ABSTRACT

MA, YANXUE. An Integrated Model for Shaped Knit Garment Design and Development. (Under the direction of Dr. Traci A.M. Lamar).

Advanced knitting technologies such as integral knitting and seamless knitting expand opportunities in unique knit garment design and development, but the lack of well-defined knowledge requirements and inadequate understanding of the development process prohibit these technologies from being fully utilized in the creation of knit garments. This research investigated in detail the design and development process for shaped knit garments in three stages.

First, a reference library was established via fundamental research that investigated the influences of different shaping techniques and knit stitch structures on knitted fabric dimensions and knitted garment shapes. This reference library supported accomplishment of fully-fashioned or seamless knit garment development in each case in stages two and three of the research. Second, a preliminary model was established based on participant observation of four case studies. Third, the preliminary model was validated and refined through mapping in-depth case studies to the model in research stage three. Additionally, interviews with industry experts were conducted to verify necessity and sufficiency of steps and components in the preliminary model. Finally, a validated and comprehensive model was developed that integrated all aspects of shaped knit garment design and development. The integrated model that delivers detailed descriptions of necessary steps and knowledge needed is useful to designers or development teams in creating unique fully-fashioned or seamless knit garments. The archival references in the reference library and components in knowledge building provide guidance in accomplishing each step in the process, evaluating outcomes of certain steps and correcting errors in knitting.

An Integrated Model for Shaped Knit Garment Design and Development

by
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DEDICATION

To my family for their love, faith, constant support and encouragement

BIOGRAPHY

Yanxue Ma was born on May 08, 1988, in Henan province, People's Republic of China. In 2006, she became an undergraduate student in Donghua University in Shanghai, China. In her senior year of college, she had a chance to participate the 3+X program that is cooperatively offered by Donghua University and North Carolina State University. Following completion of an undergraduate degree in textile engineering from Donghua University, Yanxue was admitted to the Textile and Technology Management program at NCSU where she pursued a Doctor of Philosophy degree. During that time, she also earned a Master of Textiles degree in Textile and Apparel, Technology and Management at NCSU. In the Ph.D. program, Yanxue worked as a research assistant in a project that focused on knitwear design and development. Her current interests include knitwear design, textile design and textile new product development.

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On a personal level, I really want to thank my mom and dad who are still in China and provide consistent support and love over the distance. I am also very thankful to my friends both in China and in the United States for their encouragement and advice. Supporting love from family and friends is an important motivation for me to complete the Ph.D. degree.

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1 Introduction

A well-defined product development process assists the organization to identify opportunities, create new products that meet customer demands and adopt new technology. It also improves product quality and facilitates communication among customers, designers and technicians (Ulrich & Eppinger, 1995). Although new product development processes have been widely used in many industries, they have not been consistently developed in the fashion industry, especially the knitwear industry. The design process for fully-fashioned or seamless knitwear development differs from the process used for other apparel products in several ways. First, knit garments created on fully-fashioned or seamless knitting machines are constructed directly from yarns to shaped panels or complete garments. Compared to traditionally cut and sew garments, fully-fashioned and seamless knit garments eliminate making-up processes, such as cutting, and sewing or linking. The knit garment shape is difficult to change after production. If the knit garment is not produced in appropriate shapes, the development process needs to start over. From design's perspective, it is essential to predict the garment shape and dimensions prior to knitting. Second, knit garment design includes knitted fabric design and fashion design. There is a subtle and complex relationship between fabrics knitted with different structures and fashion garment appearance. This requires that designers not only understand garment construction, but also be familiar with knitted structures and knitted fabric properties. Third, production of a knit garment is a shared effort by designers and technicians. This differs from other fashion apparel production processes where designers can create a finished garment by themselves or with a design team, but then pass the design along to a technical design team for translation to production. In current knit garment design processes, aesthetic designers focus on style development, and technicians create knit garment patterns in knitting CAD system and produce the finished garments on the machine. Because knitwear designers often have limited knowledge in knitting technology, aesthetic designs they create may be not able to knit, or may knit incompletely and inaccurately. This would lead to incorrect interpretation of these knit specifications by technicians who have limited knowledge of aesthetics and garment construction (Eckert, 2001). Communication between designers and technicians is crucial, but often challenging.

These challenges in the knit garment design process can be addressed with me by integrating style development, knitted fabric design, CAD pattern making and machine operating. Integration of creative design with knitting production can facilitate collaboration of designers and technicians, and consequently improve the performance and aesthetics of knit garments. Advancements in knitting technology, such as integral and complete knitting, provide opportunities to design and produce high-fashion knit garments in an integrated system. CAD/CAM systems and 3D body scanning and other innovative computer technologies enable one person to be engaged in the entire design and development process including aesthetic design, technical design and knit production thus improving speed and efficiency of development and providing creative designs. However, the lack of fundamental knowledge limits the use of these innovative technologies in knit garment design. The little academic literature available in knitwear development provides inadequate understanding of the design process. An effective model for knit garment development that integrates the entire design and development process with the underlying knowledge base will facilitate a successful development process. This knit garment development model could not only have application for custom garments and mass produced garments, but assist mass customized knit garment design.

1.1 Purpose of research

Competition in the knitwear market and quick changes in fashion increase the need for an effective and efficient garment development process. Fully-fashioned and seamless knitting technologies allow for fast design and production due to elimination of some or all making-up processes. However, incomplete understanding of these advanced knitting technologies and lack of a comprehensive model impede development and implementation of the design process with fully-fashioned and seamless knitting. Although published apparel development models exist, they emphasize development of cut and sew garments rather than shaped knit garments. A critical need exists to model the knitwear development process, expanding the understanding of shaped knit garment design.

This research aims to develop a model for creating fully-fashioned or seamless knit garments that integrates yarn selection, knit structure selection, garment style development, knit production, finishing and evaluation. Another goal is to explore the knowledge needed to develop knit garments and incorporate it into the integrated model. One part of this work is fundamental research that explored different shaping techniques for knitting and effects of knitted stitches and structures on knit garment dimensions. Additionally, the integrated model for shaped knit garment design is developed through sample and prototype production using potential knitting techniques. Data in the form of visual, physical and written reports of the knit garment design process were collected from several case studies with experts and undergraduate students. The comprehensive model involves knowledge building, knit garment design and evaluations. Further, data collected in those case studies and the fundamental research go to a reference library, which support application of the model and can contribute to the adoption of innovative technologies in knitwear design. It also provides a base for beginners who have little knowledge in knitting technology and machine operation.

2 Literature review

Emerging knitting technologies, such as fully-fashioned, integral and complete knitting, have altered knit garment development and production processes. Innovations in knitting machines and advances in CAD software enable the formation of shaped knitwear (Song, Wu, & Wei, 2006). They also enhance the connection of creative designers and technical designers with the garment production. To build complete knowledge needed in fully-fashioned and seamless knitting and establish a comprehensive model, literature is reviewed in two parts: fundamental knitting technologies supporting integrated design and existing knitwear development processes. Purposes of this literature review are to exploit the potential of knitting techniques in garment shaping, and to determine opportunities and challenges that enable or prohibit adoption of advanced knitting technologies from current knitwear development models.

2.1 Knitting technologies supporting integrated design

Advanced knitting technology such as seamless knitting and integral knitting enabled an integrated design of knitwear that incorporated aesthetic design and technical design. A review of shaped knit garment construction methods and shaping techniques revealed the potential of integrating the entire knit garment design and development process using these technologies.

2.1.1 Knitting fundamentals

Knitting is defined as "the process of forming a fabric by the intermeshing of loops of yarn (Denton & Daniels, 2002). Knitting is the most common method of interlooping and is second only to weaving as a method of manufacturing textile structures (Spencer, 2001). Compared to woven fabric, knitted fabric is more easily distorted due to lower restriction of yarn movement. In garment design, the stretch ability and flexibility are positive characteristics of knitted fabrics.

Knitting is divided into two fields: weft knitting and warp knitting. These two fields are based on different yarn feeding methods and loop formations. In a weft-knitting machine, yarn feeding and loop formation occur at each needle in succession across the needle bed during the same knitting cycle (Spencer, 2001), and loops are formed in a horizontal direction. In warp knitting, loops are formed in a vertical direction (Wilson, 2001). The two types of knitting are accomplished on two different types of knitting machines: a weft knitting machine and a warp knitting machine. According to the arrangement of needles and the configuration of the frame of the machine, weft knitting machines can be divided into straight bar, flat knitting, and circular knitting machines (Spencer, 2001). The circular knitting machine is popular to use due to high productivity, but it has less shaping capability compared to flat knitting machines (Chapman, 2008). Knitted structures that can be generated on circular knitting machines are limited to simple structures, such as jersey, rib and interlock. With the ability of combining different structures and transferring stitches, V-bed knitting machines allow for stitch variations in knitted fabrics and offer the potential of garment shaping.

Basic loop stitches on V-bed knitting machines include front knit, back knit, held stitch, float loop, tuck stitch and transferred stitch (Brackenbury, 1992). Brief descriptions of each are given here considering their significance in the formation of shaped knit garments. These loop variations can alter the shape of knitted fabrics. A held loop involves the needle maintaining the old loop until the next yarn feeds and generates a new loop. The held stitches are often used to form 3D shaping, such as heel and toe pouches for footwear. If a needle holds its old loop and fails to rise to achieve the new yarn, a miss stitch is formed. The missed yarn floats freely on the reverse side of the held loop. When the needle has risen to receive new yarn but has not fully formed a loop, a tuck stitch is created. Tuck stitches make the fabric wider, thicker and slightly less elastic. Stitches that are composed of held loops can be used to create diverse structures. For instance, half and full cardigan are generated with knitted loops and tuck stitches. Transferred loops are commonly used in the shaping process. The process of transferring a loop is moving a stitch from one needle to another. The two needles can be neighboring or on the opposite needle beds (Brackenbury, 1992). Transferred stitches are typically produced on flat knitting machines because the needle beds must rack.

The use of different loop stitches leads to dimensional changes in knitted fabrics. Tuck stitches and miss stitches increase fabric width but reduce length (Kayacan & Kurbak, 2008a; Kayacan & Kurbak, 2008b). Combination of the two stitches enables shaping in fabric formation. Further, changes in layouts, numbers and types of loop stitches can alter the aesthetic and performance attributes of knitted fabrics. However, existing research on knit stitches is limited to mathematical modeling, rather than aesthetics and performance. Effects of combining different loop stitches could be further explored to enhance aesthetic design of knitted fabrics.

2.1.2 Knit garment construction

Shaping is an important process in constructing knitwear, and it can be achieved after knitting or during knitted fabric formation. Main methods of making knit garments include fully cutting and sewing, cutting and sewing from tubular body width, fully-fashioned knitting and seamless knitting (Brackenbury, 1992). The evolution of knitting technologies for knit garment construction was fully reviewed in Chapman's research (Chapman, 2008). Choi (2006) has explained adoption and development of the three-dimensional seamless knitting. The following literature review will briefly introduce advantage and disadvantage of each construction method and identify the concepts of integral knitting and complete garment knitting. In this literature review, potential techniques that could be explored in seamless knitting will be discussed.

To construct a cut and sew knitted garment, designers, pattern cutters, or automatic cutting machines cut knitted fabric yardage to garment panels that are sewn together into a finished garment (Brackenbury, 1992). If knit garments panels are cut from body size tubular knit fabrics, there are no side seams to sew (Choi & Powell, 2005; Glock & Kunz, 2000), but seaming is still needed to close shoulders and insert sleeves. Conventionally, the method of fully or partly cutting and sewing is used to produce high-fashion garments with less expensive materials because the size and shape are easy to change (Fairhurst, 2008). However, waste of raw materials and high labor costs are challenges, and the process is labor intensive (Anderson, 2008). Additionally, seams at shoulders and underarms may lead to premature product failure at seams due to the stress of wearing (Clapp et al., 1994). The lead-time from fabric knitting to finished cut and sew products is long, so it is difficult to deliver quick-response products to the rapidly changing market (Anderson, 2008).

Many challenges presented by cutting and sewing can be solved by fully-fashioned knitting and seamless knitting. In fully-fashioned knitting, shaping of garment panels occurs during knitting (Fairhurst, 2008). Compared to cutting and sewing, the fully-fashioned shaping process reduces yarn waste and cutting time, but construction of a finished garment still requires skilled workers to link or seam shaped panels.

Seamless knitting can form shaped garments with minimal or no seams. Knitwear produced by this method is referred to as an “integral garment” or “complete garment”. This technique saves material cost, labor, and making-up machinery, and shortens the production sequence compared to cutting and sewing and fully-fashioned knitting (Choi & Powell 2005; Spencer, 2001). Seamless knitting technology could provide value-added high-quality knitwear quickly and economically with individualized features and in small lots as required (Wilson, 2008). Seamless knitting, especially on a V-bed knitting machine, offers great potential for unique knitted garment design (Underwood, 2009). The disadvantages of seamless knitting include increased machine set-up costs, and complexity of seamless knitting machines, and the need for operator training (Briggs-Goode & Townsend, 2011). CAD/CAM programming is a time-consuming process and requires trained designers or technicians to accomplish.

The concept of integral knitting on flat knitting machines is not consistently defined. Some references state that integral knitting and complete garments are created by the same knitting method in which the finished garments are created on the machine and require no further cutting and sewing (Spencer, 2001). On the other hand, the concept of integral knitting may be separated from the concept of complete garments. Some authors indicate that integral knitting is like fully-fashioned knitting because shaped panels are formed on the machine, but unlike fully-fashioned knitting, trims, pockets, and buttonholes can be added during the knitting process (Anderson, 2008). In this case, integral knitting requires seaming or linking to construct the final shape of the knitwear, so sewing is not eliminated in integral knitting. In complete garment knitting, the finished knitwear is directly achieved on the machine without seams. Generally, complete garment knitting is the most complex process in garment production.

No matter whether cut and sewn, fully-fashioned or seamless, garments are shaped flat fabrics that are difficult to fit to the 3D body contour, especially for larger size women (Haffenden, 2009). Although knit garments can achieve some level of fit due to inherent stretch of knitted fabrics, problems such as wrinkles and excess fabric folds still influence fit and comfort (Haffenden, 2010). To fit the body and enhance aesthetics, the shaped knit garment is not just formed in a simple tubular shape, but it can also have a 3D shape within the garment parts. Application of 3D shaping techniques in knit garment design can not only improve fit to the three-dimensional body, but also contribute to creative design with enhanced aesthetics. The following literature will introduce the concept of 3D shaping and review several methods to achieve 3D shapes within the garment parts.

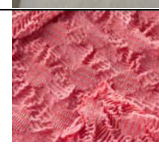
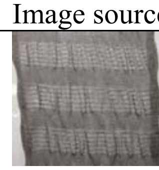
2.1.3 Potential knitting techniques: 3D shaping for knit garments

Creating knitted garment panels with three-dimensional shape has two main methods: cut and sew and 3D shaping without seams. The cut and sew techniques, such as darts or pleats, are used post knitting to transform flat fabrics into shell structures that match the 3D configuration of the human body (Shishoo, 1995). On the other hand, knit shaping techniques, such as partial knitting, stitch transferring, and changing yarns or knitted structures, are able to produce knit garments on the machine with three-dimensional shapes that follow the body contour without additional shaping process.

To create garments of stable fabrics with 3D shapes that fit the curves of the human body, garment panels are not only sewn together to construct a finished garment, but cut and sewn panels are shaped by techniques, such as darts, pleats, tucks, seams and gathers (McKelvey & Munslow, 2003). These cut and sew shaping techniques have potential to be used in knit garment design, and adaptation of these techniques will improve knit garment fit to the body. Dart shaping is done in cut and sewn garments but darts in fully-fashioned or seamless garments would create bulk that would be undesirable. Shaping techniques with knitting technology can create similar effects to cut and sew shaping techniques.

Review of academic literature and industry sources (Araujo, Fangueiro, & Hong, 2004; Lam & Zhou, 2008; Underwood, 2009) revealed a variety of methods of creating knitted garment parts with three-dimensional effects. Those methods and techniques have been compiled in Table 2.1, along with examples to illustrate each.

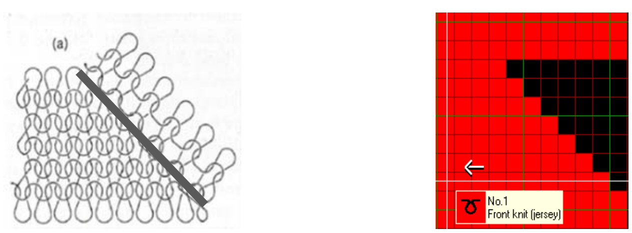
Table 2.1 3D shaped knitted fabric techniques and examples

Methods	Explanation	Examples of 3D shapes
Course shaping	Partial knitting with held stitches can form 3D shapes.	
Wale shaping	Width of the fabric is changed through transferring stitches and needle bed racking.	
Stitch architecture	Combinations of knit structures can be used to achieve 3D effects.	
Changing yarn materials	Combining yarns with different properties and shrinkages in the knitted fabric can change the fabric shape.	 Image source (Shima, 2011)
Changing structural parameters	Changing loop length, or pull down tension in different courses can create interesting surfaces and shape knitted fabrics	 Image source (Stoll, 2010)
Tubular knitting	Tubular knitting is used for complete garment development, and it can be combined with other 3D shaping techniques to achieve unique designs.	 Image source (Shima, 2011)

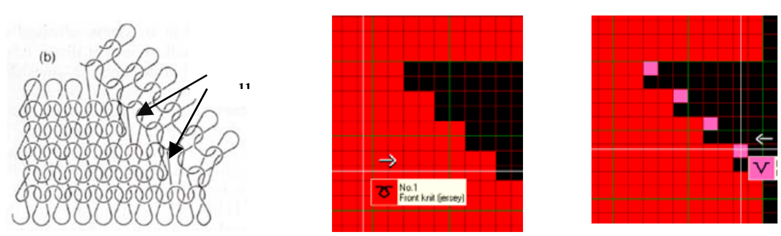
2.1.3.1 **Course shaping**

In course shaping, which is also called flèchage or partial knitting, held stitches impart shape during knitting by successively increasing or decreasing the number of working needles. Knitting happens in selected areas, and the remaining stitches are suspended and do not knit. Then, all of the loops rework after a specified number of courses. This causes the wale-wise direction of knitting to change, and the knitted fabric takes on a three-dimensional shape (Ciobanu, Lonesi, & Ciobanu, 2011). Because these held stitches can occur on one side of the knitting, on both sides, or anywhere on the width that is being knitted, course shaping is easy to apply, and it is frequently used to form 3D shapes.

Course shaping is illustrated in Figure 2.1 along with patterns created in Shima Seiki's CAD knitting program to illustrate each example. In Figure 2.1 (a), the number of knitted loops is reduced in every row. A smooth, unbroken fashioning line is generated and small floats may occur if more than one loop is reduced per course. The pattern in Figure 2.1 (b) shows that the number of knitted loops is reduced in every second course. No floats occur, but the fashioning lines have steps and small holes. To prevent the holes, tuck stitches can be added where steps occur (see the right image in Figure 2.1 (b)).



(a) Number of loops diminishes in every row



(Images of loops: adapted from Brackenbury, 1992, pp.78)

(Digital patters: created on Shima Seiki's SDS-ONE software)

(b) Number of loops diminishes every two row

Note: ■ Knit stitch ■ Tuck stitch ■ Miss stitch

Figure 2.1 Two basic methods of course shaping (Adapted from Brackenbury, 1992, pp.78)

Course shaping can be used to create a shape similar to that accomplished by sewing a dart in a cut and sewn garment part. As shown in Figure 2.2 (b), the bust dart is created by course shaping with held stitches. The two solid lines in the designed pattern (see Figure 2.2 (a)) are like stitching lines in the bust dart pattern. After knitting, stitches along these two lines form a fashioning line. As discussed previously, in the cut and sew technique, dart angles and dart length define the amount of curve given to the panel. In course shaping, the structure of the shaped area is determined by the number of stitches that are held over the number of courses. The shape of the dart can be predicted theoretically before knitting based on the number of held stitches and fashioning frequencies (Lamar, Powell, & Parrillo-Chapman, 2011). The knitted front panel with a side bust dart in Figure 2.2 (b) is the result of knitting the pattern in Figure 2.2 (a).

(a) Theoretical angle (b) Actual angle

Figure 2.2 Comparison of pattern and knitted sample (Created on Shima Seiki's software and machine)

By varying the number of held stitches and courses in the shaping segment, the fashioning lines created can be straight or curved. Each fashioning line will form a 3D geometry with its specific angle, width, height and shape (Ciobanu, Dumitras, & Filipescu, 2010). Repeats of shaping sections with different fashioning lines can develop a wide range of 3D shapes without seams, including domes and curved tubes.

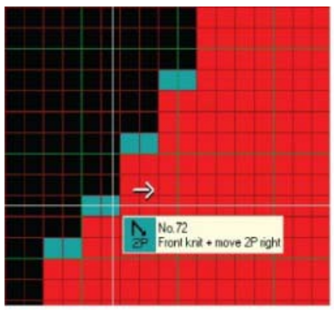
A significant benefit of this technique is versatility, because it can be applied to multiple knitted structures, such as rib or interlock, and it has few special machine requirements. If this technique is applied in small areas, a 3D effect on the surface of the fabric is created to enhance aesthetics of the knitted fabric (Penciuc, Blaga, & Ciobanu, 2010).

Main limitations of course shaping are takedown and knitting tension on held stitches (Underwood, 2009). As the shaping segment is repeated and the number of held stitches increases, the stress on the held stitches grows, especially on the edge of the shaping area. The stress on stitches may result in damaged stitches or distortion of the shaping segment (Lam & Zhou, 2008). The use of stitch pressers and sinkers might help to keep more uniform physical stress on the needles and avoid the deformation of shaped fabrics (Shima, 2004a). Stitch distortion can also be avoided by using innovative knitting machines with special takedown and stitch control systems. To reduce the potential for damage to yarns and stitches, it is useful to predict the angle and shape of the shaping area before knitting. This prediction can be made based on machines, types of yarn and knitted structures that are used.

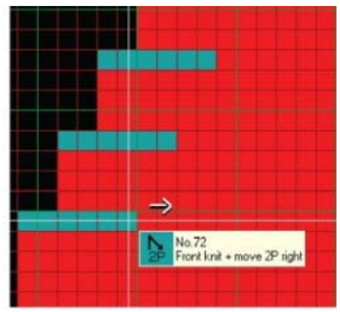
2.1.3.2 **Wale shaping**

Wale shaping is another way to change the number of working needles. Instead of using held stitches as in the course shaping method, the width of knitted fabric is widened or narrowed by transferring stitches left or right to adjacent needles. Prior to innovative V-bed knitting machines, the wale shaping technique was restricted to plain fabric, but now it can be accomplished with more complex structures, such as rib or interlock.

The main technique used in wale shaping is stitch transferring, which is completed through needle bed racking. The number of needle bed racks determines the width of the fabric. Stitch transferring may be outside transferring or inside transferring. In outside transferring, one or more stitches decreases or increases gradually on the edge, and the number of transferred stitches is the same as the number of needle bed racks (see Figure 2.3 (a)). In the case of inside transferring, the number of transferred stitches is larger than the number of needle bed racks (see Figure 2.3 (b)).



(a) 2 stitches outside narrowing



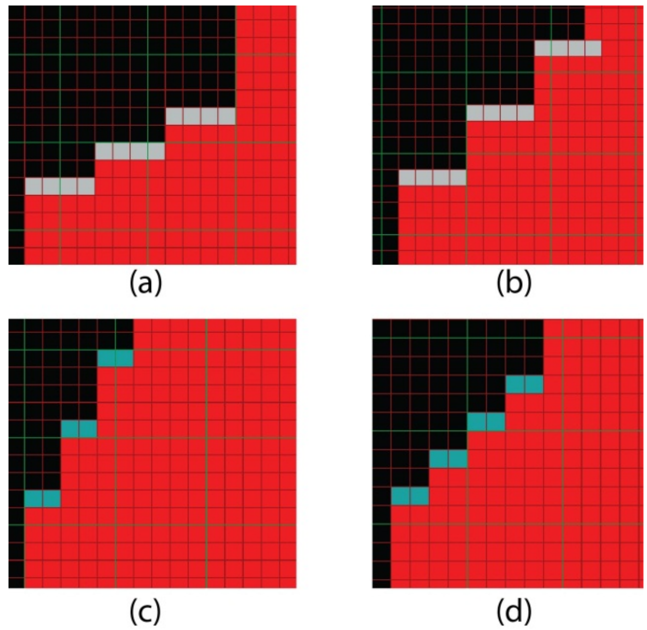
(b) 2 stitches inside narrowing

Note: ■ Transfer two stitches to the right

Figure 2.3 Designed patterns with outside and inside narrowing stitches (Created on Shima Seiki's SDS-ONE software)

For outside narrowing, double stitches are on the edge, whereas double stitches occur within the fabric, and small holes are created in the inside narrowing fabric. These double stitches and small holes are called 'fashion marks' (Brackenbury, 1992). When one or more stitches are transferred gradually over a number of courses, the width of the fabric will change. Wale fashioning is used to shape edges of garment panels in areas such as the armhole curve, a shape that would be formed by cutting in the cut and sewn method. When garment panels are assembled, the front and back armhole curves form a 3D opening for the arm or sleeve. The shape of the opening can vary by design according to the fashioning strategy. In addition to wale fashioning, knit structures used on the armhole edge and in the knitted garment panel also influence the shape of the armhole curve (Ruan, 2011).

The angle of the shaping area can be predicted and measured before knitting, because the number of transferred stitches and the fashioning frequency determine the angle of the fashioning line. As Fig. 6 illustrates, if the same number of stitches is transferred with different frequencies, the angle of shaping will vary. The more frequently the stitch narrowing occurs, the bigger the shaping angle is. This can be observed by comparing the differences among the patterns in Figure 2.4 (a) and (b) or (c) and (d). When the fashioning frequency is kept the same, more transferred stitches in the pattern will present a larger shaping angle (see Figure 2.4 (a) and (d), or (b) and (c)). When loop transferring occurs within the width of needles, 3D forms in the fabric are created. This method applied to a tubular structure imparts shaping during knitting. On complete garment knitting machines, the width of the tube can be narrowed or widened to fit the body shape. The effect is similar to the shaping imparted by a vertical dart in the cutting and sewing method. Measurement of the angle is important to impart a proper shape to fit the body. No literature was found in the field of predicting the amount of curve given by the shaping, but commercial products provide new opportunities for theoretical research to explore wale shaping in knit garment design.



(a) 3 stitches transferred in every two courses
(b) 3 stitches transferred in every four courses
(c) 2 stitches transferred in every four courses
(d) 2 stitches transferred in every two courses

Note: Transfer three stitches to the right
Transfer two stitches to the right

Figure 2.4 Shapes narrowed with different numbers of transferred stitches and fashioning frequencies (Created on Shima Seiki's SDS-ONE software)

In comparison with held stitches, transferred stitches are more complex and challenging to knit because of the continuous movement of needle beds and stitches. Especially when the yarn is less elastic, it can break easily or drop stitches may occur, so the transferring process must be very slow. Considering the two methods of stitch transferring, inside fashioning is more difficult to complete than outside fashioning, because multiple stitches are transferred. When more stitches are transferred, the potential for yarn breakage and fabric damage increases (Underwood, 2009). In general, the maximum number of stitches that can be transferred is one-third of the machine gauge, but that may vary slightly depending on different yarn properties and machine limitations (Canzler & Hiemann, 1964).

2.1.3.3 **Stitch architecture**

Combining different knitted structures is a simple way to impart shape during knitting. Shapes that are created by combining different structures can be horizontally, vertically, or otherwise imparted to the fabric (Brackenbury, 1992). When two different structures are knitted side by side, wales in the knitted fabric are bent and fabric arcing occurs, as the sample shown in Figure 2.5 In this case, the knitted fabric is not flat, and the degree of arcing is determined by adjoined structures, yarns used, and machine parameter settings (Tou, 2005). To extend Tou's results, a fabric knitted with three different structures in the course direction could have a 3D shape resulting from arcing on each side. Tou did not examine the impact of juxtaposing side by side different knit structures on the 3D shaping of the knit samples she created. But, this technique could be useful for 3D shaping of garment panels.

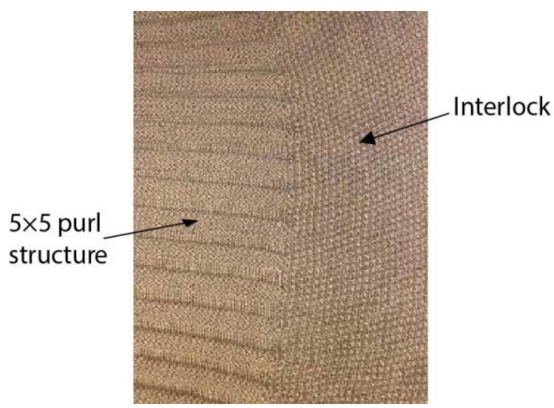


Figure 2.5 Effect of arcing with two structures knitted side by side (Created on Shima Seiki's 124-S flat knitting machine)

If different structures are knitted in a vertical direction, shapes can be generated without altering the total number of needles that are in action (Penciuc, Blaga, & Ciobanu, 2010). Figure 2.6

shows a fabric knitted with 2×2 cables in the waist area and interlock structures in the ground area. Because the extensibility and relaxed states of these knitted structures are different, the width of the fabric in each part is different even with the same number of stitches in each course. Therefore, combining different knitted structures vertically can build a shape that fits the human body, especially in the waist and bust areas of women's garments.

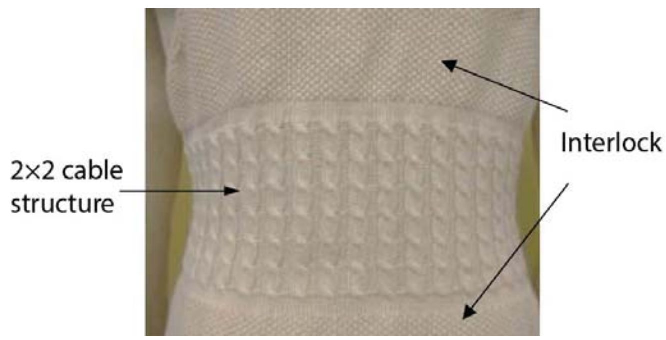


Figure 2.6 Stitch shaping with two different structures (Created on Shima Seiki's SES124-S V-bed knitting machine)

Furthermore, knitted structures can be combined in both vertical and horizontal directions. Knitted fabric can be split into several sections, each section using one stitch structure (Underwood, 2009). For example, in Figure 2.7, section A is knitted with interlock stitches, section B uses single jersey, and section C is knitted with 3×3 rib. Because the 3×3 rib structure has higher elastic recovery and is more compact in its relaxed state than the interlock structure, a gathered shape is formed on the fabric. Gathers can be used as a dart alternative to accomplish 3D shaping for fit and aesthetics in garment parts and garments. In the cut and sew method, gathers are created during the sewing process or by sewing together fabrics with differing extensibilities. In knitting, different sections with different structures can be applied to shaped-garment designs. If the area of each section is small, these sections may be used to create unique surface pattern designs.

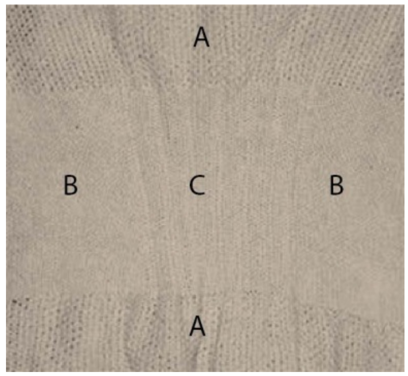


Figure 2.7 Combination of three knitted structures (Created on Shima Seiki's 124-S flat knitting machine)

Combining different knitted structures is a fast way to create 3D forms. This method is commonly used in sweater cuffs with rib structures to produce a gathered effect to the sleeve. Changing knitted structures in appropriate areas of a knit garment will create a garment shape to fit body curves (Yang & Love, 2009). However, the technique has a limited capability to form diverse shapes (Underwood, 2009), so it is often used with other shaping methods to enhance fabric textures.

The shape of knitted fabrics with combined structures is determined by shrinkage and dimensional changes of each knitted structure (Anand et al., 2002). Many studies have been conducted to analyze geometrical models of knitted structures and loop formation (Choi & Lo, 2006; Fletcher & Roberts, 1952), and the effects of knit structures on the dimensional properties of knitted fabrics have been explored (Onal & Candan, 2003). But little literature examines dimensional changes in knitted fabrics with combined structures. When different structures are knitted in one piece of fabric, the elastic recovery, dimensional properties and shrinkage of each structure are affected by its adjacent structures, so the final shape of knitted fabrics with combined structures is difficult to measure and control. Yang and Love applied a simple mathematical approach to developing knitwear silhouettes that were directly shaped by changing knitted structures (Yang & Love, 2009). Their research provides a basis to develop new ways of combining knitted structures and helps companies to maintain and enhance their existing styles. Prediction and measurement of the shape created by combining different knitted structures should be investigated in future research.

2.1.3.4 **Changing yarn materials**

Yarn materials used are critical to shape and fit of knitted garments (Alexander, 2005; Ashdown, 2007). Combining yarns made of different materials leads to varied properties in knitted fabrics, which in turn affects appearance and dimension of the fabric (Ng, Lam, & Park, 2010). Including yarns that shrink with heat and adding a heat-treatment process can produce a range of shrinkage and create fabrics with 3D surfaces (Chapman, 2008). Using yarns with different degrees of shrinkage and heat-treatment is an effective way to create seamless shaped knit fabrics (Anderson, 2004).

This technique is flexible to use along with other shaping techniques, such as changing of stitch structures. Penciuc et al. (2010) created a 3D knitted fabric by knitting full cardigan and single jersey structure with acrylic and elastomeric yarns in different areas. Because cardigan and single jersey, acrylic yarn and elastomeric types of yarn have different extensibilities and degrees of shrinkage, 3D appearance is created in the fabric.

2.1.3.5 **Changing structural parameters**

Machine parameters, such as loop length or take down tension, are critical factors that influence the shape of knitted fabrics (Zouari, Cheikhrouhou, & Sahnoun, 2008). Changing these parameters causes dimensional changes and gives the knitted fabric a unique appearance.

Traditionally, changes in stitch length occur from altering the stitch cam position at particular points. Innovative flat knitting machines with electronic control systems can change the loop length in the knitting process (Black, 2002). If a fabric is knitted with two loop lengths, the width of the fabric in the area with a small loop length is less than that with a large loop length (see Figure 2.8). The resulting fabric will have a 3D effect, and changing loop length can also be used for knitted garment shaping.

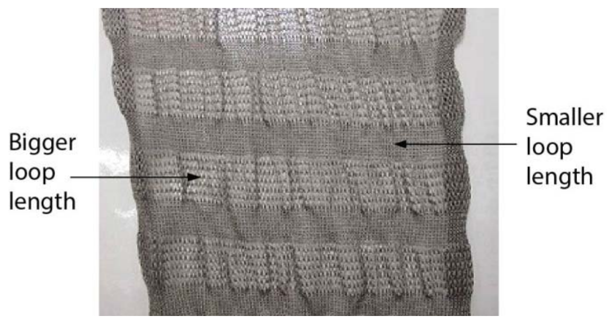


Figure 2.8 Shaped fabric with two different loop lengths (Source: Stoll, 2010, Pattern No.: 0810211)

Compared to other shaping techniques, changing loop length is not as commonly used to create 3D forms. This technique requires a more complex design process, is more challenging for the machine to knit, and the 3D shape is less apparent. In addition to loop length, take down tension is another factor that affects knitted fabric properties. With higher load on the fabric, extension increases. If the take down tension was changed in different parts of one fabric, the resulting fabric would not be flat.

2.1.3.6 **Tubular knitting**

Tubular knitting, the simplest 3D knitted shape, can be used to eliminate side seams, but further cutting and sewing are still needed to construct a 3D garment. Tubes can be produced on both circular knitting machines and flat knitting machines. In circular knitting, sizes of tubes are restricted by the machine diameter, and limited structures can be knitted. On the flat knitting machine, the width of tubes can be changed, but structures are limited to simple knitted structures that only use one needle bed. The limitation exists because tubular knitting occurs on two needle beds. The front needle bed knits in one direction, and the back bed knits in the opposite direction. When tubes are knitted with more complex structures, such as ribs or interlock, knitting machines should have multiple beds or systems to control stitches (Hunter, 2004).

Because simple knitted tubes have made few contributions to three-dimensional shaping, tubular knitting is often combined with other shaping techniques, such as course shaping, wale shaping, and changing yarns or knitted structures. In particular, for complete garment design, combining techniques is very important to producing a 3D knitted garment or creating a 3D surface in the fabric.

2.1.3.7 **Other possible 3D shaping techniques**

Some additional shaping techniques exist to form 3D shapes, such as changing cam positions, or using special knitting machines (Black, 2002). For example, Stoll's multi-gauge knitting machines enable the knitted fabric to form a 3D shape with several gauges, and the change of gauge is achieved during knitting without replacing needles or making gauge conversions (Stoll, 2011). Compared to the previously mentioned techniques, changing cam positions to create 3D forms is more complex and less effective so it is also less useful. Using special knitting machines such as multi-gauge machines or intarsia knitting machines, is an effective method but setup of these knitting machines is very expensive and requires training of designers and technicians. Complexity of machines and CAD software and requirements of training limit adoption of such innovative technologies including in the area of seamless garment knitting.

To sum up, wale or course shaping, changing of yarns and structural parameters, combining knitted structures, and tubular knitting are the commonly used and most effective methods in 3D shaped weft knitwear design. In particular, varying the number of needles in action by using held stitches and transferred stitches is an effective technique for creating three-dimensionally shaped weft knitwear. To design dramatic 3D fabrications and invent new shaping techniques, it is crucial to understand the technical constraints of each shaping method and to explore the capabilities of building 3D knitted forms.

3D shaped seamless products are available in areas of fashion, hosiery, upholstery, industrial textiles, and medical textiles (Kanakaraj & Ramachandran, 2010). 3D shaping technology with fully-fashioned and seamless knitting is expected to continue growing and have a wider range of applications (Gupta, 2011). Therefore, to apply these unique shaping techniques to knit garments, the literature review in this section explored principles and limitations of basic 3D shaping techniques. The distinctive architecture of 3D shaped knitted fabrics can not only be used in the area of technical, industrial, composite and medical textiles, but can also be applied to knitted garment design and textile embellishment. 3D shaping within knitted garment parts that can be accomplished with fully-fashioned and seamless knitting technologies has tremendous potential for knitted garment design. Such garments are comfortable and fit to the body, and the process of shaping eliminates cutting and sewing, which reduces material and labor costs and improves quality of products. Because of these benefits, 3D shaped knit garments have increasing opportunities in the knitting industry and should continue to grow.

Review of knit stitch variation and knitwear construction and 3D knit shaping techniques aims to exploit the potential of creative knitwear design. In 3D shaped knitwear design, designers are more of knitwear architects, who have knowledge about materials, machinery technology and stitch construction techniques and are able to translate ideas and new concepts into successful garments

(Mowbray, 2004). The lack of research in fundamental knowledge of knitted structures and stitches prohibits development of unique knitwear products. Designers often do not understand the effects of knit stitch variation and knit structure combination and different machinery techniques on fabric dimensions and knit garment shapes, so that they are not able to apply these techniques in fashionable knitwear design.

2.2 New product development in knitwear industry

The development of new products is necessary to maintaining a healthy organization (Urban & Hauser, 1993). Success of new products not only brings profits and revenue to the company, but also enhances its market share and avoids declination of sales (Cooper, 2001). Many researchers have noted that new product development should be the key strategy to achieve business success (Chapman, Bahill, & Wymore, 1992; Choi, 2006; Ulrich & Eppinger, 1995). New product development has been widely used in various industries, but it is not consistently developed in the fashion industry, especially the knitwear industry.

In the highly competitive knitwear industry, the short fashion cycle, globalization, rapid changes in customer demands and increased labor costs have directed companies to develop new products. Changes in manufacturing methods and processes provide new possibilities to create high-fashion knitwear (Pitimaneeyakul, LaBat, & DeLong, 2004). However, limited literature has been written about the development process for knit garments. The design cycle of a knit garment is long due to lack of effective information transfer from aesthetic design to technical design (Tsigkas & Chatzopoulos, 2009).

This section will briefly review new product development processes in the apparel industry and evaluate current knitwear development models. Also, supported technologies in the knitwear design process are mentioned. Purposes of this literature review are to identify problems existing in current knitwear development processes and to reveal the importance and necessity of developing an integrated fashion knitwear design and development model. Information gathered from current knitwear design models is used as a reference to establish the integrated model.

2.2.1 Apparel development processes

New Product Development (NPD) is defined as “the set of activities beginning with the perception of market opportunity and ending in the production, sale and delivery of a product” (Ulrich & Eppinger, 1995, p.2). Product development processes have been closely examined in past twenty years. Each product development model has different steps. For example, steps in Urban and Hauser’s NPD model (1993) are defined as opportunity identification, design, testing, introduction and life cycle management. According to Crawford and Benedetto (Crawford & Benedetto, 2003), the development process consists of opportunity identification/selection, concept generation, concept/project evaluation, development and launch. Although the product development processes as expressed in published models are varied, key functions in the development models still are marketing, design and manufacturing (Choi, 2006).

In terms of textile and apparel development, the process is different from much industrial product development. As Glock and Kunz (2000, p.85) noted “the textile and apparel product development process require design and engineering to make products serviceable, salable, producible and profitable”. Textile and apparel product development involves not only aesthetic design, which is responsible for fashion trend analysis and market research, but also technical design for style, fit and manufacturing. New product development models in textile and apparel have been reviewed by several researchers. Descriptions and comparison of apparel product development models can be found in the literature reviews of Chapman (2008), Gam (2007), Hatcher (2004) and Pitimaneeyakul (2001). There are similar steps and activities for the textile and apparel development cycle in the models. The steps typically consist of research, design and style development, pre-production of prototype, material sourcing, marketing the line, apparel production and final distribution (Burns & Bryant, 1997; Lamb & Kallal, 1992; May-Plumlee & Little, 2006). These models offering an overview for textile and apparel design are useful in developing cut and sewn knitwear, but they have not provided an adequate foundation for fully-fashioned and seamless knit garment design. Knitwear design and production include textile design, fashion design and prototype production, and the three parts are collaboratively accomplished by three teams: fashion designers, technical designers and knitting machine operators (Yang & Love, 2008). Therefore, the knitwear design process differs from general apparel design processes. A fundamental understanding of the knitwear design and development process is needed.

2.2.2 Knitwear design models

A successful knitwear design not only depends on excellent garment shapes, but it also relies on unique knitted fabric design and high quality in knitting production. Typically, the knitwear development process involves a collaboration between creative designers who create styles, colors and knitwear specifications, and the knitting machine technicians who is responsible for creating detail design in a CAD system and programming the knitting machines to produce finished garments (Eckert, 1997). The interaction between creative designers and knitting technicians requires a good communication among knitwear development teams. Compared to other industry products, the knitwear industry has a relatively short fashion cycle and faces rapid changes in customer demands. Innovative knitting technologies and other computer and information technologies have also influenced the knitwear product development process.

To provide faster knitwear development with fashion styles and good quality, researchers have proposed specific product development processes for knitwear companies. Some models can be applied to any type of knitwear production, such as mass production and mass customization. Other models may be only used in mass customization. With different knitting production methods used in knitwear design, the process for fully-fashioned seamless knit garments is different from that for cut and sewn knit garments. In order to explore potential research areas in knitwear design and establish an effective design model, current knitwear design processes are reviewed as starting points in the research.

