sleeve crown construction varies obviously for each type of sleeve, but the construction of the lower part of the sleeve remains the same. Figure C-6 shows the different sets of measurements that can be used to define a sleeve. It is a scaled down version Figure 23; the names of the measurements and points can be seen there. The construction line between the Shoulder Widest Point and the Sleeve Crown Top Point is the length of the diagonal between the underarm point and the shoulder point on the body. It is an implicit measurement, that is not given by the user. Industry normally uses two different modes to define the sleeve. In both cases the cuff width measurement is defined:

1. The underarm measurement and the sleeve widest measurement.
2. The length of the sleeve and the sleeve widest measurement.

The second construction depends on the exact shape of the sleeve crown. Only when major changes to the height of the sleeve crown occur, the underarm measurement is altered. The second definition method is more responsive to changes. The definition of the underarm measurement as a straight line as easier for the designer.

The third definition of sleeve, defining the underarm measurement or the sleeve length, the sleeve widest, the sleeve crown height and the construction line, is also used some times. It over defines the sleeve and can contain contradicting information. The definition is useful when a close sample has already been produced and additional measurement can confirm a new version. The following description of the construction of the sleeve co-ordinates is based on the first definition, which corresponds to the industrial example in Figure 4.

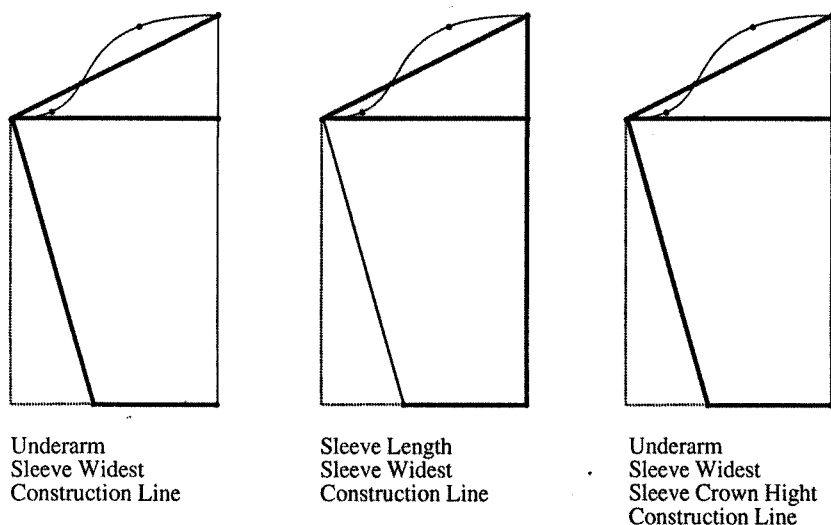


Figure C-6. Alternative Specifications of the Sleeve

The location of the sleeve points $P_{\text{sleeve widest}}$, $P_{\text{crown top}}$, $P_{\text{centresleeve}}$, P_{elbow} , P_{cuff} , $P_{\text{centrecuff}}$ can be seen in Figure 52. The sleeve as discussed here does not have a cuff. The pattern addition for a cuff is analogue to a welt on a body piece.

The sleeve widest point marks the beginning of the sleeve crown at the side.

$$P_{\text{sleeve widest}} = \text{sleeve widest} / 2$$

$$P_{\text{sleeve widest}} = 0$$

Cuff point P_{cuff} marks the beginning of the sleeve at the side at the beginning of the cuff. This point is taken as the end point of the underarm measurement. The y-coordinate is

constructed using Pythagoras theorem. In some companies the y-coordinate is taken straight as the defined underarm measurement. Designers' specifications seem to adapt to this use of the underarm measurement.

$$x_{\text{cuff}} = \text{Cuff Width} / 2$$

$$y_{\text{cuff}} = -\sqrt{\text{Underarm}^2 - (\text{Sleeve Widest} - \text{Cuff Width})^2}$$

A small number of garments have a specific measurement for the elbow, P_{elbow} . Only the width is defined. The distance between the wrist and the elbow is fixed through anatomy and therefore a default value.

$$x_{\text{elbow}} = \text{elbow width} / 2$$

$$y_{\text{elbow}} = y_{\text{cuff}} + \text{wrist to elbow}$$

The sleeve side line can have a similar shape as the body side lines, by being straight or trapeze or most commonly increasing. The same problems as for the body piece apply to the definition of auxiliary points.

Appendix C .2.5.Armhole for Set In Sleeves

The armhole for a set in sleeve consists of a straight part and a curved part which follows the body contour under the arm. The construction of the whole armhole requires three coordinates, P_{shoulder} , P_{underarm} and P_{armhole} . The armhole point, P_{armhole} , marks the beginning of the arm hole curve. The location of the point is important for the exact shape of the curve. It often constructed using a company default value, for example as 20 % of the armhole depth above the beginning of the armhole.

$$x_{\text{armhole}} = x_{\text{shoulder}}$$

$$y_{\text{armhole}} = y_{\text{shoulder}} - 0.8 * \text{armhole depth}$$

The auxiliary point for the construction of the armhole curve is constructed in exactly the same way as the auxiliary point of the construction of the neck curve. It is discussed in section 6.2.3.2. As the direction of the curve is different the signs need to be changed accordingly.

