Intelligent Support for Communication Difficulties in Conceptual Design

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Abstract.

Communication between different members of a design team is a notoriously difficult problem, especially at the early stages of the design process. In the knitwear design process the communication between knitwear designers and technicians has been identified in an empirical study as a major bottleneck. While knitwear is inherently difficult to communicate the design culture does little ease the problem. This paper argues that an intelligent design support system allows the designers to turn their typically incomplete, inconsistent and inaccurate specification of designs into a correct representation of their ideas; and thus reducing the interpretation by technicians as well as the design time. This can be achieved by automatically creating design solution suggestions based on the designers' customary specifications. This principle has been illustrated for the construction of garment shapes, which were modeled mathematically.

1. Introduction

A recurrent problem in many design domains is communication between different members of the design team involved in the different stages of concept creation, embodiment and detail design, fabrication and production. It is frequently the case that misunderstandings arise, that incorrect and/or incomplete specifications are passed from one team group to another, and that errors or inconsistencies in the design are discovered at late stages of the process. Sometimes, design problems are resolved by production or technical staff in ways that are regarded as unsatisfactory by the originating design staff, but further re-corrections may be too late or too costly to attempt. A response to this problem has been to develop broader, more integrated teams, and the introduction of ‘concurrent’ design processes.

The communication problem in design teams has also been addressed by the development of computer based models of the artefact being designed. Such models allow simultaneous access by different members of the team, and the artefact design evolves through collaborative input and evaluation from all the team [1]. However, although this may be beneficial during embodiment and detail design, difficulties still remain at the conceptual design stage.

The study reported in this paper addressed the communication problem in the knitwear design domain, where particular difficulties arise due to the nature of the artefacts being designed and the materials from which they are made. Communication problems in the design process between the fashion designers (who design the appearance of the garments) and the fabrication technicians (who realise the designs on knitting machines) are exacerbated by major differences in their respective cultures, education and careers [2]. An extensive empirical study in knitwear companies identified communication between designer sand technicians as a major bottleneck in the industrial process [3].

Computer support in the knitwear industry has so far mainly been limited to automation of the knitting machines, which has also added to the communication problems between designers and technicians. The designers still produce hand-drawn sketches for interpretation on the machines by the technicians. The study reported here has attempted to widen the scope of computer support for knitwear design by addressing

the particular needs of the knitwear designers, and their means of communication with the technicians. An intelligent computer support system is proposed which is capable of using inaccurate, incomplete and/or inconsistent sketch design specifications, and correcting and completing these using AI techniques to give the designers immediate feedback on their work. More accurate and reliable communication is thus established between designers and technicians.

2. Communication Difficulties in an Industrial Context

The study reported in this paper looked at ways to widen the scope of existing CAD systems for knitwear design and sampling by addressing the particular needs of the knitwear designers, who design the appearance of the garments, rather then the knitwear technicians, who realise the designs on knitting machines and have been the traditional users of these systems. An empirical study in knitwear companies has identified the communication between the designers and the technicians as a major bottleneck in the industrial process.

2.1 The Study

This research draws on observations in over 20 knitwear companies in Britain and Germany over a period of four years. The interaction with the practitioners ranged from one hour interviews with designers and technicians to observations in companies of up to one week. The methodology draws on the social science approach of ethnography [4] as well as knowledge acquisition techniques from artificial intelligence [5]. The study covered a wide range of companies from the suppliers of bottom of the market mail order companies to some of the world's most prestigious knitwear companies. The study placed emphasis on confirming assertions from interviews and conclusions from observations by talking to different people in the same companies about the same issues as well as addressing competitor companies.

In addition to this process of formal knowledge acquisition the first author has also worked on acquiring some of the domain knowledge of the designers and technicians herself, by attending training courses and designing garments.

2.2 Brief Background to the Knitwear Industry

The textile industry is one of the worlds major industries and the knitwear industry a substantial part within it. Western knitwear companies are under constant pressure from competition in the far east. Like all textile products, knitwear must be designed and produced under tight time pressures with the beginning of a new season in shops setting an unmovable deadline. Due to the requirements of production and the retail chains' need to select co-ordinated collections, there is a 1½ - 2 year period before designs will reach the shops.