The specific knitwear development models differ from company to company, but the typical development processes targeted to the knitwear industry follow similar steps. Eckert (2006), Pitimaneeyakul et al. (2004) and Yang (2010) in their research reviewed and described the typical knitwear development processes in different companies. According to their work, the conventional process is composed of three stages: marketing, design and sampling. Marketing research aims to determine customers' needs and provide the latest information to designers. New ideas and concepts are developed by designers who gather information from marketing, as well as from new yarns and fashion trends (Pitimaneeyakul, LaBat, & DeLong, 2004). After the concepts of yarns and structures are defined, designers will work with technicians to put the concepts into action by swatch sampling (Eckert, 2006). Technicians are primarily responsible for accessing to the CAD system and operating knitting machines (Eckert, 2001). If a prototype is knitted successfully, the design will be sent to production. If not, the design is taken back to remake and is later evaluated, or the design will be discarded. A typical knitwear design process is illustrated in Figure 2.9.

The design process for knitwear is more complex than apparel design with woven fabrics because knitwear design involves knitted fabric design and fashion garment design (Yang & Love, 2008). Knitwear designers typically work on creating design specification sheets, including colors, knitted stitches and garment shapes based on fashion trends and sales and marketing. To create accurate and producible design, designers not only need to know fashion design, but they are also required to have basic knitting knowledge about knit stitches and knitted structures properties. In the knitwear design process, technicians undertake the role of translating design specifications to knitting machine programs. In some cases, the activities of designers and technicians are completed in one company. In others, creative design from idea generation to knitwear specification creation is separated from knitwear production. The two procedures are finished in two different companies.

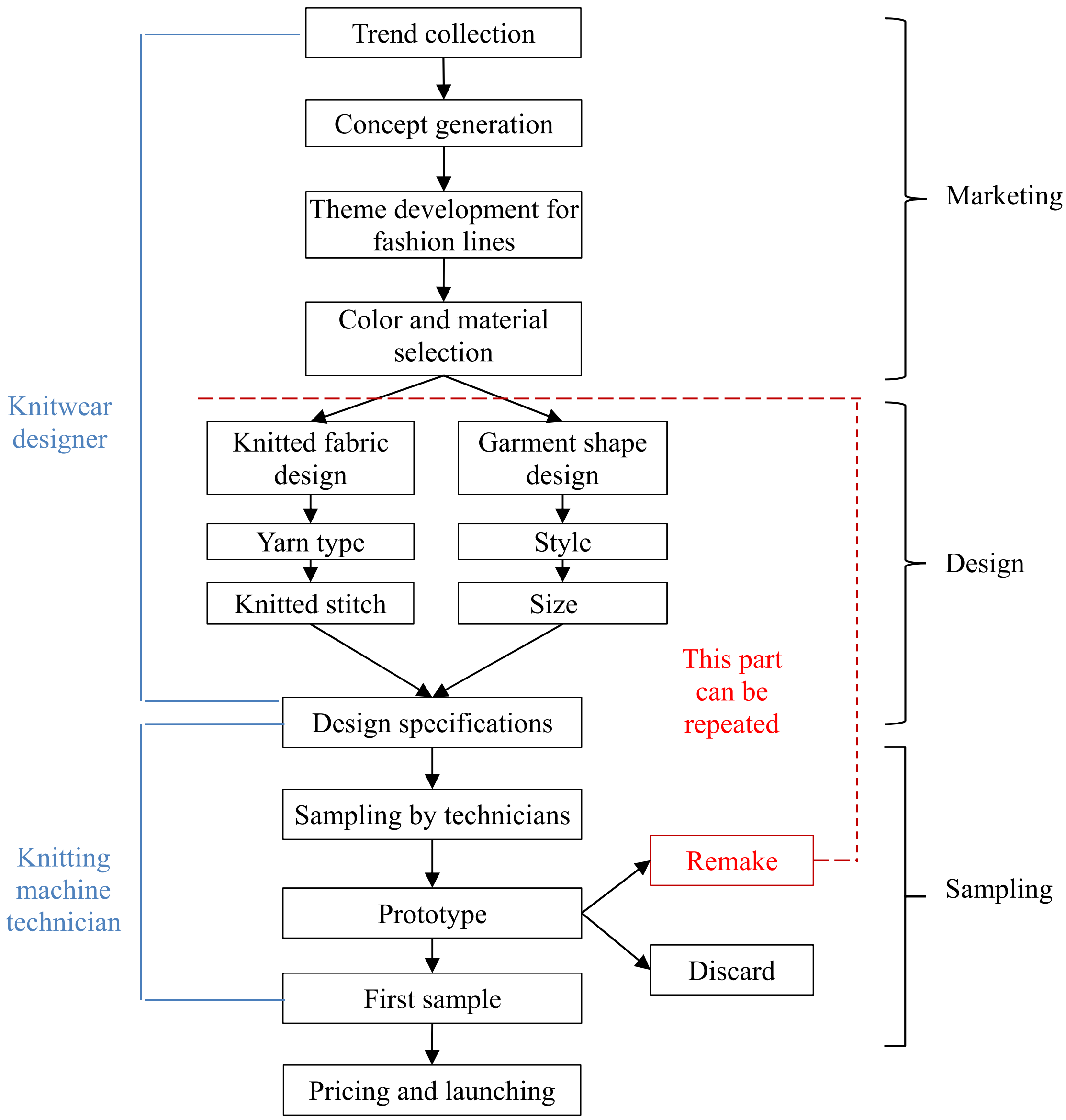


Figure 2.9 Conventional knitwear development process (Adapted from Yang & Love, 2008)

In the conventional knitwear development process, aesthetic design and technical design and production are separated and undertaken by different persons. Knitwear designers are in charge of selecting color, material, shape and creating design specifications. Technicians take over pattern development in the CAD system and prototype production. However, aesthetic and technical design in knitwear cannot be completely separated because the knit garment shape and knitted fabric design interact with each other (Eckert & Demaid, 1997). In the process shown in Figure 2.9, evaluation is only completed after prototype production, where the design and production are almost defined and finished. Rework and discard in this stage not only increases yarn waste and design time, but also increase risks in the design process. For example, from the company's perspective, failure to complete design and production results in losing customers and decreasing profits.

Eckert (2006) described a knitwear design process model with evaluation and modification in each stage (see Figure 2.10). This model uses concurrent design to enhance communication among product development teams and employ designers' and technicians' expertise throughout the process. The model is similar to the one presented previously in Figure 2.9, composed of three macro stages: market research, design and sampling. Differently, phases in each stage move back and forth according to results from evaluation. Communication among different departments is achieved by evaluation in sampling, which occurs after yarn selection, design specifications and prototype production (Eckert, 2006). Prior to sampling, technicians knit samples to make sure the designer's idea is technically feasible. The greatest concern of the designer is whether or not the knitted sample fits within the garment's intended shape (Chapman, 2008). Sampling as an important communication tool in knitwear design is very essential. However, the lack of technical knowledge by designers and misunderstanding of creative design cause repeats in sampling, which result in yarn waste and increased design time. The problematic interaction between knitwear designers and knitting machine technicians can be seen as a communication bottleneck that reduces design efficiency (Eckert, 2001).

Although research in automatically translating designers' concepts into technical language has improved the communication process (Eckert, 2001), the auto interpretation is restricted to knit garment shape rather than knitted structures. As different knit structures used in the design can cause dramatic changes in garment dimensions, the mathematical model without knit structure simulation is not sufficient to accurately connect aesthetic design and technical design. Therefore, research is needed to explore in depth the utilization and implementation of computer technology in knitwear design. Also, knowledge building of knitted structures, yarns and machine operation is essential for structure simulation.

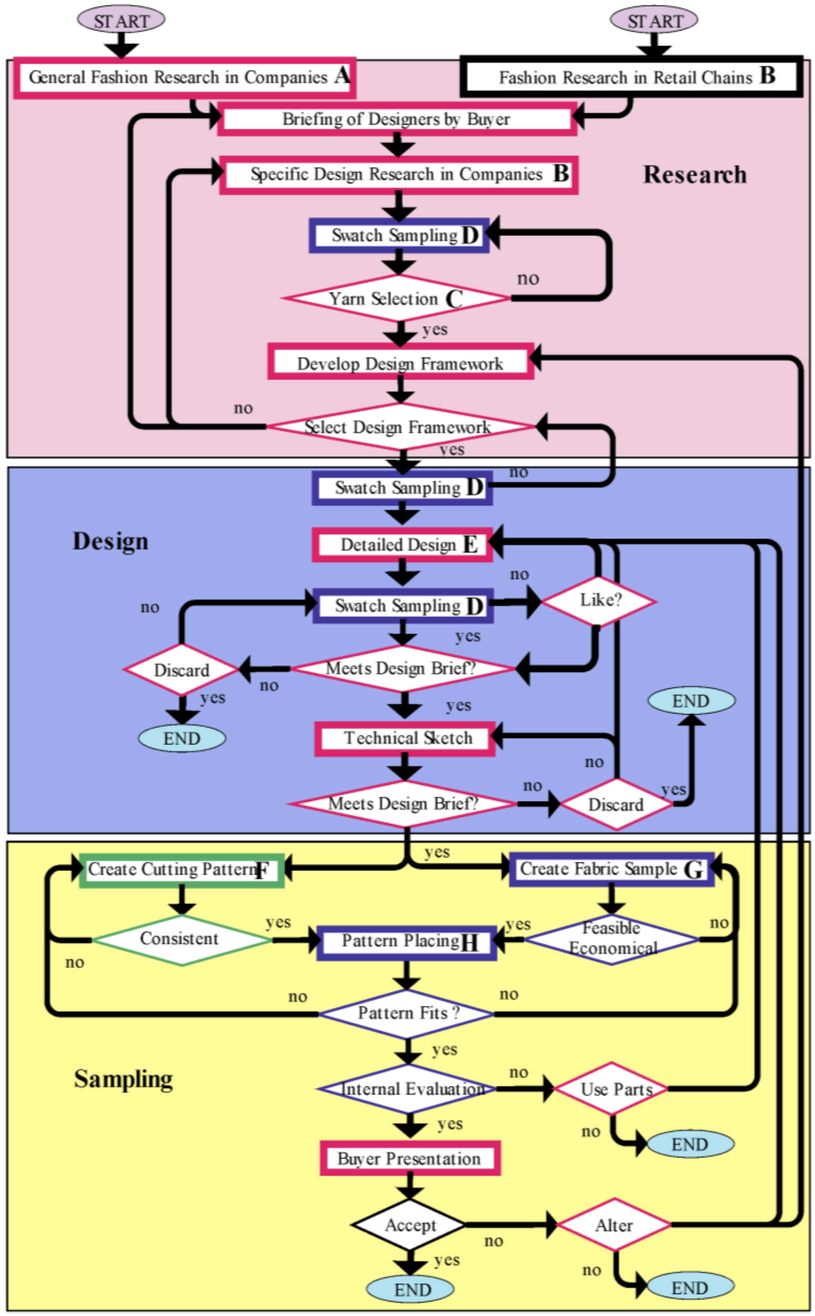


Figure 2.10 Knitwear design process with evaluation and modification (Eckert, 2006, pp.685)

Pitimaneeyakul, LaBat, & DeLong (2004) proposed an optimal product development process for knitwear through observing an actual knitwear development process in the industry. This model was developed based on Urban and Eppinger's New Product Development model (Urban & Eppinger, 1995). As shown in Figure 2.11, this process includes five steps from marketing research, designing if with cost estimation, presenting CAD printouts to customer, sample making to production line. Marketing research in Pitimaneeyakul et al.'s model emphasizes the importance of end user's needs. Usually, companies collect product information from retailers or buyers at department stores and retail stores, not end users, but failure in conducting end user research results in unmarketable products that customers won't purchase. Voice of the customer is a very important part of marketing research. Further, researchers clarified the importance of pre-costing by designers in the development process. Along with creating design sketches and making samples, designers are asked to do pre-costing to know whether the price of a design is out of range. If not, the design can not be send to next step; if the price is too high, designers can discontinue the process, saving design time and reducing waste in sampling. Additionally, Pitimaneeyakul suggested an amplified use of CAD systems and technology in knitwear design. CAD systems can easily and quickly present what designers have in mind. Presentation of a designer's idea helps technicians create technical design and also benefits customers in selecting preferred designs.

Compared to other typical knitwear design models, Pitimaneeyakul's model depicted more detailed phases in the development process. The model emphasized connection of designers and technicians with consumers (end users). Instant presentation of the designer's idea and knitted samples to customers contributes to producing products that are exactly what customers want. This may reduce risks in launching and merchandising. Information gathered from consumers is very useful and critical for a company to produce new products. Also, involvement of customers offers an opportunity for mass customization in the knitwear industry.

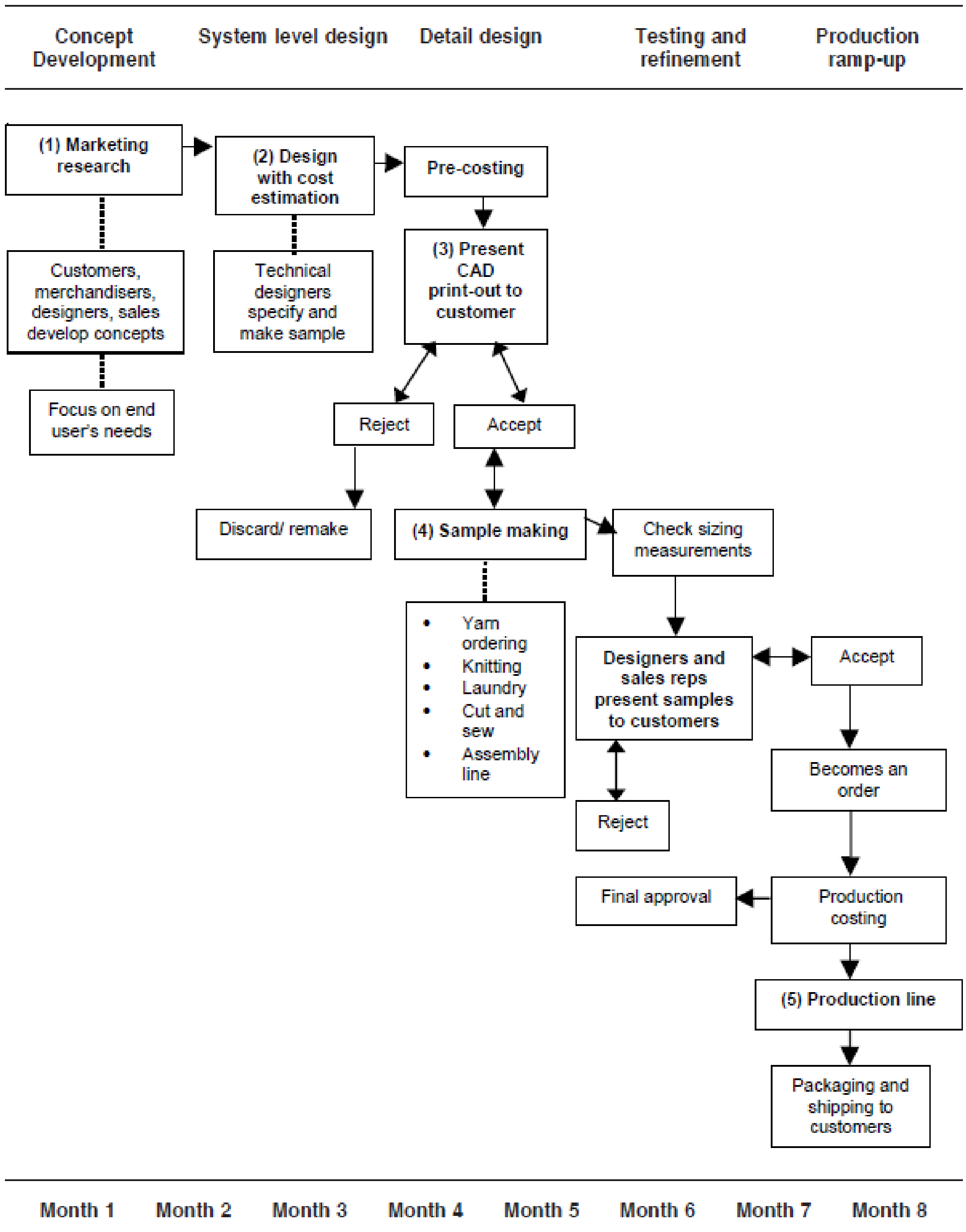


Figure 2.11 Knitwear development process with customers participation (Pitimaneeyakul, LaBat, & DeLong, 2004, pp.118)

Configuration of the development process can be illustrated in various methods, such as linear, circular and branching. The knitwear development processes presented previously are all viewed in a linear format. However, the textile design process often includes forth and back movements and parallel actions, not only linear stages. As Chapman (2008, p.184) stated in her PhD's thesis "the engineered design process for textile placement reflects the definition of an engineered design in that it is an iterative process that starts with set criteria that guide the design and manufacturing parameters from the beginning until the end of the product development cycle", the liner model without constraints and iterative actions cannot contain all criterion and requirement needed between and within each stage of design.

According to Boehm's spiral model, Chapman (2008) developed a theoretical model of engineered design process for placing fabrication properties within the shape of a product. Seamless knitting as an advanced technology in shaping is supportive of engineered designing. An integration process for textile placements was defined in Chapman's research. The model was segmented into four design phases: generation, communication, implementation, and evaluation. These phases are then divided into several activities that occur in each phase. The macro view of the integrated design process provides a comprehensive overview of the entire process and illustrates the complex interaction among the main components in the process.

Knitwear development is a process relevant to both design and manufacturing, so a comprehensive system that integrates design and production is needed to produce a successful product more efficiently and rapidly. The integrated design model developed in Chapman's research is used for textile development, but it can be used as an important reference for integrally knitted garments, particularly knitwear produced with advanced knitting technology.

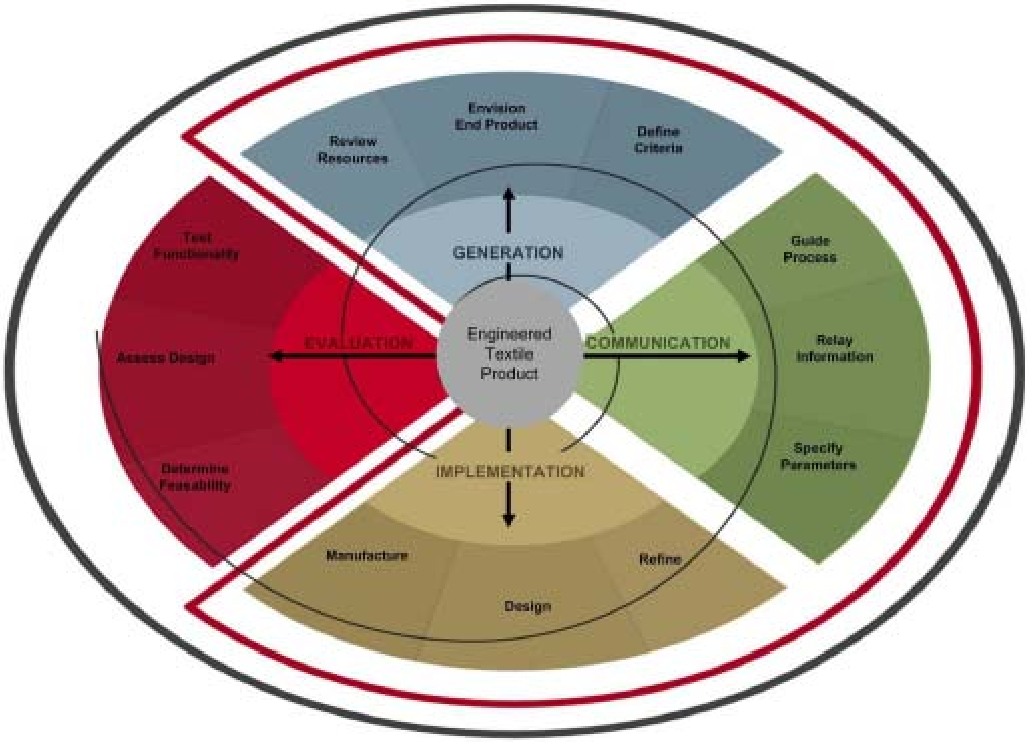


Figure 2.12 Process model for engineering textile design properties within the shape of a product (Chapman, 2008, pp.185)

Generally, the models shown previously can be used for different knitwear types, such as cut and sewn knitwear, fully-fashioned and seamless knitwear. However, because the knit garment shape is formed on the machine, the design and production processes for fully-fashioned and seamless knitwear are more complex and time-consuming than cut and sew. A specific development model for fully-fashioned and seamless knitting should be developed to enhance design efficiency and effectiveness. Yang (2010) mapped the design processes of knitwear produced on different knitting machines, such as circular knitting machines, non-seamless and seamless knitting machines. She also clarified designers' and technicians' and machine operators' activities in these processes. In her PhD research, she summarized the processes and sub-processes in a conventional computerized seamless knitwear design model based on the seamless knitwear development process in a Japanese company, Shima Seiki (see Table 2.2)

Table 2.2 Conventional computerized seamless knitwear development process (Source: Yang, 2008; Shima Seiki, 2008)

	Process	Sub-process
Undertaken by knitwear designers	Identify the design concept	
	Investigate fashion and consumer trends	
	Identify themes for fashion lines	
	Select colors	
	Decide fabric texture and garment shape	
	Create stitch pattern Create garment style	
	Specify design details	
	Complete design specification sheet	
Undertaken by knitting machine technicians	Make texture sample (test piece)	Draw the test piece in CAD system Create data for machine operation Knit texture samples
	Create garment dimensions in CAD system	Crate the garment outline in CAD system Input stitch density and convert into number of stitches
	Create garment pattern in CAD system	Manually drawing or auto-drawing Create data for machine with auto-process Carry the data to machine using portable device
	Knit, check products and complete 1st sample	Garment quality check Washing/steaming Size check Silhouette check on the body
	Production, knitting and shipping	Plan production: in-house, interstate, or overseas Production check, product confirmation & order Product inspection, finishing, shipping

The presented seamless knitwear process is still undertaken by two persons: knitwear designers and knitting machine technicians. Seamless knitwear design is more complicated than apparel design with a cut fabric procedure, because knitted fabrics are designed and produed along with knitwear construction. Designers must have sufficient knowledge in knitting to create accurate and feasible design specifications for technicians. Another problem is the technician's inappropriate interpretation of the designer's idea. Different cultures and backgrounds underlying different roles block communication in the development process. As explained previously, the two activities in knitwear design cannot be separated. Therefore, a critical need exists for collaboration between knitwear designers and machine technicians. Yang (2008) mentioned an alternative for overcoming the communication block in high-fashion knitwear design is to incorporate the roles of aesthetic designers, knitting technicians and machine operators. In Yang's research, she identified a workflow system for knitwear designers to take over roles of knitting machine technicians for 1^{st} sample production (see Figure 2.13). This is the only available model established specifically for seamless knitwear in published academic literature.The workflow enables one person to undertake roles of the designer and the technician, eliminating blocking in communicaiton. Adjustment or improvement of the design is relatively easy due to avoiding the need to explain the idea to others. In this model, procedures from marketing, to design to sampling could be done within one company, which means there is no need to employ technicians or to complete sample making and evaluation with other companies domestic or overseas. This will definitely reduce the time to market, save costs and improve efficiency.

Although the model presented by Yang is useful in developing seamless knit garments and provides an overview of an integrated system for design, fundamental knowledge needed for designers to facilicate the integrated system from idea generation to prototyping is not examined. Addtionally, a knitwear design process often portrays back and forth movements and parallel actions, processes to not occur only a linear format. In Yang's model, the process is exhibited in a sequental process from one stage to the other. Connection and interaction among different stages is not illustrated. Further, this model does not show the detailed evaluation and knowledge needed in the process. Seamless knitting continues to receive attention in the knitwear industry, but lack of knowledge building in seamless knitwear design and inadequate understanding of the design process impede seamless knit garment development.

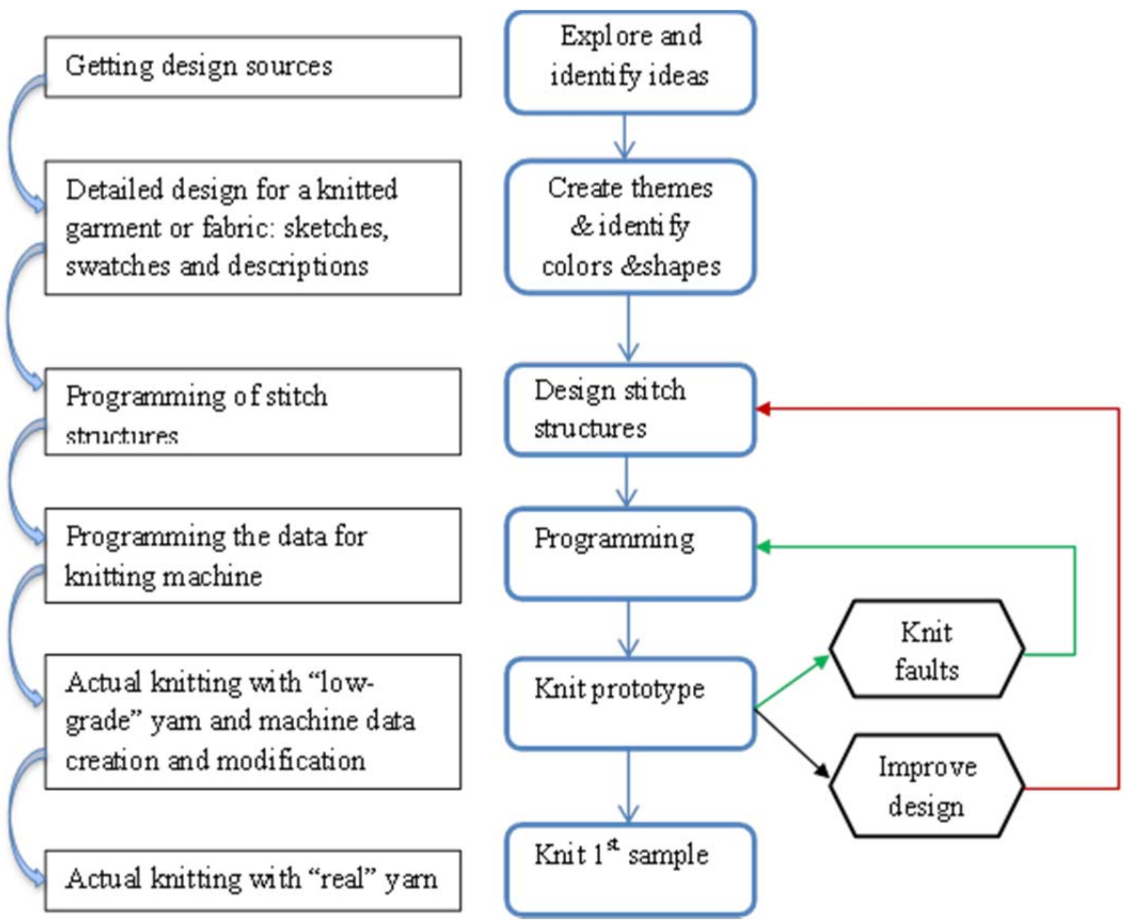


Figure 2.13 Workflow for high-fashion knitwear production undertaken by knitwear designers using Shima Seiki's WG® knitting system (Adapted from Yang, 2008)

Other knitwear development processes targeted to fully-fashioned or seamless knitting are available in mass customization. The development process of custom knitwear is different from the common knitwear development process. Companies in the knitwear industry and some researchers have explored customization in garment knitting, and they conducted different on-demand models. The design processes in these on-demand models involve the concept of allowing one person to complete the procedures from aesthetic design, pattern making in CAD systems, to prototype knitting on the machine. Review of these mass customization processes is used to explore potential methods to enhance communication and improve efficiency. Challenges relevant to the on-demand models are discussed.

In 2005, one of the leading Japanese knitting machine manufacturers, Shima Seiki, opened the first Factory Boutique Shima in Wakayama, Japan (Shima, 2005). After three years, the company added the second boutique in the same city. Shima Seiki's boutique stores have described a business concept of "on-demand" production that combines advanced knitting technology and mass customization on the retail level (Peterson et al., 2011).

In the boutique, the customers work with the personal servers, who can assist them in the entire design process. Customers can search pictures from the fashion magazines as inspiration, or they can try on displayed knit garments to select the styles they like. After customers choose the style, size, colors and materials, the shop assistant will create patterns in Shima Seiki's CAD system and send the designed pattern to manufacturing. According to the level of customization and a customer's selections, the customized knit garment is produced by different knitting methods - cut and sew, fully-fashioned knitting, and 3D seamless knitting. If the yarns and other accessories, such as buttons or labels, are kept on hand, the customized knit garment can be done within one day. Finished knitwear is usually delivered to customers within 10 days. Figure 2.14 illustrates the customization process in the Factory Boutique Shima (Peterson et al., 2011).

This process presented in Factory Boutique Shima is an application of the concept of collaborative customization identified by Gilmore and Pine (Gilmore & Pine, 1997). In collaborative customization, the company and customers work together to identify a customer's needs and create customized products in the co-design system, as illustrated in Figure 2.14. A successful co-design has heavy reliance on cooperation between customers and designers, using various kinds of knowledge involved in knit garment design. Usually, customers do not have enough knowledge of knitting technology and aesthetic design to translate their needs and desires into a concrete knitwear design. Thus, advisement from professional designers and communication with designers become crucial for customers to make decisions. Designers in a co-design process are not just computer navigators, who help customers to manipulate CAD software, but they are also indispensable advisors with abundant knowledge of knitting technology and excellent communication skills (Franke & Piller, 2002). Training of designers in aesthetic design, knitting technology and machine limitations is a chief task of companies. Knowledge built in the training is also useful to improve communication between designers and technicians, because designers with more professional knowledge can create more accurate and feasible designs. From the one whom on companies' perspective, co-design helps them build a learning relationship with customers (Pine, 1993). With the collaboration of customers and trained designers, customers have growing confidence in the company, which contributes to extending potential markets. In the co-design process, the companies will learn more about their customers, and they can use information about customers' preferences and requirements in development of other products.

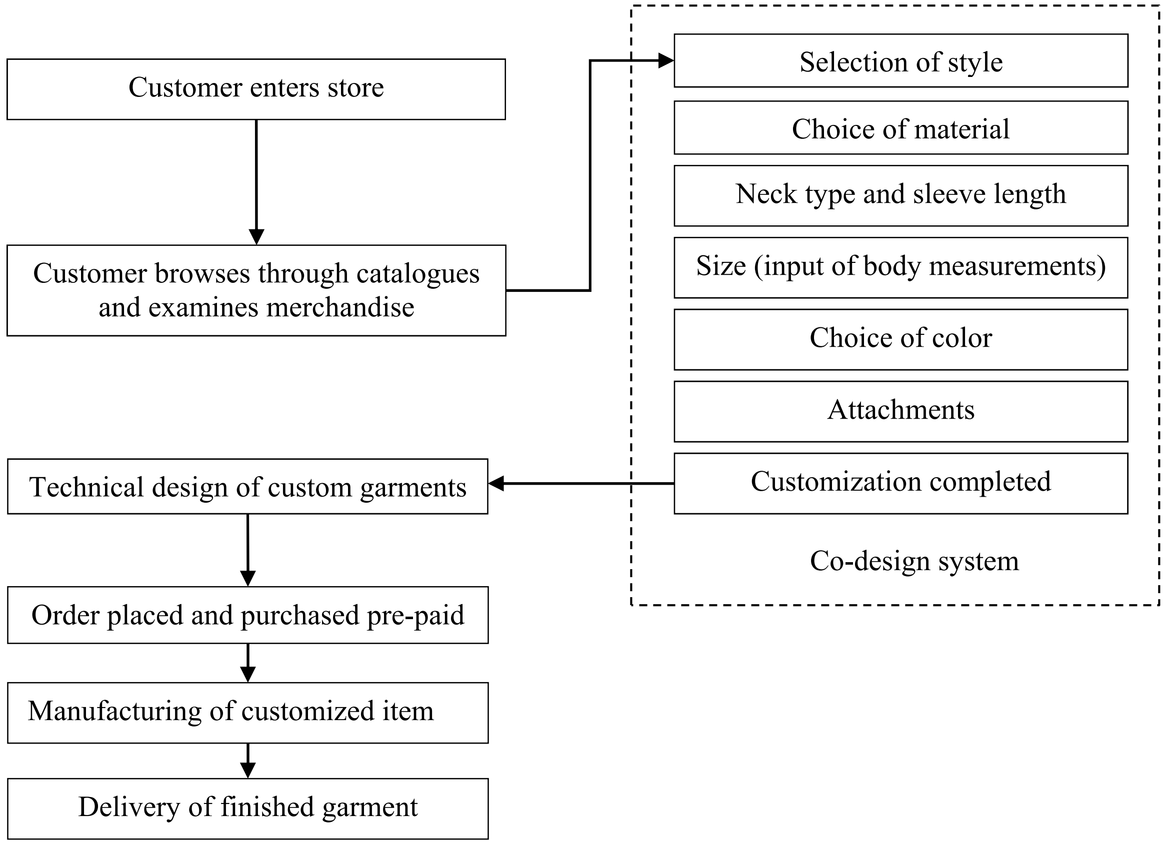


Figure 2.14 Concepts and steps in Factory Boutique Shima (Adapted from Peterson et al., 2011)

Another shop and production concept for knit garment customization called “Knit-on-Demand” was presented in a research project at the Swedish School of Textiles (Larsson, Mouwitz, & Peterson, 2009). This “Knit-on-Demand” model allowed customers to take an active part in the design process and to adapt available knit garment designs based on their requirements. The new concept of knitwear production enhances the ability of fashion knitwear industry to meet customer demands for fast fashion and addresses the problem of obsolete inventory, as all the knit garments are produced when orders are placed (Larsson, 2009). Similar to Shima Seiki’s Factory Boutique, the “knit-on-demand” business model offers customers a special shopping experience that they can design their knitwear with designers. The customized knit garment is based on a pre-designed base style and adjusted to personal size and design preferences (Larsson, 2009; Markwordt, 2010; Peterson & Ekwall, 2007). Figure 2.15 shows the process of Knit-on-Demand, and information regarding each step is presented in the following paragraphs (Peterson & Larsson, 2007):

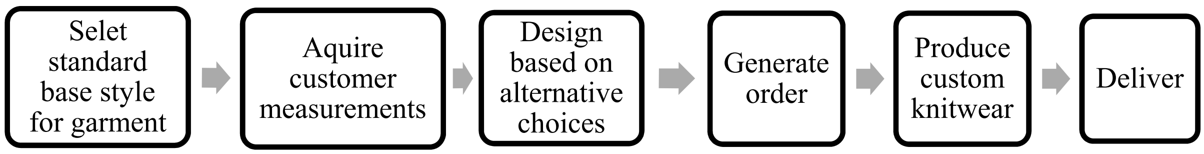


Figure 2.15 “Knit-on-Demand” process (Adapted from Peterson & Larsson, 2007)

The first step in the knit-on-demand process is to select a standard base style for the garment. After taking customers' measurements, designers work with customers to adjust the selected style from standard size to personalized fit. The “knit-on-demand” model has adopted a multiple-choice system, which allows customers to choose between alternatives styles, materials, colors, structures and details. As shown in Figure 2.16, customers have six basic knitted sweater styles to choose along with 16 different colors, buttonholes, stripes and contrasting fabrics. When the customer has finalized the design decisions, the designer assists in finishing the pattern and sending the order to production. In the “knit-on-demand” model, customers can choose not to buy the garment before actual manufacturing. After the payment is received, the order is transmitted to manufacturing. Time from order to delivery is often within two weeks.

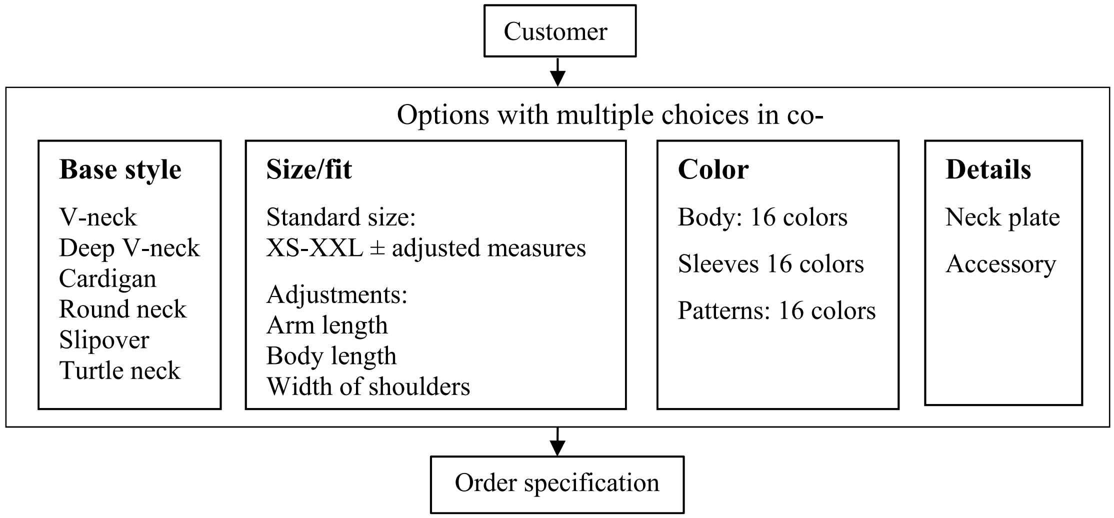


Figure 2.16 Design options in the "knit-on-demand" process (Adapted from Larsson, 2009)

As shown in Figure 2.16, customers can easily select different options and create their customized knit garments. In fact, use of a multiple-choice system is not restricted to mass customization, it will also benefit design processes of mass produced garments. In the process of mass produced knit garments, a multiple-choice system involving diverse options of garment styles, colors, yarns and knit stitch patterns allows designers to combine different choices and create new designs that can be translated into CAD patterns and machine data in a computerized system. In mass production, this will avoid misrepresenting the designer's idea, enhancing communication between designers and technicians, and improving efficiency.

Implementation of a multiple-choice system implies that companies need to identify and develop an appropriate range of basic knitwear styles, yarns, and structure patterns. The first step is to examine their target market to learn about their customers in terms of shopping behavior and preferences. After that, companies need to establish a database or system of choices including garment styles, yarn types and knitted samples with different structures. This process consumes a lot of time and labor and material costs, because companies have to test different yarns and knit abundant samples to build enough knowledge to offer viable options. One potential benefit in building the multiple-choice system is that collecting preferences and requirements of the target market, and building a data base of style, yarn, and knit structure information yields results that can be used to develop mass produced items.

Table 2.3 is a comparison of various features of the knitwear development processes that were reviewed. These features include what roles were involved in the model, the level of collaboration between designers and technicians, whether or not evaluation is completed in every stage, whether or not the functions and knowledge needed in each stage were identified, and the applicability for knitwear categories.

Table 2.3 Comparison of different knitwear development models

Source and Figure number	Model and characteristics	Roles involved	Level of collaboration	Evaluation	Knowledge building	Application
Yang & Love, 2008 Figure 2.9	Conventional knitwear development	Designer Technician	Low	After prototype production	No	All types of knit garments
Eckert, 2006 Figure 2.10	Systematic model for knit products	Designer Technician	Moderate	Every stage	Little	All types of knit garments
Pitimaneey-akul et al., 2004 Figure 2.11	A knitwear development process involved end users and computer software	Customer Designer Technician	Moderate	In few stages	No	All types of knit garments
Chapman, 2008 Figure 2.12	Engineered design model for textiles	Designer Technician	High	Every stage	Some	Engineered knit garments
Yang, 2010 Table 2.2	Conventional knitwear development using seamless technology	Designer Technician	Moderate	After prototype production	Little	Seamless knitwear

Table 2.3 Continued

Yang, 2010 Figure 2.13	Workflow for high-fashion knitwear development	Designer	High due to undertaking by one person	After prototype production	Little	Fully-fashioned and seamless knitwear
Peterson et al., 2011 Figure 2.14	Factory Boutique Shima allows for knitwear in-store shopping	Customer Designer Technician	High between customer and designers	Every step in co-design	No	Custom knit garments
Larsson et al., 2009 Figure 2.15	Knit-on-demand model with a multiple-choice system	Customer Designer	High	Every step in co-design	No	Custom fully-fashioned and seamless knitwear

Comparison of these characteristics reveals issues and problems relevant to knitwear product development. Communication between designers and technicians is the biggest challenge in current development models. Although some researchers have employed computer technology to overcome the communication bottleneck (Eckert, 2001), lack of fundamental knitting knowledge by designers and inadequate understanding of knitwear design hinder the collaboration of designers and technicians. The integrated workflow for high-fashion knitwear established by Yang in her Ph.D. research allows one person to undertake all the roles in the design and production process, avoiding involvement of technicians. This workflow has proposed a new strategy to improve efficiency in knitwear design, but it does not show detailed functions in each stage. Without sufficient understanding of the knowledge needed to implement the model, designers may not be able to successfully execute all aspects of the integrated design process. Although the idea of an integrated design process has been described in Yang's research, no substantial research has been conducted the detailed information and steps in an integration model. The integrated design model developed in Chapman's work (2008) defined the categories and components in the textile design process, but it does not provide sufficient information for knit garment development. Development of the ideal integrated system that incorporates all aspects of knit garment design and manufacturing should be further explored.

Another issue in the knitwear development process is that little evaluation has been focused on assessing the accuracy and feasibility of every selection, such as yarn, knitted structure, stitch pattern design and garment shape selection. A formal evaluation process is only taken after prototype production in most knitwear development models. If the prototype fails to pass the evaluation, it needs to be redesigned from the beginning, resulting in long development delays and poor yields of creating successful products.

Additionally, the multiple-choice system in the on-demand development models allows for automatic generation of knit garment patterns from selected options. This multiple-choice system can be used as an effective tool in co-design of custom knitwear; it can be also applied in conventional knitwear design to improve communication between designers and technicians. Challenges in implementing the multiple-choice system are to build the database including various choices and to update it consistently with fashion trends. Cost to build and update such a system is quite large, because companies must spend a lot on market research and CAD/CAM programming. Market research aims to learn about customers' demands. CAD/CAM programming is used to store the digitalized patterns with different choice combinations. This is an enormous project and requires the extensive involvement of many designers and programmers.

2.2.3 Technologies supporting knitwear development

In the knitwear industry, various mechanical and computerized systems have been developed to create knit garments effectively and efficiently (Yang & Love, 2008). As reviewed in section 2.1 three-dimensional (3D) seamless knitting techniques, which create complete garments directly from the machine, is beginning to affect the knitwear development process. In 3D seamless knitting, the finished garment is constructed during knitting, and it does not require further cutting, sewing or shaping. This 3D seamless knitwear is produced on V-bed knitting machines, which is different from circular “seamless” knitting yielding body size tubes. Seamless knitting on the V-bed knitting machine improves production efficiency, saves material and labor costs, and shortens production time in comparison to cut and sew method (Choi & Powell, 2005). Innovative knitting technology combined with 3D body scanning and an intelligent CAD system will enhance the opportunity for effective knit garment design.