Appendix C .3.Sleeves

Appendix C .3.1.Set-In Sleeve

Figure C-7 shows the outline of a garment with Set-In Sleeves, as it is created by the equation solver. Figure 51 and Figure 52 shows the body and the whole sleeve with the construction triangle for the sleeve crown. The length of construction line is the diagonal between the Underarm Point and the Shoulder Point.

$$\text{Length of construction line} = \sqrt{(x_{\text{underarm}} - x_{\text{shoulder}})^2 - (y_{\text{underarm}} - y_{\text{shoulder}})^2}$$

The Sleeve Crown Top Point, $P_{\text{crown top}}$, is the highest point of the sleeve curve. For set-in sleeves it lies in the middle of the sleeve. As discussed in section 6.2.7.2. the height of this point can alter when the sleeve crown is adapted to have the correct length. Initially the point

is constructed by forming a rectangular triangle over the sleeve widest using the construction line as the hypotenuse of the triangle. An application of Pythagoras' theorem gives.

$$x_{\text{crown top}} = 0$$
$$y_{\text{crown top}} = \sqrt{\text{length_of_construction_line}^2 - \text{sleeve_widest}^2}$$

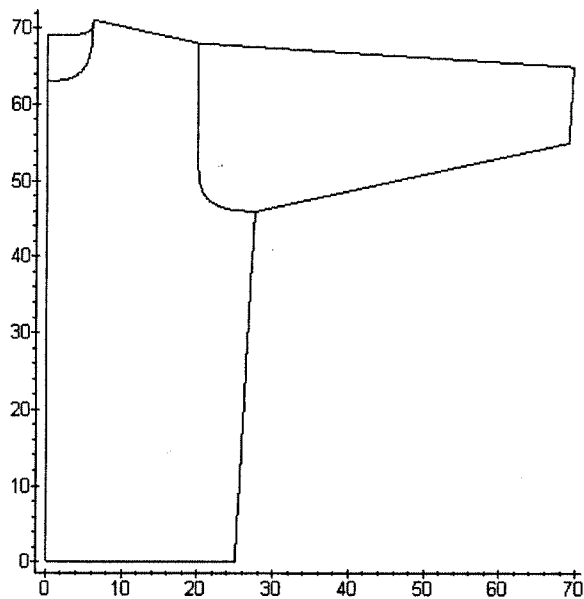


Figure C-7. Outline of a Garment with Set-In Sleeves

Appendix C .3.2.T-Sleeves

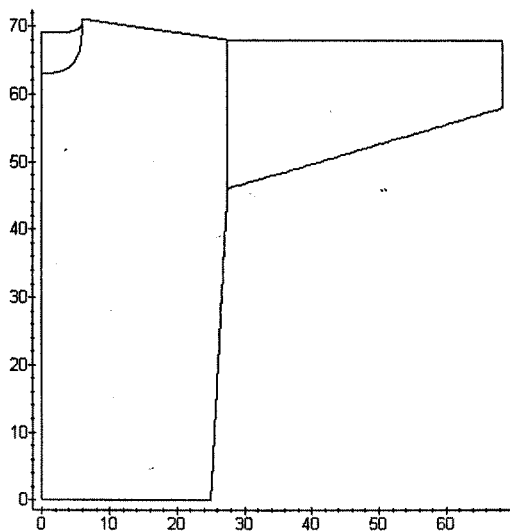


Figure C-8. Outline of a T-sleeve Garment

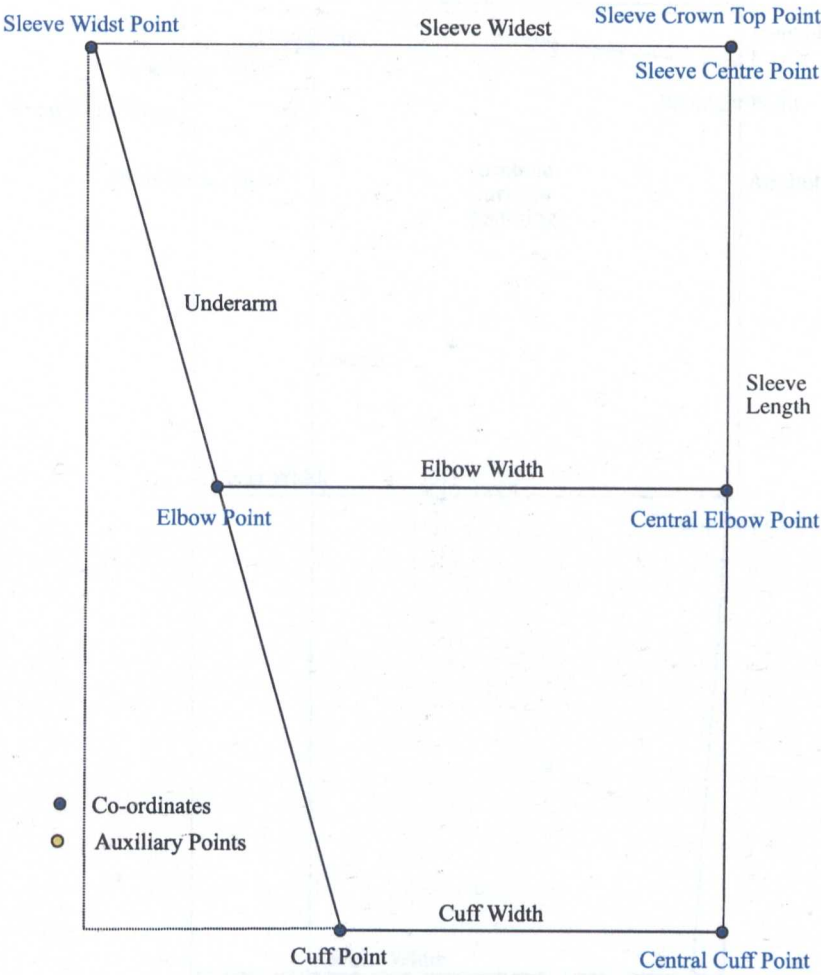


Figure C-9. T-sleeve

A T-sleeve garment is the simplest shape. Figure C-8 shows the outline of a T-sleeve Garment, Figure C-9 shows the sleeve and Figure C-10 shows the body. Instead of having a curved armhole and a curved sleeve crown both are straight lines. In the construction of a T-sleeve garment the Shoulder Point P_{shoulder} must have the same x-value as the Underarm Point P_{underarm} , all other points are the same as in a set-in sleeve garment.

$$x_{\text{shoulder}} = x_{\text{underarm}} = \text{chest width} / 4$$
$$y_{\text{shoulder}} = \text{length} - \text{shoulder drop}$$

The sleeve is completely straight at the top, so that the sleeve crown top point co-insides with the sleeve centre point, the origin of the co-ordinate system.

$$x_{\text{crown top}} = x_{\text{centre sleeve}} = 0$$
$$y_{\text{crown top}} = y_{\text{centre sleeve}} = 0$$