In knitwear the shape of the garment piece is created at the same time as the fabric itself. The pieces are either knitted or cut into shape and assembled into complete garments in the end.

Knitwear design thus combines the scope of fashion design, which is concerned with the shape of garments, and textile design, which creates woven or print patterns. The interplay between shape and form is a major difficulty of knitwear design.

2.3 Overview of the Knitwear Design Process

The designers begin by researching coming fashion trends and selecting yarns from which all the garments in a season are made. Most designers initially design fabric swatches, little samples, of possible fabrics for garments. These are combined and supplemented into the designs of garments. Designers create specifications for all garments they want to see turned into a sample garment. The technicians than take the development over. The fabric technicians program the knitting machine and knit the garment pieces. The shape technicians create cutting pattern for the shape and make up the complete garments. Fabric technicians have often already been involved in creating fabric samples to select new yarns and knitting idea swatches for fabrics. The finished sample garments are selected internally and often also by external buyers. Only once a decision has been made to produce a design will it be graded and adapted for production when necessary.

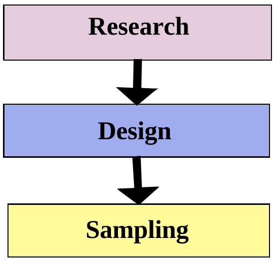


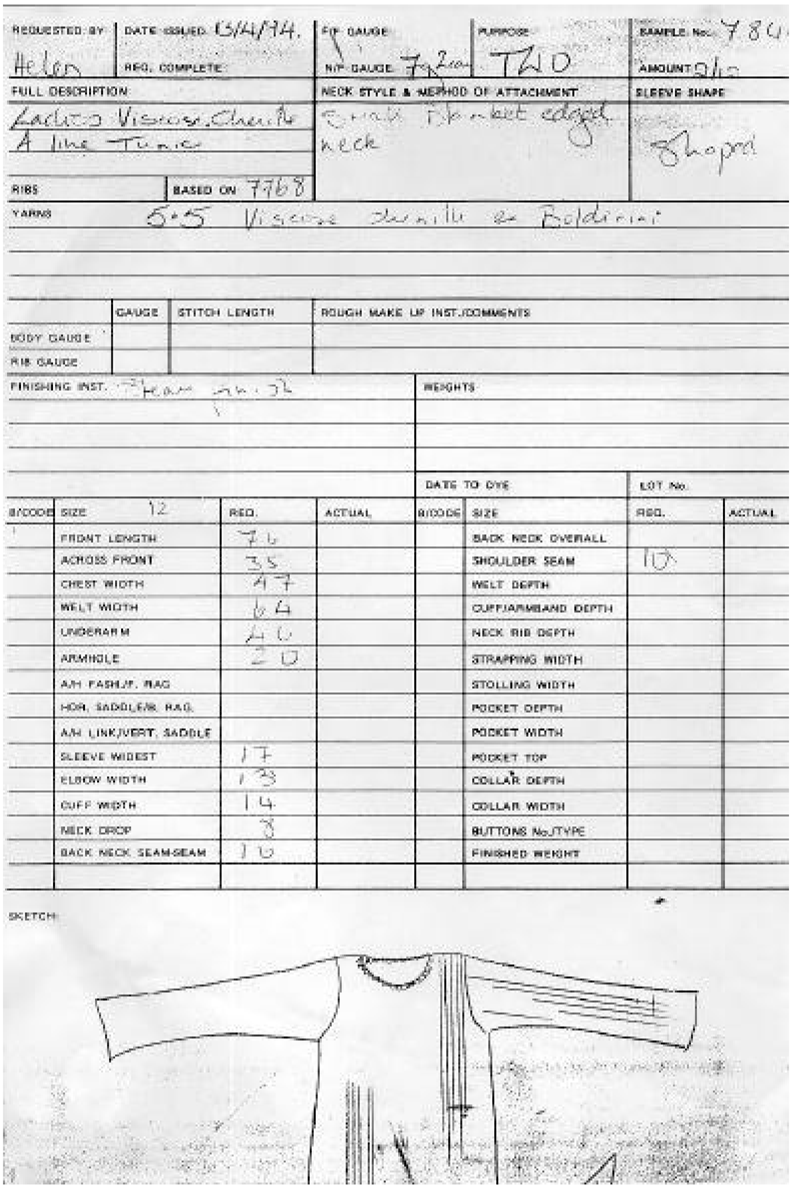
Figure 1. Basic Stages of the Knitwear Design Process