2.2.3.1 **Body scanning**

Fit problems in garments are one main reason that consumers are not satisfied with their purchases. Fit to body shape is the most import feature that consumers want to improve, if they can customize a garment (Lee, Kunz, Fiore, & Campbell, 2002). Body scanning technology has provided several approaches to improve sizing and fit in a customized garment (Xu et al., 2002). 3D body scanning techniques can capture electronically a 3D image of the body, and the scanned image helps designers adjust the garment fit (Istook, 2002). Digital format body scanning data can be automatically transferred into apparel CAD/CAM systems in order to reduce working time and human errors (Istook et al., 2003). Some researchers have created a method to manufacture garment patterns by directly converting 3D scanning measurements into 2D patterns (Choi et al., 2007). Others constructed a body form that represents the scanned body using a number of key measurements from body scanning data (Xu et al., 2002). The created body form would provide exact size information and could be used as a model for garment design. Compared to traditional manual measuring by skilled workers, 3D body scanning more quickly provides accurate measurements of customers. Using measurements taken by a 3D computerized body scanner, designers can easily create appropriate size in knit garment design.

All the body scanning technologies introduced in the cut and sewn garment production process can be used in knitwear design. Some commercial systems are able to translate body size measurements into knitting information. For instance, in Shima Seiki's SDS-ONE design system, size of customers can be measured and input to the computer, and then the system could generate garment panels or complete garment shapes that would be automatically developed into knitted stitch information (Shima, 2012). However, 3D body scanning technology still has limits in knit garment design, because translation of scanned data to cut and sewn garment panels is different from transferring digital measurements to knitted garments. Knitted garment shapes are determined by knitted structures, yarn types and machine gauges as well as machine settings. It will be significant to develop up a system that can automatically transfer body scanned data to knit garment information considering knitted structures, yarns, machine gauges and machine settings. Such a system would not only provide appropriate fit, but also shorten the design time and reduce labor costs in business. Therefore, use of 3D body scanning in knit garment production provides opportunity for further study.

2.2.3.2 **CAD/CAM for knit garment design**

Automation using computers, which can increase production efficiency and reduce production costs, has become a popular method in production processes. In CAD/CAM systems, a design can be generated rapidly and adjusted quickly, and communication among each area in the development process is improved (Istook, 2002). Lu and Wang have developed a computer-aided production system that involves size collection, pattern generation, fabric cutting and sewing, fit testing and final adjustment (Lu & Wang, 2011). The automatic production system enables highly efficient design in apparel, as it integrates all aspects of apparel development. The use of intelligent systems with CAD/CAM could be extended to knit garment production for similar efficiencies.

Main functions of knitwear CAD systems include knitted structure design, knit garment shape design, machine programming and knit garment simulation. In early years, designers needed to manually input knitting needle positions and stitch patterns, which consumed a lot of time in the design process. Modern knitwear CAD systems allow designers to choose patterns and garment styles from an available database, or use software to scan images and convert these scans directly into knitted patterns. Adoption of a CAD system makes it easy to design knit garments with different designs. Advanced knitwear CAD systems also provide visual support in simulating yarns, knitted structures and finished knitwear. Designed knitwear can be evaluated prior to manufacturing. The realistic simulation of knitted products can assist designers in selecting proper yarns and knitted structures. CAD simulation systems have been fully developed in some knitting machine manufacturing companies. Shima Seiki in Japan and Stoll in Germany are two key flat-knitting machine manufacturing companies who dominate the market of CAD software for knitted fashion garments. Shima Seiki's SDS-ONE APEX is well-known CAD software that supports high-quality flat knitting simulations. Patented Shima Seiki technology can use scanned yarn images in virtual simulation, which gives efficient evaluations and shows precise effects of the designed knit garment (Shima, 2012). Another leading company, STOLL, has developed its pattern software M1plus® (Stoll, 2012). In the M1plus® pattern design system, designers easily select patterns in the existing library, and the system is flexible so designers can draw structures themselves. The system provides technical and fabric simulation enabling users to manage their design and receive immediate feedback.

Knitwear CAD systems not only allow designers to specify their design exactly the way they want, but also ensure the efficient production of knit garments. The designed fabric or garment patterns are converted into the correct numbers of stitches based on measurements, and then the stitched patterns are transferred into machine programming (Eckert, 1997). Eckert introduced an intelligent automatic design system that generates technical designs from designers' knitting notations (Eckert, 1997). This intelligent system can give designers technical feedback during the idea generation process, so that designers can express their ideas accurately and create accurate and consistent design specifications that will be sent to technicians. The computer system contributes to overcoming the communication problems between creative designers and technical designers. CAD systems also allow CAM program simulating to check potential mistakes and detect errors before knitting, yielding higher efficiency and productivity.

In knitwear design and production, integration of CAD and CAM known as Computer Aided Knitwear Design (CAKD), potentially revolutionizes the knitting industry (Yang, 2010). Because of modern CAKD systems, knit garments could be designed and produced in a fast and convenient way. The CAKD system enables designers to complete the entire design process from aesthetic design and knitted fabric design to technical design. However, lack of fundamental knowledge in knitting technology by designers and insufficient understanding of the knit garment design process in the CAKD system always prohibit CAD and CAM systems from using in knit garment design and development. A database providing appropriate information of stitch structures and yarn types and machine settings can support CAD and CAM systems to adjust patterns and products for changes. This will significantly improve design efficiency and reduce time.

2.2.3.3 **Virtual simulation**

Advances in computer technologies have resulted in software development for realistic human motion animation and fabric drape for the virtual catwalk. Major software companies in the apparel industry are developing 3D virtual avatars to simulate garments (Watkins, 2006). Virtual try-on technology enables designers to simulate the garments on 3D mannequins or avatars (Cordier et al., 2001). A virtual garment design and simulation system presented by Durupinar and Gudukbay allows users to make changes and adjust fitting on the virtual garment (Durupınar & Gudukbay, 2007).

As Volina and Magnenat-Halmann (2000) described, the approach for garment simulation is inspired from the traditional garment making method from two-dimensional (2D) patterns to three-dimensional (3D) forms. In a 3D garment simulation, edges of 2D patterns are virtually sewn together, and the stitched 3D shaped garment is positioned on a 3D avatar. For 3D visualization of knit garments, cut and sewn or fully fashioned knitwear can be simulated by current simulation systems as they are sewn from cut or shaped knit garment panels. Shima Seiki, a Japanese knitting machine company, has developed 3D simulation in their CAD system (Shima, 2012). In Shima Seiki's system, an original 3D model can be created based on consumers' body measurements, skin color, hair color and hairstyle, etc. Simulated knit garment panels are first placed around the 3D model. They are sewn together and draped onto the body. But this method may not be suitable for seamless knit garments assembled without cutting and sewing. The seamless garment is knitted and shaped on the machine, and there is no need to sew garment panels. With current technologies, simulation of seamless garments is still challenging. No simulation system was found that enables users virtually to get dressed in seamless garments, but the simulation of seamless knit garments is essential to successful design. Seamless knitting creates a ready-to-wear garment directly from yarns, so size and shape are decided before knitting. If the finished knit garment does not meet design specifications, designers will spend a lot of time modifying the pattern and reknitting the entire garment. Adjustment of seamless knit garments after production wastes time and increases labor costs and yarn costs. Virtual simulation of seamless garments becomes necessary for designers to know the appearance and fit prior to production.

Another challenge for knitwear simulation is visualization of knitted fabrics with different knitted structures. Although current virtual technology can simulate patterns, structures and yarn geometry, the complex behaviors such as shrinkage and elasticity of knitted structures are not fully investigated. It is still difficult to evaluate knit garment dimensions with different structures due to the lack of fundamental research in effects of knitted structures on garment shaping. Number of stitches and types of knitted structures in the garment influence the knit garment dimension. Even with the same number of stitches, different knit structures lead to varied garment dimensions. If the virtual simulation for knitwear failed to feature the changed size and shape caused by different structures, designers could not accurately evaluate knitwear fit to the body. This may cause redesign of the pattern and reproduction of the knit garment, which wastes yarns and increases time in design and production. Therefore, a computer system that could provide complete information regarding influence of knitted structures to achieve proper garment size would be necessary.

2.2.3.4 **Flat/V-bed knitting technology**

Technology of knitting garments on V-bed machines has gained significant commercial acceptance in the market. Depending on different types of machines used in a company, knit garments can be produced by different methods including cutting and sewing, fully-fashioned, and seamless knitting. These production methods were introduced in detail in section 2.1.2 knit garment construction.

3D seamless knitting on flat/V-bed knitting machines is comparatively new technology in terms of application to fashion apparel, and sales of seamless products represent less than 5% of the entire knitting machinery market (Wilson, 2008). With improvements in machines and software, manufacturers and consumers will subsequently accept this knitting technique. Although this technology has vast potential in customized design, little literature is available, and most focuses on technical issues, rather than design or fashion aspects (Broega et al., 2010). One serious problem inhibiting knit garment creation is communication between designers and technicians (Eckert, 2001). Complexity in CAD/CAM programming of seamless products causes increased challenges in collaboration. More requirements exist in the design of seamless garment shapes and knitted stitch patterns as compared to cut and sew knit garments. Designers must have sufficient understanding of principles and limitations in seamless knitting. Technicians are also required to discover potential techniques to produce unique garments by testing different knitting possibilities. In order to address these problems and provide opportunities to the knitwear market, it is necessary to study the knitwear design and development process with 3D seamless knitting technology in detail in fact. Examination of the process should include not only the steps of the process but also the supporting knowledge and the evaluative procedures required for successful application.

2.2.3.5 **Other potential methods for knit garment design**

Aesthetics of knitted garments can be further enhanced with the use of textile printers and embroidery machines. A recently developed inkjet printing system is not only able to print on circular knitted fabrics but also on flat-knitted fabrics and finished garments (Gupta, 2006). After knitted fabrics are finished on the machine, they could be printed on the inkjet printer, or be embroidered on the computerized embroidery machine. One example of using printing technology with knitted garments is the Japanese design company Grace International (Peterson & Ekwall, 2007). This company produced knitted garments and printed them with colorful patterns. Because printing and embroidering are flexible to use and can quickly enhance aesthetics of products, they are viable and effective methods to decorate knitwear. In a business aspect, these methods can help companies to increase market share, because knitted garments with personal logos and images could be more attractive than regular knits in the store.

2.3 Summary of Literature

Rapid changes in fashion trends and consumers' requirements increase emphasis on fast and unique fashion. Technological advancements in knitting, body scanning, virtual simulation, and CAD/CAM have provided opportunities to increase production speed and efficiency and design innovation. One factor hindering the use of advanced knitting technologies and other computerized technologies in knit garment creation is the lack of fundamental knowledge in garment knitting. The shape of fully-fashioned and seamless knit garments is not only determined by shaping techniques, but it is also influenced by knitted structures, stitch patterns, yarn used and finishing methods. As the

3D shaping techniques introduced in section 2.1.3 demonstrate, there is abundant potential in shaping for shaped knit garment design. Because little research has been done in exploring effects of different knit structures, yarns and finishing on knit garment dimensions, designers have missed opportunities to create unique design and exploit the potential in knitwear development.

Another problem of incomplete utilization of the advanced technologies in knitwear design is insufficient understanding of the design process. Specific design and production processes for fully-fashioned and seamless knit garments are practiced in knitwear companies, but little documentation can be found in academic literature. Although several researchers have studied knitwear product development, most of that work focuses on conventional knitwear design not specific for fully-fashioned and seamless knit garments. These models reviewed in the previous chapter are useful in achieving fundamental understanding of the knitwear development process and providing an overview of the entire process. However, they fail to provide a comprehensive explanation of detailed information required in each stage, such as knowledge needed to implement the model and criterion used to assess success of the stage in developing a well-designed product. A critical need exits for examining the fully-fashioned and seamless knitwear design process using advanced technologies.

Further, a big challenge in current knitwear development models is communication among different development teams. Typically, designers are in charge of idea generation, color and yarn selection, garment style development and stitch pattern design. Activities of the technician's role include working with designers to create design specifications and producing prototypes and executing final production. According to Eckert (2001), the lack of technical knowledge by designers may lead to inaccurate and inconsistent design; technicians who have little background in aesthetics may misunderstand the designer's idea but create the product based on their own interpretation. The poor collaboration of designers and technicians results in unmarketable products and waste of time and materials. Innovative knitting technology such as integral and complete garment knitting has connected designers and technicians with the knitwear production (Lamar, Powell, & Parillo-Chapman, 2010). Computerized design and manufacturing systems and automatic simulation enables one person to accomplish all phases from style development, yarn selection, pattern design to production. Integration of aesthetic design and technical design requires designers to master technical knowledge and have the ability to fix problems in production. Complexities of digital pattern design in CAD systems and machine data programming increase skill requirements. However, there is no recognized system with detailed information for producing knit garments that integrates yarn selection, knit structure design, production and finishing. An integrated framework enabling yarn and color selection, design of structure patterns in a CAD system and production of samples and prototypes on a knitting machine is necessary to create unique design and realize the expanding opportunities for knit garments. In order for designers to implement the integrated model, basic research is needed to develop an expert knowledge base incorporating yarn, knitted structure, and production requirements and finishing.

3 Research objectives

Review of literature in the areas of advanced knitting technology and other computerized technologies demonstrates expanding potential in fully-fashioned and seamless garment knitting. However, the lack of a well-developed, readily accessible knowledge foundation that includes yarns, knitted stitch patterns, knitted structures, and knitting production prohibits potential opportunities from being fully developed in unique knitwear creation. Inadequate understanding of the shaped knitwear design and development process is another impediment in design and production of integral knit garments. The intent of this research is to establish an integrated model for fully-fashioned and seamless knit garments that incorporates all aspects of design and production such as yarn type, product shaping, knitted structures, machine operation, garment dimensions and finishing.

As shown in Figure 3.1, to achieve the goal, this research is carried out in three stages: (1) development of a reference library to investigate relationships between knit shaping techniques and knitted fabric dimensions; (2) case studies to establish a preliminary integrated model; (3) in-depth case studies and expert interviews to validate and refine the model. All of the data gathered regarding knitted structure design, garment shaping and machine settings in the three stages will be used to build the reference library to support implementing the integrated model. Objectives for each stage are as follows:

1) The objective for stage one, reference library development, was to investigate effects of different shaping techniques on knitted fabric dimensions. Literature reviewed in the previous chapter showed various opportunities to change knit garment shapes and enhance fabric aesthetics through knitted structures manipulation. However, few shaping techniques are fully used in current knitwear design, because little research has focused on how these shaping techniques influence dimensional properties of knitted fabrics. Findings from these fundamental studies will provide a basis for designers to select

proper knitting techniques to achieve the desired design. These results will be also useful for beginners to build their knowledge in knitting. One further benefit is the potential to improve fit and shape of created knit garments by applying the information contained in the reference library in garment shaping.

2) The objective for stage two was to establish a preliminary integrated model for shaped knit garment development through several case studies. Emerging new knitting technologies, such as integral knitting and complete garment knitting, provide a significant evolution in knitted product development. However, the new knitwear product design and development process has not evolved with developing technologies and the changing market. Current knitwear development models focused on general processes for cut and sewn products, but few explored the use of integral knitting and other component technologies in knitwear design and development. Additionally, the design process and knitwear production are always separated in existing models. This can lead to difficult collaboration between designers and technicians. Further, limited research emphasizes detailed concepts and fundamental knowledge needed to implement the process. The second stage of the research aimed to establish an integrated model that demonstrates an effective knitwear design and development process and the knowledge needed to support it. Data collected in this stage also enriched the reference library built in stage one.

3) The objective for stage three was to validate and refine the preliminary model. Another objective in this phase was to expand the reference library to support researchers and designers working in knitwear product design and development using the work of previous stages as well as this stage. An in-depth case study approach was used to test and validate the model developed in stage two. Further validation of the model was obtained through interviews with experts who have abundant knowledge and experience

in knitwear product development and related knitting technology. The final integrated model for shaped knit garment design would involve knowledge building and evaluation and the context of the detailed design and development process.

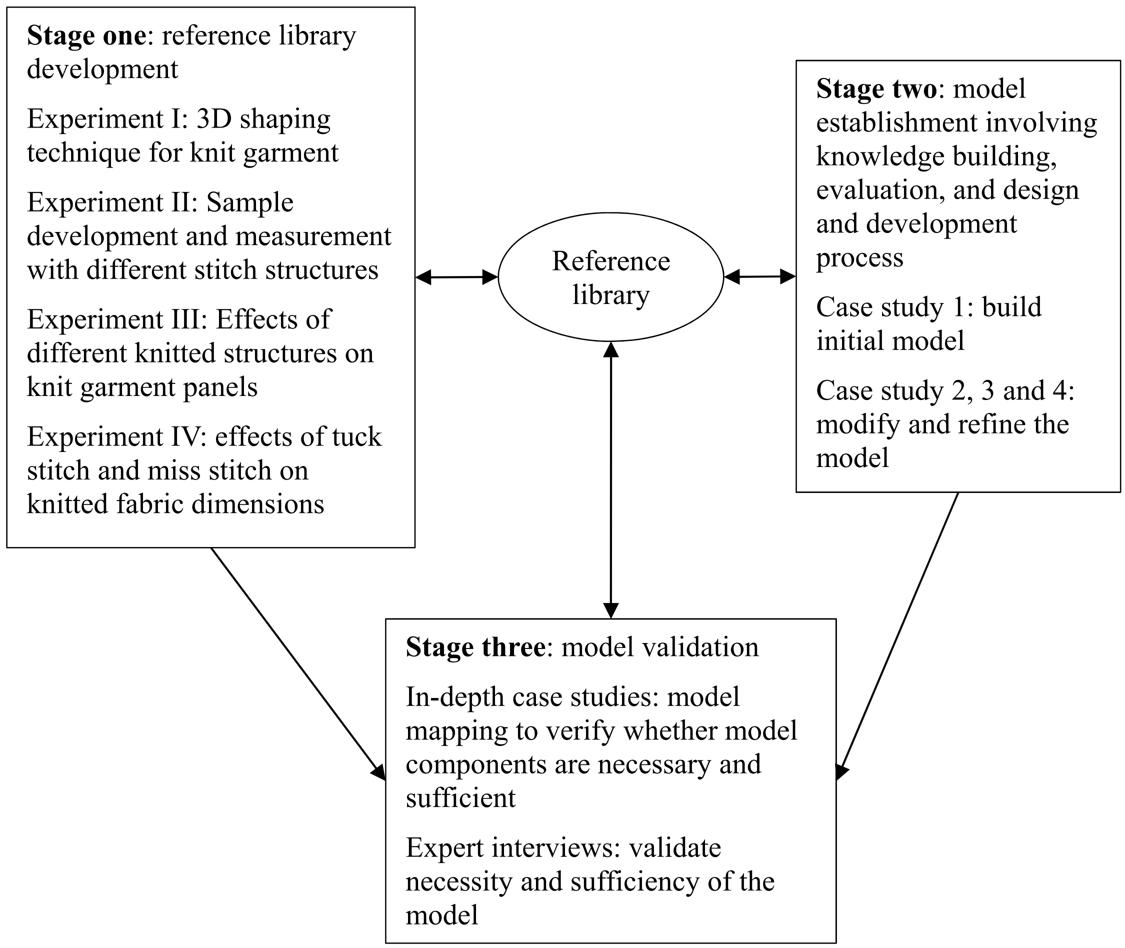


Figure 3.1 Research methodology structure

4 Research methodology and results of stage one: reference library development

To investigate the influence of different shaping techniques on knitted fabric shapes and dimensions, four experiments were employed: (1) 3D shaping technique for knit garments; (2) Effects of different knitted structures on knit garment panels; (3) Sample development and measurement with different stitch structures; (4) Effects of tuck stitch and miss stitch on knitted fabric dimensions.

4.1 Yarn and Machine and CAD software

All of the samples in the four experiments were knitted of 100% 8/2 count cotton yarns. A pilot study was conducted to test different yarn sizes of 14/1 c.c., 16/2 c.c., 20/2 c.c. and 8/2 c.c. by knitting samples of single jersey, 2×2 rib and interlock. Results of the pilot study (see Appendix A) show that, of these, one end of 8/2 cotton count yarns was the optimal choice for the 7 gauge V-bed knitting machine to be used in this work. The yarn pilot study also contributed to another research study conducted in the scope of the same project with this research (Ruan, 2011). In terms of different knitted structures with the same yarn type, the proper loop length varied. Usually, for fabrics knitted with one end of 8/2 c.c. yarns, the optimal loop length for single jersey is 9.5 mm, the optimal loop length for 2×2 rib structure is 10.00 mm, and the optimal loop length for interlock is 10.5 mm.

Shima Seiki's SDS-ONE KnitPaint software and a Shima Seiki V-bed knitting machine (SES124-S 7 gauge) were employed to create digital patterns and knit samples. In Shima Seiki's CAD software, knitted stitches are represented by different colors with specific color numbers. Designers can create various knitted structure patterns by drawing knitted stitches with different colors. As shown in Figure 4.1, one small square represents one stitch; red squares mean front knit stitches and green squares mean back knit stitches. The digital pattern in Figure 2.3 visually illustrates how to alter front knit stitch to back knit in a purl pattern.

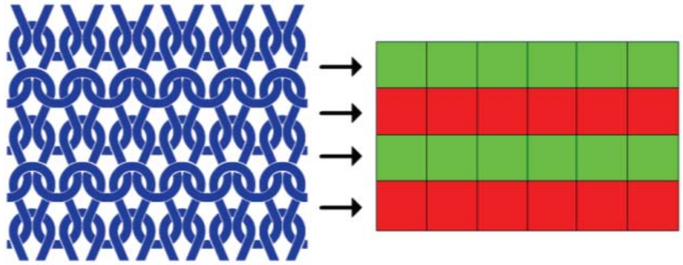


Figure 4.1 Stitch pattern and digital pattern (Source: Shima, 2004a)

The computerized v-bed knitting machines cannot work with only the digital stitch patterns. The machine settings called "option line bars" in Shima Seiki's system are needed to correctly control the knitting machine. "Option lines" are visually located on either side of the stitch pattern as shown in Figure 4.2. The options mainly include loop length for different courses, machine running speed, and take down force on the fabric. Other settings such as carrier movement and toggling on/off the digital control system (DSCS) are also controlled by the "option line bars".

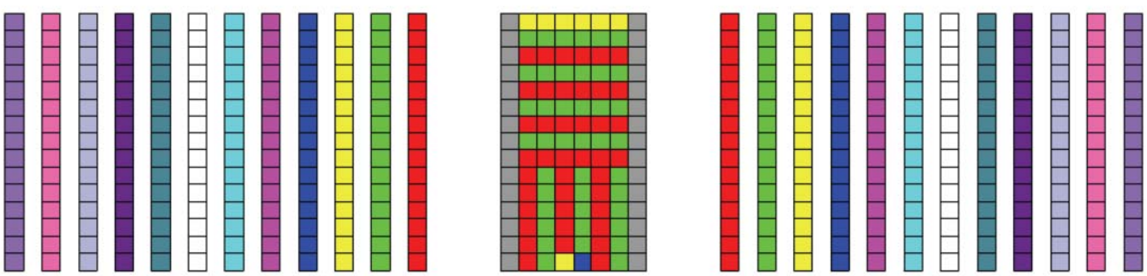


Figure 4.2 Option line bars in Shima Seiki's CAD software (Source: Shima, 2004a)

Knitted stitch and machine setting information can be recorded on a disk as knit data. Files including knit data are the connection between Computer-aided Design (CAD) and Computer-aided

Manufacturing (CAM). The machine used to knit samples in the four experiments was Shima Seiki's SES124-S 7 gauge V-bed knitting machine. This machine has great flexibility in combining knitted structures and changing stitches due to easy individual needle selection and needle bed racking. Table 4.1 describes specifications for the Shima Seiki's V-bed knitting machine.

Table 4.1 Shima Seiki's fully-fashioned knitting machine specifications

Machine type	Computerized V-bed knitting machine
Machine model	SES124-S fully-fashioned machine
Machine gauge	7 gauge
Needle type	Latch needle with transfer spring
Knitting speed	Up to 1.00 meter per second Speed of knitting cable structures and transferring stitches is smaller than regular knitting
Knitting width	About 47 inches (120 cm, 338 needles)
Take down tension	Regular knitting: 30-45
	Stitch transferring: 30-40
	Bind-off kitting: 45-50

4.2 Experiment I: 3D shaping technique for knit garment shaping

The work in this section was presented in a poster presentation at the International Textile Apparel and Association (ITAA) 2012 annual conference. As the literature review in section 2.2.2 indicated, there is great potential in shaped knit garment design to form three-dimensional shapes within garment parts. Although various studies are published on design and techniques of fully-fashioned and seamless knitting, very limited research has been carried out to exploit 3D shape knitting techniques for knit garments. One objective of this experiment was to explore the possibility of forming a predictable 3D shape using knit shaping techniques like course shaping with held stitches (Spencer, 2001) to deliver similar effects to bust darts in the cut and sewn method. To relate results to the final quality of 3D knit garments, this study also investigated the impact of finishing on the resulting three-dimensionally shaped knitted fabrics. A theoretical basis for creating different shapes of 3D fabrics in a predicable manner is proposed based on results of this work. Although body scanning techniques provide accurate data for garment design, and CAD systems are capable of simulating 3D products, no proper method or framework is available for designers and technicians to predict the fitting geometry or simulate dimensions of 3D knitted fabrics, such as angles and dart length of the shaping section.

4.2.1 Research method in Experiment I

As reviewed in section 2.1.3, course shaping with held stitches is the main technique for generating 3D shaped knitted forms. Course shaping is easy and flexible to operate, and it has fewer requirements for machine and pattern design compared to other shaping techniques such as wale shaping and changing yarns. During the knitting sequences in course shaping, the number of working needles is altered from course to course (Spencer, 2001). This can lead to changes in knitted direction and form a 3D shaped area in fabric. With the knitted structure held constant, the amount of shaping is determined by how many stitches are suspended over how many courses. The area shaped by the course shaping technique has a similar 3D effect to a sewn bust dart in cut and sewn garment panels. The dimensions in the shaped area are influenced by layout of the shaping dart. As shown in Figure 4.3, two methods were used to create a dart in this experiment. One is a symmetric layout with a single dart, and another method was to place two parallel darts with the same theoretical angle as the symmetric dart.

Method 1 Method 2

Figure 4.3 Digital patterns of two methods for dart placement (Created in Shima Seiki's SDS-ONE)

In the experiment, the number of held stitches in one shaping sequence was decreased or increased over every two courses. The number of held stitches in one shaping sequence and the dart placement method were two factors that influenced dimensions of the 3D shape. Theoretically, the angle (2α) and the length (L) of the 3D shape could be calculated by equations:

$$\text{Theoretical angle: } 2\alpha = 2 \times \tan^{-1}\left(\frac{C/cpi}{w/wpi}\right) = 2\tan^{-1}\left(\frac{wpi}{cpi} \times \frac{C}{W}\right) \quad (4.1)$$

$$\text{Theoretical length: L} = \sqrt{\left({}^{C}/_{cpi}\right)^2 + \left({}^{W}/_{wpi}\right)^2} \quad (4.2)$$

Where, cpi is course density and wpi is wale density

C represents number of courses in the shaped area

W represents number of wales in the shaped area

The sample design is shown in Figure 4.4. A knitted panel with 10 inches width and 12 inches length was chosen for this study. The number of wales and courses is calculated to be 110 wales and 180 courses based on 11 wales per inch (wpi) x 15 course per inch (cpi) measured in the relaxed state after home laundering cycles, as determined in pilot work shown in Appendix A. To compare the dimension of 3D shaped knits and darts created in cut and sewn garments, the theoretical angle of the shaping section was controlled within 20 degrees and 60 degrees. When the number of wales in the shaped area remained the same at 60 wales, the range of theoretical angles determined the number of held stitches, which could vary from three to eight in one shaping sequence. The number of courses in the shaped area decreased along with changes in the number of held stitches from three to eight in one shaping sequence. Six values for the number of held stitches and two dart placement methods yielded twelve treatment combinations. For each treatment, three samples were knitted. One entire replication of all 12 treatments was knitted before starting on the second and third replication. The order of treatments was randomized within each replication. In each sample, as shown in Figure 4.5, measurements of shaping angles at apex points and the shaping length from apex to side were collected. The shaping angle was represented by changes in wale loop direction, as the angle α shown in Figure 4.5. Shaping lengths were also measured in this experiment, which is the distance from the dart apex to the side of the panel.

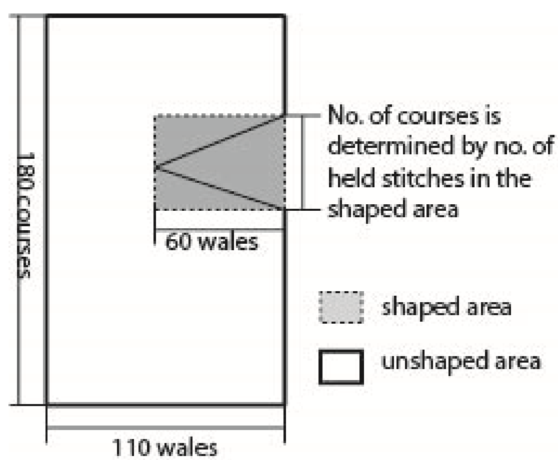


Figure 4.4 Sample design

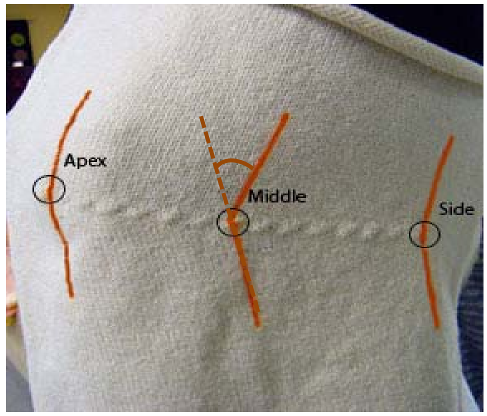


Figure 4.5 Measurement of shaping angles along the shaping line

Since finishing is an important part of the knitting process, and loop density also influences the 3D shape, knitted samples were laundered to identify the impact of finishing on the shaped fabrics and to better relate results to actual end products. The laundering procedure was based on AATCC Test Method 135-2004. Course and wale shrinkages were calculated by changes in wale and course density of the knitted fabric in the completely relaxed state after five cycles of washing and tumble drying (Heap et al. 1983). Consequently, samples were measured twice, once after knitting on the machine and then in a complete relaxation state after laundering. Data collected for each sample condition included theoretical angle, actual angle, theoretical length of the shaping line and actual length, and course density and wale density in unshaped and shaped areas. The main purpose of this experiment is to verify whether theoretical calculations can reliably predict actually 3D shapes, so differences between theoretical and actual values of the shaping angles and the shaping length were tested. The following model was used to estimate effects of the number of held stitches and the layout of dart shapes on the deviation of 3D shapes from the actual value from the theoretical value.

$$Y_{ijk} = \mu + B_i + \alpha_j + \beta_k + (\alpha\beta)_{jk} + \varepsilon_{ijk}$$

Where, $\varepsilon_{ijk} \sim iid\ (0, \sigma^2)$

Y_{ijk} is the difference between actual and theoretical value;

μ is the overall mean of differences between theoretical and actual values;

B_i is the block effect at level i, i= 1, 2, 3;

α_j is the effect of the number of held stitches at level j, j = 1, 2, 3, 4, 5, 6;

β_k is the effect of the layout of dart shapes at level k, k = 1, 2;

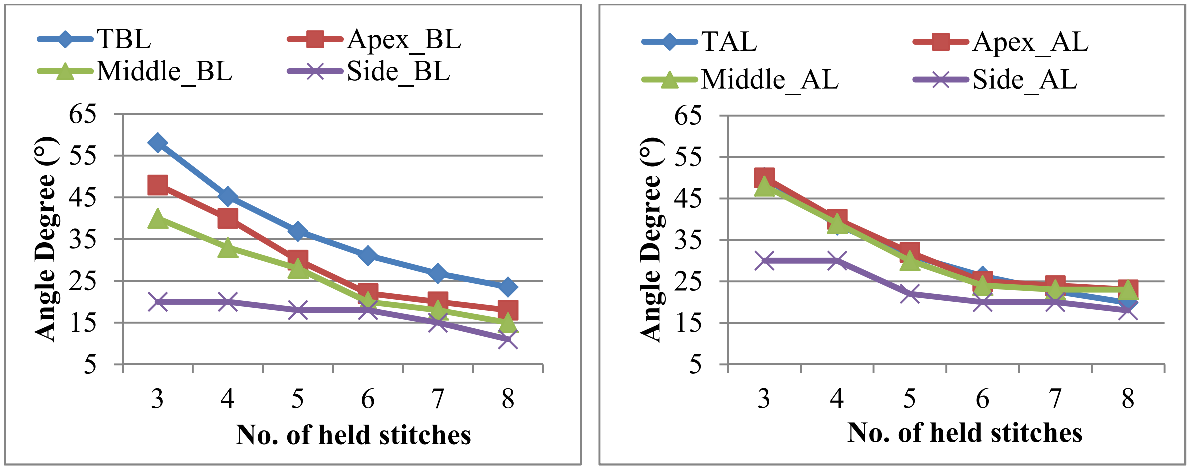
$(\alpha\beta)_{jk}$ is the interaction effect between two factors.

4.2.2 Results of Experiment I

4.2.2.1 **Shaping angle**

According to the equation 4.1, shaping angles are determined by loop density and number of held stitches. In terms of theoretical calculations, loop density in the shaped and unshaped area is constant. The theoretical angles were only changed by number of held stitches in the shaping area. The more held stitches involved in a shaping sequence, the smaller the theoretical shaping angle is. Preliminary results in shaping angles were consistent with theoretical calculation.

As shown in Figure 4.6, all actual shaping angles followed the trends predicted by mathematical calculations, especially after laundering, but shaping angles at the three points differed. Although the actual angle at the "side" point is significantly different from the theoretical value, less than seven degrees difference after laundering on the outside edge of the shaping area will not have a practical influence on either the shaped area in a knitted garment or the fit of a shaped garment. Thus, in the experiment, only shaping angles at the apex point were analyzed.



(a) Before finishing (b) After finishing

Note: TBL is theoretical value before laundering
TAL is theoretical value after laundering

Figure 4.6 Shaping angles with different number of held stitches before and after finishing

According to ANOVA of differences between actual and theoretical shaping angles at the apex point, there was no block effect ($F(2, 22) = 0.26$, $p = 0.77 > 0.05$), and the number of held stitches in the shaped area was the only factor that showed a significant effect ($F(5, 22) = 56.74$, $p < 0.0001$). The layout of dart shapes has no effect on the deviation of actual shaping angles from theoretical values ($F(1, 22) = 1.46$, $p = 0.24 > 0.05$). This means that design of a symmetric single dart can create the same effect as the design of parallel double darts. However, one benefit of two darts shaping with small angles is improved fit to the three-dimensional body. The 3D shape created with two darts has the same shaping effect but a little smoother curve than the sharp angle given by one big dart.

Mean difference between actual and theoretical shaping angles at each level of the number of held stitches are shown in Table 4.2. Besides the level of 3 held stitches, Least-square Means (LSMEANS) at other levels all showed that they did not equal to zero. This indicated that statistically significant differences between theoretical predictions and actual measurements of shaping angles existed. The difference between theoretical and actual values grows when the number of held stitches in one shaping sequence is increased. However, the biggest difference was only 1.1 degree, which would be not substantial enough to change the 3D shape in practice. Therefore, theoretical calculations are able to predict the shaping angle of a 3D shape prior to production.

Table 4.2 Effects of number of held stitches on differences between theoretical and actual shaping angles at Apex

Number of held stitches	Mean difference * between actual and theoretical shaping angle (degrees)	Pr > |t|
3	0.043	0.39
4	0.27	<0.0001
5	0.29	<0.0001
6	0.44	<0.0001
7	0.53	<0.0001
8	1.13	<0.0001

*Standard error is 0.050 in Table 4.2

4.2.2.2 **Shaping length**

Results of ANOVA for the shaping length indicated that both the number of held stitches and the layout of dart shapes have effects, and there was an interaction (F 5, 22) = 12.17, $p < 0.0001$). According to the theoretical equation, the shaping length is reduced with increased the number of held stitches in the shaping area. As shown in Table 4.3, when the number of held stitches in one shaping sequence is 7 or 8 and a single dart layout is used, P value indicates that differences between the actual shaping length and the theoretical calculation are statistically zero. In addition, the actual shaping lengths are statistically different from the theoretical values; in fact, they are all less than 0.2

inches which would have little impact on fit in a 3D shaped knitwear and would probably fall within production tolerance. This means that the actual length of 3D shapes could be predicted by theoretical calculations. In addition, results in Table 4.3 reveal that mean differences between actual and theoretical shaping lengths are always smaller when a single dart layout is used than when the area is shaped with double darts. Thus, the actual length of the shaping area can be predicted by calculated values in actual knit garment shaping, especially when a single dart layout is designed in the shaping area.

Table 4.3 Interaction effect on differences between theoretical and actual shaping length

Number of held stitches	Layout of dart shapes	Mean difference * between actual and theoretical shaping length (inches)	Pr > |t|
3	1	0.079	< 0.0001
3	2	0.18	< 0.0001
4	1	0.077	< 0.0001
4	2	0.15	< 0.0001
5	1	0.041	< 0.0001
5	2	0.13	< 0.0001
6	1	0.019	0.04
6	2	0.16	< 0.0001
7	1	0.016	0.07
7	2	0.18	< 0.0001
8	1	0.01	0.26
8	2	0.19	< 0.0001

*Standard error is 0.0086

4.2.2.3 **Loop density and shrinkage**

Theoretical equations (4.1 and 4.2) for the shaping angles and the shaping length state that the loop density and the number of held stitches decide the 3D shapes, but in calculations based on actual mean measurements, the shaping angle and the length of the shaping section are only determined by the number of held stitches in a shaping section, because the wale density and course density are considered to be constant numbers. The loop density used to predict shaping angles and lengths was based on the unshaped single jersey fabrics knitted with the same machine settings as the shaped fabrics. In fact, the loop density in shaped areas and unshaped areas differed. This results in differences of the shaping angles and the shaping length between theoretical values and actual measurements. Although most differences are not significant, changes in the loop density cannot be ignored. Comparison of the loop density in the shaped area before and after laundering can be used to explain some phenomena in the results of the shaping angles and lengths. Generally, wale density in shaped areas remains the same as unshaped areas, but course density in the shaped areas is always larger than in the unshaped area. According to the equations (4.1 and 4.2) for prediction, larger loop densities lead to smaller shaping angles and shorter shaping lengths. Further, in order to examine the impact of finishing, the concept of “shrinkage” was used to compare the loop density before and after laundering. Preliminary results indicate that shrinkage in shaped areas is smaller than that in unshaped areas, which means, finishing has different impacts on shaped and unshaped areas. In shaped areas, shrinkage in the horizontal direction is almost the same as in unshaped areas, but shrinkage in the vertical direction changes substantially, and it is different even at the three points along the shaping line. From apex to side in the shaped area, the shrinkage decreased. As shown in Figure 4.8, when the shaping angle decreased, variations among apex, middle and side were reduced. Large shrinkage on the side of the shaped part explained why the shaping angles at the side point were changed more than other points after laundering.

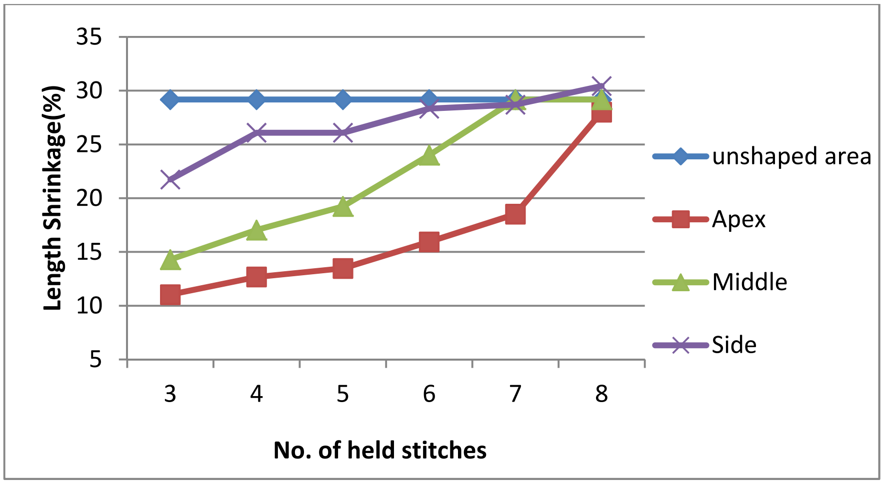


Figure 4.7 Shrinkage in the vertical direction in the shaped area

4.2.3 Conclusions and limitations in Experiment I

In conclusion, the actual shaping angles and the lengths of the shaping section are similar to the theoretical calculations, especially after laundering, suggesting it is possible to use mathematical calculations to predict the shape of 3D knitted fabrics, and the effect of finishing must be considered. Theoretically, the 3D shape is related to the loop density and the number of held stitches. However, the loop density in the shaped area is difficult to calculate before knitting, so theoretical angles and lengths are not exactly the same as actual measurements. Results of this study revealed that the course density in the shaped areas is always higher than the unshaped area. Different points along the shaping line have different loop densities, usually, the course density is reduced at the side. Designers should consider the changes in loop density and shrinkage when they want to predict the 3D shape prior to actual production.

In this study, the high predictability by mathematical calculations for the shape of 3D knitted fabrics was demonstrated, so designers can use them as references in 3D shaped knit product design. Results obtained in this work provide understanding of three-dimensional shaping for knitted products, and they are also useful for designers to create unique and innovative designs. Results of this study will contribute to the database supporting implementation of the model to be developed in this research. In future work, researchers can explore the range of fit shaping feasible with this 3D shaping technique and relate this to fit on the body. This research was limited in terms of shaping techniques, yarns, machine gauge, and knitted structures. As innovative knitting technology has provided many opportunities to create three-dimensional shapes within a complete garment part, future research can focus on additional shaping techniques such as wale shaping, using different yarns or knitted structures.

4.3 Experiment II: effects of knitted structures on knitted garment panel size

4.3.1 Integral garments with different knitted structures: size, shape and implications for fit

Research in Experiment II aimed to explore effects of different knitted structures on the shape of knit garment panels. This work was presented in BIFT-ITAA Joint Symposium in March, 2012 in Beijing, China, and it was published in an edited book – Fashion Dialogue 2012 BIFT-ITAA Joint Symposium Research and Teaching Papers. The remainder of this section is the published paper. The citation for the manuscript is given below.

Lamar, T. & Ma, Y., (2012). Integral garments with different knitted structures: Size, shape, and implications for fit. In M. Littrell (Ed.), *Fashion Dialogue 2012 BIFT-ITAA Joint Symposium: Research and Teaching Paper* (pp. 101-106). Beijing, China: China Textile & Apparel Press.

INTEGRAL GARMENTS WITH DIFFERENT KNITTED STRUCTURES: SIZE, SHAPE, AND IMPLICATIONS FOR FIT

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ABSTRACT

Advancements in fully-fashioned and seamless knitting technologies make it possible to create integral knitted garments with diverse structures. This paper examined the influence of knitted structure on the size and shape of integral knit sweater panels. Three commonly used knitted structures - single jersey, rib and interlock - were analyzed. Results presented in this paper show that changing knitted structure significantly affected knitted garment panel size. Results from the research could be useful to predicting knit garment size prior to knitting based on loop density, structure, and size of basic pattern. Results are also useful in understanding how structures can be varied and combined in different ways to enhance aesthetics and fit of integral knitted garments.