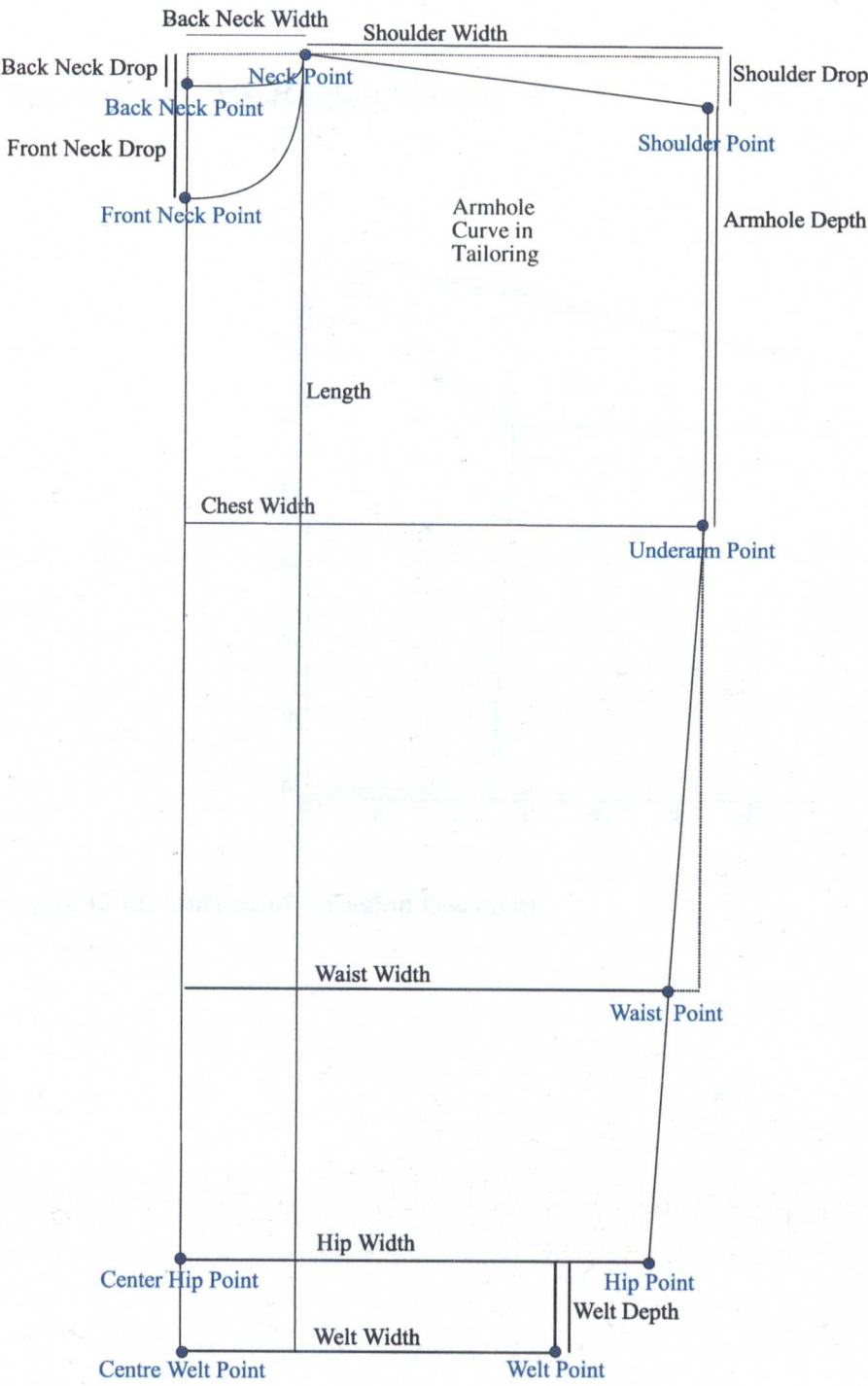


Figure C-10. Body of a T-sleeve Garment

Appendix C .3.3. Raglan Sleeves

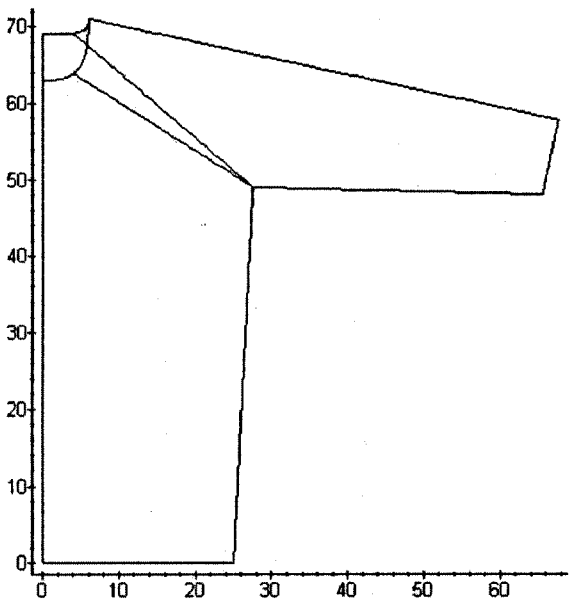


Figure C-11. Outline of a Raglan Garment

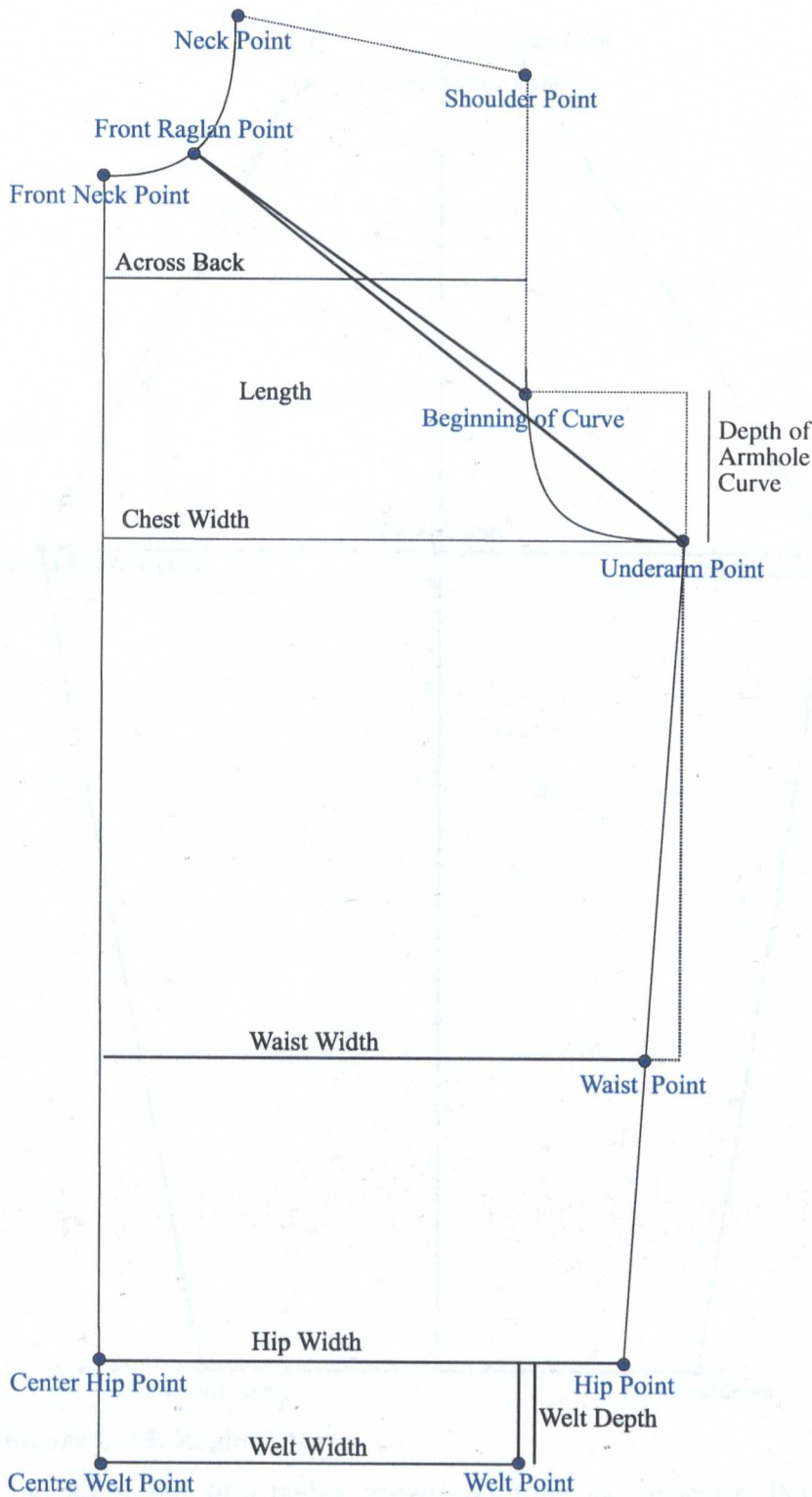


Figure C-12. Front of a Raglan Garment

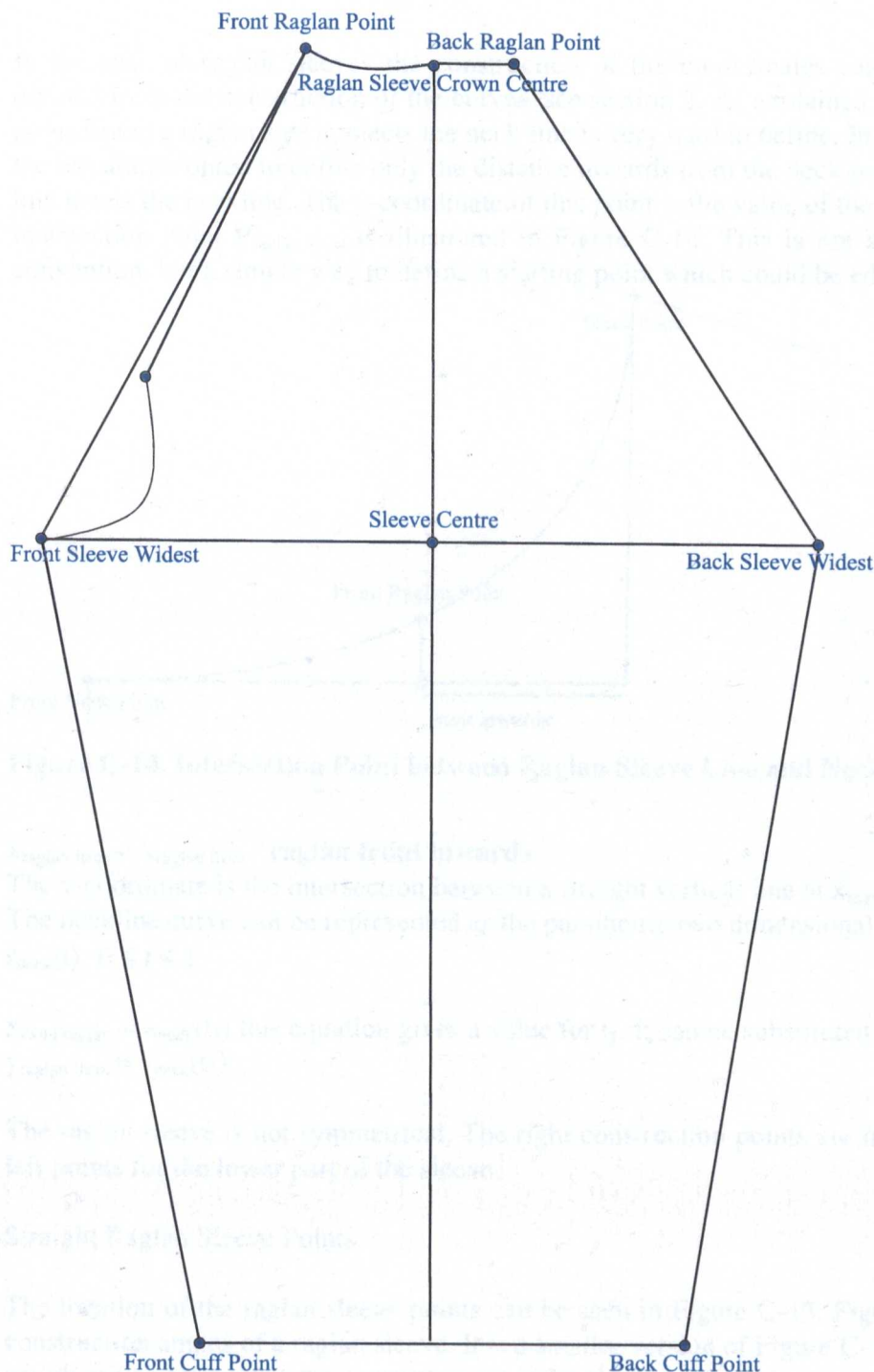


Figure C-13. Raglan Sleeve

The sleeve line of a raglan sleeve goes from the Underarm Point or the Armhole Point directly into the neckline. In most cases the neckline is divided by the sleeve line. The upper part of the neck line is continued onto the sleeve. Figure C-11 shows the outline of a raglan garment produced by the equation solver, Figure C-12 shows the front (the back neck curve back sleeve line is omitted to avoid confusion) and Figure C-13 shows the sleeve. Initially the front piece is constructed in the same way as a set in sleeve garment and the raglan line is drawn in. The sleeve is started with the sleeve widest line and the sleeve line and the remaining neck curve is rotated to fit the sleeve widest line. Raglan sleeves are not symmetrical, because the front and back neck line are rarely the same. Again the origin is placed at the intersection line between the sleeve widest and the centre of the sleeve crown, $P_{\text{centre sleeve}}$.