In current industrial practice this is a nearly a linear process (Figure 1). Designers create their designs; when they have finished most of their designs, these will be handed over to technicians. While the technicians sample the garments the designers have already moved on to designing for the next season.

2.4 Communication Difficulties

Communication between the different participants of the design process is problematic. Designers complain that the designs that they specified are not created. Technicians complain that designers do not have the expertise to design garments which are technically feasible. Both assertions were found to be largely true in the observed companies.

The technicians work through the specified designs. They interpret the designers' concept specifications. As long as the technicians think they understand the designs, no more contact between the designers and technicians exists until the technicians can present an embodiment solution suggestion to the designer. At this point the designers evaluate the solutions and specify modifications if necessary. In this way designs are modified until the designers and technicians are satisfied and the price points are met; or time runs out. Many designs are brought to the market in a not fully refined state.



REQUESTED BY: Helen
DATE ISSUED: 15/4/94.
REQ. COMPLETE:
F/F GAUGE:
N/P GAUGE: 7g 2col
PURPOSE: TWD
SAMPLE No.: 784
AMOUNT: 9/10
FULL DESCRIPTION: Ladies Viscose Chenille A line Tunic
NECK STYLE & METHOD OF ATTACHMENT: Small blanket edged neck
SLEEVE SHAPE: Shaped
RIBS:
BASED ON: 7768
YARNS: 5·5 Viscose chenille & Boldrini

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

FINISHING INST.: Steam [illegible]
WEIGHTS:
DATE TO DYE:
LOT No.:

B/CODE	SIZE 12	REQ.	ACTUAL	B/CODE	SIZE	REQ.	ACTUAL
	FRONT LENGTH	76			BACK NECK OVERALL		
	ACROSS FRONT	35			SHOULDER SEAM	10	
	CHEST WIDTH	47			WELT DEPTH		
	WELT WIDTH	64			CUFF/ARMBAND DEPTH		
	UNDERARM	40			NECK RIB DEPTH		
	ARMHOLE	20			STRAPPING WIDTH		
	A/H FASH./F. RAG				STOLLING WIDTH		
	HOR. SADDLE/R. RAG.				POCKET DEPTH		
	A/H LINK/VERT. SADDLE				POCKET WIDTH		
	SLEEVE WIDEST	17			POCKET TOP		
	ELBOW WIDTH	13			COLLAR DEPTH		
	CUFF WIDTH	14			COLLAR WIDTH		
	NECK DROP	8			BUTTONS No./TYPE		
	BACK NECK SEAM-SEAM	10			FINISHED WEIGHT		

SKETCH:

Figure 2 Industrial Example of a Knitwear Specification

Like all experts, technicians interpret the concept design specification in the light of their own previous experience of the designers and their work; and their knowledge of textiles. In fashion it is however necessary to see designs in the context that will be fashionable when the garment will come to the market. Technicians are not included in the conceptual design research process. This has the consequence that new designs can look much more similar to pervious designs then the designers have intended.

The only record of the design process is the specification such as that shown in Figure 2. Designers produce initially sketches for their designs, which they tend not to keep; and do not show to the technicians. If the designers and the technicians discuss a design it happens in unrecorded conversation in an informal set-up. Swatches of previous sample versions are not kept. The design specifications are kept for at most two years in most of the observed companies.