Key Words: knit apparel, sizing knits, integral knitting, sweater

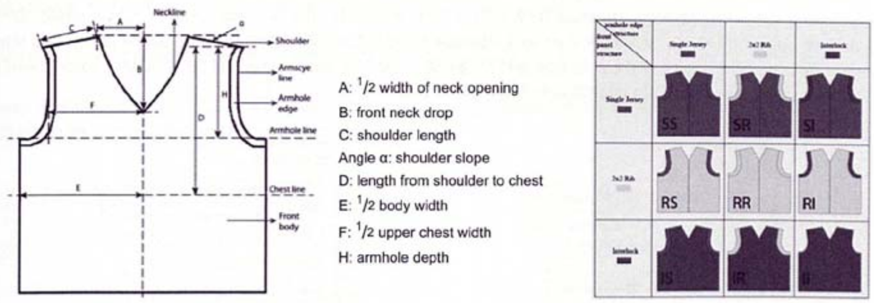
1. INTRODUCTION

Innovations in knitting machine technology, such as integral knitting, provide new opportunities for designers to create dramatic knitted garments (Phillips, 2002; Tellier-Loumagne, 2005). Advanced knitting machines enable the formation of fully-fashioned or seamless garments and enhance the ability to shape different knitted structures (Song, Wu, & Wei, 2006). Unlike cut and sewn garments which are shaped after fabric formation, the shape of the garment or garment panels is formed during the integral knitting process. Integral knitting reduces material waste and labor costs, and knit garments are comfortable to wear due to minimal seams (Choi & Powell, 2005). Because the shape of integral knitted garments and components cannot be changed after knitting, understanding the impact of changing knit structure is vital to controlling size and fit of a garment. Interplay among knitting variables, such as knit stitch, loop length, and tension, and the final shape presents a major challenge for knitwear design (Eckert, Cross, & Johnson, 2000).

Some researchers have investigated design and techniques for integral or seamless knitting (Broega, Catarino, & Biolo, 2010; Ruan, 2011; Yang & Love, 2009). Other researchers have focused on the effects of combining different structures on the shape of resulting knitted fabrics (Tou, 2005). Because different knitted structures have varied shrinkage and elastic recovery, the size and shape of garment panels knitted with different structures will differ. Practitioners use this to advantage. For example, knitting machine manufacturers, such as Stoll and Shima Seiki, often juxtapose knitted structures with different properties to produce innovative shaped knitted garments (Shima Seiki, 2012; Stoll, 2012). However, very limited research has been carried out to examine the relationship between knit structures and size and fit of integral garments, a critical aspect of knitted garment design. For efficient knit design and development, it is highly desirable for such differences to be predictable. Commercial knit apparel producers may rely on the elasticity of the fabric structure to accommodate larger sizes with smaller garments, enhancing productivity and reducing raw material cost. However, this practice significantly alters the fit intended by the designer who may have selected an alternate structure for its aesthetics while desiring to maintain the original fit of a knit garment pattern. This paper focuses on knit sweater panels exploring the size variation introduced by changing knitted structure. To quantify size and shape, body width and length, neckline shape, and shoulder fit were analyzed.

2. METHODS

A v-neck sweater front panel pattern with a set-in sleeve was chosen for this study. Shima Seiki's CAD system calculated the number of courses and wales and the fashioning strategy for knitting the single jersey front panels in the "Basic" size. Calculation was based on 11 wpi (wales per inch) x 15 cpi (courses per inch) measured in the relaxed state after one home laundering cycle, as determined in pilot work. The body of the front panel was knitted with one structure, and edges of armholes with another structure (see Figure 1 (a)), yielding nine (9) stitch structure combinations (see Figure 1 (b)). For each combination, ten samples were knitted (n=90) and twenty measurements were collected, half on each side of the sample. For knitting and raw material efficiency, the length of the front panel was shortened to approximately waist length.



(a) Front panel shape and measurements

(b) Structure combinations (adapted from Ruan, 2011)

Figure 1. Sweater panel shape, measurements and structures

All of the samples were knitted on Shima Seiki's V-bed knitting machine (SES 124-S 7 gauge) under the same takedown tension using 100% 8/2 count cotton yarns, identified as the optimal size in pilot work. Panels were knitted using single jersey (S), 2×2 rib (R) and interlock (I) weft-knit structures, identified as most used in the knitwear industry (Ward, 2010). Table 1 shows notations and stretch characteristics of each knitted structure. All samples were knitted with the same number of wales and courses and the same fashioning parameters, so changes in the front panel size could be attributed to different knit structures.

Table 1. Knitted structure notation and general characteristics (Horrocks & Anand, 2000; Brackenbury, 1992)

Knitted structure	Notation	Elasticity
Single jersey (S)		More elastic in horizontal than in vertical direction
2 × 2 rib (R)		Good elasticity, especially in horizontal direction
Interlock (I)		Low elasticity, good dimensional stability

To facilitate measuring, pointelle holes marking measurement points were knitted into the same course and wale intersections of each panel. After knitting, panels were relaxed and stabelized by washing according to AATCC Test Method 135-2004 and steaming. Panels were carefully pinned without distortion of knitted loops on a padded blocker, aligning wales and courses with the lines of a grid printed on the blocker. Pinned samples were scanned using a Zeutschel OS 12000® book scanner. After scanning, images were cropped, rotated to align the scanned grid with the screen grid, and calibrated. Measures A, B, C, D, E, F, H and angle α (see Figure 1 (a)) on both left and right side were collected. Adobe Photoshop® CS5, Autodesk AutoCAD® 2011, and Adobe Illustrator® were used for digital processing and measuring.

Because knit shapes are easy to distort in attempts to stabelize, visual inspection and box plots were used to check for outliers. One measure of 1/2 neck opening width from a completely interlock panel was identified as an outlier and was removed from analysis to improve precision and confidence. Remaining data were analyzed using two-way Analysis of Variance (ANOVA) and a $p<0.05$ level of significance to compare the means of each sample combination. If ANOVA results revealed a significant difference in mean measurements, t-tests were used to characterize the specific differences and test whether each was statistically significant.

3. RESULTS AND DISCUSSION

3.1 Effects of knitted structures on neck shape

Two-way ANOVA for 1/2 width of neck opening (measure A) revealed significant effects for front body structure [$F(2, 170) = 17050.3$, $p < .001$] and armhole edge structure [$F(2,170) = 7.11$, $p=0.001$). The 1/2 neck width of single jersey ($M=3.84$, $SD=0.082$) and rib bodies ($M=2.43$, $SD=0.090$), rib and interlock bodies ($M=5.53$, $SD=0.11$), and single jersey and interlock bodies differed significantly ($t(118)= 185.64$, $p <0.001$, $t(117)= 84.38$, $p <0.001$, and $t(117)= 101.26$, $p <0.001$, respectively). The direction and range of the differences are illustrated in figure 2.

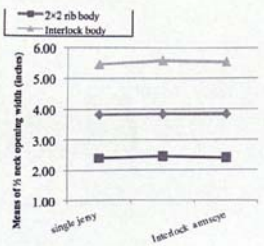


Figure 2. Effects of front body structure and armhole edge strucutre on 1/2 width of neck

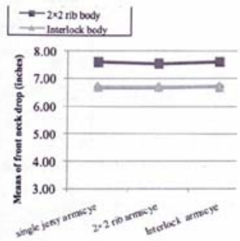


Figure 3. Effects of front body structure and armhole edge structure on front neck drop

Although the effect of armhole edge structure on neck shape is significant, further analysis revealed the difference to be trivial (0.06"). But, presence of the effect led the authors to investigate the size of the fully single jersey panel in relation to the predicted "Basic" size. Selected measures are compared in Table 2. The substantial difference in back neck width between predicted and actual garments would have a dramatic impact on fit and may be partially driven by the effect of stitching at the armscye. The size is calculated based on continuous knitting in a sample, where armscye shaping requires stitch transfers creating a tighter structure with shorter loop lengths. Armsyce edges are also bound off which can tighten the stitching at the lower armscye. Together, these effects may pull the top of the v-neck front opening down and away from center, in effect widening it. So both the impact of fashioning and machine bind off settings must be considered and optimized in any effort to predict knit garment size and fit.

Table 2. Predicted and actual measurements for "Basic" size sweater panel knitted completely in single jersey

Measure	Description	Predicted	Actual SS (mean)	Difference
B	Front Neck Drop	6.31 inch	6.68 inch	0.38 inch (5.8%)
E x 2	Chest Width	19.28 inch	19.9 inch	0.62 inch (3.2%)
A x 2	Neck Width	5.5 inch	7.65 inch	2.15 inch (39%)

The front neck drop (measure B) is only influenced by front body structure [$F(2,171)=1859.32$, $p<0.001$]. As shown in Figure 3, the difference in neck drop between bodies of interlock ($M=6.71$, $SD=0.087$) and single jersey ($M=6.68$, $SD=0.64$), differ significantly from that of rib body ($M=7.58$, $SD=0.12$), ($t(118)=53.56$, $p <0.001$, and $t(118)=52.03$, $p <0.001$, respectively).

3.2 Effects of knitted structures on shoulder fit

Shoulder fit is determined by the shoulder length (measure C) and the shoulder slope that indicates the angle in relation to horizontal (angle α) (Cooklin, 1990). Results of two-way ANOVA reveal that front body structure and armhole edge structure have a significant impact on both shoulder length [$F(2,171)= 4732.53$, $p <0.001$, $F(2,171)=185.15$, $p<0.001$, respectively] and shoulder slope [$F(2,171)=6472.07$, $p<0.001$, $F(2,171)= 103.66$, $p<0.001$, respectively]. The interaction also has a significant effect on both shoulder length [$F(2,171)=16.76$, $p<0.001$] and shoulder slope [$F(2,171)=28.28$, $p<0.001$].

Generally, interlock structure in the front body area increases the shoulder length, and 2×2 rib structure reduces the shoulder length (see Figure 4). The presence of interaction effects illustrates that the direction and amount of the change is not consistent across body structures. The rib armhole edge structure has less impact on the shoulder length of a single jersey body than on the other body structures. Differences in shoulder slope among body structures of up to 14.72 degrees (in the case of front panels knitted with 2×2 rib and interlock structure with armhole edges knitted with single jersey), as can be observed in Figure 5, would have a dramatic impact on the shoulder fit. A change of armhole edge structure over levels of front body structure leads to small, but inconsistent, differences in the shoulder slope, even though the differences are statistically significant. The results of shoulder shape analysis reinforce the importance of considering both the fashioning techniques and structure, and the machine bindoff settings in efforts to predict size variation based on knit structure change.

3.3 Effects of knitted structures on front panel size

Two-way ANOVA results reveal that front body structure had a significant impact on the front panel width [$F(2,171)=18381.2$, $p<0.001$]. No interaction effect or effect for armhole

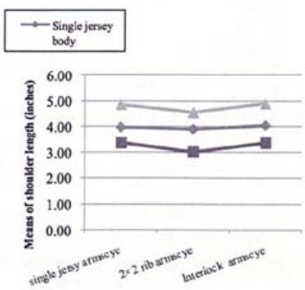


Figure 4. Effects of front body structure and armhole edge structure on shoulder length

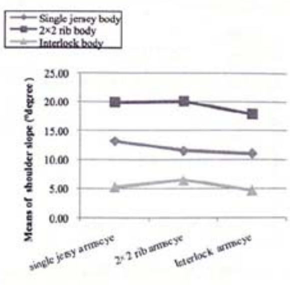


Figure 5. Effects of front body structure and armhole edge structure on shoulder slope

with interlock in the front body area is much larger than that of samples knitted with single jersey. Samples knitted with 2×2 rib structure have the smallest front panel width. The difference in front panel width between 2×2 rib and interlock structure is up to 6.8 inches, which would have a dramatic effect on the fit of the resulting garment.

Similarly, $^1/_2$ upper chest width is highly influenced by front body structure [$F(2,171)=9890.56$, $p<0.001$], but also by armhole edge structure [$F(2,171)=27.92$, $p<0.001$]. No interaction effect was found. Compared to samples knitted with single jersy in the body area, 2×2 rib structure decreases the $^1/_2$ upper chest width by 2.3 inches, and interlock structure increases it up to 2.6 inches (see Figure 7). The differences due to armhole edge structure are roughly one quarter inch or less, which is small enough not to require accomodation in developing knit garment patterns.

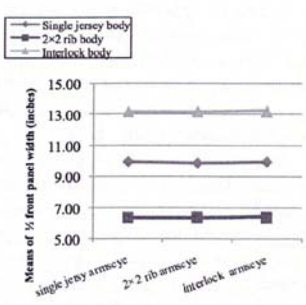


Figure 6. Effects of front body structure and armhole edge structure on $^1/_2$ front panel width

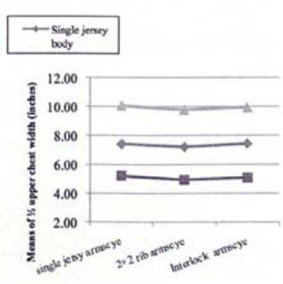


Figure 7. Effects of front body structure and armhole edge structure on $^1/_2$ upper chest width

Two-way ANOVA results showed front body structure [$F(2,171)=644.35$, $p<0.001$], and to a lesser degree by armhole edge structure [$F(2,171)=16.52$, $p<0.001$] have statistically significant effects on the front body length, and there is an interaction [$F(2,171)=4.12$, $p<0.003$]. As shown in Figure 8, 2×2 rib structure in the body area increases the panel length as compared to single jersey and interlock structures. In terms of interaction effects, results of t-test show differences are significant, but they are all less than one quarter inch, which has little practical implication for designing patterns for integral knit garments.

In addition, front body structure [$F(2,171)=542.07$, $p<0.001$], and armhole edge structure [$F(2,171)=67.38$, $p<0.001$] have statistically significant effects on the armhole depth, and there is an interaction [$F(2,171)=7.47$, $p<0.001$] (see Figure 9). The differences among mean armhole depth ranged from 0.47 inches to 1.36 inches, and the rib armhole structure had a lesser effect combined with the rib body structure than with other structures. The differences are substantial enough to alter the fit of a garment and thus require accomodation in the design process. This merits further investigation to better understand shaping and size of the armscye area and its impact on the garment shape in relation to different knitted structures.

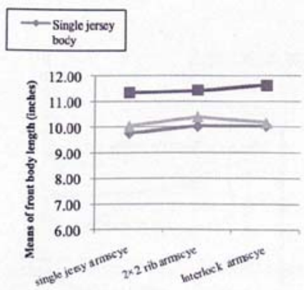


Figure 8. Effects of front body structure and armhole edge structure on front panel length

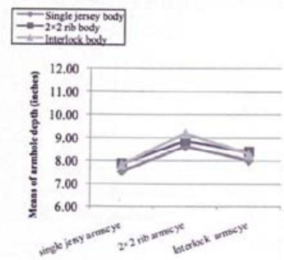


Figure 9. Effects of front body structure and armhole edge structure on armhole depth

4. CONCLUSION

In conclusion, knit structure variation has been demonstrated to dramatically influence the shape and size of a knitted sweater component. It follows that changing the structure in the body area and on the armhole edge fashioning area in complete garments can be expected to lead to significant changes in the knitted garment size and shape. Figure 10 graphically compares the mean shapes of left-side front panels knitted in three structures. Compared to the single jersey sweater panel, the panel knitted with rib structure is much narrower and longer. Knitted front panels with interlock structure are much wider than those of other structures, but the length is similar to jersey. Combinations of two different structures in the front body area and on the armhole edge have little effect on the body and armscye widths, but they influence the armcye depth and panel length.

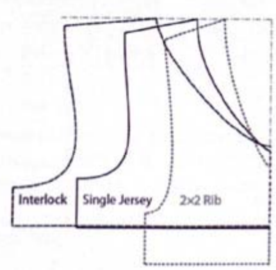


Figure 10. Graphical comparison of front panel shapes knitted with three different structures

Even considering the variations in elasticity afforded by different structures, the fit of garments constructed of these panels would be dramatically different.To achieve similar shape, size, and fit in sweater panels of the three structures studied, the number of wales would need to be reduced (~ 33%) to knit with interlock, and the number of wales increased (~36%) and courses decreased (~15%) to knit with rib in comparison to panels knitted with single jersey. Because the focus of this study was the influence of knitted structure on the sweater panel shape, yarn, loop length, and takedown tension were kept constant at 9.5 mm. The optimal loop length varies by structure, and changes in loop length will affect resulting shape and size. For example, increasing loop length provides more yarns to each loop, which in turn would increase the panel width.

Broader adoption of integral and seamless knitting technologies would be facilitated by enhanced understanding of the relationships among knitting variables and final garment shape and size, reducing the need for time consuming prototypes. Results from this research can be used to predict the size and improve the fit of integral garments in the design process. Data regarding influences on size and shape could be used to adjust knitting patterns to achieve similar fit with different structures, and manipulate structures to manage fit. However, such calculations would need to also compensate for changes in variables such as loop length and the variation that comes from fashioning and machine settings. Additionally, documenting interactions among different structure combinations will contribute to understanding sizing of integral knitting. Because of limitations in yarns, machines, and knitted structures, future research can test the learnings by application to prediction of size and shape in knitting. It would also be useful to expand the study to explore different yarns, other knitted structures, or knitting machines of different gauges.

ACKNOWLEDGMENT

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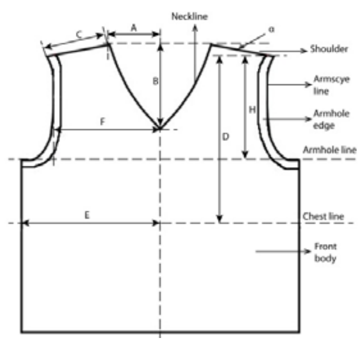
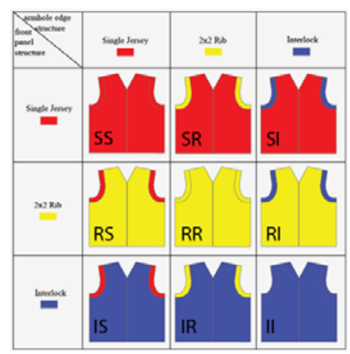
4.3.2 Further analysis in Experiment II

After the preliminary results of this study were published in the journal, data collected in this experiment was further analyzed considering effects of measurement position (left versus right of the garment panel) on garment panel size. Knitted samples and measurements used in further analysis remained the same as those in the published paper. As shown in Figure 4.8 (a), the body of the front panel was knitted with one structure, and edges of armholes were knitted with another structure. Three knitted structures – single jersey, 2×2 rib and interlock were involved for each factor, yielding nine treatment combinations (see Figure 4.8 (b)). For each combination, ten samples were knitted. The 90 samples were randomly selected and knitted on the machine (Ruan, 2011). Seven measurements were collected on each side of the sample.



Measurements:
A: ½ width of neck opening
B: front neck drop
C: shoulder length
Angle α: shoulder slope
D: length from shoulder to chest
E: ½ body width
F: ½ upper chest width
H: armhole depth



(a) Front panel shape and measurements

(b) Structure combinations (adapted from Ruan, 2011)

Figure 4.8 Sweater panel shape, measurements and structures

In the further analysis of Experiment II, position of the measurement on left side or right side of the garment panel was analyzed as a split-plot factor. Front body structure and armhole edge structure were two whole-plot factors. The model used to analyze effects of each factor is divided into the whole-plot analysis and the sub-plot analysis, as shown below.

$$Y_{ijkl} = \mu + \alpha_i + \beta_j + \alpha\beta_{ij} + \eta_{k(ij)} + \theta_l + \alpha\theta_{il} + \beta\theta_{jl} + \alpha\beta\theta_{ijl} + \varepsilon_{ijkl}$$

Where, $\eta_{k(ij)}$iid ~ (0, ${\sigma_\eta}^2$), ε_{ijkl}iid ~ (0, ${\sigma_\varepsilon}^2$) are mutually independent.

Y_{ijkl} is the mean value of each measurement;

$\eta_{k(ij)}$ represents whole plots random effects among samples ;

ε_{ijkl} represents split plots random effects and random noises between locations within a sample;

μ is the overall mean of measurements;

α_i is the effect of the whole-plot factor – front body structure at level *i, i*= 1, 2, 3;

β_j is the effect of the whole-plot factor – armhole edge structure at level j, j = 1, 2, 3;

$\alpha\beta_{ij}$ is the interaction effect of front body structure at level *i* and armhole edge structure at level *j*;

θ_l is the effect of the split-plot factor – position of measurements at level *l* (left or right), *l* = 1, 2;

$\alpha\theta_{il}$ is the interaction effect of front body structure at level *i* and position of measurements at level *l;*

$\beta\theta_{jl}$ is the interaction effect of armhole edge structure at level *j* and position of measurement at level *l;*

$\alpha\beta\theta_{ijl}$ is the interaction effect of front body structure at level *i*, armhole edge structure at level j, and position of measurement at level *l*.

4.3.2.1 **Effects of knitted structures on ½ width of neck opening (measure A)**

According to the results, front body structure ($F(2,81) = 1349.9$, $p < 0.0001$) and armhole edge structure ($F(2, 81) = 5.58$, $p = 0.005$) have significant impacts on the width of neck opening. No interaction effects existed between the two factors. As shown in Table 4.4, for effects of the front body structure, means of the ½ neck opening width are significantly different from each othe. Also, the differences introduced by changing the front body structure are not only statistically meaningful, but they are also substantial enough to make a change in neck opening width. Although the effect of armhole edge structure on width of neck opening is statistically significant, further analysis revealed the maximine difference of 0.6 inches to be trivial. Thus, varying front body structures would be the main method to cause changes in neck opening width.

Table 4.4 Effects of front body structure and armhole edge structure on ½ neck opening width

Whole-plot factor	Levels	Means* of ½ neck width (inches)
Front body structure	Interlock	5.53
	2×2 Rib	2.43
	Single jersey	3.84
Armhole edge structure	Interlock	3.93
	2×2 Rib	3.96
	Single jersey	3.90

*Standard error is 0.013

Additionally, effects of measurement position on ½ neck opening width interacted with front body structure ($F(2, 81) = 3.18$, $p = 0.047$). As shown in Table 4.5, only when the front body structure is interlock, the difference introduced by varied measurement positions between left and right of the garment panel is statistically significant, but 0.06 inches difference is still too small to cause a change in knitting practice.

Table 4.5 Interaction effects of measurement position and body structure on 1/2 neck width

Measurement position / Body structure	Mean* of ½ neck width (inches)		Difference# of ½ neck width between left and right (inches)	Pr>|t|
	Left	Right		
Interlock	5.5	5.56	-0.06	0.004
2×2 rib	2.43	2.42	0.01	0.58
Single jersey	3.83	3.84	-0.01	0.50

*Standard error is 0.017; #Standard error is 0.019

4.3.2.2 **Effects of knitted structures on front neck drop (measure B)**

The front neck drop was influenced only by front body structure ($F(2, 81) = 1450.0$, $p < 0.0001$). As shown in Table 4.6, the differences in neck drop between bodies of interlock structure and single jersey differ significantly from that of rib structure in the front body. Changing the front body structure from 2×2 rib to single jersey also caused a significant difference in front neck drop, the differences introduced by changing interlock structures to single jersey structures was only 0.03 inches that were not significant either statistically or practically. Additionally, positions of measurements between left and right side of the garment panel did not affect the front neck drop.

Table 4.6 Comparison of front neck drop between different levels of front body structure

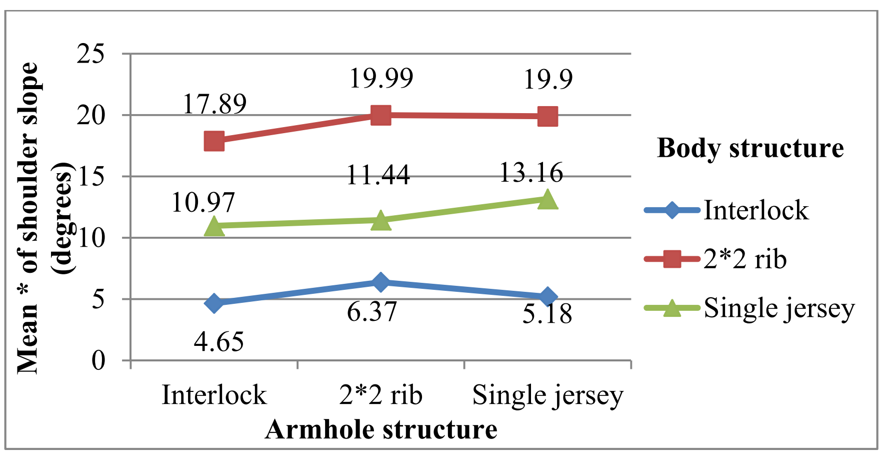
Compared levels	Mean difference* (inches)	Pr > |t|
Interlock – 2×2 rib	-0.86	<0.0001
Interlock – Single jersey	0.03	0.11
2×2 rib – Single jersey	0.89	<0.0001

*Standard error is 0.019

4.3.2.3 **Effects of knitted structures on shoulder slope (Angle α)**

Results of analysis revealed that position of measurements ($F(1, 81) = 7.62$, $p = 0.0071 < 0.05$), and front body structure ($F(2, 81) = 5688.57$, $p < 0.0001$) and armhole edge structure ($F(2, 81) = 90.53$ $p < 0.0001$) have significant impacts on shoulder slope. Although the shoulder slopes measured on the left and the right of the panel had a statistically significant difference, an average difference of 0.23 degrees can be acceptable in garment knitting.

According to ANOVA results of whole-plot analysis, the interaction of front body structure and armhole edge structure also has a significant effect on the shoulder slope ($F(4, 81) = 24.38$, $p < 0.0001$). Figure 4.9 shows the interaction of front body structure and armhole edge structure on means of shoulder slope. Further analysis for effects of front body structure and armhole edge structure showed differences of armhole slope in samples with different treatments were either statistically or practically significant.

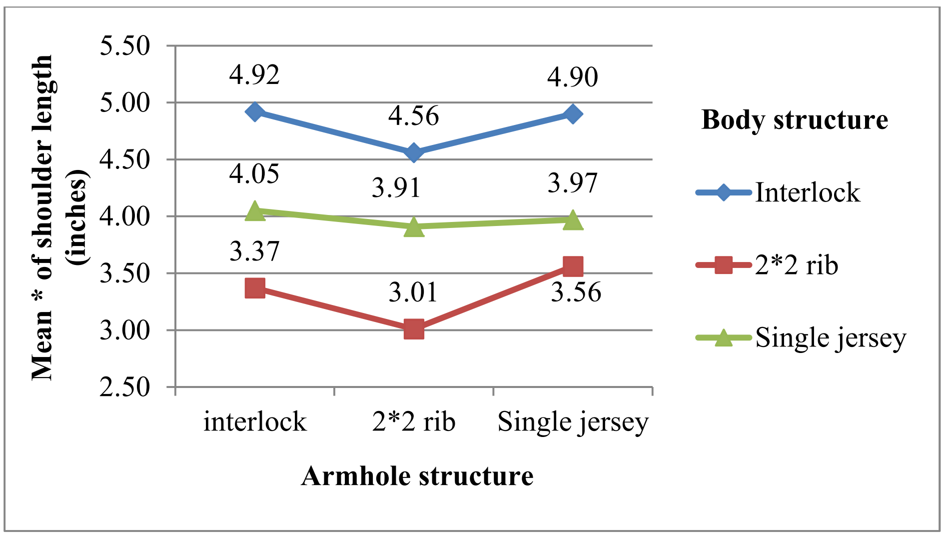


*Standard error is 0.16

Figure 4.9 Interaction effects of front body structure and armhole edge structure on shoulder slope

4.3.2.4 Effects of knitted structures on shoulder length (measure C)

According to results of whole-plot analysis, the shoulder length was influenced by front body structure ($F(2, 81) = 2299.65$, $p < 0.0001$) and armhole edge structure ($F(2, 81) = 79.54$, $p < 0.0001$), and there was an interaction between them ($F(4, 162) = 29.91$, $p < 0.0001$). As shown in Figure 4.10, changes of shoulder length caused by varying front body structure could lead to significant differences in shoulder fit of knitted garments, but differences introduced by changing armhole edge structure have little influence on shoulder fit.



*Standard error is 0.021

Figure 4.10 Interaction effects of front body structure and armhole edge structure on shoulder length

According to split-plot analysis, measurement positions had no impact on shoulder length, but effects of the front body structure interacted with the position of measurements ($F(2,81) = 5.16$, $p < 0.008$). When the front body is knitted with the same structure, shoulder slope on the left differs from that on the right side, but the difference of shoulder length between left and right side is only significant when the front body area is knitted with interlock structure (see Table 4.7). Comparison of ANOVA analysis showed that effects of measurement position on shoulder length of knit garment panels were similar to effects on neck opening with. This demonstrated that machine knitting could have an impact on shoulder fit and neckline shape, but the influence would be of little importance in knit garment development.

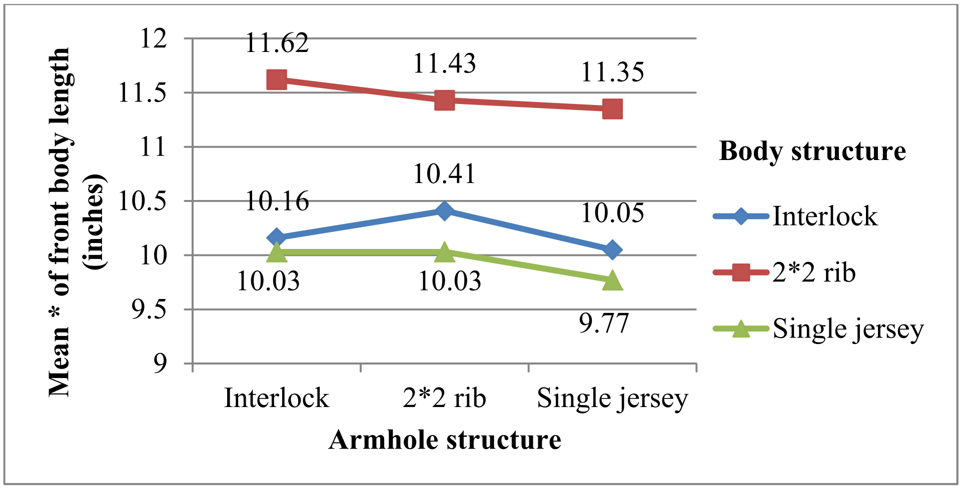
Table 4.7 Interaction effects of measurement position and body structure on shoulder length

Measurement position / Body structure	Mean* of shoulder length (inches)		Difference# of shoulder length btween left and right (inches)	Pr>|t|
	Left	Right		
Interlock	4.81	4.78	0.03	0.002
2×2 rib	3.24	3.25	-0.01	0.53
Single jersey	3.97	3.98	-0.01	0.47

* Standard error is 0.013; #Standard error is 0.010

4.3.2.5 **Effects of knitted structures on body length (measure D)**

Analysis results showed front body structure ($F(2,81) = 468.26$, $p < 0.0001$) and armhole edge structure ($F(2, 81) = 12.01$, $p < 0.0001$) had statistically significant effects on the front body length, and there was an interaction ($F(4, 81) = 2.99$, $p = 0.023 < 0.05$). As shown in Figure 4.11, when the front body structure remains the same, changing armhole edge structure results in less than one quarter inch difference, which has little practical implication for designing patterns for knitted garments. The position of measurements has no effect on body length.



*Standard error is 0.065

Figure 4.11 Interaction effects of front body structure and armhole edge structure on body length

4.3.2.6 **Effects of knitted structures on ½ body width (measure E)**

Results of whole-plot analysis revealed that front body structure had a significant impact on the front panel width ($F(2, 81) = 13646.7$, $p < 0.0001$). There is no interaction effect or effect of armhole edge structure. The body width with interlock structure in the front body area is much larger than that of samples knitted with single jersey. Samples knitted with 2×2 rib structure have the smallest front panel width (see Table 4.8). The difference in front panel width between rib and interlock structure is up to 6.8 inches, which would have a dramatic effect on the fit of the resulting garment. Additionally, according to results of split-plot analysis, 1/2 body width measured on the left side of the panel differed from measures on the right side ($F(1, 81) = 5.10$, $p = 0.027 < 0.05$), but the difference was only 0.05 inches (see Table 4.9), which was too small to influence the panel size. Therefore, ½ body width of front garment panels was mainly influenced by the body structure.

Table 4.8 Effects of front body structure on ½ body width

Body structure	Means* of 1/2 body width (inches)
Interlock	13.19
2×2 rib	6.38
Single jersey	9.92

* Standard error is 0.029

Table 4.9 Effects of measurement position on ½ body width

Measurement position	Means* of 1/2 body width (inches)
Left	9.81
Right	9.86

* Standard error is 0.021

4.3.2.7 Effects of knitted structures on ½ upper chest width (measure F)

Half upper chest width was highly influenced by front body structure ($F(2, 81) = 7900.64$, $p < 0.0001$) and armhole edge structure ($F(2, 81) = 26.14$, $p < 0.0001$). No interaction effect was found. Compared to samples knitted with single jersey in the body area, 2×2 rib structure decreases the 1/2 upper chest width by 2.3 inches, and interlock structure increases it up to 2.6 inches (see Table 4.10). The differences due to armhole edge structure are roughly one-quarter inch or less, which is small enough not to require accommodation in developing knitted garment patterns (see Table 4.10). Similarly to ½ front panel width, ½ upper chest width measured on the left was also smaller than measurements on the right up to 0.04 inches (see Table 4.11), which was statistically significant but not in knitting practice. This means effects of measurement position on both ½ front panel width and ½ upper chest width could be of little consideration.

Table 4.10 Effects of front body structure and armhole edge structure on ½ upper chest width

Whole-plot factor	Levels	Means* of ½ upper chest width (inches)
Front body structure	Interlock	9.93
	2×2 Rib	5.08
	Single jersey	7.36
Armhole edge structure	Interlock	7.49
	2×2 Rib	7.30
	Single jersey	7.57

*Standard error is 0.027

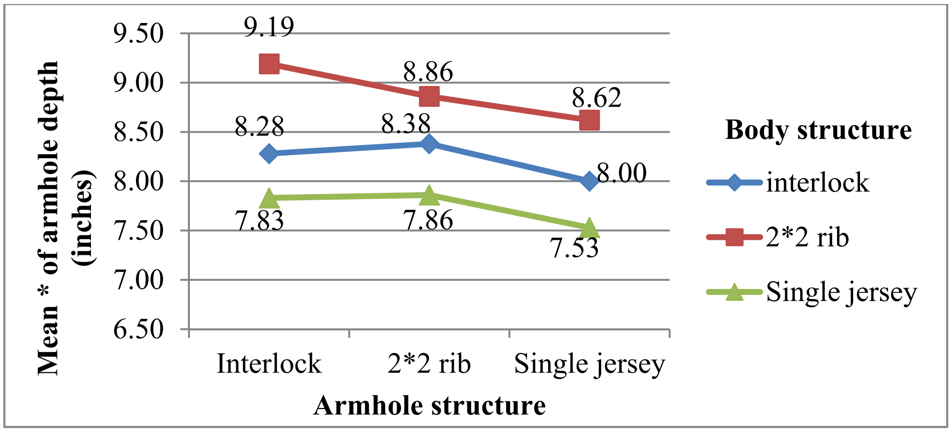
Table 4.11 Effects of measurement position on ½ upper chest width

Measurement position	Means* of ½ upper chest width (inches)
Left	7.43
Right	7.47

*Standard error is 0.018

4.3.2.8 **Effects of knitted structures on armhole depth (measure H)**

Front body structure ($F(2, 81) = 414.09$, $p < 0.0001$) and armhole edge structure ($F(2, 81) = 51.48$, $p < 0.0001$) had statistically significant effects on the armhole depth, and there was an interaction ($F(4, 81) = 5.71$ $p = 0.0004$). As shown in Figure 4.12, differences among mean armhole depth ranged from 0.47 inches to 1.36 inches, and the rib armhole structure had a lesser effect combined with the rib body structure than with other structures. The differences are substantial enough to alter the fit of a garment armhole shape. However, statistical results did not show any impact of measurement position on the armhole depth.



*Standard error is 0.049

Figure 4.12 Interaction effect of front body structure and armhole edge structure

In conclusion, further analysis of data collected in the Experiment II revealed that measurements gathered in different positions between left and right side of the garment panel might differ. ½ panel width, ½ upper chest width, shoulder length, shoulder slope, and ½ width of neck opening measured on the left side of the panel differed from measures on the right side. In terms of shoulder length and ½ neck opening width, effects of measurement position depended on front body structure. However, all differences between measurements on the left or right were less than 0.2 inches, which were not substantial enough to affect size of knitted garment panels, and these differences could be tolerated in knitting practice. This further analysis provided in-depth understanding of size and fit of shaped knit garments created on knitting machines.

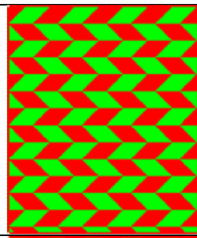
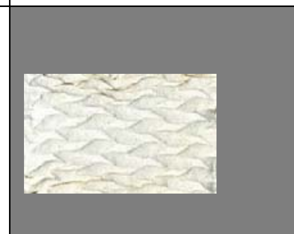
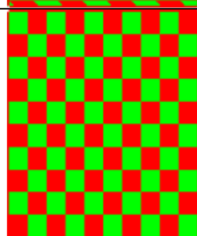
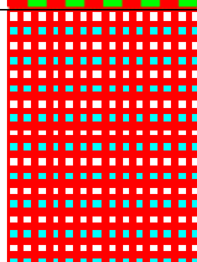
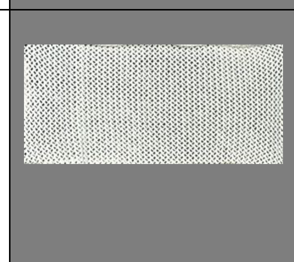
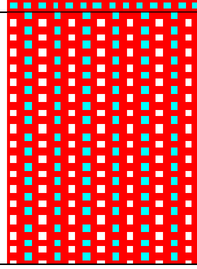
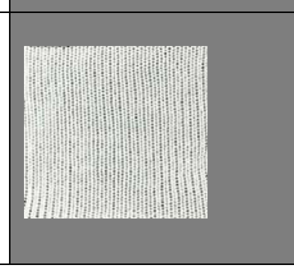
4.4 Experiment III: Sample development and measurement with different stitch structures

In knitted fabric or knitted garment design, varying knit stitches is a main method used to create different surface effects and dimensions. However, little published research addressed effects of different knitted structures on knitted fabric dimensions and properties, and there is no fundamental base for knit garment designers to develop knitted fabrics with novelty structures. In Experiment II, samples involving the same number of courses and wales but different novelty stitch structures were knitted, and data of sample width and sample length were collected to provide a base for designers to create knitted products with different stitch structures. This will facilitate implementation of the model developed in this research.

In this study, the researcher who was inspired by the knitted fabric collection in the lab in the College of Textiles at NCSU and in various textbooks created a series of novelty knit fabrics using front and back knit stitches, tuck stitches, miss stitches, and transferred stitches. All of the samples in Experiment II were knitted at 100 wales and 120 courses, using 8/2 c.c. 100% cotton yarns. They were relaxed by washing and drying according to AATCC Test Method 135-2004. After laundering, those samples were stabilized by steaming on a steam table. For each sample, results in sample width and length and machine settings such as optimal loop length and take down tension were recorded to build a reference library. Physical samples and digital files of those samples were also documented in the reference library, providing a base for other designers or users to get inspiration or generate new ideas.

Preliminary results indicated that different stitch structures could dramatically change knitted fabric dimensions. For example, designed patterns, digital images and dimensions of four samples were illustrated in Table 4.12. Samples 1 and 2 were designed with front and back knit stitches, samples 3 and 4 were produced with front knit and transferred stitches. They were all knitted with the same number of wales and courses and the same type of yarns, but arrangement of stitches in the four samples differed. Measurements of length and width showed that knitted fabric dimensions could be substantially changed by varying stitch structures. Comparisons of fabric widths and lengths between sample 1 and sample 2 or between sample 3 and 4 revealed that even using the same knitted stitches but making different motifs could considerably influence knitted fabric dimensions and appearances.

Table 4.12 Comparison of knitted fabrics with different stitch structures

Sample code	Pattern in CAD software	Digital image of knitted fabric	Sample width	Sample length
Sample 1			10 inches	6.4 inches
Sample 2			9.6 inches	7.7 inches
Sample 3			13.5 inches	6.3 inches
Sample 4			9.5 inches	8.8 inches
Note: (1) patterns were created in Shima Seiki's SDS-ONE, and samples were knitted on Shima Seiki's SES124-S V-bed knitting machine; (2) front knit stitch back knit stitch transfer one stitch to right transfer one stitch to left				

Findings observed in Experiment III stated a general idea of knitted fabric design with different stitch structures. This leads to an in-depth investigation to design knitted fabrics in a predictable manner. In the research of Experiment IV, effects of tuck stitches and miss stitches on single jersey fabrics were explored. The intent of Experiment IV was to find a predictable method to evaluate dimensions of fabrics knitted with different stitch structures.

4.5 Experiment IV: Effects of tuck stitches and miss stitches on knitted fabric dimensions

Changing knitted stitches is an easy method used to alter knitted fabric dimensions, as shown in section 2.1.3 and also Experiment III. It is easy and flexible to apply different knitted stitches in knit pattern design but with little predictability in how finished dimensions will be impacted. Tuck stitch and miss stitch are two commonly used stitches to change the fabric appearance and dimensions. Several researchers have examined mathematical models for tuck stitches and miss stitches (Kayacan & Kurbak, 2008a; Kayacan & Kurbak, 2008b). These models are useful in knitted fabric simulation, providing a theoretical prediction of fabric appearance. In the research noted above, it was proven that tuck stitches and miss stitches can reduce the fabric length, but little research has been carried out to explore the influence of these knitted stitch variations in fabric design or garment design. As shown in Experiment III, different arrangements and numbers of varied stitches involved in creating stitch patterns will cause differences in fabric dimensions and appearance. Understanding the impact of varied stitches such as tuck and miss stitch on knitted fabrics is crucial to control dimensions and ultimately fit of a garment knitted with different stitches. Different dimensional properties introduced by the use of varied stitches will provide potential to create knitted fabrics with unique shapes and improve aesthetics in a predictable way.