In the case of raglan sleeves the construction of the co-ordinates can not be completely divided from the construction of the curves, see section 2. As explained previously the exact point where a raglan sleeve meets the neck line is very hard to define. In this implementation the author has opted to define only the distance inwards from the neck point where the sleeve line meets the neckline. The y-coordinate of this point is the value of the neckline curve. The intersection point $P_{\text{raglan front}}$ is illustrated in Figure C-14. This is not a standard industrial convention, but a simple way to define a starting point which could be edited.

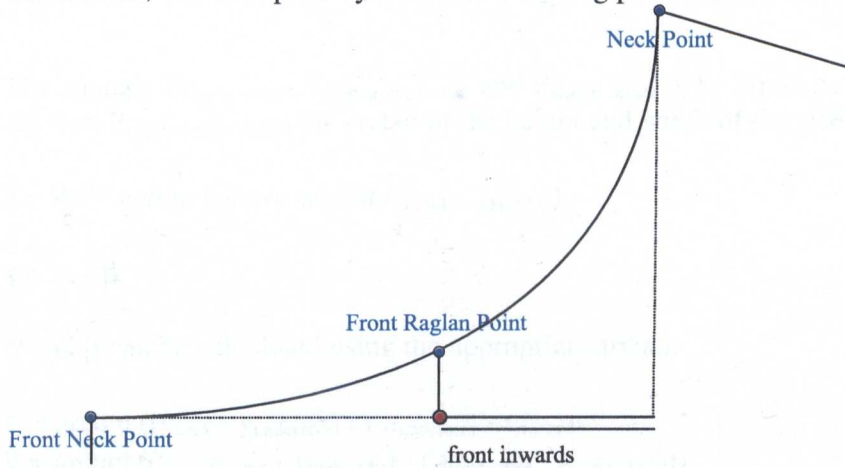


Figure C-14. Intersection Point between Raglan Sleeve Line and Neckline

$$x_{\text{raglan front}} = x_{\text{raglan front}} - \text{raglan front inwards}$$

The y-coordinate is the intersection between a straight vertical line at $x_{\text{raglan front}}$ and the curve. The neckline curve can be represented as the parametric two dimensional curve

$$r_{\text{neck}}(t) \quad 0 \leq t \leq 1$$

$x_{\text{front raglan}} = x_{\text{neck}}(t_1)$ this equation gives a value for t_1 . It can be substituted to gain

$$y_{\text{raglan front}} = y_{\text{neck}}(t_1)$$

The raglan sleeve is not symmetrical. The right construction points are mirror images of the left points for the lower part of the sleeve.