Defining Knitwear is Difficult

Knitwear is inherently difficult to define. There is no simple notation, which is both complete and easy to use. Each CAD system has its own notation, mostly using colour codes with over 10 different colours for a standard design. Most designs are specified by sketches. As the example in Figure 2 shows the sketches can be inaccurate and ambiguous.

Design and technical considerations are very closely linked in the knitwear, as this simple example shows (see [6]): A garment has a design with overall motifs, which the designer has designed before specifying the garment, say a duck 20 stitches wide. In the specified yarn the garment width comes out at 110 stitches. This provides space for 5 ½ ducks and gives the following options:

- one ½ duck at the end
- two ¼ ducks at both ends
- five ducks across and 5 plain stitches at the side
- a garment width of 100 or 120
- plain stitches between the ducks
- design a different duck

The motifs also have to fit lengthways. The designer would have specified the ducks on grid paper and drawn a sketch with five ducks across. The technician has to pick one option and produce a sample.

In the knitwear design culture the communication problems are often not realised as such and not counteracted through management. Eckert and Demaid [7] suggest a restructuring of the design process on concurrent engineering principles.

3. Similarities between Knitwear and Engineering Design

Knitwear design, like most other textile and craft based design domains has been largely neglected so far by design research. However, it can contribute to the understanding of other design domains, especially engineering, by making certain aspects more salient.

3.1 General Similarities

Knitwear design, like architecture, is a mixture of aesthetic and technical considerations in balancing the visual appearance of the garment and the technically realisable. Many of the communication problems arise concerning designs where the technical implementation has effects on the appearance of the design. The visual appearance of the product can also pose a significant constraint on engineering design, primarily of consumer products. In knitwear design the artistic aspect of the design process is highlighted. Subjectivity as an important influence on design is openly acknowledged and an emphasis is placed on individual designers versus general patterns. This highlights the needs for the adaptability of the computer support system to the needs to individual designers.

Unlike engineering design, the overall knitwear design culture has not been touched so far by design theory or theoretical management ideology. Companies develop a way that works more or less for themselves without ideological commitment. Aspects of the design process can therefore be observed and discussed independent of theoretical considerations.

Team Working

The collaboration within a design team is a notoriously difficult problem in all design domains when people with different backgrounds, training and aims have to work together on one product. These problems can include:

- little overlapping expertise.
- different cognitive styles when a person with an analytical thinking style has to collaborate with a natural designer who employs an oscillation between problem specification and solution conjecture style.

- hidden assumption made by different groups.
- different interpretations of words, such as design, specification etc.

In many companies design teams are frequently regrouped. Team members do not know individual hobby horses. Each group has its own social set-up with team members playing power games and pushing hidden agendas.

Whilst an engineering team can have dozens or even hundreds of people, as in an aeroplane design team, knitwear design is shared by two main groups. The designers represent the aesthetic and artistic side, who think like typical designers in terms of completed solutions. Their knowledge is often tacit, and they cannot explain their reasoning. On the other hand the technicians have technical knowledge and try to analyse problems in a systematic manner.

Knitwear design teams show many of problems of engineering teams in a nutshell. In the small team it is possible to unpack individual contributing factors.

4. Intelligent Design Support

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.

4.1 Critiquing Systems

Critiquing system are concerned with evaluating a design or part of it as part of an intelligent design environment; see Hägglund [8] for an introduction; and Silverman [9] 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. [10]. Active critiquing is monitoring the designers' actions and interrupts the design process to point out errors and give guidance. The ability of a system to critique actively is ultimately limited by its ability to know the users' goals. Miller [11] 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. [12], for a good overview of their concerns and approaches.

4.2 Automatic Solution Suggestions

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. These 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 [13], for an introduction and Todd and Latham. [14,15] for a detailed review of current cased-based reasoning systems with special reference to their use in design) It will be argued in section 5.5 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 [16] 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. The possible solutions need to be evaluated either by a human, as in Todd and Latham [17] in the generation of creative art forms; or tested by a machine against predefined constraints. Shape grammars can be combined with genetic algorithms to increase the search space or reduce the initial start up cost of finding the generation rules. Rosenman [18] shows how building forms can evolve in combination with shape grammars. Schnier and Gero[19] shows how genetic algorithms can learn suitable representations and thereby gather domain knowledge. The problem with genetic algorithms is however the definition of a suitable fitness function for the specific problem.