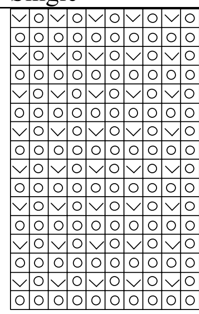
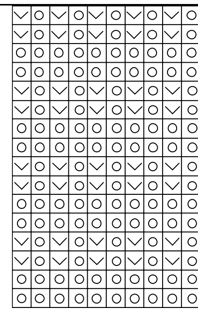
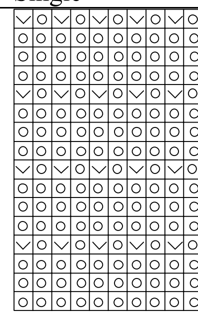
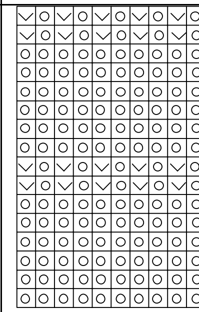
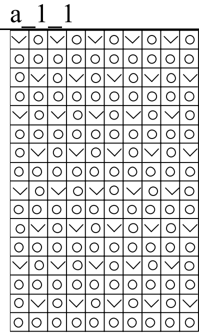
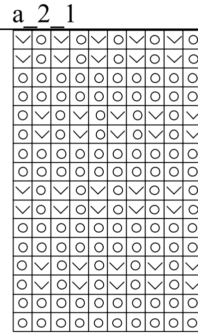
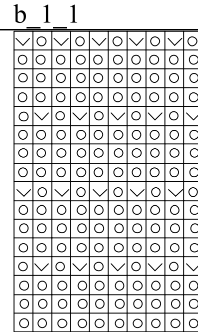
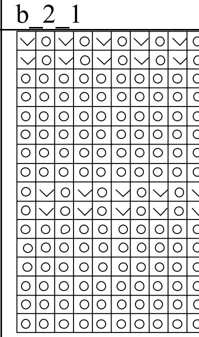
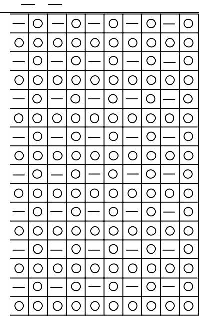
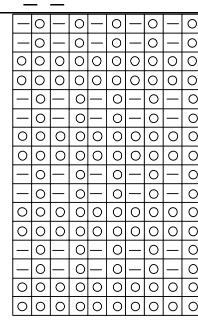
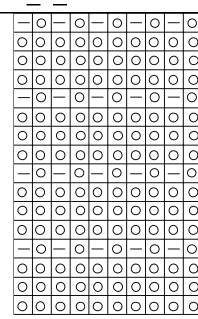
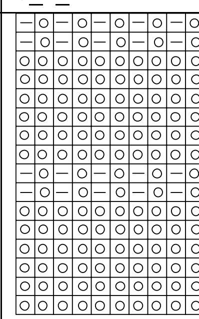
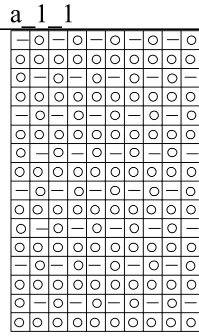
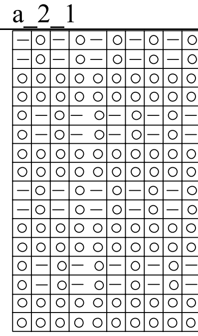
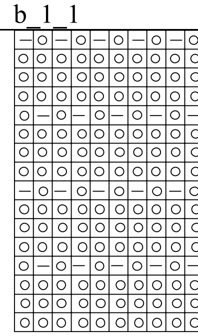
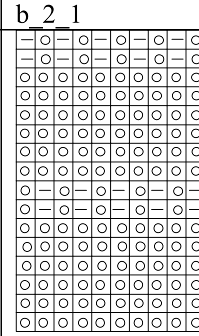
The main goal for experiment IV in research stage one is to investigate the effects of tuck and miss stitches on dimensional properties of knitted fabrics. It focuses on dimensional variations of sample length, width and thickness introduced by changing stitch designs, layouts, and numbers and types of tuck or miss stitches in a fabric knitted of the same number of courses and wales.

4.5.1 Research method in Experiment IV

Samples composed of different stitches were knitted for a total of 100 wales by 160 courses, which mean the total stitch number of each sample was 16000. Table 4.13 illustrates independent variables and their levels in the experiment. Varied stitches amongst single jersey in this experiment include tuck stitch and miss stitch, and they were used separately in knitted samples. The number of varied stitches (tuck stitches or miss stitches) involved in one sample has two levels: 4000 tuck stitches or miss stitches amongst 16000 front knit stitches and 2000 tuck stitches or miss stitches amongst 16000 front knit stitches. Stitch design is considered an arrangement of tuck or miss stitches in a wale direction, and it has two levels: single stitch and double stitches. As shown in Table 4.13, if two tuck stitches or miss stitches are not in adjacent courses, this layout creates patterns with single tuck or single miss, whereas, the stitch design of double tucks or misses means two tuck or miss stitches are adjacent in a wale direction. For stitch layouts, the arrangement of courses composed of single or double varied stitches (tuck or miss stitches) can be straight or offset.

Consequently, in this study, the two types of varied stitches – tuck stitch and miss stitch were investigated in separate experiments. In each experiment, two levels of stitch design, and two categories of stitch layout, and two numbers of tuck or miss stitches created 8 treatment combinations. The experiment was designed in 3 blocks or replications of 8 treatments for a total of 24 knitted samples. In addition to those treated samples, the other 24 plain samples were knitted with only front knit stitches in comparison to the treated samples knitted with both front knit stitches and varied stitches. Knitted patterns in Table 4.13 illustrate the stitch design of the knitted samples for different treatment combinations.

Table 4.13 Independent variables and their treatment levels

Sample design			Number of tuck or miss stitches in each sample (2 levels)			
			4000 (group a)		2000 (group b)	
			Stitch design (2 levels)		Stitch design (2 levels)	
			Single	Double	Single	Double
Varied stitches in sample: tucks	Stitch layout (2 levels)	Straight layout	 a_1_1	 a_2_1	 b_1_1	 b_2_1
		Offset layout	 a_1_2	 a_2_2	 b_1_2	 b_2_2
Varied stitches in samples: misses	Stitch layout (2 levels)	Straight layout	 a_1_1	 a_2_1	 b_1_1	 b_2_1
		Offset layout	 a_1_2	 a_2_2	 b_1_2	 b_2_2
Knit pattern notation: single jersey tuck stitch miss stitch						

All the samples were knitted on Shima Seiki's V-bed knitting machine (SES 124-S 7 gauge) under the same take down tension using 100% 8/2 count cotton yarns, identified as the optimal size in pilot work. After knitting, samples were conditioned in the lab with constant temperature (20±2º) and constant humidity (65%±2%) for 24 hours for dry relaxing, and then they were wet relaxed by washing and drying according to AATCC Test Method 135-2004. After laundering, the samples were stabilized by steaming. For each sample, according to ASTM D1777 – 96, ten measures of thickness were randomly collected on a digital thickness tester, and then the ten values were averaged. Wale density and course density were averaged from five measurements that were randomly taken in the sample. Then, sample width and length were calculated based on averaged wale density and course density. Means of thicknesses, widths and lengths in samples were compared to those of plain single jersey fabrics. Percentage of dimensional differences between treated samples and plain fabrics were analyzed. The percentage was calculated by

$$\text{Percentage of differences} = \frac{measure\ of\ treated\ sample - measure\ of\ plain\ sample}{measure\ of\ plain\ sample} \times 100\%$$

A positive percentage means dimensions of treated samples were greater than plain fabrics, whereas a negative value indicates the use of varied stitches reduced dimensions compared to plain samples. The model used to evaluate effects of the number of tucks or misses, stitch design and stitch layout on fabric thickness, width and length was

$$Y_{ijkh} = \mu + B_i + \alpha_j + \beta_k + \theta_h + \alpha\beta_{jk} + \alpha\theta_{jh} + \beta\theta_{kh} + \alpha\beta\theta_{jkh} + \varepsilon_{ijkh}$$

Where, ε_{ijkh} ~iid (0, σ^2)

Y_{ijkh} is the percentage of dimensional differences between treated samples and plain samples;

μ is the overall mean of percentage of changes in measurements;

B_i is the block effect at level i, i = 1, 2, 3;

α_j is the effect of the number of tucks or misses at level j, j =1, 2 (4000 or 2000);

β_k is the effect of stitch design at level k, k = 1, 2 (single or double);

θ_h is the effect of stitch layout at level h, h = 1, 2 (straight or offset);

$\alpha\beta_{jk}, \alpha\theta_{jh}, \beta\theta_{kh}$ are two-way interaction effects of two factors;

$\alpha\beta\theta_{jkh}$ is the three-way interaction of the three factors – varied stitch number, stitch design and stitch layout.

4.5.2 Results of Experiment IV

Compared with single jersey, fabrics with either tuck stitches or miss stitches have reduced length. Miss stitches can reduce fabric width a little, but tuck stitches always increase fabric width. Figure 4.13 shows the general trend of width and length of samples knitted with different stitches, numbers of varied stitches and different layouts. Sample codes along the horizontal axis indicate two groups with different numbers of varied stitches amongst plain structures (group a = 4000 tuck/miss stitches, group b = 2000 tuck/miss stitches). The first number in the sample code means level of stitch design, and the second number denotes level of stitch layout. Variations in sample width and length introduced by different numbers of varied stitches were large, in particular with tuck stitches. This could be easily observed through comparing tuck width and tuck length in group a and group b. Different layouts of varied stitches in the samples caused changes in width and length. However, effects of miss stitches on sample width were very small. Statistical calculations and results will be introduced in following sections.

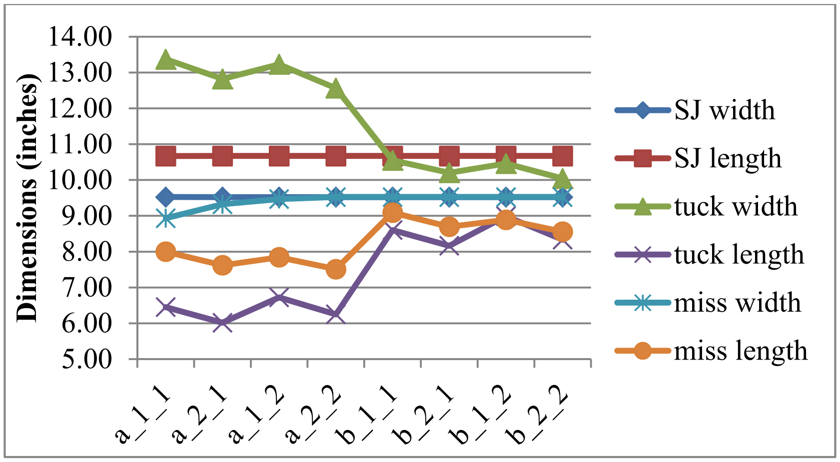


Figure 4.13 Comparison of sample length and width between tuck/miss stitches and single jersey

Results in sample thickness showed that the thickness of single jersey fabric could be increased when tuck stitches and miss stitches were added. Knitted fabrics with tuck stitches are thicker than miss stitches because of held stitches in tuck stitch structures. As shown in Figure 4.14, the number of tuck stitches or miss stitches and layouts can influence the fabric thickness.

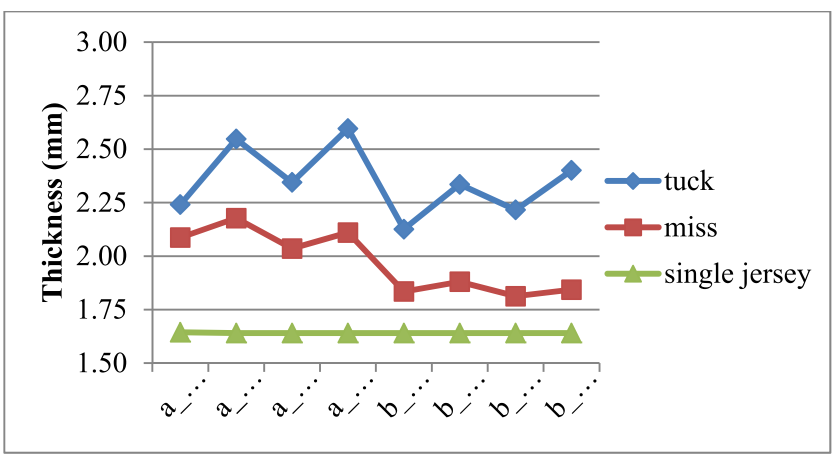


Figure 4.14 Comparison of sample thickness between tuck/miss stitches and single jersey

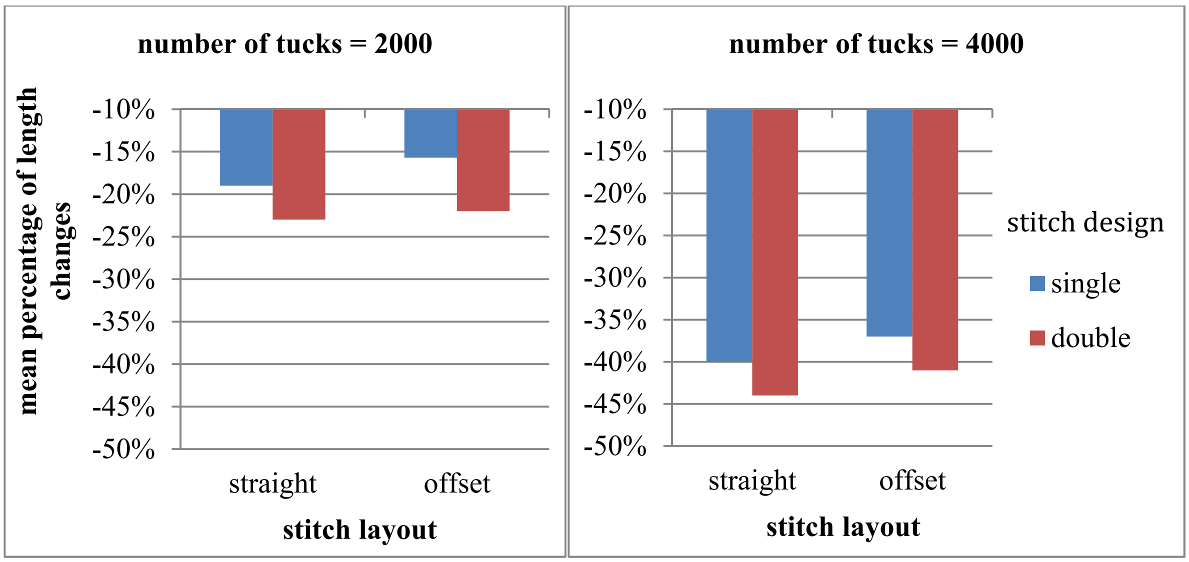
4.5.2.1 **Length of samples knitted with tuck stitches**

According to ANOVA results in Table 4.14, the length of samples knitted with tuck stitches was influenced by the number of tucks, stitches design and stitch layout, and they interact. This means that for different numbers of tuck stitches, the effects on sample length between stitch design and stitch layout is different.

Table 4.14 ANOVA table for sample length with tuck stitches

Source	Numerator DF	Denominator DF	F value	Pr > F
Block	2	14	1.00	0.39
Number of tucks	1	14	61009.00	<0.001
Stitch design	1	14	3025.00	<0.001
Stitch layout	1	14	961.00	<0.001
Number*Design	1	14	49.00	<0.001
Number *Layout	1	14	25.00	<0.001
Design*Layout	1	14	49.00	<0.001
Number*Design*Layout	1	14	49.00	<0.001

Samples treated with tuck stitches had shorter lengths than plain fabrics. As shown in Figure 4.15, in comparison to plain fabrics, the length of samples knitted with tucks and offset layouts is reduced less than using straight layouts, and the use of double tuck stitches results in shorter length compared to the use of single tuck, no matter how many tuck stitches are involved. Although changes in sample length caused by varying layout of tuck stitches were statistically significant, the biggest difference between the two percentages of length changes was only 3%, which may not have a significant impact in practice. In comparison, the use of double tuck or single tucks could affect sample length, no matter whether straight or offset layout was used and no matter how many tuck stitches were involved in the sample. However, the differences caused by varying stitch design from single tuck to double tucks were only substantial enough to affect knitting practice when an offset layout was adopted (see Figure 4.15). Additionally, results of Least-square Means (LSMEANS) showed that increasing the number of tuck stitches in the samples could dramatically change the length. No matter which stitch layout and stitch design were used, increasing the number of tucks twice caused a significant difference of sample length.



*Standard error is 0.0012 %

Figure 4.15 Interaction effects of the number of tucks, stitch design and stitch layout on length

4.5.2.2 Width of samples knitted with tuck stitches

In samples knitted with tuck stitches and front knits, the number of tucks was the only factor that influenced the sample width ($F(1, 14) = 9.3$, $p = 0.0087 < 0.05$). Table 4.15 presents the mean percentage of sample width changes caused by adding tuck stitches in the sample. When the number of tucks was 2000, the width of treated samples was increased 15.3% compared with the plain sample width. When the number of tucks was increased twice, the width of treated samples was enlarged more than twice up to 36.5% compared to plain fabrics.

Table 4.15 Effects of the number of tuck stitches on width

Number of tucks	Means of percentage of width changes
2000	15.3%
4000	36.5%

*Standard error is 0.049 %

4.5.2.3 **Thickness of samples knitted with tuck stitches**

ANOVA results of sample thickness with tucks revealed two two-way interactions between the number of misses and stitch design ($F(1, 14) = 841.0$, $p < 0.001$) and between stitch design and stitch layout ($F(1, 14) = 289.0$, $p < 0.001$), and a three-way interaction ($F(1, 14) = 25$, $p < 0.001$). This means effects of one factor depends on the other two factors.

Figure 4.16 graphically shows interaction effects of the three factors on differences of thickness between treated samples and plain samples. No matter which stitch design and stitch layout were used, samples knitted with more tuck stitches were thicker than plain fabrics. Also, whether the number of tucks was 2000 or 4000, and whether stitch layout was straight or offset, double tucks design always increased the thickness more than single tuck design. For effects of stitch layout on the thickness, as shown in Figure 4.16, no matter how many tuck stitches were involved in the samples, the use of an offset layout substantially increased the thickness when the samples are designed with single tuck. However, when samples were designed with double tucks, the difference between a straight layout and an offset layout was small. This demonstrated that effects of varying stitch layout from straight to offset on thickness were more significant when single tuck was used than when double tucks were used.

*Standard error is 0.0012 %

Figure 4.16 Three-way interaction of number of tucks, stitch design and stitch layout on thickness

4.5.2.4 Length of samples knitted with miss stitches

For length of samples knitted with miss stitches and front knits, the two-way interactions and the three-way interaction were not significant. Main effects on the sample length were the number of misses ($F(1, 14) = 3246.35$, $p < 0.0001$), stitch design ($F(1, 14) = 424.71$, $p < 0.0001$), and stitch layout ($F(1, 14) = 56.49$, $p < 0.0001$). Comparisons of levels in each factor are show in Table 4.16.

Table 4.16 Effects of the number of misses, stitch design and stitch layout on length

Factors	Levels	Means of percentage * of length changes
Number	2000	-17.7%
	4000	-27.5%
Stitch design	Double	-24.4%
	Single	-20.8%
Stitch layout	Offset	-23.2%
	Straight	-21.9%

* Standard error is 0.0012 %

Results of t-tests indicated that the average percentage of length changes caused by varying the number of miss stitches from 2000 to 4000 was up to 9.8%, which was both statistically and practically significant ($t(22) = 56.98$, $p < 0.001$). The effect of stitch design on length changes was statistically significant ($t(22) = -20.61$, $p < 0.001$). Samples designed with double misses were 24.4% shorter than plain samples, and the design of single miss stitches reduced the sample length up to 20.8% compared to plain knit, but the difference between the two values was only 3.6% which would not significantly impact knitting practice. Similarly, changing stitch layout from straight to offset could lead to a statistically significant decrease in sample length ($t(22) = -7.52$, $p < 0.001$), but 1.3% length changes would not cause a meaningful change in fabric dimensions in practice.

4.5.2.5 **Width of samples knitted with miss stitches**

According to results of ANOVA (see Table 4.17), the number of misses, stitch design and stitch layout have significant impacts on the width, and there were three two-way interactions and a three-way interaction. However, further analysis revealed that interaction effects were extremely small. When the number of miss stitches involved in the treated samples was 4000, width of samples designed with single miss stitches and straight layout was only changed 6% compared to plain knit. When the number of miss stitches was 2000, no changes of width existed among samples knitted with different treatments.

Table 4.17 ANOVA table for sample width with miss stitches

Source	Numerator DF	Denominator DF	F value	Pr > F
Block	2	14	2.03	0.15
Number of tucks	1	14	164.61	<0.001
Stitch design	1	14	38.16	<0.001
Stitch layout	1	14	119.45	<0.001
Number*Design	1	14	38.16	<0.001
Number *Layout	1	14	119.45	<0.001
Design*Layout	1	14	18.29	<0.001
Number*Design*Layout	1	14	18.29	<0.001

4.5.2.6 **Thickness of samples knitted with miss stitches**

According to results of ANOVA in Table 4.18, the three-way interaction was not significant, but all three two-way interactions were significant. The three charts in Figure 4.17 illustrate how the number of misses, stitch design and stitch layout influenced sample thickness.

Table 4.18 ANOVA table for sample thickness with miss stitches

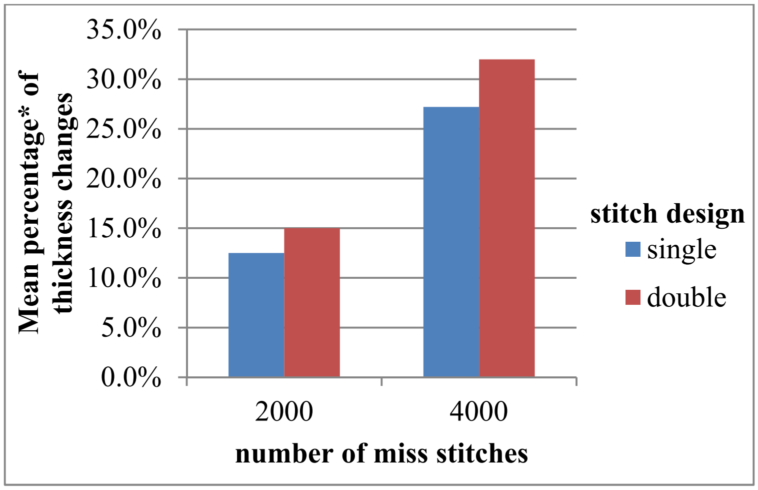
Source	Numerator DF	Denominator DF	F value	Pr > F
Block	2	14	0.47	0.64
Number of tucks	1	14	16846.7	<0.001
Stitch design	1	14	903.47	<0.001
Stitch layout	1	14	420.00	<0.001
Number*Design	1	14	91.47	<0.001
Number *Layout	1	14	67.20	<0.001
Design*Layout	1	14	16.80	<0.001
Number*Design*Layout	1	14	0	1

In the interaction between the number of miss stitches and stitch design, averaged over stitch layout, regardless of single miss stitch design or the double miss stitches design used, samples with a greater number of miss stitches were significantly thicker than those with fewer miss stitches. This means increasing the number of miss stitches could increase knitted fabric thickness. When the number of miss stitches remained the same, while varying stitch design from single miss to double misses, sample thickness was increased but the differences were very small and not practically significant (see Figure 4.17 (a)).

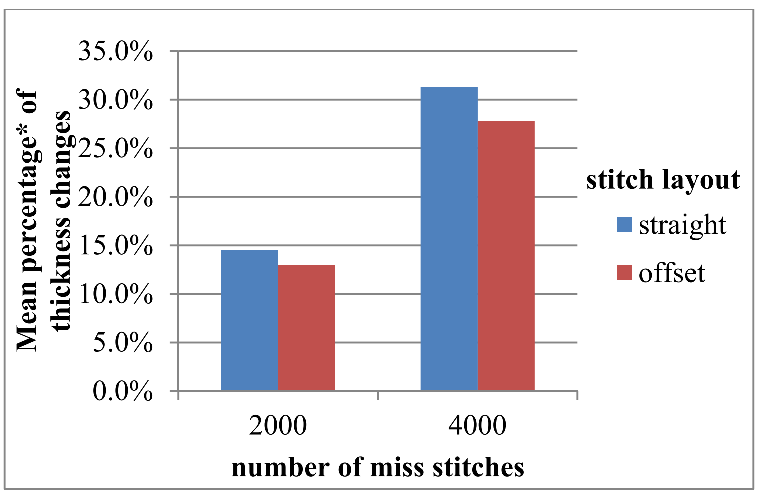
In the interaction between the number of miss stitches and stitch layout, averaged over stitch design, no matter if the straight layout or the offset layout was used, the number of miss stitches in the samples significantly influenced knitted fabric thickness. The differences of the average percentage of thickness changes between the two levels in the number of miss stitches were more than 25%, which would significantly impact knitted fabric thickness in practice. However, when the stitch layout was altered from an straight layout to an offset layout, changes in thickness of samples knitted with the same number of miss stitches were too small to be considered in practical knit fabric design (Figure 4.17 (b)).

In the interaction between stitch design and stitch layout, averaged over the number of miss stitches, all pairwise comparisons of levels in stitch design and stitch layout showed that sample thickness of any treatment combination differed from the other one; but, the differences were too small to cause a difference in knitting practice (Figure 4.17 (c)).

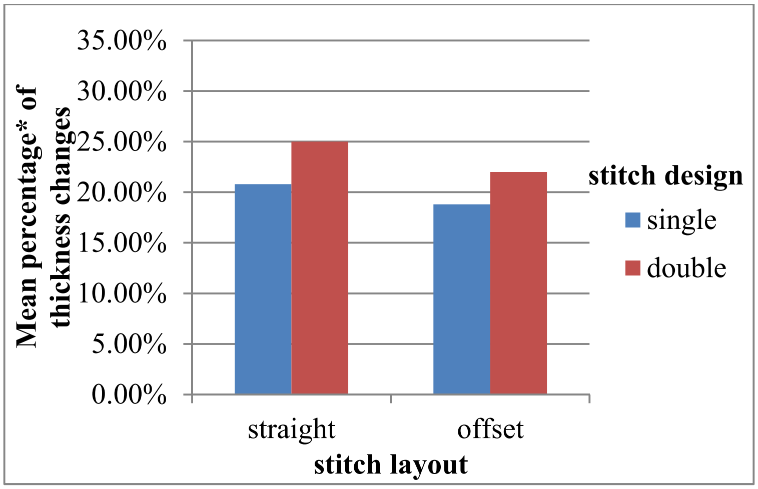
Figure 4.17 Two-way interactions of number of misses, stitch design and stitch layout



(a) Interaction between the number of misses and stitch design



(b) Interaction effects of the number of misses and stitch layout



(c) Interaction effects of stitch design and stitch layout

*Standard error is 0.0012 in (a), (b) and (c)

4.5.3 Conclusions and limitations in Experiment IV

In samples knitted with tuck stitches and front knit stitches, stitch design (single tuck and double tucks) and stitch layout (straight and offset) have no effect on knitted fabric width. The width is only influenced by the number of tuck stitches involved in knitted fabrics. When the number of tuck stitches is increased, knitted fabrics have greater width, but fabric length will be reduced. Results of the experiment indicate that knitted fabric length is influenced by different numbers of tucks, stitch designs and layouts. When the use of single tuck is changed to double tuck stitches, the fabric length is reduced. The difference is significant for practice, only when an offset layout design is adopted. This means if knitted fabrics are designed with a straight layout of tuck stitches, the use of single tuck or double tucks has no impact on the length. In terms of knitted fabric thickness, increasing the number of tuck stitches in the fabric can significantly increase the thickness. Changing the design of tuck stitches from a straight layout to an offset layout also increases fabric thickness, but the difference is only practically significant when the design of single tuck stitch is used.

In samples knitted with miss stitches, knitted fabric width is similar to the width of plain fabrics, especially when the number of miss stitches in the fabric is small. Thus, in actual knitted fabric design, effects of miss stitches on fabric width may not need to be considered. In terms of knitted fabric length, knitted fabrics using double miss stitches are longer than those designed with single miss stitch. The length of fabrics designed with an offset layout is shorter than that of fabrics designed with a straight layout. However, effects of stitch design and stitch layout on fabric length are not significant in practice. The number of miss stitches in the fabric is the main effect on fabric length. Similar to adding tuck stitches, increasing the number of miss stitches in the fabric can reduce the length, but the change in fabric length introduced by adding miss stitches is less significant than adding tuck stitches. Miss stitches can increase fabric thickness. More miss stitches make the knitted fabric thicker. According to statistical results, the fabric thickness is also influenced by different stitch design and layout; however, their effects caused small changes that should be of little practical consequence.

In conclusion, changes in the number of tuck or miss stitches amongst plain stitches fabrics, and stitch design and layout can create different tuck stitch structures or miss stitch structures. Fabrics knitted with these varied stitch structures will have different dimensions in width, length and thickness. Findings in this experiment can provide a basic understanding of the effects of varied stitch structures on knitted fabric dimensions. Results in sample dimensions will contribute to a knowledge base for the implementation of an integrated model for knit garment design and development. In this research, only tuck stitches and miss stitches within a single jersey structure were explored. Other knitted stitch structures such as the use of tuck and miss stitches within an interlock structure could be investigated in further research. To extend the knowledge base, these stitch structures could be knitted on different types of knitting machines and created by different yarns.

5 Research Methodology in stages two and three

A multiple and participant observation case study approach was chosen to explore the integrated design and development process for fully-fashioned and seamless knit garments. A multiple case study approach allows for gathering enough information and achieves in-depth understanding of the product development process (Merriam, 1998). Yin (2010) believes that multiple case study research helps to establish replication of results and is essential for testing the validity and reliability of results. The case studies in this research are knit garment design and development projects.

Yin (2010) considered participant observation as an effective data collection technique in a case study research. Participant observers were engaged over a period of time to observe and explore behavior and collect information. In this research, participant observation was used as a key approach in each case to observe the knit garment design and development process and gain an in-depth understanding of the process, as well as investigate the knowledge needed for successful knitwear design and development. The researcher worked as an observer with limited participation in case studies for shaped knit garment design and development.

Completion of a fully-fashioned or seamless knit garment requires both fabric design and garment construction. Knit garment designers not only need to undertake design and programming of knit stitch patterns, but they also undertake the fashion design. This differs from traditional cut and sewn knit garment design, where fabric design, fashion design and technical design are separated and accomplished by different persons or development teams. In fully-fashioned and seamless knitting, the garment shape is decided during knitting, so the design and development process is more complex and has greater requirements for designers or knitwear development teams compared to cut and sewn garments. To understand in-depth the design and development process in fully-fashioned and seamless knitting, the researcher completed training on Shima Seiki programming and machine operation for the fully-fashioned and seamless garment knitting machines. The researcher gained the ability to design knit garments in CAD systems and to operate knitting machines. The researcher practiced roles of a knitted fabric designer, fashion designer and a machine operator and could examine the details and knowledge needed in the process. Results from participant observation in stage two of the research were used to document the design and development process and develop a model for creating shaped knit garments.

In order to establish a reliable model, the researcher validated the model in two approaches. One was an in-depth case study, which would be conducted to test whether fresh knitwear designers with basic training could finish their designs following the steps of the model established in the previous stage. The in-depth case study could also assist in assessing whether the components in knowledge building and evaluation are necessary and sufficient to support the knit garment design and development process. Another approach to validating the model was a review by industry experts in the field of knitwear design and development through telephone interviews with several open-ended questions. Results of expert interviews verified whether or not steps and components in the model were valid and reliable. Also, comments and feedback from experts were used to refine the model.

5.1 Case study selection

In stage two, the case study research was aimed to develop a model for producing knit garments that integrated style design, yarn selection, structure design, prototype production and finishing. A collective case study approach was used to achieve detailed understanding of the process. The case study research was undertaken through participation and observation of multiple knit garment design and development projects. Cases for knit garment development in this study included the entire design and development process from aesthetic design to technical design to machine operation. In the case study research, the researcher worked closely with professors or undergraduate students from the College of Textiles at North Carolina State University to create design concepts.

Typically, because undergraduate students had limited knowledge in knitting technology and machine operation, the researcher was responsible for digital pattern design in the CAD system, sample knitting and prototype production in collaboration with the undergraduates.

The first case study was participation and observation in a seamless knitted garment design and development project. Knitted garments created in this project were juried into the BIFT-ITAA 2012 joint symposium conference and were presented in a fashion design and research exhibition. Design of the knitted garments included two parts: a seamless knitted dress and a sleeveless cardigan. Both fully-fashioned and seamless knitting technologies were used in this project to create the unique knitted dresses. An initial framework for full-fashioned and seamless knit garment design was established. This case study attempted to incorporate fully-fashioned and seamless knitting technology into the integrated design and development process that involved knitwear style development, optimal yarn selection, knitted structure design, garment shaping, pattern making in a CAD system, CAM programming and knit production.

The second case study explored the integrated design process for a seamless dress, which was designed for a high profile client for the 2011 Cotton Couture fashion show at NCSU, Raleigh, NC. This project created another shaped dress, entitled Painted Dress, using the same knitting techniques as in the design of the client's dress. The dress named "Painted Desert" was exhibited in a juried fashion show at the 2012 ITAA's annual conference. These two dresses were knitted on the Shima Seiki's WholeGarment® knitting machine. Extra knitted pieces with three-dimensional shapes were seamed to the lower edge of the dresses for decoration and shaping. Development of both dresses followed the initial framework developed in case one, so observation and participant experience in knit garment design and development process of the second case were used to modify and validate the initial model. This is an effective and useful method to develop a reliable model in case studies.

Projects in case one and case two were completed through co-design of the researcher and Professor Traci Lamar in the College of Textile at NCSU. Projects in case three and case four were at the request of NCSU undergraduate students majoring in textile and fashion design. Case studies three and four focused on fully-fashioned knitting. The workflow for fully-fashioned knit garment design was documented and compared with the initial model developed in project one and two. The design and development process documented in case three and four facilitated development of an integrated model for either fully-fashioned or seamless knit garments. Finally, in stage two, a preliminary model based on these four case studies was established. This model integrated the entire design and development process and knowledge needed to support the process.

Research in stage three was aimed to validate and refine details of the preliminary model. Participants in the in-depth case study were undergraduate or graduate students or faculty in the College of Textiles at NCSU who had basic knowledge in knitting and who asked the researcher to help them create fully-fashioned or seamless knit garments for their classes or creative scholarship projects. In this stage of the research, three undergraduate students who had limited knowledge in knitting were trained to use CAD software and operate fully-fashioned or seamless knitting machines. When they were able to design digital patterns and operate machines individually, they followed the steps in the preliminary model to create their own design and produce the finished products. Additionally, the other two case studies were accomplished with a professor in the College of Textiles at NCSU. In the in-depth case studies, the researcher worked as an observer with limited participation to examine whether participants could complete their knit designs following steps in the model. Observation and communication with participant designers regarded whether the model provided sufficient and necessary information to support each step. Designs created in the case studies were included in the results of the dissertation with participants' names. Institutional Review Board (IRB) approved the use of participants' feedback and designs in the research. The IRB approval letter was attached in Appendix B.

5.2 Data collection and analysis of case studies in stage two

It is difficult to comprehend the design and development process and explore knowledge needed in the process without experiencing it. Participant observation provides insight that may not be obtained by outsiders (Yin, 2010). Thus, participant observation is the main method used to collect data in case studies of stage two. Engagement of the researcher in the knit garment design and development process gave insight into the role of each part in the process and enhanced understanding of fundamental knowledge needed to complete a successful design. Data was collected in a digital document format including information of notes, digital knitting programs in CAD software and machine settings and physical information of knitted samples and test pieces. Designers and co-designers' knitting background and knowledge level, design process mapping, the evaluated components, and knowledge needed were documented for each case and then analyzed. Data sources collected in this stage of the research comprised the following aspects:

- Designed pattern with various structures in SDS-ONE knit software
- Knit data files of technical settings on the machine
- Knitwear design specification sheets including model measurements, number of stitches in the design, and types of yarns used
- Physical samples of knitted fabrics and finished garments
- Records of challenges and solutions encountered by the researchers and designers
- Training notes used for teaching new knitwear designers to design and produce knit garments using Shima Seiki's system and machines

Data collected in each case went to a database, which provided references for other designers to create their own design. This database combined with results obtained in stage one of the research were physically documented as a reference library in an open lab in the College of Textiles at North Carolina State University. The reference library includes information of yarns, dimensions and digital patterns of knitted samples, machine settings for different knitted fabrics and garments, and findings of experiments in stage one of the research relevant to 3D shaping techniques, shrinkage and influences of knit stitches on fabric dimensions. This reference library supports designers in completing the design and development process of shaped knit garments.

Following data collection, information and conclusions drawn from participant observation in each case were transcribed into a graphic model that support the integration of shaped knit garment design and development. An initial model was built in case one, and then it was revised and validated in case two, three and four. Comparisons of the revision in the models were used to analyze in-depth the knowledge foundation and the workflow of fully-fashioned and seamless knitwear design and development.

5.3 Data collection and analysis on in-depth case studies in stage three

Data in the in-depth case studies was collected by observing the design and development process and communicating with participants. When participants made arrangements to create a design, first, the researcher asked them several questions to learn about their previous experience and knowledge in knitting. The questions included: 1) Have you taken any class for knitting? 2) Do you have experience in knitted product design? If so, what kind of knitted products have you created? 3) Do you have experience of using CAD/CAM systems? Based on participants' answers to the questions, the researcher made an effective plan for training participants to use CAD/CAM knitting software and operate the machines. The training contents are shown in Table 5.1.

Table 5.1 Training of CAD and CAM systems

Knitting method	Content	Task
Fully-fashioned knitting	1. Pattern design in CAD system	• Design patterns with different structures • Learn stitch colors and option lines in CAD system • Design shaped front and back garment panels • Understand meaning of option lines and machine settings
	2. V-bed knitting machine operation	• Set up yarns; adjust yarn tension • Be familiar with machine parts such as encoder and carrier • Adjust loop length and take down tension for different structures or different rows in garment panels • Run fully-fashioned knitting machine • Read and correct common errors in knitting, such as damaged needles or failed comb movement
Seamless knitting	1. Introduction of seamless knitting	• Learn features and benefits of seamless knitting • Understand seamless knitting procedure
	2. Seamless pattern design	• Create garment patterns existed in CAD pattern library • Adjust knitted structures, garment shapes and option lines of digital garment patterns
	3. Seamless knitting machine operation	• Set up yarns; adjust yarn tension • Be familiar with machine parts such as encoder and carrier • Adjust loop length and take down tension for different structures or different parts of seamless garment • Run seamless knitting machine • Machine maintenance: fix damaged needles

Having learned the basic knowledge of CAD/CAM knitting systems and machine operation, participants created their own design referring to knitted samples in the reference library, and completed their fully-fashioned or seamless knit garments following steps in the preliminary model. If participants individually finished their work, the researcher asked them to estimate whether components in knowledge building and evaluations were sufficient and necessary to guide them. If participant designers failed to complete some steps such as digital pattern design or machine operation, the researcher assisted them to finish those steps. This still validated that the knowledge documented in the model was required to complete the process steps, and that the researcher was needed to fill in the knowledge gaps when encountered by designers.

Data collected in the in-depth level case studies was used to refine the model and examine its validity. Data from direct and limited participant observation of the design and development process was organized into execution and evaluation steps and the knowledge needed to support the process. The steps for fully-fashioned or seamless knit garment execution and evaluation were mapped to the preliminary model established in stage two. If the process in the in-depth case study coincided with the steps in the preliminary model, results of mappings confirmed the validity of the model. Otherwise, the preliminary model needed to be revised to encompass a wider variety of situations. Also, analysis of information gathered in the in-depth case studies assisted in assessing whether the components in knowledge building were necessary and sufficient to support designers in accomplishing the design and development process.

5.4 Interview instrument development

To provide enhanced validity to the preliminary integrated model established in stage two, industry experts in fully-fashioned and seamless knitting were consulted to review the model and share their opinions about it. Fully-fashioned and seamless knitting technologies are not widely used in the knitwear industry, and there are few experts specifically in this area, so qualitative data through telephone interviews was collected to analyze both the necessity and sufficiency of components in the established model.

The interview instrument was designed with several open-ended questions, under assistance of experts in questionnaire design. Glicken (2003, pp.269) indicated that answers to open-ended questions on an instrument were not pre-determined so that the participants could answer anything they believed to be relevant. Open-ended questions in this study allowed participants to give unexpected answers and provide their opinions or comments to the model. Their thoughts and feedback to the study were valuable in model validation and model refinement.

First, NCSU's Institutional Review Board (IRB) approved the interview. The IRB approval letter was attached in Appendix C. As shown in Appendix D, the interview instrument consisted of five parts – an email to request consent for participation, a brief script for phone call interview, basic information of participants, description of the model, and assessment of the model. First, an email to request consents for participation was sent to potential participants, following the requirements of the principal investigator's IRB. In the second part, contact information and knitting experiences were collected from each participant. Knitting experiences helped identify participants' level of expertise. Specifically, participants were asked to state their job title, responsibilities in their current position, types of knitted products they designed or produced, and length of experience and working hours per week in knitting or knitted product development. Part three of the instrument provided a brief description of the integrated model and stated the main purpose of this research. Part four contained eight open-ended questions relevant to the preliminary model. Question one asked participants to evaluate overall steps in the integrated model for fully-fashioned and seamless knit garment design and development. The purpose of questions two, three and four was to assess necessity and sufficiency of components in knowledge building to support the design and development process in major phases. Questions five, six and seven asked if participants thought components in the model's evaluation could reflect information needed to move forward to the next phase of the design and development process. Question eight was used to obtain experts' opinions and feedback regarding the importance of knowledge building and evaluation involved in the integrated model.

5.5 Sample selection and interview procedure

The researcher compiled a list of possible expert participants by contacting companies that develop fully-fashioned or seamless knitting and professors at universities whose research areas concern knit garment design. Interviewees were required to have experience in fully-fashioned or seamless knitted product design and development. Possible participants were contacted via e-mail to ask if they would be willing to participate in the study by completing a telephone interview. Following e-mail solicitation, the researcher gave the participants phone calls to set up an interview time. When the participants consented to join in the study, they were sent a consent e-mail formally requesting participation with an attached instrument to prepare for the telephone interview with the researcher. Answers to the questions in the interview were recorded for audio documentation and accuracy of later analysis.

5.6 Data collection and analysis in interview

Interviews for this study were conducted over a five-week period during Spring 2013. For each participant, a telephone interview was conducted, following the predetermined set of questions in the interview instrument. The telephone interviews ranged around 30 minutes. Sixteen people were invited to participate in the study, but only 14 of them were self-identified as experts in fully-fashioned and seamless knitting. Of the 14 potential participants, 13 responded to the invitation. Three of the 13 responding experts declined participating in the interview due to hectic schedules. Thus, a total of 10 experts consented to complete the interview. Responses of the ten industry experts to the eight open-ended questions were used to verify the validity of components in the model. Based on their comments and feedback, the model was refined when necessary.

6 Results of stage two: preliminary model establishment

The research sample in stage two consisted of four case studies. Referring to the reference library built in stage one, the researcher was involved in as a participant observer and was responsible for fully-fashioned or seamless knit garments design and development in collaboration with designs in the four case studies.

6.1 Case study one

A seamless knitted dress and a sleeveless cardigan sweater were created in case one. Front and back views of knitted garments created in case one are illustrated in Figure 6.1.

(a) Front view (b) Back view

Figure 6.1 Knit dress in ivory created in case one

The researcher's experience and observation of participating in this case were consolidated into an initial model. Figure 6.2 shows the initial model, which is composed of three parts: knowledge building, design and development process and evaluation. Based on the researcher's observation, the process for developing the fully-fashioned cardigan and the seamless knitted dress encompassed steps from style development, yarn selection, sizing and shapes, CAD pattern making, CAM programming, pre-production, knitted prototype production to finishing. Evaluation after the steps of yarn selection, CAM programming and pre-production was necessary in the design and development process. Evaluations acted as decision gates for the knit garment design to either pass through or be redirected back to previous steps for refinement. Also, to indicate the knowledge needed in the design and development process, the research developed knowledge building that reflected the knowledge components needed to complete each relevant step in the process.