Straight Raglan Sleeve Points

The location of the raglan sleeve points can be seen in Figure C-13. Figure C-16 shows the construction angles of a raglan sleeve. It is a smaller version of Figure C-13 and Figure C-12, which can be referred to for a complete set of labels.

The Sleeve Crown Top, $P_{\text{raglan crown top}}$ is the centre of the Sleeve, but rarely the highest point on the sleeve crown. $P_{\text{raglan crown top}}$ is constructed by using the distance between the Underarm Point, P_{underarm} and the Neck Point, P_{neck} . A is the length between these two points. B is the length between the underarm point, P_{underarm} , and the Front Raglan Point, $P_{\text{raglan front}}$.

$$A = \sqrt{(x_{\text{underarm}} - x_{\text{neck}})^2 + (y_{\text{neck}} - y_{\text{underarm}})^2}$$

$$B = \sqrt{(x_{\text{underarm}} - x_{\text{raglan front}})^2 + (y_{\text{neck}} - y_{\text{raglan front}})^2}$$

$$x_{\text{raglan crown top}} = 0$$

$$y_{\text{raglan crown top}} = \sqrt{A^2 + \text{sleeve_widest}^2}$$

In the following only the construction of the Front Raglan Sleeve Points, $P_{\text{front raglan sleeve}}$, is discussed, the back point, $P_{\text{back raglan sleeve}}$, are constructed in the same way.

The angle between the sleeve widest line and the line connecting $P_{\text{sleeve widest}}$ and $P_{\text{front raglan}}$ is $\gamma + \delta$.