4.3 Examples of Related Systems

Papamicheal et al. [20] describes the Building Design Advisor (BDA) developed at the Lawrence Berkeley National Laboratory to include climate and site considerations into the design of a building. 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 side. Rooms and buildings can be edited in a specific editor, 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.

The IDIOM system [21]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 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. [21] also review other case based architecture systems.

5. Supporting Knitwear Designers

5.1 Existing Support

Knitwear design - like most other design domains - can be supported in two fundamentally different ways:

- By providing solutions or supporting the creation of solutions to sub-tasks as they occur within the existing design process while maintaining the design culture. Automatic or semiautomatic design support is given for problem solving tasks to the people who traditionally undertake this task in the design process. The division of labour only changes radically once the tasks of a participant have been taken over by the support system to the degree that this person is no longer required; or needs to be given different tasks.
- Using CAD systems as a way to overcome structural problems in the design process by giving different participants access to information and expertise of their colleagues.

Commercial CAD systems have over the last few years automated the programming of a knitting machine, by creating a high level specification language which can be compiled into a programming language for knitting machines similar to assembler. These systems use default values and question the user for some missing information. They try to represent the specified design as closely as possible, even if the program they have specified does not make sense. The systems require that every stitch on the garment is specified. They do not allow tentative solutions and require a great commitment of time and energy to produce any results. In spite of their marketing claims these systems are still mainly used by fabric technicians to program knitting machines, rather than by designers.

CAD technology has blurred the division between the tasks of all participants. Designers use CAD systems increasingly to create and specify their same types of designs and fabric technicians create garment shapes for garments that are knitted to shape. However the work pattern of designers and technicians has changed little over the observed period of four years. The systems have speeded up individual tasks enormously, but over the same period knitwear designs have become technically much more complex. The trend to more complexity is still continuing with technicians pushing the CAD systems to their limits to access the full scope of hand knitting.

5.2 Overcoming the Bottleneck

Communication problems occur when different members of a design process, in this case the knitwear designers and technicians, do not understand the assertions, specification and background knowledge of other members of the design team. A CAD system can help to overcome this by giving different members of the design team access to the expertise of their colleagues. Early and tentative designs in most domains are specified incompletely, inconsistently and inaccurately. In knitwear design a complete description of a design would require a great commitment of time and technical skills, which designers do not have.

An intelligent CAD system can overcome communication problems by enabling designers to specify their designs accurately, without requiring great time investment and expertise. In the approach presented in this paper the role of the system is to take the designers customary specification and turn them into suggestions that can be evaluated visually. Knitwear designers are used to receiving solution suggestions, because technicians show them swatches or garments which the designers can evaluate. The CAD system gives designers the opportunity to tweak their specifications or modify the solution suggestions until the design corresponds to their initial idea or they prefer the suggestion. The system is responsible to assure internal consistency and technical correctness of the design. At the same time the computer generated design specification can be used as a starting point for technicians to make adaptations to the properties of individual yarns.

Eckert [3] has illustrated this principle for the construction of garment shapes. The measurements defined by the designers (see Figure 2) are turned into a cutting pattern and an outline sketch of the garment. Inconsistencies and missing values are detected in the process of calculating the garment shapes. The designers can evaluate the shape and adapt it to their design idea.