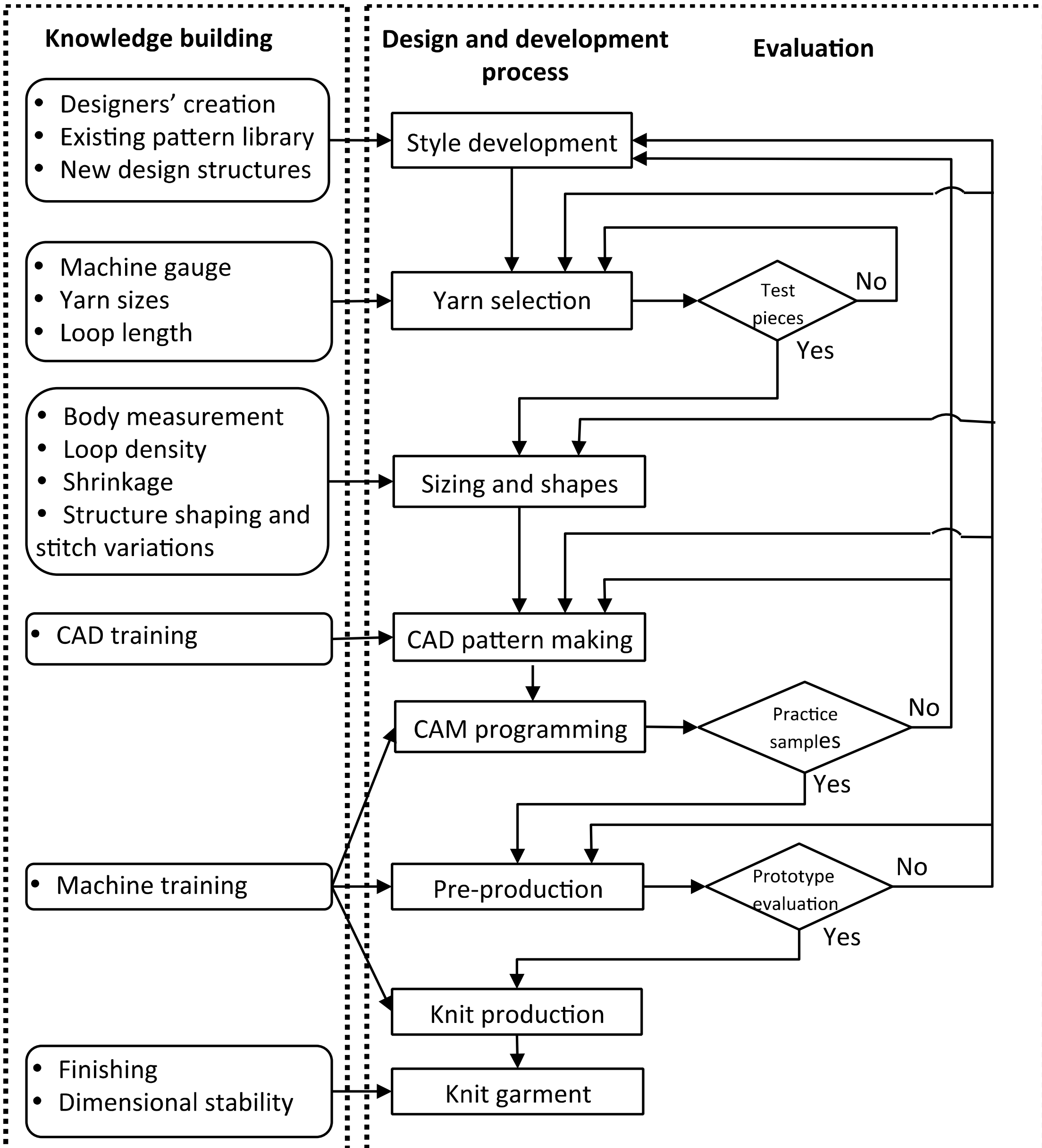


Figure 6.2 Initial model developed in case study one

Shapes of fully-fashioned and seamless knit garments design are formed during knitting, so style development in the first step integrates both fashion design and knitted structure design. Design of garment styles and knitted structures depended on designers' creation with novel structures, or inspiration from fashion trends, or referring to an existing pattern library built in stage one. Once a basic style was created, the designers needed to consider whether the specific style or shape could be knitted on the machines. For example, in case one, the sleeveless cardigan sweater was designed as one piece of shaped fabrics with two armholes. Width of the shaped fabric was limited to the number of needles on the fully-fashioned knitting machine. To create the cardigan sweater with the designed size, the designers selected an interlock structure as the main structure, because interlock structures widen the fabric in comparison to single jersey structures with the same number of stitches. Accomplishment of knitted structure selection referred to physical samples in the reference library built and findings obtained in stage one of the research. To summarize, in style development, designers were required to undertake fashion design of knitted garments, and they also had to know some limitations in garment knitting.

In the step of yarn selection, the designers were responsible for both aesthetic and technical description. Aesthetic description involved determination of yarn color and materials that could match to the design. Technical selection was aimed to select optimal yarn size that was suitable for the machine gauge. A proper yarn size is crucial in knit garment development, and it influences accomplishment of steps that follow in the design and development process. In order to select proper yarns, knowledge of machine gauge and yarn characters such as size, elongation and twist is of prime importance. Following yarn selection, the designers knitted five test samples to determine a suitable loop length for designed garments. Loop length means the length of one knit loop. On Shima Seiki's knitting machines, loop length can be controlled within each course. The five test samples were knitted with five levels of loop length including 9 mm, 9.5 mm, 10 mm, 10.5 mm, and 11 mm. The range of tested loop length was influenced by the yarn and machine used, as well as knitted fabric design. When designers wanted to create knitted fabrics with loose textures, they chose relatively thin yarns and increased loop length. The proper loop length for different knitted structures may vary. If more than one knitted structure was involved in a knit garment, it would be necessary to knit additional test samples to find proper loop length for each structure. For instance, in case one, the yarns selected were 8/2 c.c. 100% cotton, and three knitted structures – interlock, 2×2 cable, and single jersey were used. Their proper loop lengths were respectively 10.5 mm, 10 mm and 9.5 mm. Also, loop density of each structure was different and it was calculated depending on the selected test sample. When the selected yarns passed through the first evaluation, the design moved to the next step for sizing and shape.

In case study one, the shape of the seamless dress was adapted from an existing pattern in the pattern library of the CAD system, whereas the design of the sleeveless cardigan was innovative. Sizing and shaping of the seamless knit dress were easy to achieve because the CAD system could automatically create a digital pattern based on input measurements. However, the size and shape of the cardigan had to be manually determined by the designers. Its unique shape employed shaping techniques such as knitted structure combination and wale shaping with transferred stitches. First, the designers had to consider the placement of different knitted structures. For example, the waist area was knitted with 2×2 cable structures to narrow the fabric and improve fit. Second, according to body measurements and loop densities determined in the previous step, the designers calculated the number of stitches for the digital pattern. The information gathered in this step was very useful in the next step of CAD pattern making and programming. Furthermore, in case one, a key to complete garment sizing and shape was to utilize different knitted structures in one garment. Documented information in the reference library provided a base for the designers to understand effects of different knitted structures or stitches on knitted garment size and shape. For example, in sleeveless cardigan knitting, an interlock structure was used as a main structure, and 2×2 cable structure was applied in the waist area to shape the waist. Structure selection referred to dimensions of physical samples respectively knitted with interlock structure and 2×2 cable structure in experiment III in stage one of the research.

To design patterns in CAD systems requires CAD training for designers, as well as building enough knitting knowledge to transfer aesthetic design to technical design. For the seamless dress in this case, its digital knitting pattern was adjusted from an existing pattern in the library. The designers input body measurements into the CAD system, which automatically generated a sized digital pattern blank, and then the designed knitted structures were added to the pattern. Therefore, CAD pattern making and CAM operation for the seamless dress were easier than CAD/CAM for the unique cardigan sweater design.

In cardigan sweater knitting, the designers needed to create the digital patterns by themselves. This required designers having enough knowledge in using CAD software and understanding digital pattern making methods in fully-fashioned knitting. Prior to knitting a garment prototype, practice samples were knitted to test the possibility of knitting difficult parts in the design, such as novel knitted structures and unique garment shapes, and then, the knitted practice samples were evaluated. If the practice samples were knitted with acceptable quality, the digital pattern and machine settings for the difficult parts were applied to the entire design, and the design was moved to the next step of pre-production. If the practice samples failed to pass the evaluation, the design was redirected back to previous steps to identify the problems and refine the design. The designers were required to identify which steps to go back to for improvement and figure out the problems for disapproval in evaluations. Usually, the steps of CAD pattern making and programming for practice samples were repeated several times until a good quality piece was knitted.

To assure the knit garment could be successfully knitted on the machine, a prototype was generated in pre-production before the final product was finished. When the prototype in pre-production worked well, the digital pattern of the prototype was sent to final production. If the prototype did not pass the evaluation, previous steps from style development, yarn selection, CAD pattern making to CAM programming and knitting on the machine were revisited to solve the problems in pre-production. For example, in case one, one problem in prototype knitting was tight binding stitches on the edge. A simple pilot study was completed to investigate bind off knitting techniques. This study revealed bigger loop length and higher take down tension would lead to looser binder stitches on the edge. Different settings for loop length and take down tension in bind off knitting should be applied when different knitted structures were used. Data collected in the pilot study went to the database in the reference library, which will be useful for other designers to make correct settings in bind off knitting.

After being taken off the machine, knitted garments were washed and dried to achieve their completely stable status. Fancy yarns and ribbons were used to embellish the knit garments.

To sum up the initial model built in case one, eight steps were involved in the design and development process, and evaluation was carried out after yarn selection, CAM programming of knitted samples, and pre-production of prototype. The vital knowledge needed to support relevant steps included understanding of effects of knitted structures on knitwear size and shape, garment shaping methods, machine gauge, yarn size, loop length, loop density, shrinkage after finishing and CAD/CAM programming and machine operating. The knowledge of making digital programs and operating fully-fashioned and seamless knitting machines were acquired through training.

Design of the sleeveless cardigan and the seamless dress in case one was juried into 2011 BIFT-ITAA joint symposium fashion and design research exhibition. The initial framework for shaped knit garment design and development was presented in the international conference – 2011 BIFT-ITAA joint symposium and was published in an edited book (Lamar & Ma, 2012). The citation for the manuscript is given below.

Lamar, T. & Ma, Y., (2012). Knit dress in ivory: an exploration in integral knitwear design. In J.R. Campbell (Ed.), *Fashion Dialogue 2012 BIFT-ITAA Joint Symposium: Research Exhibition & Fashion Show* (pp. 021-022). Beijing, China: China Textile & Apparel Press.

BIFT-ITAA
2012 Joint Symposium
国际联合研讨会

"Fashion Dialogue 2012"
Designer-Educator
Research Exhibition

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Knit Dress in Ivory: An Exploration in Integral Knitwear Design

Integral and seamless knitting that can create a complete garment with minimal or no cutting and sewing provides many opportunities for designers. But, innovative knitting technology and advanced CAD systems introduce unique challenges. Currently, there is no recognized system for creating unique integrally knitted fashion garments from idea generation to knit production. Creation of these products typically requires the skills of both aesthetic designers and technical designers, communication between whom has been a bottleneck in knit garment design (Eckert 2001). The purposes of the study were to provide a fundamental understanding of applying knitting techniques to knitted fashion products, and to explore the process for integral knitwear design. This research investigated how knitted fabric structures could be juxtaposed to provide shape and texture to a fashion item. A designer's perspective workflow for creating seamless knitted fashion garments was developed, and the knowledge base needed for successful execution of conceived designs was defined.

To build a knowledge base that describes how knitting techniques and knitted structures influence pattern development and knit garment size, a physical library of samples knitted with various yarn sizes and different structures were created. Measurements of two-dimensional and three-dimensional shapes obtained in these samples were collected. Ultimately, the dress and overdress were knitted of 8/2 c.c. 100% cotton yarns using full-fashioned and whole garment knitting techniques. As can be seen in the images shown in Figure 2, variations in knitting structure provide shaping at the waist and ruffled effect at the front of the overdress as well as aesthetic design elements. The finished pieces were embellished with manual yarn insertion techniques. The research employed Shima Seiki's SDS-ONE KnitPaint software and Shima Seiki's SES124-S and Shima Seiki's SWG-V (7 gauge).

Based on this work, a framework of fashion knitwear design was established (See Figure 1). Figure 1 shows the workflow of creating an integrally knitted fashion garment and the knowledge building for designers. The design process integrates seamless knitwear style development, optimal yarn selection, knitted structure design, knitwear size and shaping, pattern making in CAD system, CAM programming, and knit production. Decisions at each step influence the variables of following steps. For example, selected style has an impact on optimal yarn selection, and the yarn size also affects sizing of the knitted garment. Additionally, this research also identified knowledge areas supporting creation of integrally knitted fashion garments, and techniques for building the knowledge base.

In the research, new findings about sizing of seamless knits with different structures and techniques are important to shape the garment on the machine. The workflow that was established in this research can be used by designers or technical designers to create unique knitted fashion garments.

Reference:
Eckert, C. 2001, "*The communication bottleneck in knitwear design: analysis and computing solutions*", *Computer Supported Cooperative Work*, vol. 10, pp. 29.
Shima Seiki 2004, "*Shima Seiki Instruction Manual*".

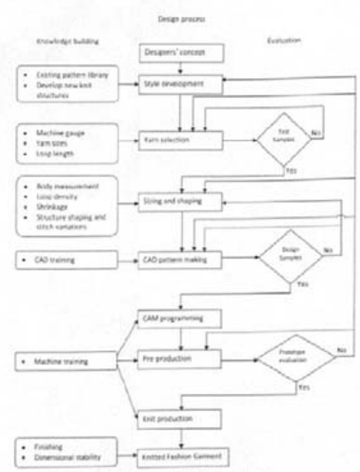


Figure 1 Framework of integral knit garment design

6.2 Case study two

The designers created a fully-fashioned dress following steps in the design and development process of the initial model, but some components in the initial model were modified based on the researcher's participant experience and observation in case two. Figure 6.3 shows the fully-fashioned dress developed in this case study and exhibited in 2012 Cotton Couture Fashion show at NCSU, Raleigh, NC.

Figure 6.3 Fully-fashioned knit dress developed in case study two (Designed by Kyle O'Donnell)

In the design and development process, the researcher found that the steps of CAD programming and CAM operating were repeated for garment shape or style evaluation and knitted structure evaluation. When garment shape and knitted structures used in the design are both complex and unique, it is difficult to evaluate them together in one practice sample. In this case, evaluation of the garment shape or style and evaluation of novelty knitted structures was separated in two steps. Take the design in case two as an example. A shaped hood was designed on the top of the back panel, and waved textures achieved by combining front and back knit stitches were involved in the front and back fully-fashioned panels. Both the garment shape and the waved textures were novelty, so it was necessary to test the possibility of knitting unique shape and novel structure before pre-production. Based on the researcher's experience and observation, one effective way to design knittable and appropriate garment shape and novelty structure is to knit and evaluate them separately. If the special garment shape did not pass the evaluation, designers could focus only on the shape refinement, because the bad quality of the garment shape was always related to fashioning stitches rather than novel knitted structures. Likewise, quality assessment of fabrics knitted with novel structures was not relevant to the garment shape. Designers could easily address the quality problems with separate evaluations in the process. Later, in full-scale evaluation, both special garment shape and novel knitted structures were tested in one piece to be sure garment shape and knit structure worked together. As seen in Figure 6.4, another change in the model was the terminology used in the first evaluation after yarn selection. The term "Test pieces" used in the initial model was changed to "yarn evaluation", which made this step clear and easy to understand.

Moreover, necessity and sufficiency of components in knowledge building were validated through results of case two. The researcher realized it is particularly crucial for designers to understand knitted structure shaping and knitted stitch variations in garment sizing and shapes. Also, appropriate machine settings such as loop length and take down tension for different garment shapes and different knitted structures are important. Most quality problems in garment knitting are caused by improper machine settings. In order to enrich the reference library, practice samples of unique garment shapes and innovative knitted structures were sorted and saved in a physical format, and optional machine settings for them were documented in the library.

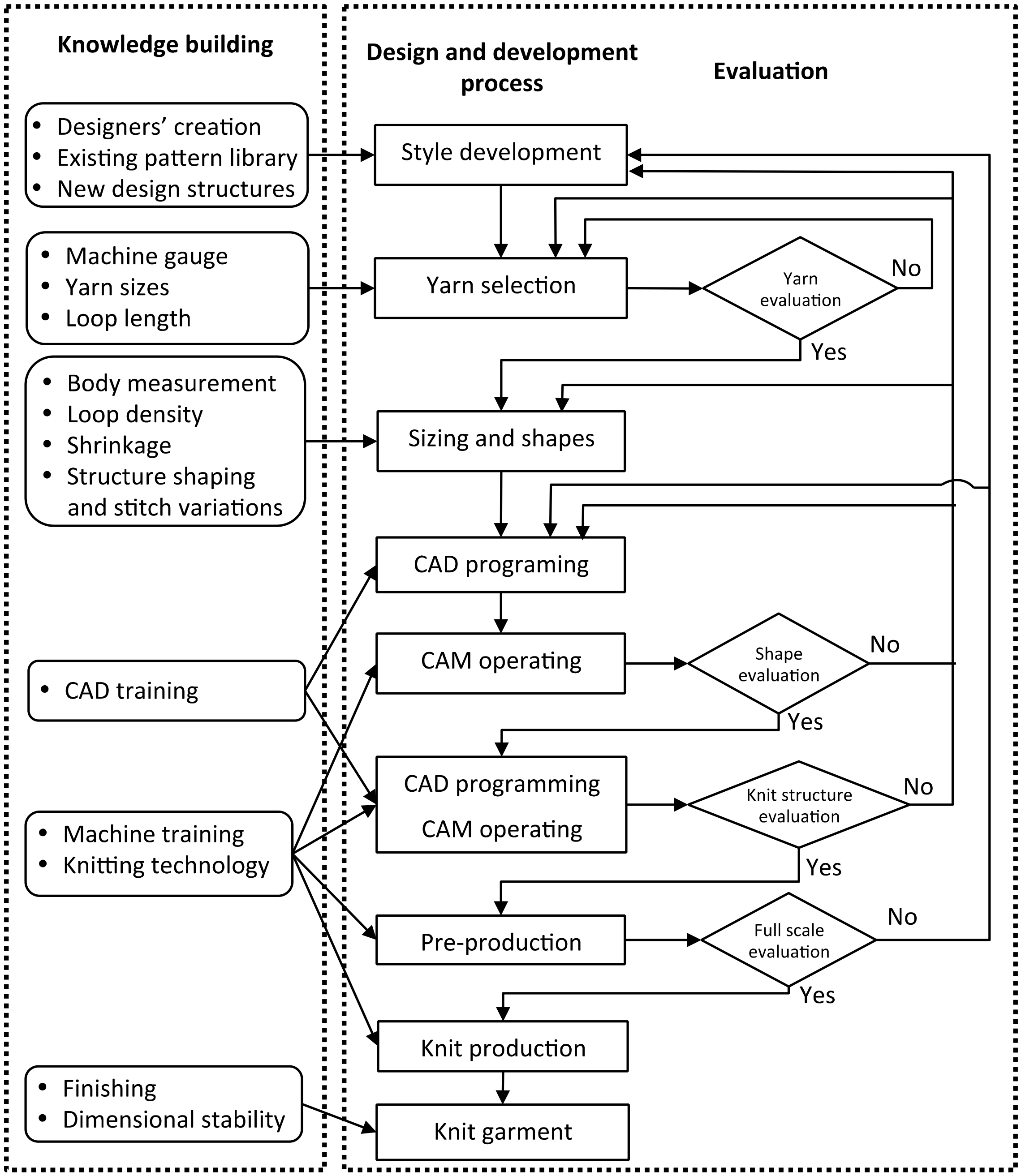


Figure 6.4 Model modified after case study two

6.3 Case study three

Two seamless knitted dresses were produced on Shima Seiki's WholeGarment® knitting machine (see Figure 6.5). Steps to complete the seamless knitted dress were similar to the steps in case two. However, it is important to note that garment shape evaluation in seamless knitting was refined to a quarter-scale or a half-scale evaluation. In seamless garment knitting, CAD pattern making and CAM operation are more complex than fully-fashioned knitting, so it takes more time to create digital patterns for seamless garment shapes and knit them. Quarter-scale or half-scale prototype knitting allows designers to test the knit ability of innovative shapes in a short time with reduced amounts of yarns used. Results of the 1/4 or 1/2 scale evaluation can guide designers to create a full-scale prototype, but the disadvantage is that the full-scale digital pattern needs to be re-created and the machine settings for 1/4 or 1/2 scale may not work in full-scale knitting.

Figure 6.5 Two dresses developed in case study three

Additionally, in case three, the design and development process was segmented into three phases: garment style generation, digitalized design via CAD/CAM, and knit garment production. The intent of phase one was to generate an appropriate knit garment style through style development, yarn selection and sizing and shapes. The next phase was digitalized design such as digital pattern making and programming and machine settings in CAD/CAM systems. This phase attempted to evaluate the garment shape and knitted structures prior to prototype production. For instance, the shape of the seamless dress created in case three was very unique, so a half-scale piece was knitted and evaluated before full-scale production. The purposes of phase two were to evaluate knitting quality of test samples and to assure the creative knitted structures and/or garment shapes could be successfully knitted on the machine. Knitting data gathered in phase two such as digital patterns of test samples and machine settings provided important information for production in the next phase. The third phase for knit garment production included pre-production of a full-scale prototype and production of a finished garment. In this phase, the knitted dresses were laundered, steamed and embellished to be well finished garments. The model developed in case two was refined to the model shown in Figure 6.6.

Knowledge needed to support relevant steps in seamless garment design and development differed a little from that to create fully-fashioned knit garments. Because the finished garment was constructed on the seamless knitting machine without further sewing or linking processes, it was important for designers to know seamless garment construction techniques and understand principles and limitations of seamless knitting. Compared to fully-fashioned knitting, CAD/CAM systems are more complicated in seamless knitting. Sufficient CAD/CAM training of designers is critical to produce a seamless knit garment successfully. For example, in case three, the seamless garment style was adapted from an existing single jersey knit pattern from the pattern library in the CAD system. Designers adjusted the garment shape and added varied knit stitches to the original digital pattern.

This requires designers sufficiently understanding pattern making and programing in CAD knitting systems. However, training of CAD/CAM in seamless knitting is always the most difficult and time-consuming part in the knit garment design and development process.

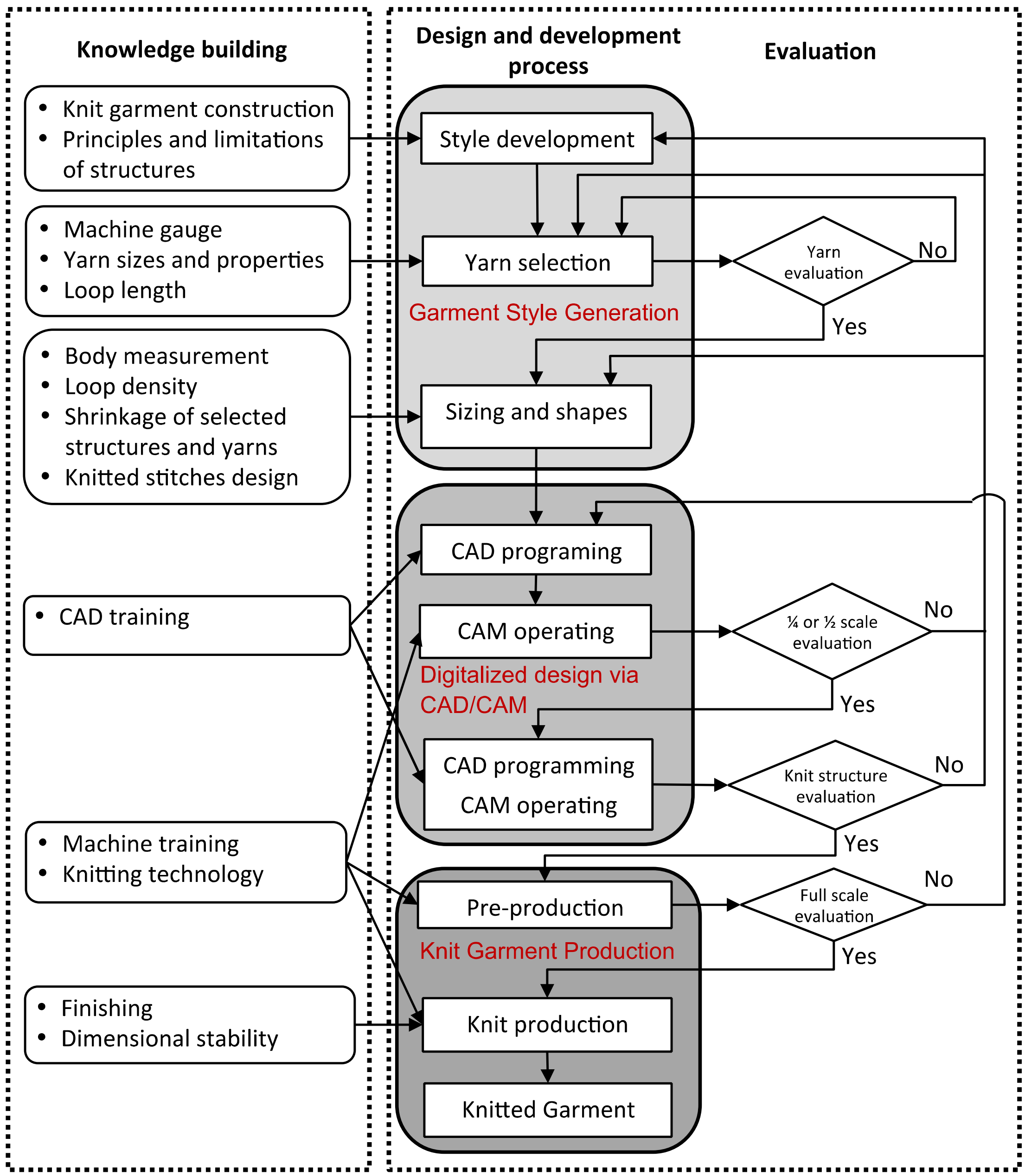


Figure 6.6 Model modified after case study three

6.4 Case study four

A fully-fashioned dress (see Figure 6.7) was knitted in case study four at the request of an undergraduate student for her class project. Documentation of the fully-fashioned dress contributed to validating and refining the model developed in previous cases.

Figure 6.7 Knit dress developed in case study four (Designed by Suzanne Atkinson)

According to the researcher's participant observation, the design and development process in this case study followed most steps in the modified model after case study two. However, a step of design modification was added prior to pre-production. This step aided in modifying garment design for knit production in the next phase. Even the small or full scale test piece and knitted structures were approved in evaluation in terms of knitting quality, and the designers were still able to adjust the design based on results of the evaluation. For example, in case study four, the special lace-effect structures were achieved by combining mesh structure and 5*5 link structure. Knit structure evaluation indicated that the special combined structure could be knitted on the fully-fashioned knitting machine and meet design specification. However, after assessing the samples knitted with the special structures, the designer wanted to adjust the way to combine the mesh structure and link structure. In this situation, there was no need to start over through CAD programming and CAM operating and knit structure evaluation again. An easy method was to modify the design and send to the next phase for pre-production. If the prototype was not approved in full-scale evaluation, it would be sent back to the step of design modification. Additionally, in the third phase of the design and development process, a step of laundering was added after pre-production, because shrinkage of the full-scale prototype remarkably influenced the finished garment size and fit. It would avoid many potential fitting problems to evaluate the finished garment fit before the prototype was sent for final production.

As shown in Figure 6.8, another refinement in this model is that components in each evaluation are added to reflect information needed to make a decision. The components could guide designers to make correct decisions in evaluations. For example, in yarn evaluation, selected yarns should meet production requirements such as machine gauge, as well as design requirements of color, materials, textures and hand. The main purpose of quarter-scale or half-scale knitting was to assess the possibility of knitting unique shapes. Knitting quality concerns such as no dropped stitches or successful stitch transferring were the key components to evaluate. If the quarter scale or the half scale had good quality, the design could move forward to knitted structure design. For knitted structure design, it is challenging to know performance and appearance of knitted structures before they are produced on the machine. Especially when the knitted structures are designed in creative and special textures, their practical knitting effects and dimensions are almost impossible to simulate in current CAD knitting software. In this situation, test samples knitted with novel structures could support designing the ideal knitted structures. Therefore, knitted structure evaluation was aimed to assure the machine is capable of knitting the novel structures and verifying whether designed structures matched the garment design. In phase three, knit garment production, two evaluations were carried out after pre-production and laundering. Components in full-scale evaluation included evaluating whether the prototype met design requirements of knitted structures and garment shapes, and assessing the prototype for knitting quality concerns such as no dropped stitches. When the knitting quality was approved, the prototype was laundered to release knitting tension and reach its stable status. The shrinkage evaluation was to examine the size of the finished prototype. Dimensional changes after laundering must be considered in knitted garment design. Usually, shrinkage was measured in half-scale evaluation and knitted structure evaluation, but it might vary in full-scale knitting. Shrinkage evaluation after prototype production is very crucial, and it is the last chance to adjust garment fit and size before final production. To make a precise decision, designers or technicians must have adequate knowledge in dimensional stability of different knitted structures and must understand laundering effects on knit garments' sizes and shapes.

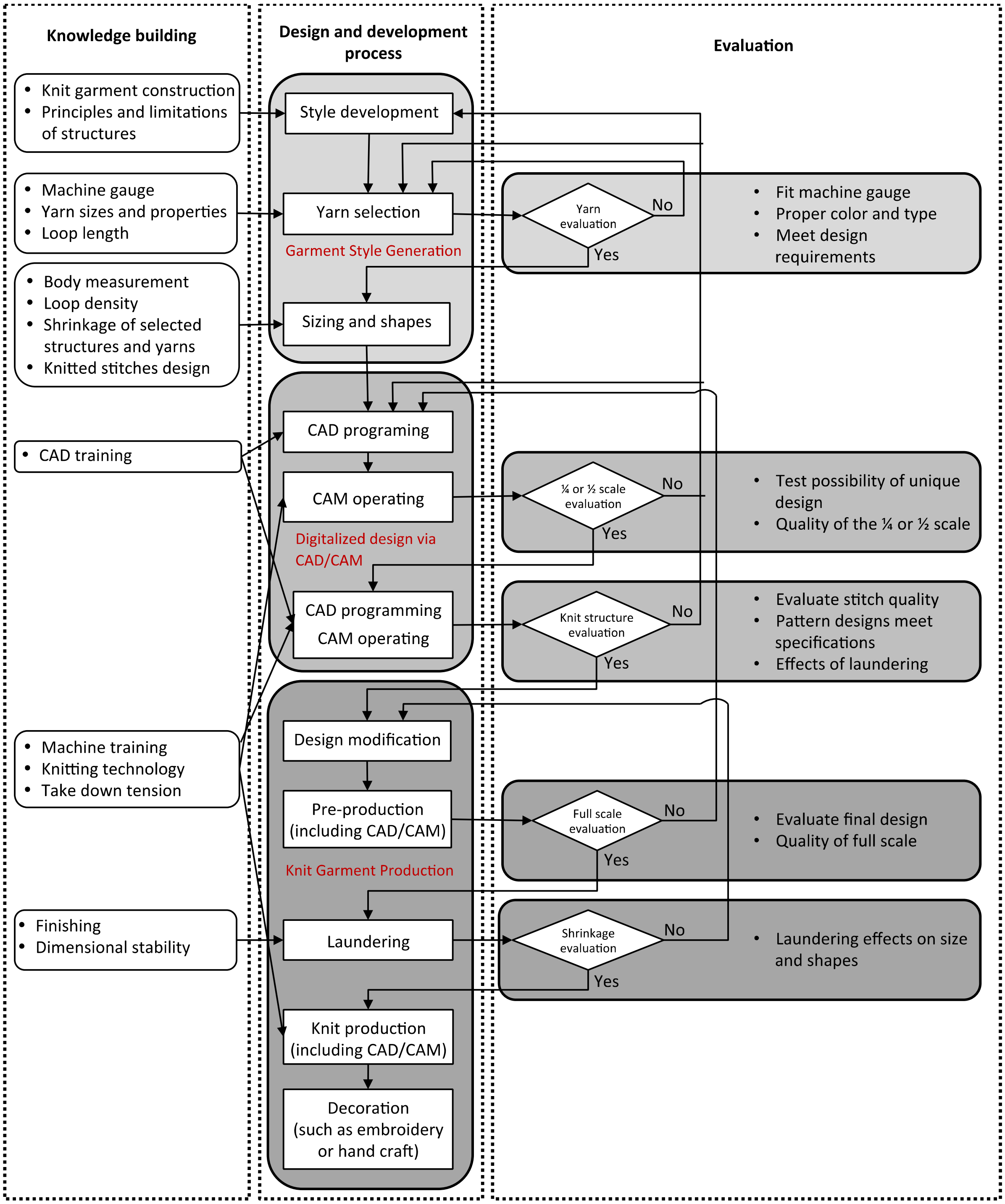


Figure 6.8 Model modified after case study four

6.5 Summary of results in stage two

Comparison of the four models developed in each case study helped establish a preliminary integrated model for shaped knit garment design and development (see Figure 6.9). The preliminary model is organized around the design and development process found in the center of the model. Knowledge building and evaluation support each step of the process. Following the steps in the model enables a designer or a product development team to accomplish the entire knit garment development process from style development through prototype production.

Components in knowledge building developed and then refined in the four case studies are reassembled and listed in the knowledge building of the new integrated model. They illustrate the knowledge necessary to complete relevant steps. Generally, knowledge of knitted structure design and CAD/CAM knitting systems and machine operation obtained through training are most important to creating a successful shaped knit garment using fully-fashioned or seamless knitting technology. For knitted structure design, designers have to understand the effects of different knitted structures on knitted fabric shapes and understand how to combine different knitted stitches or structures. Also, understanding of dimensional stabilities and shrinkage of each structure is required in knitted structure design. In CAD/CAM training, designers need to learn how to translate aesthetic design into digital patterns in CAD systems and how to operate computer-driven knitting machines. More importantly, in prototype production, designers should be capable of selecting optimal yarns for certain gauge knitting machines and determine appropriate machine settings such as loop length and take down tension for different knitted structures and garment shapes. In the aspects of evaluation, components in each evaluation are aimed at guiding designers or development teams to make correct decisions regarding moving forward to the next step.

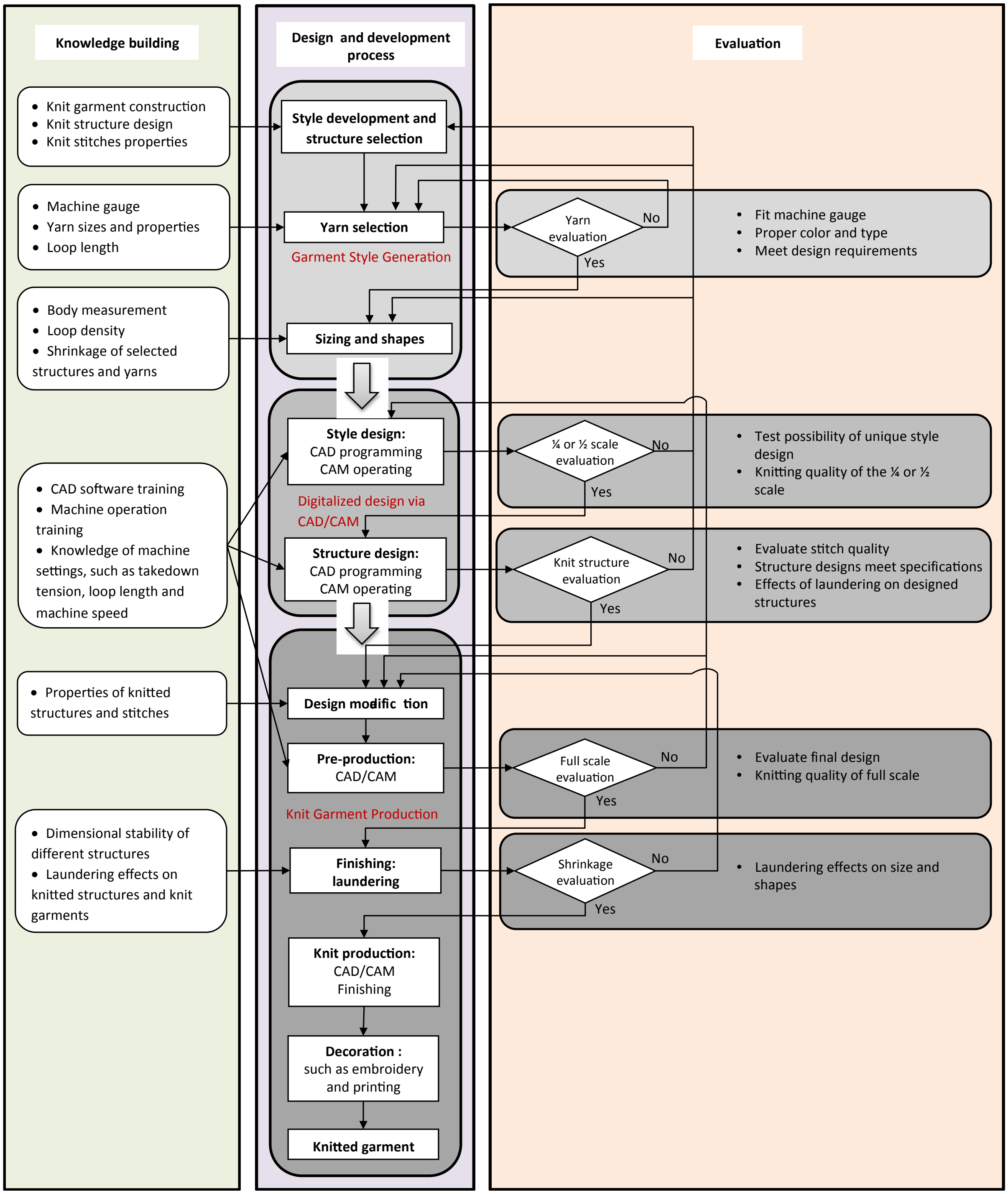


Figure 6.9 Preliminary integrated model for shaped knit garment design and development

Another important section of the preliminary model was the reference library built through data collection in stages one and two of the research. The reference library encompassed yarn selection, machine setting, fabric dimension, 3D shaping, and shrinkage. A pilot study of yarn selection was accomplished via testing samples of different yarns with different structures. Results in the pilot study could assist designers in selecting proper loop length for different structures with different yarns on different machines. All the physical knitted samples created in stage one of the research and case studies in stage two were documented along with their digital patterns, sample size, machine settings and stitches and yarns used. Documented information of shaped garments created in each case study included digital pattern, machine settings and measurements. Also, errors relevant to digital pattern making or machine operating that occurred during knitting were recorded in a notebook with solutions. Additionally, findings of fundamental research in stage one were involved in the reference library, providing a base for designers to design novel knit structures and garment styles and shapes.

The use of the previously discussed reference library is illustrated in Figure 6.10. Accomplishment of each phase in the design and development process refers to specific references in the reference library. In the first phase of the design and development process, the references for fabric dimensions and 3D shaping give a base for designers to select proper knitted structures and shapes for their design. The yarn selection emphasizes aesthetic selection of yarn colors, fibers and textures, as well as optimal yarn size fitting the machine gauge. The reference of yarns is useful in both phase two for yarn selection and phase three for knit production. Steps in phase two mainly refer to machine settings in the reference library. Also, in prototype production, the reference of shrinkage of knitted structures could help addressing fitting problems.

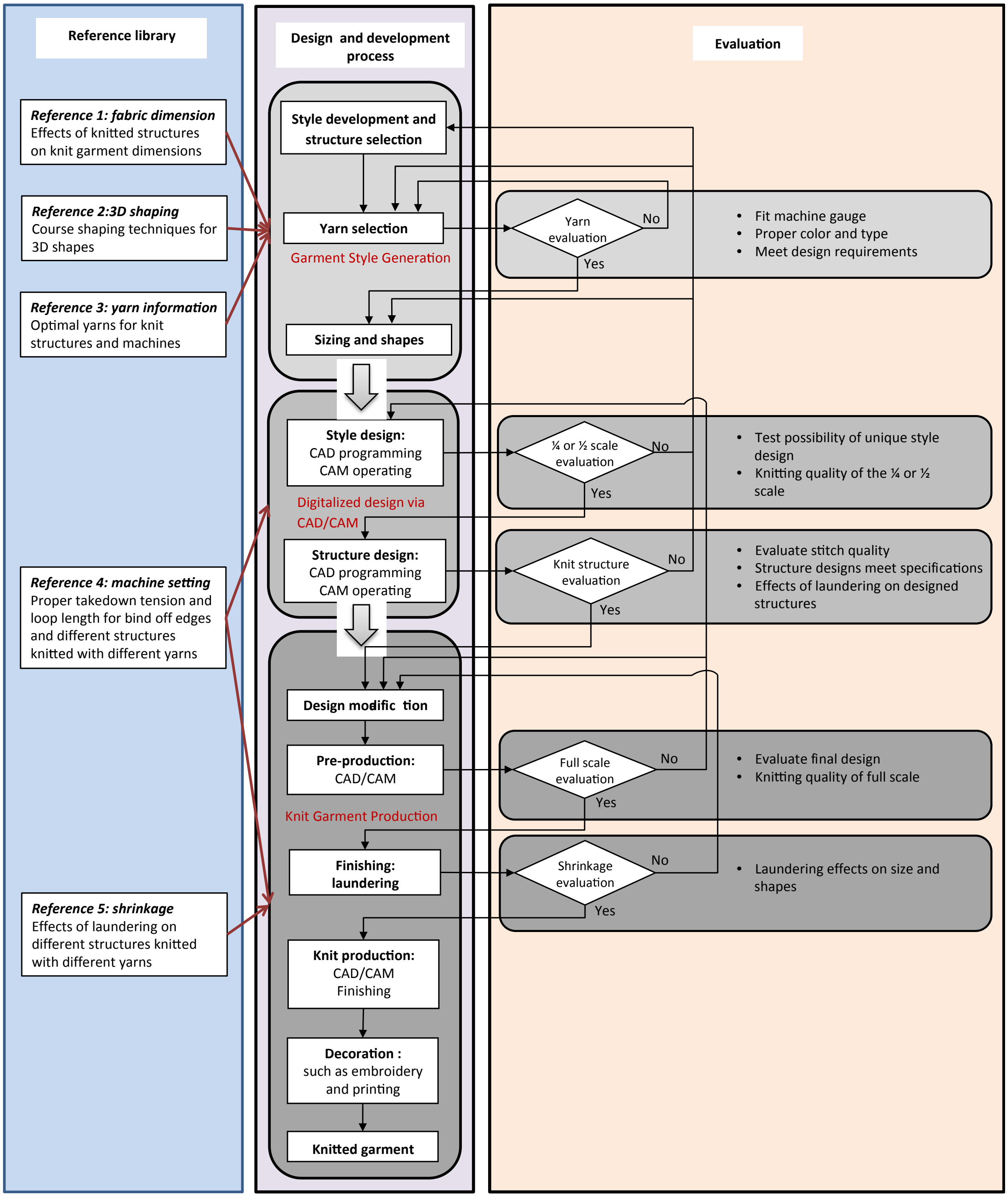


Figure 6.10 Supportive references for execution and evaluation steps

7 Results of in-depth case studies in stage three

The first objective in this research required establishment of a design and development model for fully-fashioned and seamless knit garments, integrating execution and evaluation processes and knowledge needed to support process steps. In stage two of the research, a preliminary model was established through participant observation of four case studies. Validation is an important step to develop a reliable and valid model. Hence, in stage three of the research, two approaches were applied to validate and refine the preliminary model: (1) Mapping of the model via five in-depth case studies, (2) Model review by experts. In-depth case studies in the first method of validation differed from case studies accomplished in phase two. In the stage three in-depth case studies, the researcher did not fully participate in design and development of shaped knit garments but worked as an observer with limited participation. Direct observation and limited participant observation of the shaped knit garment design and development process were used to verify whether the process steps and the knowledge and evaluation components were necessary and sufficient to support designers in creating their own designs. Method two was accomplished by having the model reviewed by experts in the field of fully-fashioned and seamless knitwear design and development. Information obtained in the in-depth cases is found in this chapter, and results of expert interviews are reported in chapter 8.