The triangle $P_{\text{sleeve widest}}$, $P_{\text{raglan crown top}}$ and $P_{\text{sleeve centre}}$ is by construction rectangular. The top angle at $P_{\text{raglan crown top}}$ is the arctan of the height and width of the sleeve crown.

$$\delta = 90^\circ - \arctan(\text{sleeve widest} / y_{\text{raglan crown top}})$$

$$\gamma = \alpha - \beta$$

α and β can be calculated using the appropriate arctan.

$$\alpha = \arctan((y_{\text{neck}} - y_{\text{underarm}}) / (x_{\text{underarm}} - x_{\text{neck}}))$$

$$\beta = \arctan((y_{\text{raglan front}} - y_{\text{underarm}}) - (x_{\text{underarm}} - x_{\text{raglan front}}))$$

The Front Raglan Sleeve Point, $P_{\text{front raglan sleeve}}$, has the co-ordinates:

$$x_{\text{front raglan sleeve}} = x_{\text{sleeve widest}} + \cos(\gamma + \delta)$$

$$y_{\text{front raglan sleeve}} = y_{\text{sleeve widest}} + \sin(\gamma + \delta)$$

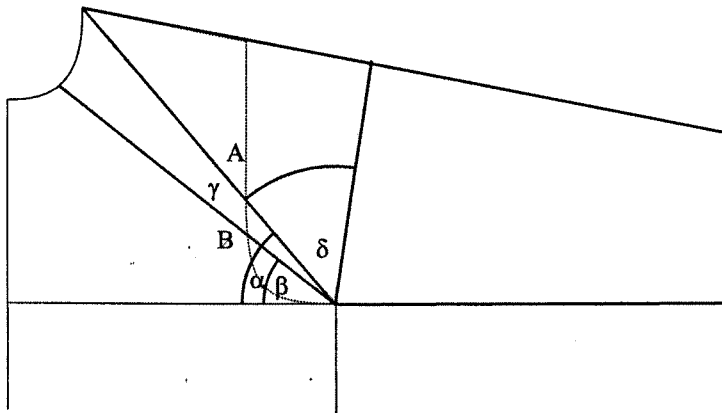


Figure C-15. Construction of Raglan Sleeve before Rotation

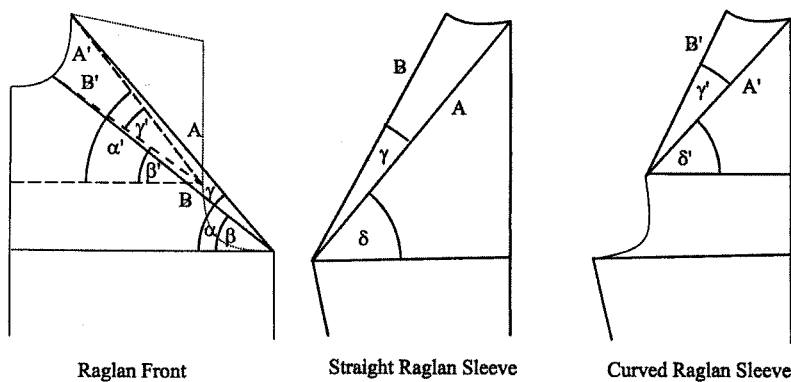


Figure C-16. Construction of Raglan Sleeves

Curves Raglan Sleeve Points

Curved Raglan Sleeve

The curved part of the raglan sleeve crown is the mirror image of the armhole curve at the front. The end point of the curve is $P_{\text{raglan curve sleeve}}$. This point has relative location to $P_{\text{sleeve widest}}$, as P_{armhole} has to P_{underarm} .

$$X_{\text{raglan curve sleeve}} = X_{\text{sleeve widest}} + (X_{\text{underarm}} - X_{\text{armhole}})$$

$$Y_{\text{raglan curve sleeve}} = Y_{\text{sleeve widest}} + (Y_{\text{armhole}} - Y_{\text{underarm}})$$

Figure C-17 shows a variety of sleeve forms that can be constructed with the same basic approach as the curved raglan sleeve, by mirroring the beginning of the arm hole curve for the beginning of the raglan sleeve.

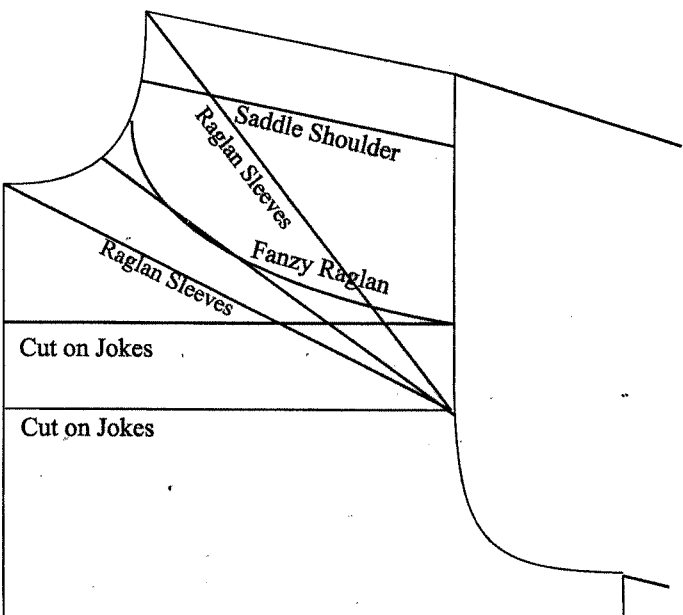


Figure C-17. Variety of Sleeve Constructed using the Curved Raglan Construction

Appendix C .4.Creation for Cutting Patterns from Co-ordinates

The cutting patterns are normally created by drawing straight line with the help of a ruler and drawing free hand curves to connect these lines. In this implementation the cutting pattern are made up by connecting the co-ordinates with straight lines or curves.