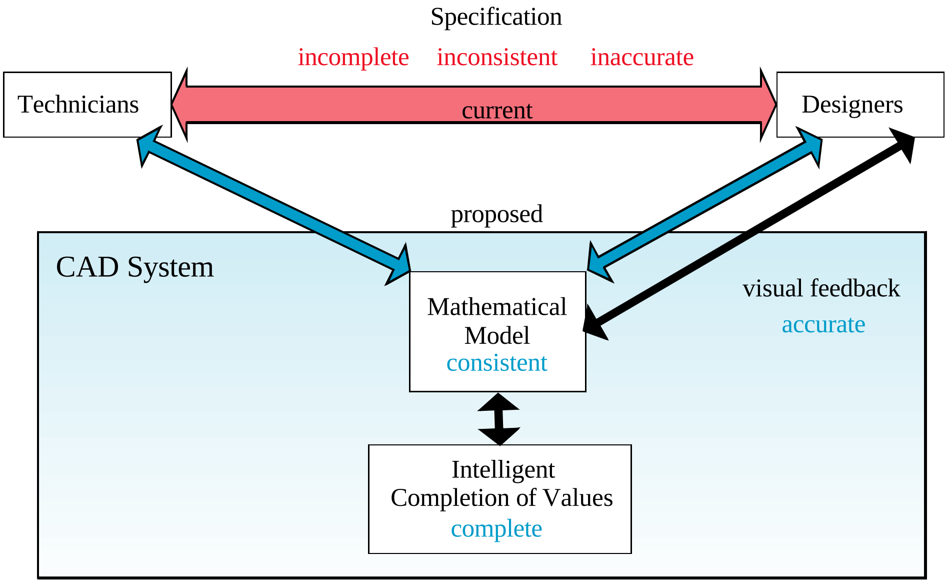


Figure 3 Overcoming the Communication Problems for Garment Shapes through a Mathematical Model as part of an Intelligent CAD System

5.3 Shape Construction

The definition of the shape of a knitted garment has in principle two different stages:

- The definition of the shape the final garment will have once it is finished.
- The definition of the shape the individual pieces of the garment.

Knitted fabric stretches (think of the rib on a sweater). These stretch properties have to be taken into consideration for the construction of each garment. The skills of the technicians lie in knowing what allowances to make for each fabric (to date the stretch properties of knitted fabric are not sufficiently understood to automate or even support this process). However when the designers are defining their designs they do not yet know the exact fabric.

Currently the shape technicians interpret the designers’ specified measurements in the light of the brief verbal description of the garment, for example “A-line ladies tunic” as in Figure 2, at the same time as they are making allowance for the specified fabric. Many interviewed designers complained that the shape technicians ignore the outline sketches. The designers rarely get feedback on their design specification other then seeing a completed garment after great time and resources have been invested.

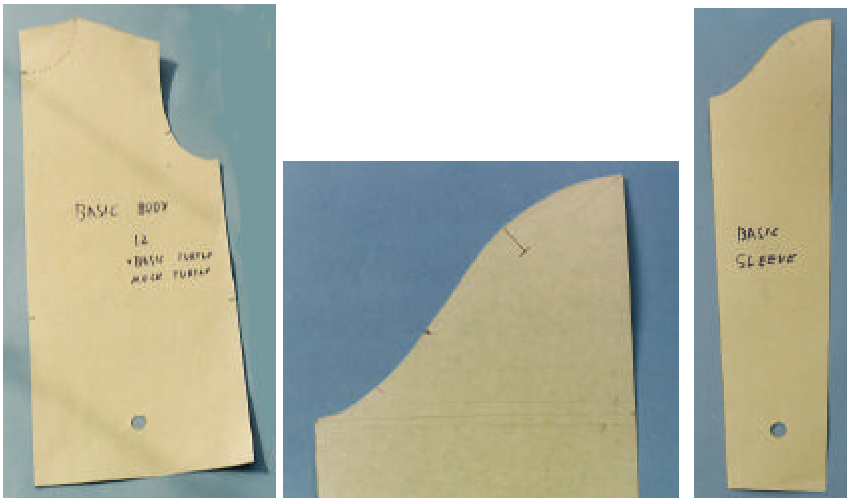


Figure 4. Set-in Sleeve Cutting Pattern, Body and Sleeve and Sleeve Crown Detail construction after [22]

A typical garment has two different cutting patterns, one for the front and the back and one for the sleeves. When the garment is assembled the different pieces need to fit together. The classical shape of the sweater has set-in sleeves (Figure 4). The sleeve shape poses an interesting mathematical problem, because two curves, the armhole curve and the sleeve crown curve, need to have the same length. The rough shape of the curves has evolved over centuries to give maximum freedom in arm movement. The exact shape of the curves is different for each company and garment. The armhole depth, sleeve length, sleeve width and the length of these curves are dependent measurements. Their specifications often create inconsistencies.