7.1 In-depth case study one

A seamless sleeveless knitted dress was produced in the first in-depth case study (see Figure 7.1). The student designer had basic knitting knowledge including aspects such as knitted structure formation, knitwear construction methods, and loop density calculation. She had experiences in knitted product design and had created sweaters on hand knitting machines, but she had never used CAD/CAM systems in computer-driven seamless knitting. According to her knowledge and experience in knitting, she completed a basic training in CAD/CAM knitting software and fully-fashioned and seamless knitting machine operation. The training referred to contents and tasks listed in Table 5.1 (see Chapter 5). The short-term training enabled the designer to create her seamless knitted dress following steps in the preliminary model. The designer finished phase one – *garment style generation* – by herself and completed *digital design* and *prototype production* with the researcher's assistance.

Figure 7.1 Seamless knit dress created in in-depth case study one (Designed by Morgan Cox)

Observation of the design, development and evaluation process for creating a seamless knitted dress in this case was presented in a table representation. Table 7.1 provides a summary of mapping in-depth case study one to the preliminary model. Design, development and evaluation steps in this case were listed on the left of the table. The contents in the knowledge needed column indicate necessary knowledge in completing specified steps. References indicate that the designer has referred to some materials in the reference library built in stages one and three of the research. The use of references also elucidates the essentiality of a reliable and applicable database in knit garment design and development.

Table 7.1 Summary of in-depth case study one

<table>
<tr><th>Phases</th><th>Steps</th><th>Results</th><th>Knowledge needed</th><th>References</th></tr>
<tr><td rowspan="4">Garment Style Generation</td><td>Style development and structure selection</td><td>Created a draft of a seamless knit dress
Selected knitted structure</td><td>• Seamless garment construction
• Limitation in seamless knitting
• Effects of knitted stitches combination</td><td>Physical samples in the library</td></tr>
<tr><td>Yarn selection</td><td>Selected yarn color, material and size</td><td>• Yarn materials, color and size
• Machine gauge
• Methods to change loop length</td><td>Pilot study of yarns</td></tr>
<tr><td>Yarn evaluation</td><td colspan="3">Knitted test swatches to identify proper loop length and loop densities of different knitted structures</td></tr>
<tr><td>Sizing and shape</td><td>Learned shrinkage of the selected yarns
Calculated loop densities
Decided garment shape and size</td><td>• Body measurement
• Loop density calculation
• Shaping methods in seamless knitting</td><td></td></tr>
<tr><td rowspan="5">Digital Design via CAD/CAM</td><td>Style design</td><td>Created digital patterns of a full-scale dress;
Knitted a dress with plan structures under assistance of researcher.</td><td>• CAD programming of seamless garment and CAM machine operation
• Machine settings such as loop length, take down tension and machine running speed</td><td>Documents of machine settings in the library</td></tr>
<tr><td>Full-scale evaluation</td><td colspan="3">Tested possibility for knitting the unique garment style and shape;
Evaluated knitting quality of fashioning stitches;</td></tr>
<tr><td>Structure design</td><td>Produced twelve samples knitted with different novelty structures using selected yarns</td><td>• CAD programming of square samples
• Machine operation
• Shrinkage of knitted structures</td><td>Physical samples in the library</td></tr>
<tr><td>Knit structure evaluation</td><td colspan="3">Evaluated stitch quality and performance of yarns in knitting novel structures;
Identified ideal structures matched to the design;</td></tr>
<tr><td>Design modification</td><td>Modified garment design</td><td></td><td></td></tr>
<tr><td>Knit Garment Production</td><td>Pre-production</td><td>Knitted prototypes</td><td>• Machine operation
• Machine settings such as loop length, taken down tension and machine running speed</td><td></td></tr>
</table>

Table 7.1 Continued

Knit Garment Production	Prototype evaluation	Evaluated knitting quality; Repeated steps for design modification and pre-production three times until the prototype met design requirements;		
	Finishing	Washed, dried and steamed the knitted dress	• Dimensional stability of knitted structures • Finishing effects on garment size and shape	Results of fundamental research
	Shrinkage evaluation	Assessed the size of the finished knit dress after laundering		
	Embellish final garment	Added a hand-embroidered collar to the dress.		

7.1.1 Design and development process

In the first phase, *garment style generation*, the designer intended to knit a seamless one-piece dress with a fitted bodice and an A-line skirt. First, the designer worked closely with the researcher to interpret her design into a knittable pattern. Another feature of her design was novel knit structure patterns on the seamless dress. Referring to knitted samples in the reference library, the designer selected three novel structures and redesigned them into three new knit structures. Second, based on the draft generated in the first step, the designer selected optimal yarns in terms of color, material and size. Yarns used not only met requirements of the design, but yarn size was also important to fit machine gauge. In machine knitting, machine gauge determines the distance between two needles and thus influences sizes of yarns that can be knitted on the machine. For different materials, units of the yarn size varied among wool, cotton and synthetic materials, yet designers must be able to convert one yarn system to another in selecting proper yarn sizes. In this case study, a pilot study of different yarns conducted in previous research assisted the designer in selecting yarns that could be potentially knitted on the seamless knitting machine. Preliminarily, the designer nominated four possible types of yarns – 2/8 count 100% wool (gray), 3/8 count 100% wool (gray), 2/20 count 100% wool (orange), 2/20 count 100% wool (dark green). Following completing *knitted structure* *design* and *yarn selection*, the next step was to evaluate the selected yarns and identify proper loop length. Yarn test swatches using different loop length settings were knitted with the four types of yarns, and then they were washed and dried. Based on the look and hand, the test swatch knitted with 2240 yds./lb. gray wool yarns matched the seamless knit dress design. The proper loop length was 10 mm, and course density of the best-matched swatch was 12 courses/inch and wale density was 9 wales/inch. After identifying loop length and loop density, the next step was *sizing and shape*. In this step, body measurements determined size specifications, and possible shaping methods to form unique garment shapes were discussed. This required that the designer have knowledge of shaping techniques in seamless knitting, such as narrowing and widening of tubular knits. When the dress style, size and shape, yarns and knitted structures were determined, the design process could move forward to next phase – *digital design via CAD/CAM*.

Following the steps in phase two of the model, the designer first created a digital pattern for a full-scale dress with a plain structure and knitted it on the seamless knitting machine under the researcher's assistance. Instead of evaluating a quarter-scale or a half-scale prototype, a full-scale dress was evaluated. This was because the shape of the designed dress was not difficult to knit and plenty of yarns were available for the project. Thus, there was no need to knit a smaller scale prototype. The main purpose of the first full scale evaluation was to verify whether the designed garment style could be knitted on the machine. If the style could not be produced due to technical limitations, the design should be sent back to the previous phase for modification. The second purpose was to assess knitting quality of the test piece. In machine knitting, if the design is knittable, bad quality can be traced to broken needles and/or improper machine settings. In this case, machine settings such as loop length, take down tension and machine running speed for different parts of the dress were different. For instance, optimal take down tension for the A-line skirt was 40-50, which differed from tension for armhole shaping and shoulder connection that was 45-55. The initial machine settings in this case were pulled from documents in the reference library and adjusted as necessary. Another step in phase two of the model was *knitted structure design* and *evaluation*. The designer created digital patterns of the three novel knitted structures that were designed in phase one of the process, and then knitted them into 100 wales by120 courses swatches using the yarns selected after yarn evaluation. Comparison of those knit structure test swatches helped in finding the best-matched structure for the design. Also, knitting quality of the samples was evaluated for inspection of dropped stitches or evidence of broken needles. Finally, according to results of style test piece evaluation and knitted structure evaluation, the designer modified her design, and sent the modified pattern to the next phase for *prototype production*. Observation of phase two – *digital design via CAD/CAM* – exposed that the order of *style design* and *knitted structure design* could be reserved. When the garment style is not very special or complex, it is not necessary to evaluate the style or shape separately from knitted structure evaluation. Designers can knit and evaluate novelty knitted structures first, and then apply the most suitable one to the digital garment pattern. Knitting quality and effects of the novelty knitted structure on garment size and shape can be examined at the same time. This can provide relatively accurate and useful information for *prototype production* in the next phase. For example, in this case study, the first full-scale piece was knitted with a plain structure, but the prototype was knitted with designed novelty structures instead of plain structures. Although the evaluation of the plain full-scale piece could provide referential machine settings for *prototype production*, these settings might be improper in full-scale prototyping. Also, because the novelty knit structures could influence knit garment size and shape, style evaluation of the full-scale piece without considering knitted structure effects could not provide accurate information for size adjustment. This implied a new digital garment pattern needed to develop for prototype production in the next phase, which in turn, increased garment design and development time. Therefore, designers could conduct *knitted structure design and evaluation* first, and then evaluate the style and shape of the garment knitted with designed novel structures, in order to shorten design time and reduce yarn cost and improve development efficiency.

When digital design was finished in the CAD and CAM system, the digital pattern and knitting data were sent to the last phase for *prototype production*. First, a prototype of the full-scale dress was knitted in *pre-production* to evaluate knitting quality. Following steps in the preliminary model, if the prototype had bad quality or did not meet designer's requirements, the design would be stopped and moved backward to previous steps for *style design*, *knitted structure design* or *design modification*. After the prototype was approved in knitting quality evaluation, it was finished by washing and drying to achieve its stable status. It was also evaluated concerning garment size and fit after finishing. If the finished prototype was not approved in shrinkage evaluation, it would go back to *design modification* for size adjustment. In this case study, the steps for *design modification*, *pre-production* and *finishing* were repeated three times until the prototype met all design requirements. A challenge to knitting the seamless dress were layout of novelty knit structures on the seamless garment pattern, because appearance and dimensions of novelty knitted structures in the finished dress was hard to visualize and simulate in the current CAD system. The designer had to modify the digital pattern and knit it several times to achieve appropriate placement of the novelty structure on the seamless dress. Finally, after knitting two prototypes, the designer produced a satisfactory dress, and then embellished it with a hand-embroidered collar.

7.1.2 Validity of components in knowledge building

Observation of the execution and evaluation process for creating the seamless dress and communication with the designer verified that most components in knowledge building of the preliminary model were necessary but they were not sufficient. Additional components were added based on results of this case study. These are detailed in following sections.

In *garment style generation*, the designer was responsible for designing inspired knitted structures, creating the dress style, selecting yarns and determining garment size and shape. The most important knowledge needed to complete *knitted structure selection and design* was comprehension of different knitted stitches and their combinations. In this case study, because the designer had experience in using a hand-knitting machine and was familiar with knitted stitches, it was easy for her to select structures for her design. In terms of *yarn selection*, the designer should have enough knowledge of color design, yarn size and material, loop length and machine gauge. The knowledge of yarn color and material contribute to aesthetic design, whereas an understanding of yarn size, machine gauge and loop length enables designers to select proper yarns that can be knitted on specific machines. According to observation in this case, *sizing and shape* of a seamless dress required designers understand seamless garment construction methods, body measurements and loop density.

The principal knowledge needed to complete steps in phase two was training of CAD knitting software and knitting machine operation. The designer declared that learning of digital pattern design in CAD knitting software and operation of the seamless knitting machine were very challenging, although she had experience in using other CAD software and hand-knitting machines. CAD/CAM training was the most crucial component in the process for completing the seamless knitted dress. The training enabled the designer to create digital patterns of knitted structures and seamless knitted garments in a CAD system. However, individually operating the machine was not achievable in a short-term training period, so in this project, the researcher operated the machine in prototype production. Based on the researcher's participant observation, knowledge of machine settings, especially for loop length, take down tension, and machine running speed were of extreme importance in knitting production.

In addition, awareness of dimensional stability of different knitted structures and laundering effects on knitted garment shape and size were required in evaluating knitted garment fit. In particular to seamless knitting, the garment shape and size are determined on the machine. Changes after knitting consume a lot of time and effort to resize the pattern or modify knitted structures and reknit the garment. Therefore, the knowledge of dimensional properties of different knitted structures would positively support execution of seamless garment production.

7.2 In-depth case study two: model mapping

A series of fully-fashioned knit garments was produced in this case study. Figure 7.2 shows two of the four dresses created in this project. The participant designer has taken classes relating to knitted textile design and knitted fabric technology, and she had a strong background in art design. In the second in-depth level case study, the participant designer emphasized texture design in fully-fashioned knitting, and she created nine 100 wales by 120 courses samples knitted with creative textures. These samples and their digital patterns were documented to enhance the reference library. The designer also explored placement of various novelty structures in knitted garment design. In terms of CAD/CAM systems, although the designer had experience in using digital textile design software, it was the first time for her to learn fully-fashioned CAD/CAM systems. According to the designer's knowledge and experience in computer-driven machine knitting, a basic training of CAD/CAM software and fully-fashioned machine operation was provided. After taking the basic training, the designer was able to create her own fully-fashioned knit dresses following steps in the preliminary model. In the design and development process, the designer was responsible for garment style generation and novelty knitted structure design, and the researcher assisted her in style design and prototype production.

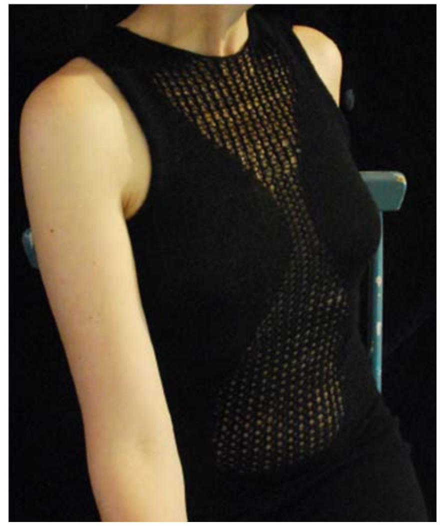


Figure 7.2 Fully-fashioned knit dress created in in-depth case study two (Designed by Clare Connolly)

Table 7.2 is a summary of results of in-depth case study two, depicting actual steps and knowledge needed to complete the four fully-fashioned garments. Most of them matched the steps in the preliminary model, but some steps differed. References in the table state designers can refer to the reference library for inspiration or production information.

Table 7.2 Summary of in-depth case study two

Phases	Steps	Results	Knowledge needed	References
Garment Style Generation	Style development and structure selection	Created a draft of a fully-fashioned knit dress with special texture designs	• Fully-fashioned garment construction • Limitations in fully-fashioned knitting • Effects of knitted stitches combination	Physical samples in the library
	Yarn selection	Selected yarn color, material and size	• Yarn materials, color and size • Machine gauge • Methods to change loop length	Pilot study of yarns
	Yarn evaluation	Knitted test swatches to find proper loop length and loop densities		

Table 7.2 Continued

Digital Design via CAD/CAM	Structure design	Created novelty knitted textures by combining different stitches	• CAD programming of square samples • CAM Machine operation • Shrinkage of knitted structures	Physical samples in the library
	Knitted structure evaluation	Evaluated stitch quality and performance of yarns in knitting novel textures; Identified ideal knitted textures for the design;		
	Style design	Created digital patterns for full-scale test pieces Knitted fully-fashioned garment panels	• CAD programming of shaped panels • CAM machine operation • Machine settings such as loop length, taken down tension and machine running speed	Documents of machine settings in the library
	Full scale evaluation	Assessed knitting quality and garment size of the full-scale test garment; Test whether selected yarns is suitable to knit shaped pieces; Evaluate appearance of knitted textures on garment panels;		
	Design and modification	Modified garment design and size	• Knitting defect troubleshooting	
Knit Garment Production	Pre-production	Knitted modified panels Sewed/linked front and back panels	• Machine operation • Machine settings such as loop length, take down tension and machine running speed	
	Prototype evaluation	Evaluated knitting quality; Repeated steps for design modification and preproduction twice until the prototype met designer requirements;		
	Finishing	Washed and dried the fully-fashioned garments	• Dimensional stability of knitted structures • Finishing effects on garment size and shape	Results of fundamental research
	Shrinkage evaluation	Assessed the size of the finished knit dress after laundering		
	Repair	Fixed dropped stitches in neckline fashioning		

7.2.1 Design and development process

In *garment style generation*, the designer first drew several drafts of knitted dresses with various textures. A primary goal of this project was to explore application of novelty knitted textures in fully-fashioned knit garment design. The designer planned to create four fully-fashioned dresses knitted with special layouts of novel structures. Design of the novel knitted structures was inspired by the knitted samples in the reference library. Nine unique knitted structures were created through combining different stitches such as front knit, back knit, double knit and transferred stitches. Second, suitable yarns were selected depending on design specifications of color, hand and materials and knitting requirements such as fitting to the machine gauge and having elastic enough for fashioning. In this project, 2/8 count 100% wool yarn (white), 9/2 count 100% cotton yarn (natural color) and 2/12 count 100% wool yarn (black) were selected referring to results of the previous pilot study. For each yarn, five test swatches were knitted with five levels of loop length in order to identify proper stitch settings. Usually, yarn test swatches would be knitted with different structures, but in this project, to simplify the design process and save time, only the single jersey structure was used in yarn swatch knitting. According to the look and hand of the test swatches, the designer selected the 9/2 count natural color cotton yarn and the 2/12 count black wool yarn to use. Those yarns were evaluated again in the following steps when they were used to knit novel structures. The last step in garment style generation was *sizing and shape*. Loop density of plain fabrics determined in yarn swatch evaluation was used to estimate the size of front and back garment panels. Also, fashioning methods such as combining different knitted structures and fashioning with transferred stitches were discussed in this step to form the designed garment shape.

The next phase in the design and development process is *digital design via CAD/CAM*. The principal purposes of this phase were to prepare digital patterns of knitted structures and garment panels for prototype production and to evaluate whether the novel knit structures and the garment shape could be successfully knitted on the machine. In this case study, *knitted structure design* was accomplished prior to *style design*. The digital patterns of the nine unique structures designed in the last phase were translated into 100 wales by 120 courses test samples in the CAD system and then knitted on the machine with the identified yarns in the step of *yarn selection*. In knitted structure evaluation, some dropped stitches were inspected in the samples knitted with transferred stitches.

Usually, bad stitch quality such as dropped stitches and broken needles are caused by improper machine settings. In this case study, after knitting another test sample with transferred stitches, the researcher observed that knitting transfer stitches needed lower machine running speed, higher take down tension than knitting regular stitches. In regular knitting of front and back stitches, the optimal take down tension was 35-45, the loop length was 9.5 mm and the machine running speed could be as high as 1m/s. However, for transferred stitches, the take down tension should be increased to 40-45, and it was better to reduce the machine running speed to 0.8 m/s so that the loops were successfully moved from one needle to another. Observation of *knitted structure design and evaluation* indicated that knitting different novel knit structures required varied machine settings. To enhance design efficiency and richen the reference library, physical samples and machine settings for different knitted structures created in this case study went to the database in the reference library to support future work. Another component of knitted structure evaluation was to assess whether the selected yarns matched design of those novelty structures. Effects of yarns cannot be neglected in *knitted structure design*, because different yarn colors, materials and sizes used in knitting can result in different appearances and shapes of knitted fabrics, especially when the fabrics were designed with novelty structures combining different knit stitches. In this case study, results of knitted structure evaluation indicated that the two types of yarns selected in phase one performed well in knitting the novelty structures. According to appearance and shape of the test samples, the designer selected three knitted structures out of nine that most closely matched her original design. The next step in phase two was *style design*. First, the designer created digital patterns of front and back panels with single jersey structures according to body measurements and estimated loop density obtained in the step of *sizing and shape*. Second, the designer placed the novelty knit structures on the digital pattern with different layouts. Next, the fully-fashioned garment panels were knitted on the machine and sewed into four full-scale test garments. The style evaluation assessed knitting quality of the test garments, performance of novelty knitted structures in the full-scale garments, and evaluated whether the garment size and shape fitted to design requirements. It is important to note that placement of the novelty knit structures affects garment size and shape. Even in two patterns knitted with the same number of stitches and the same novelty knitted structures, different layout of the knit structures could lead to variation in garment size and shape. In this case study, all the test garment panels were knitted with the same number of stitches but different knitted structures, resulting in varied garment size. Thus, when knitting quality of the test piece was approved, the size was adjusted according to style evaluation results. Then the designs were sent to the next phase for prototype production.

In *pre-production*, the modified front and back panels were knitted and then sewn together, generating four prototypes. Evaluation was conducted after both knitting on the machine and finishing. The intent of prototype evaluation after knitting was to detect bad knitting quality such as dropped needles and to assess whether the prototype met design specifications in terms of knitted textures. In this project, because of inappropriate knitted structure design, the designer did not approve one prototype out of four. The design returned to the step of *knitted structure design*. Another problem met in prototype evaluation was dropped stitches in neck shaping, which might have been caused by failure of transferring stitches. To assure the neckline could be smoothly shaped, take down tension on the fabric must be strong enough to pull down knitted fabrics, so that the loops can be successfully transferred between front and back needle beds. Therefore, the take down tension was increased from 40-50 to 45-55 in the neckline shaping area to avoid dropped stitches. When all the garment panels passed the knitting evaluation, they were finished through washing, drying and steaming, and then the panels were sewn on the side and shoulder to be complete garments. Knitted garments shrink after finishing, so the intent of finished garment evaluation is to quantify shrinkage and assess the garment size and shape after finishing. In the case study, the size and shape of the four prototypes performed very well, so there was no change to the garment panels. However, if the finished prototype is too small or too large, designers need to go back to the step of *design modification* to adjust the garment panel size depending on evaluation results.

7.2.2 Validity of components in knowledge building

According to direct observation and limited participant experience in the fully-fashioned knit dress design and development process, the researcher verified whether the components in knowledge building in the preliminary model were necessary and sufficient to support creation of fully-fashioned knit garments. In general, knowledge components developed through previous research were important in this case study, but additional knowledge was needed.

In the first phase of *garment style generation*, an understanding of fully-fashioned garment construction and limitations in fully-fashioned knitting was essential to design knittable garments. Those knowledge components enabled the designer to create producible designs. In knitted garment design, the designer needed to design garment style as well as knitted structures that would have an impact on the garment style and shape. Combining different stitches is a common and effective method in knitted fabric design that not only generates special knitted textures, but it also varies dimensions of knitted fabrics. Therefore, basic knowledge of the effects of different knitted stitches or structures on fabric dimensions and garment fit would support producing appropriate shape and size in knitted garment design. In reality, referring to findings of the fundamental research documented in the reference library (see Chapter 3), designers would have general ideas of relationships between knitted stitches/structures and knitted fabric dimension or garment size. Another important step in knitted garment style generation was *yarn selection*. In this case study, the knowledge of yarn materials and color design benefited the designer in matching yarn to her design, while understanding the relationship between machine gauge and yarn size assured the selected yarn could be used on the knitting machine. In the next step, *sizing and shape* of fully-fashioned garments, the designer should be aware of body measurements and loop density. Loop density was the key factor that influenced garment size, and it varied when alternative knitted structures were used or machine settings such as loop length or take down tension were changed. Additionally, shaping techniques such as fashioning with transferred stitches and combining knitted structures were used in this case study. Comprehension of those shaping methods in fully-fashioned knitting was very beneficial to creating dramatic designs.

In *digital design via CAD/CAM*, the ability to make CAD programs for fully-fashioned garment panels and operate fully-fashioned knitting machines was important, but training in CAD/CAM software and machine operation was the most difficult portion in the entire design and development process. In the project, after taking basic training, the designer was able to create digital patterns for novelty structures and fully-fashioned garment panels, and the designer could also individually set up the machine including threading yarns and adjusting top tension and side tension on yarns. However, machine operation was still challenging, because some unexpected errors occurred during knitting, which required highly skilled machine operators to resolve. In the case study, the designer produced knitted samples and garment panels with the assistance of the researcher. Observation in knitting practice implied that take down tension, loop size (length) and machine running speed were the three crucial factors to knit a product with good quality. To find correct machine settings, the designer referred to machine settings for other garments in the reference library built during phase two of the research, and adjusted the settings based on the evaluation results.

In addition to CAD/CAM training, fashioning methods such as narrowing and widening are worth understanding in *style design*. The designer was required to read and adjust digital patterns in fashioning areas, so that she could easily modify shape and size of garment panels when necessary. Also, an understanding of shaped garment formation procedures on the machine guides the designer in making a feasible CAD program and avoiding potential errors during knitting. For example, in the case study, the number of transferred stitches for armhole shaping was limited to four, because knitted structures in the armhole area were designed with double knit stitches, and half of the knit stitches were still on the back needle bed when armhole narrowing occurred. Racking of the back needle bed during narrowing would pull the back loops left or right. More transferred stitches leads to more racking, which generates higher tension on regular knit stitches on the back needle bed, resulting in higher risk of broken needles or broken yarns. If the designer knew the fashioning procedure, she could confirm the correct number of transferred stitches to avoid damaging needles or yarns when knitting.

Finally, in prototype production, in addition to training in CAD programming and CAM machine operation, the knowledge of dimensional stability of different knitted structures and finishing effects on knitted garment shape and size was necessary. The designer should realize the size of the finished garment differed considerably from the garment just knitted on the machine. In fully-fashioned knitting, garment panels were produced on the machine and then sewn together to be a finished garment, so sewing or linking techniques were also necessary in this case study.

7.3 In-depth case study three: model mapping

A seamless open structure sweater was produced in in-depth case study three (see Figure 7.3). This project was completed by request of an undergraduate student for his class project. The designer had limited knowledge in knitting and this project was his first experience with knitted garment design. In terms of CAD and CAM, the designer had used regular CAD systems such as Lectra, Kaledo for knitting, as well as Adobe Photoshop and Adobe Illustrator, but he never tried CAD/CAM systems for knitted garment programming. Having taken basic training in CAD knitting software and seamless knitting machine operation, the participant designer had certain capability to design simple and basic knitted structures in the CAD system and run seamless knitting machine under the researcher's assistance. In this project, the designer produced a seamless sweater following steps in the design and development process of the preliminary model, but few process steps were skipped due to unnecessary of completing these steps.

Figure 7.3 Seamless open structure sweater created in in-depth case study three (Designed by Alexey Stepankov)

Execution steps and knowledge needed in the seamless sweater design and development process were summarized in Table 7.3. The references that supported the participant designer to complete specific steps are also involved in this table.

Table 7.3 Summary of in-depth case study three

Phases	Steps	Results	Knowledge needed	References
Garment Style Generation	Style development and structure selection	Designed loose style sweater Created a sweater draft	• Seamless garment construction • Limitation in seamless knitting • Knitted structures properties	Physical samples in the library
	Yarn selection	Selected yarn color, material and size	• Yarn materials, color and size • Machine gauge • Methods to change loop length	Pilot study of yarns
	Yarn evaluation	Knitted test swatches to identify proper loop length and take down tension		
	3-piece knitting	Generated three pieces of fabrics knitted with different widths	• Relationship between loop density and fabric width	
	Sizing and shape	Learned shrinkage of the selected yarn Identify separate loop density for knitting sleeves and garment body Decided garment size and shape	• Body measurement • Loop density calculation	
Digital Design via CAD/CAM	Style and structure design	Created digital pattern for a half-scale sweater with 2×2 rib structures Knitted half-scale test piece	• CAD programing of seamless garment and CAM machine operation • Machine settings such as loop length, taken down force and machine running speed • Understanding of seamless garment formation procedures on the machine	Documents of machine settings in the library
	Half-scale evaluation	Evaluated knitting quality; Tested possibility of knitting a loose style garment;		
	Design and modification	Created digital pattern for a full-scale sweater		
Knit Garment Production	Pre-production	Knitted full-scale prototype	• Machine operation • Machine settings such as loop length, taken down force and machine running speed	
	Full scale evaluation	Evaluated knitting quality; Repeated steps for design modification and preproduction twice until the prototype met designer's requirements;		
	Finishing	Washed and dried the loose style sweater	• Dimensional stability of knitted structures • Finishing effects on garment size and shape	Results of fundamental research
	Shrinkage evaluation	Assessed the size of the finished knit dress after laundering.		

7.3.1 Design and development process

First, the designer wanted to knit an open structure sweater using seamless knitting technology. Creation of an open structure in seamless knitting can be achieved through increasing loop length, using thin yarns and adjusting take down tension. In this case study, the designer planned to knit the sweater with single jersey or 2×2 rib structure, because these simple knitted structures allow for flexible changes in loop length and take down tension. For *yarn selection*, the important principles were that the yarn was thin enough to an open structure but strong enough to knit on the seamless machine. According to the design and knitting requirements, the designer selected 20/2 count polyester yarn to knit the sweater. To explore the capability of the seamless machine to knit an open structure, ten yarn test swatches were knitted on the machine. Five of them were knitted with single jersey structure and five different loop lengths, and the rest were knitted with 2×2 rib structure and five different loop lengths. Although increasing loop length is an effective method to make knitted structures more open, it is important to note that formation of large loops requires both large loop size and high take down tension. Based on the results of yarn swatch evaluation, the designer decided to knit the sweater with 2×2 rib structure, large loop size (14 mm) and high take down tension (45-55). Loop density of the swatch with preferred knitting result was counted and later used in garment sizing.

To evaluate the open structure seamless garment, a small-scale digital pattern for the sweater was developed in the CAD system and knitted on the seamless knitting machine. The small-scale garment was knitted with 2×2 rib structure, which was selected in yarn swatch evaluation. Results of small-scale evaluation indicated both garment style and the open structure met the design using the selected yarns and machine settings identified in yarn evaluation. After that, a full-scale digital pattern was programmed and produced, generating the first full-scale prototype. However, dropped stitches occurred in the area of garment body and sleeves connection. This meant machine settings such as take down tension (45-55) and machine running speed (1 m/s) tested in the small scale knitting did not work in full-scale prototyping. In fact, take down tension in full-scale knitting should be higher than that in small-scale knitting, because take down tension on seamless knitting machine is related to actual working needles (fabric width). Fully-scale prototype knitting requires more working needles on the machine than small scale. In this case, take down tension should be increased up to 50-60 in full-scale knitting, even with the same loop length and yarn used in small scale knitting. Therefore, it can be seen that small-scale knitting cannot always provide optimal settings for full-scale production. Unless limited or expensive yarns are used, or the seamless garment has a very special shape, it is not necessary to knit a small-scale test piece in *style design and evaluation*. A full-scale test piece in phase two of the development process could provide more reliable and accurate information for *design modification* and *prototype production* in phase three of the process.

In this case study, full-scale prototype production was repeated twice. The first prototype had dropped stitches along a line on the back panel, which were caused by a broken needle on the back needle bed. After the bad needle was replaced, another full-scale prototype was knitted. The second prototype was approved in knitting quality evaluation, and then was washed and dried. After laundering, the body of the finished garment fitted well, but the sleeves turned out to be too long for the model. The fact that actual sleeve lengths differed from estimated measurements resulted from varied loop density in the area of sleeves and garment body. During knitting, the same take down tension was provided to both sleeves and garment body, but their knitting widths were different. As stated previously, active working needles and take down tension influence actual loop size of knitted fabrics. Sleeve width is shorter than knitted garment body width, which means there are fewer working needles in sleeve knitting. Different working needles resulted in different loop sizes between sleeves and garment body, yielding different loop densities. The number of knitted stitches in the digital garment pattern was calculated based on body measurements and loop density input in the

CAD system. In this project, the designer used the same loop density for sleeves and garment body, so that the number of knitted stitches in the digital pattern was not accurate. This was the reason why actual sleeve length differed from expected measurements. To avoid the difference and inaccuracy, the designer calculated new loop density of sleeves, and inputted separate loop density for sleeve knitting and garment knitting in the CAD system. The modified pattern was knitted and finished. The reknitted prototype met most design requirements, and the only defect was one dropped stitch found on the back hem. Fortunately, the dropped stitch could be mended, so the garment did not need to be knitted again.

7.3.2 Validity of knowledge components

The seamless sweater design and development process in in-depth case study three was much simpler than that in previous cases. Complex and novelty knitted structure design was not required, and *yarn selection* was easy to accomplish because only one type of yarns was used. However, particular knowledge was still needed to complete the process, even though it is not complicated. Direct observation and partial participant experience verified which knowledge components were useful in the case and which were not.

In *style development and knitted structure selection*, it was important for the designer to understand seamless knit garment construction methods and limitations of seamless knitting. For example, to create an open structure sweater, the designer needed to know basic methods to create open structures in seamless knitting. When a new garment style is created, designers should at least know limitations of machine knitting, so that they can create producible knits. In terms of knitted structure selection, comprehension of knitted structure properties enabled the designer to select appropriate knit structure that matched the design. In this case study, because it was easy to change machine settings for simple knit structures, the designer explored plain structure and 2* 2 rib structure, and then he decided to use the latter one due to its high elasticity.

The knowledge needed in yarn selection and evaluation included yarn material, color, size, machine gauge, and loop length. Furthermore, loop density calculation and body measurements were necessary knowledge components in *sizing and shape*. In this step, if the designer realized there was a difference between the loop density of the sleeves and the loop density of the garment body, 3-piece knitting could be implemented to obtain accurate loop densities for fabrics knitted with different widths. Even for the loops with same loop length, actual loop density of the sleeves and garment body differs due to the changed number of working needles in sleeve knitting and garment body knitting. So, loop density differs due to knitting with variation between narrow knitting width (sleeve) and wide knitting width (garment body). Also, the direction to be stretched in wear is different. As shown in Figure 7.4, there is a high possibility of having a size difference when converting sleeves and garment body to the number of stitches using the same loop density rather than designing for the width difference (Shima Seiki, 2000).

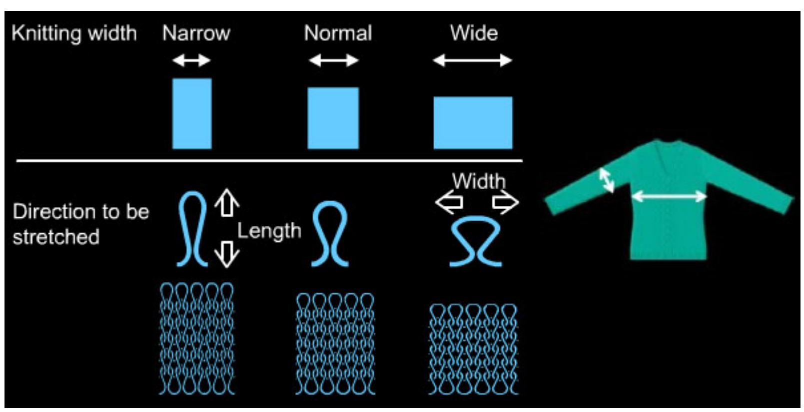
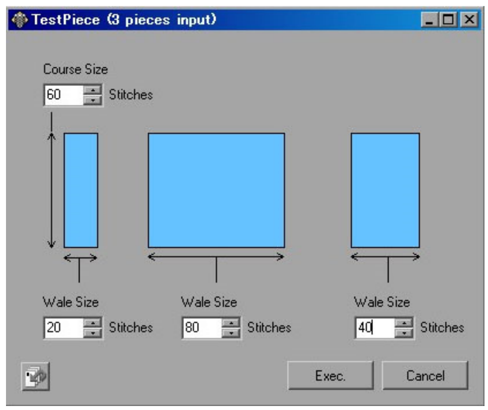


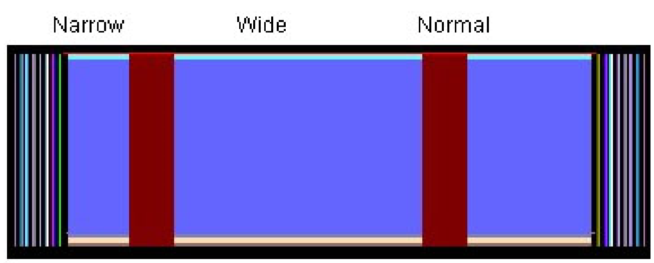
Figure 7.4 Illustration of 3-piece knitting (Shima Seiki, 2004b)

In the CAD system for seamless garment pattern development, normal input converts measurements of garment sleeves and body to the number of stitches using the same loop density.

Three-piece input can convert measurements to the number of stitches with more accurate loop density for garment body and sleeves. 3-piece knitting considers the loop density associated with knitting width variation and provides different loop densities for sleeves and garment body. Figure 7.5 illustrates three-piece input and digital patterns in Shima Seiki's CAD system. Three test pieces are designed with the same number of curses but different wales. After finishing, loop density of the different width pieces can be determined.



(a) 3 pieces input in Shima Seiki's CAD system (Shima Seiki, 2004b)



(b) Digital pattern for 3-piece knitting (Shima Seiki, 2004b)

Figure 7.5 3-piece knitting in in-depth case study four

In this project, 3-piece knitting was not used before the step of *sizing and shape*. As a result, the finished prototype was not approved in *shrinkage evaluation* in the following steps. This implied that understanding the influence of knitting width on loop density was necessary in seamless garment knitting.

In the next phase, *knitted structure design and evaluation* were carried out along with *style design and evaluation*. CAD programming and CAM machine operating were the most important components in knowledge building, but they were very challenging. For machine operation, settings such as loop length, take down tension and machine running speed were crucial factors. Proper machine settings facilitated knitting a garment that would meet specifications. Proper loop length identification depended on results of yarn test swatches in yarn evaluation, and setting take down tension and machine running speed required referring to documents in the reference library.

In knit garment production, in addition to training of CAD/CAM, an understanding of finishing effects on garment size and shape was also necessary to produce a garment that met size specifications. Moreover, shrinkage and its impacts on garment size should be evaluated in yarn evaluation, knitted structure and garment style evaluation in phase two of the process, not delayed until finished full-scale prototype evaluation.

7.4 In depth case study four: model mapping

The participant in this case study was a professor in the College of Textiles at NCSU. She had enough knowledge in knitted fabric design and fashion design, and had taken basic training in knitting CAD software and machine operation. In this project, the participant designer cooperated with the researcher to design a seamless dress, make knitting programs and operate seamless knitting machine (see Figure 7.6).

(a) Front view (b) Back view

Figure 7.6 Seamless knit dress created in in-depth case study four

Execution of the seamless knitted dress followed the process steps in the preliminary model, but the actual process varied from some specific steps. Comparison of the preliminary model and the case study process steps facilitated validating and refining the model components. Table 7.4 presents the actual steps and knowledge needed and references used to accomplish the seamless dress.

Table 7.4 Summary of in-depth case study four

Phases	Steps	Results	Knowledge needed	References
Garment Style Generation	Style development and structure selection	Created a draft of a seamless knitted dress Selected knitted structures	• Seamless garment construction • Limitation in seamless knitting • Knitted structure design	Physical samples in the reference library
	Yarn selection	Selected yarn color, material and size	• Yarn materials, color and size • Machine gauge • Methods to identify loop length	Pilot study of yarns
	Yarn evaluation	Knitted test swatches to identify proper loop length		
	3-piece knitting	Generated three pieces of fabrics knitted with different widths	• Relationship between loop density and fabric width	
	Sizing and shape	Learned shrinkage of the selected yarn Identify separate loop density for knitting sleeves and garment body Decided garment size and shape	• Body measurement • Loop density calculation • Shaping methods in seamless knitting	
Digital Design via CAD/CAM	Structure design	Created digital patterns for potential knitted structures; Knitted test samples	• CAD programming of square samples • CAM Machine operation • Shrinkage of selected yarns and knitted structures	Physical samples in the reference library
	Knit structure evaluation	Evaluated stitch quality and performance of yarns in knitting novel structures; Confirmed ideal structures matched to the design;		
	Style design	Created digital pattern for a full-scale dress Knitted the dress on seamless knitting machine	• CAD programming for seamless garments • Seamless knitting machine operation • Machine settings such as loop length, taken down tension and speed • Understanding of seamless garment formation methods on the machine	Documents of machine settings in the reference library
	Full-scale evaluation	Tested possibility of knitting unique structures on seamless garment; Evaluated knitting quality and garment size after laundering;		
	Design modification	Modified structure design and garment size	• Knitting defect troubleshooting	

Table 7.4 Continued

Phases	Steps	Results	Knowledge needed	References
Knit garment development	Pre-production	Knitted modified full-scale prototype	• Seamless knitting machine operation • Machine settings such as loop length and taken down tension	
	Prototype evaluation	Evaluated knitting quality; Repeated steps for design modification and preproduction five times until the prototype met designer's requirements;		
	Finishing	Washed, dried and steamed the prototype	• Shrinkage of knitted garment • Garment size and fit to the body	Results of fundamental research
	Shrinkage evaluation	Assessed the size of the finished knit dress after laundering.		
	Repair	Hided unexpected knots; Mended repairable dropped stitches		

7.4.1 Design and development process

In general, design and development of the seamless knitted dress in this case were accomplished following process steps in the preliminary model through garment style generation to prototype production. First, the designer created a draft of a knitted dress, and she employed seamless knitting technology to produce the dress. Second, the designer selected four knitted structures that might match to her design, referring to physical knit samples in the reference library. Those selected knitted structures were redesigned into new novelty structures that would go to the reference library to provide inspirations for future designs. The next step in the phase was *yarn selection*. The designer not only needed to consider aesthetic aspects in terms of color, material and hand, but she also had to choose yarns with suitable size that could fit to machine gauge. In this project, the golden core-spun yarn was selected. To evaluate the selected yarn, five test swatches were knitted with single jersey structure and five different loop lengths. According to tightness, look, and hand of the five test swatches, the designer identified an optimal loop length of 10 mm for the design, and the take down tension setting applied in yarn swatch knitting was 40-50. Before the step of *sizing and shape*, 3-piece knitting, as described in section 7.3.2, was implemented to acquire accurate loop density for knitting sleeves and garment body. A loop length of 10 mm and take down tension setting of 40-50 identified during *yarn evaluation* were used in 3-piece knitting. Then, the three test pieces were washed, dried and set in the same conditions as planned for the actual knitted dress. Loop density of the narrow width piece was used to calculate the number of knitted stitches for sleeves, whereas the garment body was converted to the number of stitches using the loop density of the wide width piece. In the step of *sizing and shape*, in addition to accurate loop densities, size specifications depending on body measurements were used to convert the designed dress to the number of stitches. Also, in this step possible shaping techniques such as tubular narrowing and widening in forming unique garment shapes were discussed.