Appendix C .4.1.General Lines

The body is built up by the following lines:

- **Shoulder**
The shoulder line P_{neck} - P_{shoulder} is always a straight line
- **Welt**
If the garment does not have a welt the bottom is represented by a straight line between the $P_{\text{centre hip}}$, and P_{hip} .
Traditionally when the garment has a welt it is narrower then the fabric above it, straight lines are drawn as shown in Figure C-3.

$$P_{\text{centre hip}} - P_{\text{hip}}$$

$$P_{\text{centre welt}} - P_{\text{welt}}$$

$$P_{\text{welt}} - P_{\text{auxwelt}}$$
- **Side Lines**
Figure C-4 shows the traditional straight sidelines. All point, if they exist, are connected by straight lines in the order: P_{hip} , P_{side2} , P_{waist} , P_{side} , P_{underarm} . If one of these points are missing the adjacent point are connected directly. Some garments with shaped sidelines have curves between the side point1 and the waist, and the waist and the side point2, as shown in Figure C-5. These curves can also be modelled by cubic Bézier curves in the same way as neck curves.
- **Neck**
Rounds necks are represented by cubic Bézier curves using $P_{\text{front neck}}$ and P_{neck} , or $P_{\text{back neck}}$ and P_{neck} as the end points of the curve.

Square necks and V-necks are straight lines between the control points. A V-neck is defined by a straight line between the $P_{\text{front neck}}$ and P_{neck} . Square neck consists of straight lines between $P_{\text{front neck}}$ and $P_{\text{square aux}}$ and $P_{\text{square aux}}$ and P_{neck} , where

$$x_{\text{square aux}} = 0$$

$$y_{\text{square aux}} = y_{\text{front aux}}$$

A straight boat neck is formed by a straight between the shoulder points. A curved boat neck is in principle a very elongated round neck and constructed in the same way as a cubic Bézier curve.

The lower part of the sleeve

- The construction of the lower part of the sleeve is analogue to the construction of the lower part of the body. Straight lines connect:

$$P_{\text{centrecuff}} - P_{\text{cuff}}$$

$$P_{\text{sleeve widest}} - P_{\text{cuff}}$$

$$P_{\text{centrecuff}} - P_{\text{crown top}}$$

If the sleeve has a cuff or points where the angle of the sleeve side line is changed then this is treated as in the case of the body. All most always the lines on the side of the sleeves are straight. Only Batwing sleeves can have a curved sideline between $P_{\text{sleeve widest}}$ - P_{cuff} . It can be constructed as a cubic Bézier curve.

Appendix C .4.2. Set-In Sleeves

The armhole for knitted set-in sleeves is represented by two lines. A straight line connecting the P_{shoulder} - P_{armhole} and a cubic Bézier curve between P_{armhole} - P_{underarm} .

The sleeve is represented by a Bézier curve between $P_{\text{sleeve widest}}$ - $P_{\text{crown top}}$.

Appendix C .4.3. T-Sleeves

A T-sleeve garment has a straight line connecting P_{shoulder} and P_{underarm} . $P_{\text{sleeve widest}}$ and $P_{\text{centre sleeve}}$ are also connected by a straight line..

Appendix C .4.4. Raglan Garments

- Straight Raglan Sleeves

See Figure C-13 as an illustration of a typical raglan sleeve and Figure C-12 of a Raglan body. The P_{underarm} connected with $P_{\text{raglan front}}$ by a **straight** line. The neck line curve is initially constructed as for a set sleeve garment. In the case of a cubic Bézier curve, the t -value, t_1 , at the intersection point is calculated, see section 4. The curve is displayed between the Front Neck and the Interpolation Point, $t \in [0, t_1]$. The same applies to the back neck.

The sleeve is not symmetrical and needs to be constructed as a full pattern, see Figure C-13. A straight line connects the $P_{\text{left sleeve widest}}$ with $P_{\text{front raglan sleeve}}$ and likewise the mirrored point $P_{\text{left sleeve widest}}$ with the $P_{\text{back raglan sleeve}}$.

The remainder of the Front Neck Bézier curve is rotated, so that $P_{\text{raglan front}}$ is mapped onto $P_{\text{front raglan sleeve}}$ and P_{neck} onto $P_{\text{raglan sleeve crown}}$. The curve is displayed in the range $[t_1, 1]$. The remainder of the Back Neck curves is mirrored and then displayed in the same way as the front neck curve.

- Curved Raglan Sleeves.

A cubic Bézier curve connects the underarm point with the arm point in the same way as for set-in sleeves. P_{armhole} is connected to $P_{\text{front raglan}}$ with a straight line. The rest of the neck construction remains the same as for straight raglan sleeves.

At the beginning of the sleeve crown the cubic Bézier curve of the armhole is mirrored at the front half of the raglan sleeve and copied on the back half. A straight line connects $P_{\text{raglan curve sleeve}}$ and $P_{\text{front raglan}}$. Likewise for the back half. The rest of the construction is the same as for straight raglans sleeves.

Appendix C .5. Two Dimensional Outlines

The two dimensional outline of the garment represents the assembled garment spread out on a flat surface. This constitutes an accurate mathematical representation of the sketch outlines, that designers produce normally. The outline shows the angle between the sleeve and the body. This angle is important because it determines how much freedom of movement the garment gives in the arms.

The calculation of the outlines is based on the completed calculation of the cutting patterns. The construction of the sleeve crown does not show directly in the visual representation of the two dimensional outline. However the sleeve crown curve needs to be constructed accurately to provide correct values for the sleeve crown height and width. By manipulating the Sleeve Centre Point $P_{\text{centre sleeve}}$ the user can easily manipulate the sleeve shape in a way that can be retranslated into a legal solutions.

Appendix C .5.1. Set-In Sleeves

Figure C-7 shows a complete two dimensional outline of a garment with set in sleeves as it is created by the equation solver. Figure C-18 below illustrates the construction of two dimensional outlines.