5.4 Mathematical Models

The mathematical model of garment shapes is used to create cutting patterns (and through them garment outlines) from the verbal description of the garment and the measurements specified by the designers. The mathematical model assumes that the measurements are complete and consistent. Reasoning to correct measurements belongs to a different part of the system, see below.

The endpoints of lines and curves on cutting patterns can be represented as points in a coordinate system. The mathematical model of garment curves needed to fulfil a number of requirements:

- 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.
- 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.

Bézier curves [23,24] were chosen for the following reasons:

- The manipulation of Bézier curves is fairly intuitive. 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 is fairly simple.
- Bézier curves give easy control over the end tangent vectors, which is an import domain constraint.

5.5 System Architecture

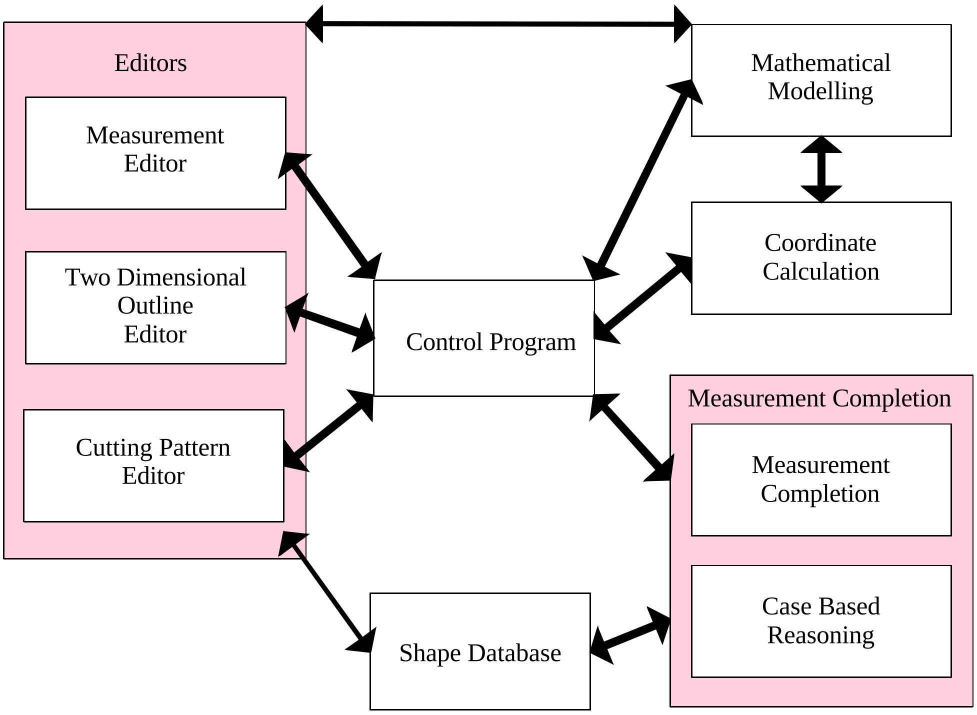


Figure 5. Overview of the Control Flow of the Garment Shape Design Module

A control program controls the interaction between the different components of the system. The user can use three different editors:

- The measurement editor to input the verbal description of the garment and the measurements
- The two dimensional outline editor which display the automatically created garment outline. The outline can also be manipulated.

The cutting pattern editor, in which the automatically displayed cutting patterns can be modified or created using conventional pattern cutting techniques. This editor can serve as well a specific work environment for shape technicians to create adaptation to the shape.

The mathematical model of the garment shapes is integrated with the calculation of the co-ordinates. Internal consistency of the input measurements can be achieved by prioritising input measurements in adjusting inconsistent ones accordingly. From the observational work it is reasonable to assume that designers know the broad dimensions of a design, such as length or width, but are likely to guess dependent measurements, such as sleeve width or use measurements from pervious garments. Successful results have been achieved by iteratively moving the sleeve width and the sleeve crown height.

Measurement completion could be achieved in two different ways:

- Using default values for missing measurements or applying a simple calculation to adapt basic measurements to the proportions of the garment. For example the missing chest measurement could be derived by altering the chest measurements of the sample size the same proportion as an other measurement has changed from the size measurements, such as ratio of the width of the garment at the hip to the hip measurement. A similar approach has been successfully employed by [20 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 [21] active critiquing and user preferences could be in included.
- By applying case based reasoning from similar garments to model the behaviour of the shape technicians in interpreting the designers specifications.

6. Effect on the Design Process

The support system allows designers to create complete and consistent specifications which correspond to their design ideas. The communication problems in the supported areas are overcome through reliable specifications. This can have wider consequences for the design process, as designers and technicians trust each others specifications, they might also trust each other’s assertions in other issues and treat each other with greater respect.

The number of samples required during the sampling process decreases as the specified design is closer to the designers’ initial idea and surplus samples due to misinterpretations can be avoided. It is however possible to the released time again will be invested into creation of more complex or more innovative designs.

References:

[1] **Maher, M.L. et al**. (1997) *Formal Aspects of collaborative CAD*, Key Centre of Design Computing, Sydney, Australia.
[2] **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.
[3] **Eckert, C.** (1997) Intelligent Support for Knitwer Design, PhD Thesis, The Open University, Milton Keynes, U.K.

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

[5] **Tunnicliff, A. and Scrivener, S.** (1991) 'Knowledge Elicitation for Design', *Design Studies*, Vol 12 No 2, pp. 73 - 80.

[6] **Eckert, C**. (1990) *Prototype of an Intelligent CAD System for Knitwear Design*, MSc Thesis, Department of Computing Science, University of Aberdeen, Aberdeen, UK.

[7] **Eckert, C**. **and Demaid, A.** (1997), 'Concurrent Design', *Proceedings of the 78th World Conference of the Textile Institute*, Thessaloniki, Greece.

[8] **Hägglund, S.** (1993), 'Introducing Expert Critiquing Systems', *Knowledge Engineering Review*, Vol 8 No 4, pp. 281-284.

[9] **Silverman, B.G.** (1992) 'Survey of Expert Critiquing Systems: Practical and Theoretical Frontiers', *Communications of the ACM*, Vol 35 No 4, pp 106 - 127.

[10] **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.

[11] **Miller, P.** (1986) Expert Critiquing Systems: Practise-Based Medical Consultation by Computer, Springer-Verlag, New York, USA.

[12] **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

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

[14] **Voss, A.** (1996) 'Towards a methodology for case adaptation', *Proceedings of 12th European Conference on Artificial Intelligence*, John Wilney, Chicester, UK.

[15] **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.

[16] **Stiny, G** (1980) Introduction to shape and shape grammars, *Environment and Planning B: Planning and Design*, Vol 7, pp. 343-351.

[17] **Todd, S and Latham, W.** (1992), *Evolutionary Art and Computers*, Academic Press, London.

[18] **Rosenman, M.** (1996) 'The generation of form using an evolutionary approach', *Proceedings of Artificial Intelligence in Design '96*, Kluwer Academic Publishers, Dordrecht, Holland.

[19] **Schnier, T. and Gero, J**. (1996), 'Learning Genetic Representations', *Proceedings of Artificial Intelligence in Design '96*, Kluwer Academic Publishers, Dordrecht, Holland.

[20] **Papamicheal, K, LaPorta, J. Chauvet, H, Trzcinski, T. Thorpe, J. and Selkowitz, S.** (1996) 'The Building Design Advisor', *Proceedings of ACADIA '96*.

[21] **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

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

[23] **Bézier, P.** (1968) 'How Renault uses numerical control for car body design and tooling' *Paper SAE 6800010*, Society for Automotive Engineers.

[24] **Faux, I. And Pratt, M.** (1979) *Computational Geometry for Design and Manufacture*, Ellis Horwood.