The representation of the body is exactly the same as the body piece of the cutting patterns. The sleeve is represented by two points, which define the end of the sleeve. The angle δ gives the angle by which the sleeve is moved from the horizontal. It is constructed as follows:

$$\begin{aligned}\delta &= 90^\circ - \alpha - \gamma & \gamma &= 90^\circ - \beta \\ \delta &= 90^\circ - \alpha - \gamma = 90^\circ - \alpha - (90^\circ - \beta) = \beta - \alpha\end{aligned}$$

β is the angle between the sleeve construction diagonal and the horizontal at the Underarm point.

$$\beta = \arctan (\text{armhole depth} / \text{armhole width})$$

α is the top angle of the sleeve construction triangle

$$\alpha = \arctan (\text{sleeve width} / \text{sleeve crown height})$$

$$\gamma = 90^\circ - \beta$$

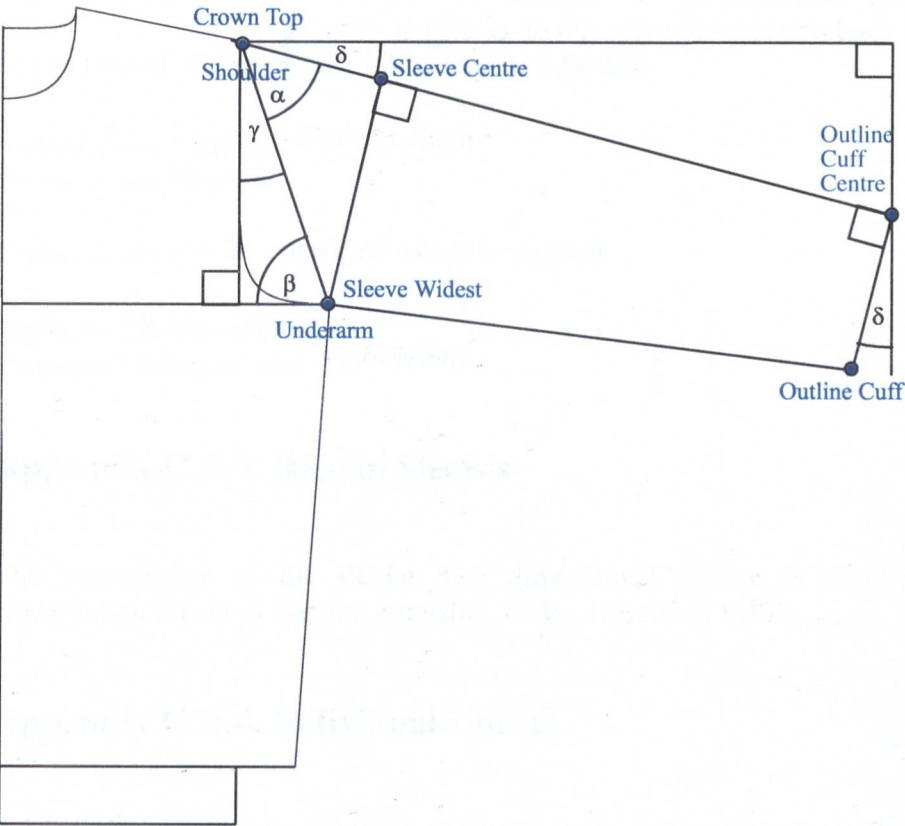


Figure C-18. Construction of the Outline of a Garment with Set in Sleeves

$$\delta = 90^\circ - \alpha - \gamma = 90^\circ - \alpha - (90^\circ - \beta) = \beta - \alpha$$

The top end of the cuff on the projected sleeve is marked by $P_{\text{outline cuff centre}}$ is. It can be calculated applying simple trigonometry. If the sleeve length is not an input value, it can be calculated simply $\text{Sleeve Length} = y_{\text{crown top}} - y_{\text{centre cuff}}$

$$x_{\text{outline cuff centre}} = x_{\text{shoulder}} - \text{Sleeve Length} * \cos(\delta)$$

$$y_{\text{outline cuff centre}} = y_{\text{shoulder}} - \text{Sleeve Length} * \sin(\delta)$$

$P_{\text{outline cuff}}$ can also be calculated using the angle δ

$$x_{\text{outline cuff}} = x_{\text{outline cuff centre}} - \text{Cuff Width} * \sin(\delta)$$

$$y_{\text{outline cuff}} = y_{\text{outline cuff centre}} - \text{Cuff Width} * \cos(\delta)$$

To create the outline x_{shoulder} and $x_{\text{outline cuff centre}}$, $x_{\text{outline cuff centre}}$ and $x_{\text{outline cuff}}$, $x_{\text{outline cuff}}$ and x_{underarm} , are connected by straight lines

Appendix C .5.2. T-Sleeves

Figure C-8 shows the two dimensional outline of a T-sleeve garment created by the equation solver. The construction is very simple as no top angle between the body and sleeve needs to be considered. This gives the following co-ordinates:

$$X_{\text{outline cuff centre}} = X_{\text{shoulder}} - \text{Sleeve Length}$$

$$Y_{\text{outline cuff centre}} = Y_{\text{shoulder}}$$

$P_{\text{outline cuff}}$ can also be calculated using the angle δ

$$X_{\text{outline cuff}} = X_{\text{outline cuff centre}}$$

$$Y_{\text{outline cuff}} = Y_{\text{outline cuff centre}} - \text{Cuff Width}$$

Appendix C .5.3. Raglan Sleeves

The construction of the Raglan two dimensional outline is exactly analogue to the construction for set in sleeves, but using the P_{neck} instead of the P_{shoulder} .

Appendix C .5.4. Individual Curves

Most shape technicians construct their curves in cutting pattern in the same way for all garments. Most companies seem to have a distinctive house style. This is one of the reasons why the garments of one company fit individuals better than those of other companies. It is important in an automatic shape construction to take this differences into consideration, because otherwise the curve suggestions would not look right to the designer or shape technician.

The curves can be adapted to individual characteristics in the automatic calculation of shapes by changing the default location of the interpolation points or the end points of the curve. See 5.3.1. for the construction of the interpolation point. What ever curve is favoured in a company it intersects the construction line. This value can be recorded. The location of the arm hole point can also be altered to determine the height of the curved part of the armhole curve.

In the case of the neck curves the end points are fixed, but the exact shape can be manipulated by moving the interpolation on the construction diagonal.

The exact shape of the sleeve curves can be manipulated by changing the location of the control points. The three interpolation points are constructed as offsets from fractions of the construction diagonal. This can also be adapted in accordance with changes to the arm hole curve.