In second phase – *digital design via CAD/CAM*, the designer accomplished *knitted structure design* and *style design* and *evaluation* of them. The goal of the second phase was to prepare workable and reliable digital patterns for prototype production. First, the novel knit structures designed in step one were translated into digital patterns in the CAD system, and then they were knitted into four 100 wales by 120 courses samples. The four samples were evaluated to detect bad stitch quality including aspects such as dropped stitches, broken yarns, or small holes. In this case study, one sample out of four had broken yarns and small holes. This bad quality sample was knitted with many transfer stitches, which increased knitting difficulty. To solve the defect and improve transfer stitch quality, the loop length was increased to 10.5 mm, the take down tension was adjusted to 45-55, and the machine running speed was reduced to 0.8 m/s for stitch transferring. Optimal machine settings including loop length, take down tension and machine running speed for each novel structure were recorded and later used in prototype production. Additionally, evaluation of novel knit structures helped in identifying the matched structure to the original design. According to appearance and dimensions of the four knit structure samples, the designer selected one novel structure most closely matched to her design. In *garment style design*, a sweater pattern with parachute style was selected from an existing pattern library in the CAD system. The designer input calculated loop density and body measurements into the CAD system and created a full-scale digital pattern for the seamless dress. After that, the designer applied the selected knitted structure to the garment pattern and knitted the adjusted pattern on the seamless knitting machine. Evaluation of *garment style design* assessed how the novelty knitted structures performed in a full-scale seamless garment and whether the parachute style could be knitted on the specific machine. When the special garment style could be knitted, knitting quality would be evaluated. If the first full-scale test garment did not have good quality, the designer should inspect the machine, check the digital pattern, and adjust machine settings to improve knitting quality. In this case study, a big hole existed on the back panel in the area of parachute knitting. This was caused by failure in transferring stitches, resulting from weak or bad clips of needles on the machine. To enhance knitting quality, all the needles on both front and back needle bed were inspected in replacing bad needles or bending weak clips. Additionally, the garment style evaluation reflected incorrect stitch design and improper layout of novelty knitted structures. Based on results of style evaluation, the garment pattern was modified. Moreover, size of the first full-scale test garment was evaluated in this step, and fortunately it met size specifications. However, if the test piece has fitting problems, garment size needs to be adjusted before moving to next phase for prototype production.

In *pre-production*, the modified garment pattern was knitted, creating a full-scale prototype. Bad knitting quality such as dropped stitches, broken yarns, holes or knots was the main component to inspect in prototype evaluation. In this project, the first full-scale prototype was not approved in the evaluation because of unsuccessful stitch transferring. To ensure transferred stitches could be formed successfully, the design was modified and knitted five times, so five prototypes with corrections were produced until the last one met quality requirements. Corrections of each test prototype included adjusting take down tension and reducing machine running speed. Consequently, the optimal take down tension for this dress was 45-60, and the suitable machine running speed was 0.6 m/s. After that, the qualified prototype was laundered and steamed to achieve the stable status. *Finishing* is a crucial step in the entire development process, because knit garments always have distinct shrinkage in finishing. In this project, results of shrinkage evaluation indicated the prototype fit very well. However, if the prototype failed to meet size specifications, the design would be modified and knitted again. It is important to notice that shrinkage of garment size in finishing was assessed in knitted structure and garment style evaluation and finished prototype evaluation. Although knit garment size had been assessed in style evaluation in phase two, the finished garment should be measured again, because the digital pattern was modified after style evaluation. Finally, an approved knit prototype was created. In this case study, the last step of the development process was repair. Even though the knit garment passed both prototype evaluation and shrinkage evaluation, some repairable dropped stitches still existed. Thus, the designer mended the dropped stitches and hid the small knots in the dress.

After the project was completed, physical samples and digital patterns of the novelty structures and the seamless knit dress and notes of machine settings such as loop length and take down tension, and machine running speed all went to the reference library, providing references for future works.

7.4.2 Validity of knowledge components

Observation and limited participant experience in this case study proved that knowledge components in the preliminary model were necessary, but additional knowledge was needed and specific components such as training of CAD and CAM should explained in details.

To develop seamless knit garment style, the designer not only needed to know knit garment construction methods, but she was also required to understand limitations of seamless knitting and effects of knitted structures on garment look. Seamless knitting is the most complicated method to construct knit garments. The garment shaping process is finished during knitting. Therefore, comprehension of limitations in seamless knitting can help the designer create producible design and avoid unnecessary mistakes in knitting practice. Additionally, knitted structures or stitches were also important components in knowledge building. Unlike cut and sewn garments, seamless garment design includes both fashion design and fabric design. In the knitting process, knitted fabrics are created at the same time during garment shaping. Knitted structures or stitches used in the design directly influence garment style and shape. This requires knitwear designers to understand how to combine different knit stitches and their impacts on garment size and shape. According to observation of the researcher, the knowledge needed in *yarn selection* included yarn color, yarn material, size and machine gauge. For *sizing and shape*, body measurement, loop density and loop length were the main components in knowledge building. Body measurements provided size specifications for the seamless dress. Loop density and body measurements determined the number of stitches in garment knitting. As stated previously, actual loop density of knitted fabrics is related to fabric width, take down tension and set loop length on the machine. This requires designers understand the relationship among those four factors and be able to input accurate loop densities achieved by 3-piece knitting. Loop length is another critical parameter in machine settings. In addition to its influence on fabric tightness, loop length has an impact on stitch transferring. Small loop length makes it hard to transfer stitches, but too big loop length will lead to open structures and require high take down tension. Therefore, optimal loop density and loop length are extremely important in generating an appropriate style for a knit garment.

In phase two of the design and development process, knowledge building in the preliminary model indicated that CAD software training and machine operation training were the most important components. Observation in this case study exposed detailed components in CAD/CAM training. CAD training enabled the designer to make CAD programs for knitted samples and seamless garments, including how to interpret knitted structure design into machine language and how to create and adjust digital garment patterns. For machine operation, detailed components in CAM training involved threading up yarns, adjusting machine settings, repairing or replacing bad needles and running both fully-fashioned and seamless knitting machines. Moreover, comprehension of seamless garment formation procedures was useful in CAD programming and machine operation. If designers understand shaping procedures of sleeves and garment body, they can effectively control and adjust machine settings for different parts of the garment before knitting and promptly correct or avoid some potential errors during knitting.

The knowledge needed in knitted prototype production was similar to the knowledge needed in digital design via CAD/CAM. Particularly, seamless knitting machine operation and machine settings were primarily important. Additionally, shrinkage of the prototype in finishing was discussed in this phase. It was essential for designers to understand the effects of finishing procedures such as washing, drying and steaming on garment size and shape.

7.5 In-depth case study five: model mapping

The participant designer in the in-depth case study four also created a seamless sleeveless knit tank for another design (see Figure 7.7). The design and development process of the sleeveless tank and the knowledge needed were investigated as a new case study. Results of this case are summarized in Table 7.5.

Figure 7.7 Seamless tank created in in-depth case study five

Table 7.5 Summary of in-depth case study five

Phases	Steps	Results	Knowledge needed	References
Garment Style Generation	Style development and structure selection	Created a draft of a seamless tank Selected potential knitted structures	• Seamless knit garment construction • Limitation in seamless knitting • Knitted structure design	Physical samples in the reference library
	Yarn selection	Selected yarn color, material and size	• Yarn materials, color and size • Machine gauge • Methods to identify loop length	Pilot study of yarns
	Yarn evaluation	Knitted test swatches to identify proper loop length and loop densities		
	Sizing and shape	Calculated loop density Decided garment size and shape	• Body measurement • Loop density calculation • Armhole and neckline shaping in seamless knitting	
Digital Design via CAD/CAM	Structure design	Knitted four samples with different knitted structures	• CAD programming for samples • Fully-fashioned machine operation • Shrinkage of knitted structures	Physical samples in the reference library
	Knit structure evaluation	Evaluated stitch quality and performance of yarns in novelty structure knitting; Confirmed ideal structures matched to the design;		

Table 7.5 Continued

Digital Design via CAD/CAM	Style design	Created digital pattern for a full-scale tank Knitted the tank on seamless knitting machine	• CAD programming for seamless garments • Seamless knitting machine operation • Machine settings such as loop length, taken down tension and speed • Understanding of seamless sleeveless knitwear formation procedures on the machine	Documents of machine settings in the reference library
	Full-scale evaluation	Tested possibility of knitting unique structures and garment shapes; Evaluate knitting quality and garment size after laundering;		
	Design modification	Modified garment design and size	• Knitting defect troubleshooting	
Knit Garment Production	Pre-production	Knitted full-scale prototype	• Seamless knitting machine operation • Machine settings such as loop length, taken down tension and speed	
	Prototype evaluation	Evaluated knitting quality; Repeated steps for design modification and preproduction four times until the prototype met designer's requirements;		
	Finishing	Steaming	• Finishing effects on knit garment size and shape	Results of fundamental research
	Shrinkage evaluation	Assess the size of the finished knit dress after steaming		

7.5.1 Design and development process

The design and development process for creating the sleeveless knit tank in this case was almost the same as the steps in in-depth case study four. First, the designer generated an idea for knitting a sleeveless tank on the seamless knitting machine. Second, the designer selected four matched knitted structures from physical samples in the reference library. Third, possible yarns were explored in terms of color, material and size. Because yarn color determined garment color, the designer first confirmed the color best matched up with her design. Material was also considered in *yarn selection*, because it influenced garment hand and look. The most important component to consider in this step was yarn size, which must fit the machine gauge. Finally, two ends of bundled polypropylene yarns were used to knit the garment. To test the selected yarn, five single jersey swatches were knitted with different loop lengths. Evaluation results showed that the optimal loop length was 11 mm and the proper take down tension setting was 45-60. Loop density of the swatch with preferred knitting result was calculated and input in the CAD system for garment sizing. The last step in garment style generation was *sizing and shape*. Body measurements determined garment size specifications. Also, the designer explored potential shaping methods in achieving the particular shape of the knit garment. Shaping methods used in this project included a combination of different knitted structures, tubular narrowing and widening.

First step in second phase of the design and development process was *knitted structure design*. Four knitted structures selected from the reference library were knitted into100 wales by 120 courses samples. Evaluation of these samples indicated that the four structures could be successfully knitted using the selected yarn with machine settings gained in yarn evaluation. According to appearance and shapes of the four samples, the designer picked two of them that perfectly matched her design. Another important step in phase two was *style design*. An existing pattern in the system's pattern library was developed with single jersey structures as a base, and then it was adjusted to meet the designed garment shape and two special knit structures were applied according to the original design. After the first full-scale test garment was knitted and finished, the designer estimated its knitting quality and size. Style evaluation implied the unique garment style and novelty knit structures were possible to knit on the specific seamless knitting machine. However, the test garment had some dropped stitches and unsuccessful transferred stitches in armhole shaping and neckline shaping areas. At first, the designer thought the dropped stitches and bad transferred stitches were caused by the same reasons of failed stitch transferring in last project. Nevertheless, after adjusting machine settings and lowering machine running speeds, some dropped stitches still existed. The designer realized the yarn used might be another reason for the bad quality, because the synthetic yarn used was not twisted and was too slippery to knit especially when transferring stitches. To improve knitting quality but keep the hand and texture of the fabric, the yarn was treated with 1.56 twists per inch to increase its friction during knitting. Another full-scale test garment was knitted using twisted yarns. Additionally, in style evaluation, the designer found size of the test garment was smaller than expected measurements. Although the same loop density was input into the CAD system in creating the digital pattern for the entire garment, in fact final loop densities for the two novelty knit structures used in the garment design were different. This was the reason that resulted in smaller garment size than expected measurements. According to evaluation results, the garment size was modified and the design moved forward to the next phase for prototype production.

In *pre-production*, the modified garment pattern was knitted and finished and evaluated. Knitting quality of the full-scale prototype was the main evaluation component. Results of prototype evaluation both before and after finishing indicated the prototype met all design requirements, including good quality and right size. If the prototype was not approved in either prototype evaluation or shrinkage evaluation, the steps for *design modification* and *prototype production* and *finishing* should be repeated until a satisfactory prototype was produced.

7.5.2 Validity of knowledge components

As stated in Table 7.5, accomplishment of *style development and structure selection* required the designer to know limitations of seamless knitting, methods to combine knitted stitches and effects of different knitted structures on garment shape. Knowledge needed in *yarn selection* included yarn materials, color design, yarn size and machine gauge, and loop length. For *sizing and shape*, in this case, the designer had the ability to take body measurements and calculate loop density, as well as understood principles and limitations of armhole shaping and neckline shaping. Shaping methods in sleeveless seamless knit garments differ from cut and sewn garments. The shape of the armhole and neckline is determined by fashioning frequency and the number of transferred stitches in one fashioning sequence. Understanding of armhole and neckline shaping methods allowed the designer to adjust the armhole or neckline shape correctly. Yarns used for garment fashioning should be elastic enough to facilitate stitch transferring. Appropriate machine settings such as slow machine running speed and high take down tension were required to transfer stitches in armhole and neckline shaping.

In phases two and three, an important component in knowledge building was CAD/CAM training. As the participant stated, CAD/CAM programming was the most time-consuming and challenging part in the design and development process, but it was definitely important and necessary in an integrated model of shaped knit garment design. Basic training in the knitting CAD and CAM system included digital pattern programming, yarn set up, machine setting adjustment and running knitting machines. Machine maintenance such as replacing bad needles or cleaning needles support the knitting process, and it was alternative knowledge but not essential.

To conclude, the knowledge needed in in-depth case study four and five was similar. Observation of execution steps in the two projects proved the validity and necessity of most components in the knowledge building, but additional knowledge was needed to support the design and development process. Those extra knowledge components observed in the in-depth case studies would be added to the final developed model.

7.6 Discussion of model mapping in in-depth case studies

The design and development processes for creating fully-fashioned or seamless knit garments in those five in-depth case studies were mapped to the model established in stage two of this research. As described previously, the preliminary model consists of three parts – the design and development process found in the center of the model, and evaluation components and knowledge building to support steps of the process. A reference library was developed in this research, providing a base for designers to select yarns, design knitted structures, form garment size and adjust machine settings. In stage three of the research, to validate and refine the model, actual steps of the execution and evaluation process in the five cases were compared with steps in the preliminary model. Also, the references used and the knowledge needed in each case study was observed and analyzed. Comparison of model components between the preliminary model and in-depth case study process steps validated the established model and revealed additional information needed in the design and development process. Section (7.6.1) reported results of validation of process steps and evaluation components in the model, and validity of knowledge components was discussed in section 7.6.2.

7.6.1 Validity of the design and development process and evaluation

In phase one for *garment style generation*, all the five in-depth cases followed process steps in the preliminary model from style development through garment sizing and shape. A minor change shown in case two and case four was that knitted structure was selected and then designed rather than just picking matched structures from the reference library. Components in yarn evaluation such as yarn color and size were necessary in all cases, and hand was an additional component that should be assessed. Based on observation of the five case studies, design requirements in yarn evaluation represented look and hand, as well as fabric tightness and dimensions. In the traditional knitwear development process, aesthetic designers are responsible for color design and material selection, whereas technical designers or machine operators take over selection of yarn size that must fit to knitting machines. However, in an integrated model for fully-fashioned and seamless knit garment development, designers are supposed to undertake both aesthetic design and technical design. They not only need to consider style, color and hand of designed garments, but they should also assure the selected yarns be knitted on specific machines.

Results of the five cases in phase two of digital design via CAD/CAM exposed that *style design* and *knitted structure design* could be reversed or accomplished together. The order of the two steps depends on the complexity and uniqueness of knitted garment style and knitted structures. If the knitted garment is designed in a unique shape or style that is not selected from the existing pattern library in the CAD system, it is better to knit the garment shape or style with single jersey structures rather than complex knitted structures to test whether the unique shape can be knitted on specific machine. When the knitted garment style is simple but knitted structures are complex and novel, knitted structure evaluation will be more important than garment style evaluation. In this case, *knitted structure design and evaluation* can be accomplished prior to *style design and evaluation*. However, in some circumstances, either knitted structures or garment style is selected from the existing reference library, so knitted structures and garment style can be evaluated together, generating a quarter- or half- or full-scale test prototype before prototype production. One important point that needs to be declared is that the use of a quarter-scale or a half-scale in *style design and evaluation* may be not necessary in most cases. According to results of the five in-depth case studies, only in case three was a half-scale garment used, but data analysis of the half-scale design in section 7.3.1 indicated that machine settings used in half-scale knitting differed from full-scale. Evaluation results of a half scale cannot provide accurate machine settings and garment size for full-scale production. However, when the yarns used are expensive or limited and the garment style is specifically unique, it will be necessary to knit a small-scale test garment to test the possibility of knitting the special style and shape. Otherwise, a full scale is more meaningful in *style design and evaluation*. Following sampling approval for knitted structures and garment style, the digital pattern is modified in the CAD system, and the modified design is sent to the next phase for prototype production. *Design modification* is a necessary and important step before prototype production, because the garment size, shape and knitted structures can be adjusted in this step according to results of previous evaluations.

The intent of phase three in the preliminary model is to produce a qualified prototype for manufacturing. The process in the five in-depth case studies followed steps from *pre-production*, *full-scale evaluation*, *finishing*, *shrinkage evaluation* and *embellishment*. In *pre-production*, prototypes were knitted and then assessed in full scale evaluation, which evaluated whether the prototype could meet design specifications and inspected bad knitting quality such as dropped stitches or broken yarns. In fully-fashioned knit garment development, the shaped garment panels should be sewn or linked together to form a complete garment before finishing. After finishing such as washing, drying or steam pressing, the finished prototype was evaluated regarding color, hand, garment size and shape. Shrinkage of knitted garments in finishing and its impacts on garment size and shapes are important components to assess after prototype production, as well as knitted structure and garment style evaluation. Embellishing the finished garments was only involved in cases one and two. Thus, the step of knit garment decoration can be optimal but not necessary. When designers or development teams approve the finished prototype, digital patterns and machine settings of the prototype will be sent to the next phase for manufacturing.

Observation of the design and development process in the five in-depth case studies revealed that accomplishment of specific steps had referred to the reference library. For example, in *knitted structure selection and design*, all the participant designers reviewed the knitted samples in the reference library for inspiration. In test garment knitting, the initial machine settings in all the cases were pulled from documents in the reference library. This indicated that the reference library was essential in building an integrated model for shaped knit garment design and development. To enhance the reference library, digital patterns, machine settings and physical samples of knitted structures and knit garments created in the five in-depth cases were also saved in the library for further designs.

7.6.2 Validity of knowledge building

One important objective of this research is to investigate knowledge needed to create fully-fashioned or seamless knit garments. A knowledge building was established in stage two of the research according to data gathered from participant observation. However, according to results of in-depth case studies in stage three, not all the knowledge components in the preliminary model were necessary and additional components should be added to the building.

In *garment style generation*, designers are responsible for creating garment styles, designing knitted structures, selecting proper yarns and identifying garment size and shape. An in-depth understanding of principles and limitations in seamless or fully-fashioned knitting enables designers to create producible design and avoid unnecessary mistakes or rework in knitting practice. This could significantly improve design efficiency and reduce design time. For *knitted structure selection and design*, designers should know different knitted stitches such as front and back knit, tuck, miss, held stitches and transferred stitches and be able to combine them to create novel structures. Also, an understanding of the effects of different stitches or structures on knit fabric or garment size and shape is supportive in *knitted structure selection and design*. In *yarn selection*, the knowledge needed can be divided into two parts: one is aesthetic aspect regarding colors, materials and hand; another is relevant to technical selection that yarn size must fit the machine gauge. Furthermore, results of the five cases indicated that designers should know how to identify an optimal loop length for a design and understand the effects of loop length variation on appearance and dimensions of knitted fabrics. For example, in in-depth case study two, increasing loop length was used as a method to form an open structure garment. In the step of *sizing and shape*, the knowledge of body measurements and loop density are necessary. In particular to loop density, it was related to fabric width. Thus, for seamless knit garments with sleeves, different loop densities for sleeves and garment body can be achieved through 3-piece knitting. The other knowledge component – shrinkage of knitted structures and yarns – shown in the preliminary model was not involved in all in-depth case studies, but it was needed in the following steps for knitted structure evaluation.

In *digital design via CAD/CAM*, training in CAD/CAM systems and machine operation is vital. It is not possible to accomplish the design and development process without enough knowledge of CAD/CAM programs and knitting machine operation. Participants in the five cases all reported that programming digital patterns in CAD/CAM systems and operating fully-fashioned and seamless knitting machines were the most important but difficult section in the entire process. Results of the in-depth case studies showed that training in CAD/CAM systems should involve digital pattern design and making knit programs, and the knowledge needed in machine operation included adjusting machine settings, as well as threading up yarns and adjusting yarn tension and solving simple mechanical problems. Additionally, in machine operation, an understanding of shaping procedures on the machine can support designers to detect errors during knitting. For example, in cases three and four, dropped needles which were caused by the failure in stitch transferring existed in the areas of garment shaping. If the designers knew how the machine worked during garment shaping, they could adjust settings in solving those problems. Therefore, shaping methods in seamless knitting and fully-fashioned knitting and garment formation procedures on the machine help in troubleshooting, so they should be added to the knowledge building.

Finally, in phase three of the process, the knowledge needed in *pre-production* was the same as digital design via CAD/CAM. One additional component that may be needed is to repair bad parts and maintain the knitting machine. For example, in case three dropped stitches that were caused by broken needles existed in the prototype. Replacement of the bad needles was required to improve the knitting quality. Also, in case four, big holes formed in parachute knitting resulted from weak or bad needle clips. In order to solve the problem, the designer had to know how to inspect and repair bad needle clips. Therefore, in some cases, the knowledge to read error messages and address unexpected problems during knitting is necessary. If a fully-fashioned garment is developed, the knowledge of sewing or linking is needed. In the step of *finishing*, the designers are required to understand shrinkage of knitted garments in finishing and variations of garment size and shapes after finishing.

To sum up, results of the five in-depth cases demonstrated that the process in the preliminary model captured the main steps in design and development of fully-fashioned or seamless knit garments, but some steps in the model could be refined for broader application. Additionally, results of the five in-depth case studies verified that most of the components in knowledge building and evaluation were necessary but they were not sufficient to cover every garment variation. According to results of those in-depth case studies, several potential refinements to the model were identified. Some refinements implied adding new components or omitting unnecessary components in the model. Some refinements were simple terminology changes.

- Additional steps in the design and development process:
  1) Test pieces knitted with different widths might be needed to identify different loop densities for sleeves and garment body in seamless sweater knitting, so *3-piece knitting* can be added as an alternative step before *sizing and shape*.
  2) The steps of *style design* and *knitted structure design* in phase two of the process can be reversed or accomplished together. So in the model, design and evaluation of the knit structures can be placed first followed by assessing the garment style. Then, the test garment for style can be designed with single jersey structures or novelty knit structures depending on different situations.
  3) The steps from *design modification*, *pre-production* to *finishing* might be repeated until a qualified prototype was knitted, but repetition of these steps was not graphically illustrated in the preliminary model. Therefore, the refined model should graphically show the loop among *design modification*, *pre-production*, *prototype evaluation*, and *finishing* and *shrinkage evaluation*.
  4) In fully-fashioned garment development, *linking or sewing* is needed, so an alternative step of *linking or sewing* should be added to the model.

- Additional components in the knowledge building:
    1) The knowledge of limitations of fully-fashioned and seamless knitting should be added to the model components for *garment style generation*.
    2) An understanding of shaping methods and garment formation procedures on knitting machines supports designers detecting errors during knitting, so this component is needed in knowledge building.
    3) In addition to adjusting machine settings listed in knowledge building in the preliminary model, machine operation training should also include methods to thread yarns, and adjust optimal top and side yarn tension, and solve simple mechanical problems such as bad needle replacement.
- Refinements in evaluations:
    1) Quarter-scale or half-scale evaluation after *style design* is not necessary unless the designed garment has a unique style or yarns used are expensive and/or limited. A full-scale test garment is most useful to evaluate knit garment size and shape and provide meaningful feedback for design modification. Thus, full-scale evaluation can be added in the ¼ or ½ scale evaluation in the model.
    2) In knitted structure evaluation, selected yarns are assessed again when knitting novelty knit structures. An additional component – performance of selected yarns should be involved in this evaluation.
    3) Shrinkage in finishing can be effectively assessed in knitted structure evaluation and garment style evaluation in phase two, not delayed until full-scale prototype evaluation in phase three of the process, so the component for quantifying shrinkage can be added in each evaluation in the model.

4) A few refinements in evaluations are related to terminology changes. According to results of the in-depth case studies, full scale evaluation can be altered to prototype evaluation and shrinkage evaluation can be changed to finished prototype evaluation. The changed terms directly indicate the purpose of the two evaluation processes.

8 Results of experts interview in stage three

To verify the validity of the process steps, knowledge components and evaluation components in the preliminary model, interviews were conducted to obtain opinions from experts regarding their comments of the model. Analysis of responses from interview experts assisted in refining the preliminary model. 16 potential participants were invited to participate in the interview, and one of them was self-identified as non-expert in fully-fashioned and seamless knitting so was eliminated from the samples. Of the 15 qualified experts, 14 responded to the request and 10 completed the interview for a response rate of 66.7%.

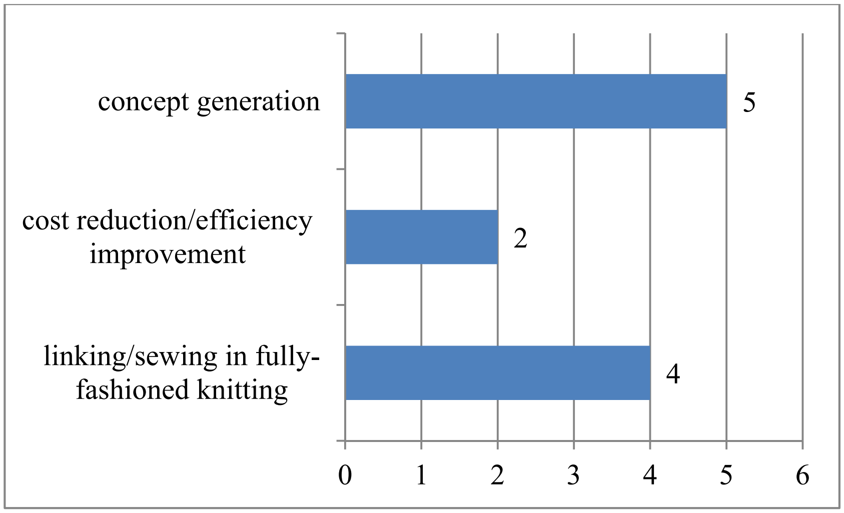
8.1 Expertise of participants

Questions in the interview instrument were divided into two parts: 1) background information about participants and 2) questions to validate the model. Background questions sought to identify participants' level of expertise in fully-fashioned or seamless knitting so asked about job title and duties, and experience in knitting or knitted product development. Analysis of responses to the five questions about participants' backgrounds indicated that all of the 10 participants worked in technical consulting and knit garment design related fields. Of the 10 participants, 8 stated that their duties were communication with customers and technicians to fix technical problems in knitting. One was a professor at the university teaching knitwear design. One was a sweater designer, who was only responsible for knitwear aesthetic design and had limited experience in manufacturing, so this participant's input was valuable in part of the model related to aesthetic design rather than technical design. Also, the 10 participants indicated that they all designed or produced fully-fashioned or seamless knitted products. The other two questions regarding participants' experience were "How many years of experience do you have in knitting or knitted product development?" and "How many hours do you work on knitting or knitted product development per week?" 5 of the 10 respondents had more than 10 years of experience in knitting and knitted product development, and 4 of them had more than 20 years of experience. Only one had less than 10 years of experience in knitted product development. In terms of work hours, 9 of the10 respondents worked at least 40 hours per week in knitting or knitted product development, and one participant worked more than 20 hours in knitting per week. Based on participants' titles, duties, experience and work hours in knitting, all the ten participants had sufficient experience in fully-fashioned and seamless knit garment design and development, and they were identified as experts.

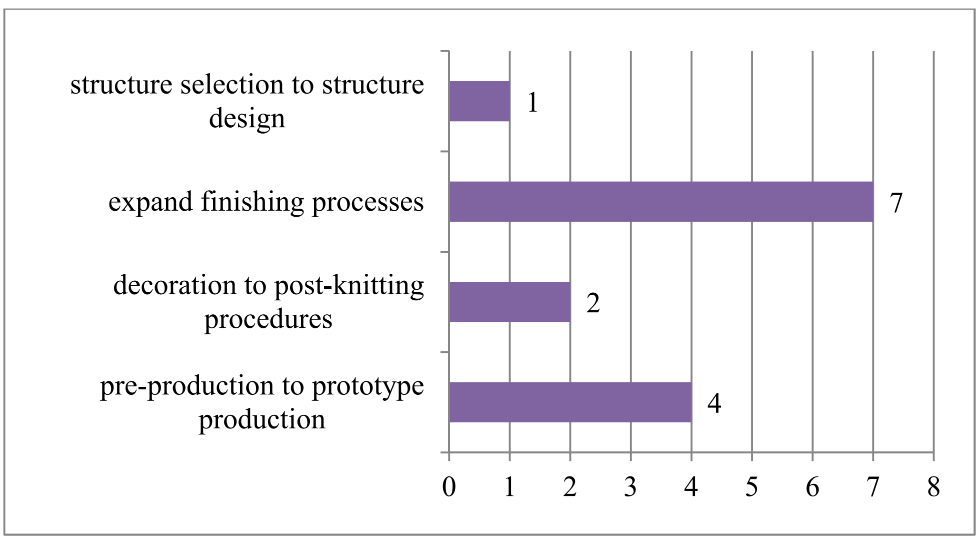
8.2 Comments from participant experts

Responses to the eight open-ended questions in the questionnaire aided in validating and refining the preliminary model. Participants were asked to verify necessity and sufficiency of the process steps, evaluation and knowledge components in the model. Throughout the interview, participants had the opportunity to provide comments on any additional steps and information for the shaped knit garment design and development process. To analyze comments from participant experts, the number of respondents for a given comment was counted to assign a frequency. Comments with high frequency were important for model refinement, but less frequently mentioned comments might also be valuable for particular businesses or market niches. Furthermore, comments provided by experts were classified into two categories: model adjustment and terminology change. Model adjustment implied adding or omitting some process steps and model components; whereas, participants' comments on terminology change indicated that a different term might better describe a step or model component.

Interview open-ended question one stating, "Do you think that the design and development process captures the steps necessary to design and develop a fully-fashioned or seamless knit garment?" allowed participants to validate the process steps in the model (see Appendix D). The ten participant experts all indicated that model steps captured mostly the necessary steps, but additional steps could be added into the model, including (1) concept generation, (2) cost reduction and production efficiency improvement, and (3) linking or sewing for fully-fashioned knit garments. As shown in Figure 8.1 (a), of ten participants, five thought concept generation was necessary before garment style generation. They pointed out that concept generation in knitwear development could include ideas of design, target market analysis, cost forecasting and design and production time estimation. Another comment from participant experts concerned adding another step for reducing cost and improving production efficiency after prototype production. One of the two experts commented on this step saying, “Designers and technicians could collaborate to think about methods to reduce cost and improve production efficiency according to results of knitted structure evaluation and style test piece evaluation.” Another expert when commenting on efficiency improvement stated, “In some cases, the number of transferred stitches in a design could be reduced to shorten knitting time.” The comment regarding cost reduction and production efficiency improvement will be discussed in-depth in analysis of interview question seven. The last comment relevant to model adjustment was about linking or sewing. Four participants indicated linking or sewing should be an additional step after prototype production in fully-fashioned knitting. Additionally, most participant experts commented about terminology used in some process steps. A summary of terminology changes to the steps in the model is listed in Figure 8.1 (b). One participant in the interview mentioned that structure selection in the first process step could be changed to knitted structure design. Although only one expert talked about this terminology, it was a very valuable comment. In knitted fabric design, most designers select knitted structures in the pattern library as a reference then they often combine different structures or alter some knitted stitches to design a new structure. The term of knitted structure design implied a wider consideration than knitted structure selection. The most mentioned step by the participants was laundering in phase three. Seven out of the ten respondents thought the term “laundering” which is shown in the model, was not sufficient to describe the step of finishing. For example, one respondent commented, “Finishing processes in knitwear production were not limited to washing and drying. Steam pressing, blocking, felting especially for wool, and dyeing of gray fabrics might be adopted depending on material and design requirements." Therefore, those possible finishing methods should be included in the model. Also, two respondents thought printing or embroidery for decoration was not sufficient. They suggested additional procedures such as adding buttons or pockets and trimming end yarns could be added in the step of decoration. Those decoration methods provided by respondents all belonged to procedures after knitting; thus, the term used for the step of decoration could be changed to "post-knitting procedures", which would include printing, embroidery, adding buttons/pockets, or trimming end yarns. Another terminology change mentioned by four respondents was to use prototype production instead of preproduction in phase three. One of the four respondents stated, "The term "pre-production" was misleading for reviewers. From my perspective, pre-production is a part of manufacturing in the factory; thus it will be too late to evaluate shrinkage in pre-production." Another participant doubted preproduction aided to produce prototypes and stated that, "If full-scale prototypes are knitted in preproduction, the name of this step can be changed to 'prototype production' with less confusion." From an industry perspective, pre-production could be part of manufacturing in a factory. However, in the model, the intent of pre-production was to knit a qualified prototype that met all design requirements, as one participant stated, " Normally, several modified prototypes for garment style are knitted with corrections until the garment is stable and not making holes or damages." Therefore, the term "preproduction" used in the preliminary model could be altered to "prototype production".



(a) Additional steps in design and development process



(b) Terminology change of process steps

Figure 8.1 Comments from participant experts in interview question one

The second open-ended question in the interview asked participants to certify whether the components in knowledge building were necessary and sufficient to support the first phase of the design and development process – knit garment generation. Of the ten respondents, three confirmed the knowledge components were both necessary and sufficient for designers to accomplish style development, structure design, yarn selection, size and shape. However, one participant stated, “Knitted stitches properties in the knowledge building are probably not necessary, because designers always focused on aesthetic design of stitch structures not stitches properties.” It is true that aesthetic design is important in knitted structure design, but knitted stitches properties in the knowledge building mean influence of different knit stitches on fabric dimensions and appearance. For example, tuck and miss stitches can reduce fabric length but increase fabric width; therefore, their use in knitted structure design will influence garment size and shape. Additionally, six participants thought the knowledge components in phase one were not sufficient. As shown in Figure 8.2, extra knowledge components mentioned by the six experts included trend analysis, shaping methods and impact of fabric width on loop density. Two experts thought trend analysis was necessary in the knowledge building to support idea generation. The aim of trend analysis was to identify fashion color, knitted stitches and garment style for knitwear design. Four experts mentioned the necessity of understanding shaping methods in fully-fashioned and seamless knitting, as one of them stated, “In garment style generation, an understanding of shaping techniques enables designers to create producible design.” Thus, principles and limitations of fully-fashioned knitting should be included in the knowledge building of the model. The last knowledge component recommended adding in phase one was the influence of fabric width on loop density. One expert commented that fabrics of different widths might have varied loop densities, saying, “On seamless knitting machines, take down tension was set as a constant value, but actual tension on knitted fabrics differed due to different fabric widths. This influenced actual loop size and loop density between sleeves and body in garment knitting.” Another participant, again commenting on relationship between loop density and fabric width, stated that, “In seamless knitwear development, designers should use different loop densities for different parts of the garment, so that they could accurately adjust knit garment size." Although few respondents mentioned that fabric width had an impact on loop density, a need to measure different loop density of fabrics knitted with different widths exists in seamless knit garment development. The comment concerning loop density and fabric width corresponded with 3-piece knitting in the in-depth case studies discussed in the last chapter. An understanding of the relationship between loop density and fabric width could be an alternative component in knowledge building to support 3-piece knitting in the seamless knitwear development process.

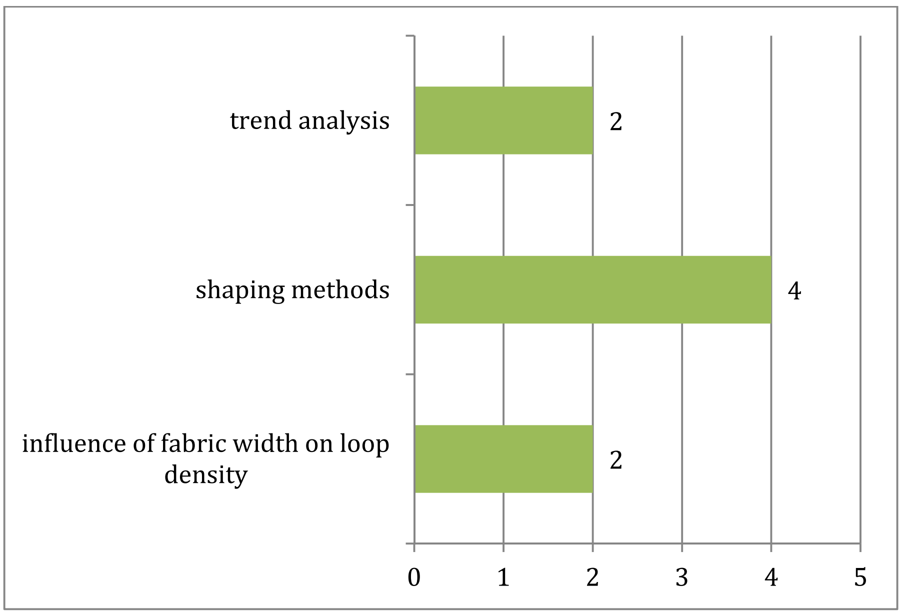


Figure 8.2 Additional knowledge components needed to support garment style generation

The next question in the interview sought to validate necessity and sufficiency of the knowledge components in phase two of the design and development process. Data gathered in this question showed that nine of the ten participants thought the components in the knowledge building were both necessary and sufficient. Only one expert mentioned that additional knowledge might be needed to support machine operation. This expert thought designers needed to understand how knitting machines worked and be able to set up yarns and machines before knitting. The expert also pointed out understanding of fully-fashioned or seamless garment shaping methods was still important in digital design and prototype production. If designers have sufficient knowledge of garment shaping, they can properly adjust a digital pattern or promptly correct errors during knitting.

Interview question four aided in validating the knowledge components in phase three of the design and development process. All ten experts in the interview agreed that training of CAD/CAM and dimensional stability of different knitted structures and laundering effects on knitted structures and knitted garment size were necessary knowledge to complete knit garment production. However, six participants provided additional knowledge needed in this phase concerning linking/sewing, machine maintenance, and ability to repair bad quality. The frequency of the three comments mentioned by the six experts is compared in Figure 8.3. Two respondents who commented on the step of linking or sewing in the process of fully-fashioned knit garment development also recommended adding the knowledge of linking and sewing in the knowledge building. Additionally, four experts thought designers should have the ability to repair bad quality, such as mending dropped stitches or hiding small knots. Also, two experts pointed out a need to understand machine maintenance, such as cleaning needles, and replacing bad needles or jacks. However, the last two knowledge components – machine maintenance and bad quality repair are supportive but not necessary in knit garment design and development because in the industry, technician are after responsible for maintaining knitting machines and repairing bad quality on knit garments after production.

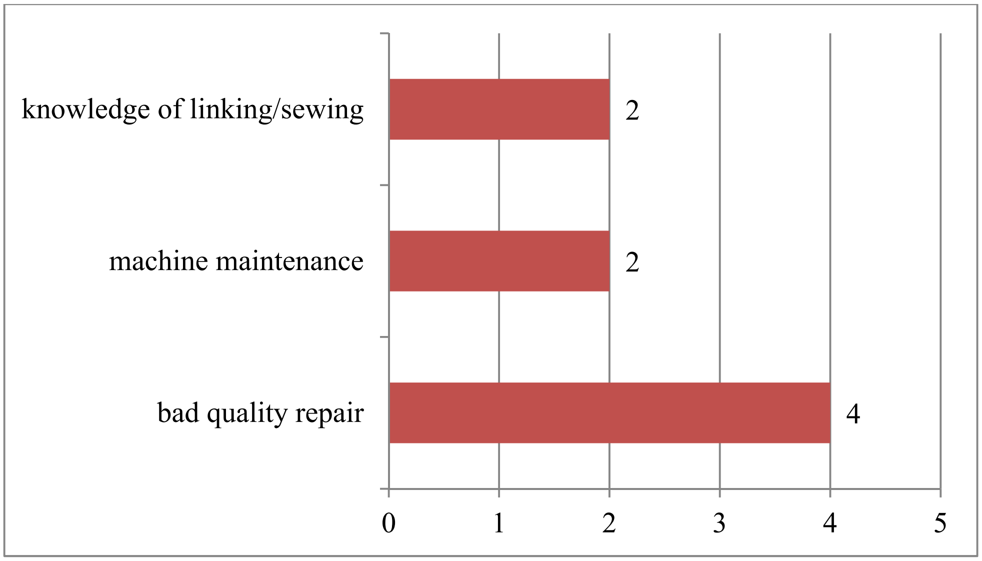


Figure 8.3 Additional knowledge components needed to support prototype production

Interview question five verified the validity of components in yarn evaluation, asking, "In phase one of the design and development process – garment style generation, do you think the components in evaluation are necessary and sufficient to support knit garment development?" All ten participants believed that components in yarn evaluation provided enough information for designers to make a proper decision and move forward to the next step, but they provided their own thoughts regarding changes of terminologies used in the evaluation. One participant questioned the definition of "Yes" and "No" in the model, stating, "The term of 'yes' or 'no' used in decision gate is confusing. Although I understand it means approved or not approved, I think detailed explanation of the two terms should be added in a legend." Another comment mentioned in this question was the change of "yarn evaluation" to "yarn test swatches evaluation". Participant experts implied that test swatches were commonly used to determine yarn color, size, and material and stitch setting (loop length/loop size) depending on feel and look of the yarn test swatches. Therefore, instead of yarn evaluation, the term – yarn test swatches evaluation could clearly present the purpose of this evaluation as a method to select proper yarns.

The evaluation components in phase two of the design and development process were validated in interview question six. In the interview, one participant declared that she was not familiar with CAD/CAM in knitting, so she could not answer this question. One participant totally agreed with the components in the evaluation. However, a majority (8 of 10) of participants commented on 1/4 or 1/2 scale evaluation. Five participant experts believed evaluation of a 1/4 or 1/2 scale garment was not necessary and they suggested knitting full-scale pieces to test garment style. For example, one of them stated that, "Knitting a small scale is not helpful in full scale knitting, because machine settings of a small scale and a full scale are different and digital patterns of the full-scale garment need to be redesigned, which wastes design time." Three participants in the interview indicated 1/2 or 1/4 scale evaluation should be kept in the model. They thought adoption of small-scale garments depended on customer requirements, complexity of a design and price of yarns. One participant expert said, "Some customers would like to see a small scale prototype before they decide to place an order." Consequently, two comments on a quarter, half, or full-scale evaluation in phase two need to be considered in refining the model. In addition to changes in style design, the participants also provided some comments about knitted structure evaluation. Seven of the ten participants thought the evaluation components were necessary and sufficient to guide designers in completing knitted structure design. However, three participant experts indicated that performance of selected yarns could be evaluated again in this step. One of the three experts stated that, "In knitted structure evaluation, it may be interesting to evaluate selected yarns when they are knitted with special structures, so I recommend to add performance of yarns as an additional component in knitted structure evaluation." Furthermore, one participant pointed out that loop density of swatches knitted with special structures could be calculated and then used in design modification to improve garment fit. Another comment relevant to garment fit was to evaluate shrinkage in finishing after both style design and knitted fabric design. Four participants talked about the necessity of shrinkage evaluation either after knitting test pieces for garment style or after knitting swatches for novelty knitted structures. They specified that shrinkage in finishing should be assessed as early as possible in the knitting process because it was an important step to improve garment fit. Figure 8.4 summarizes responses to question six in the interview.

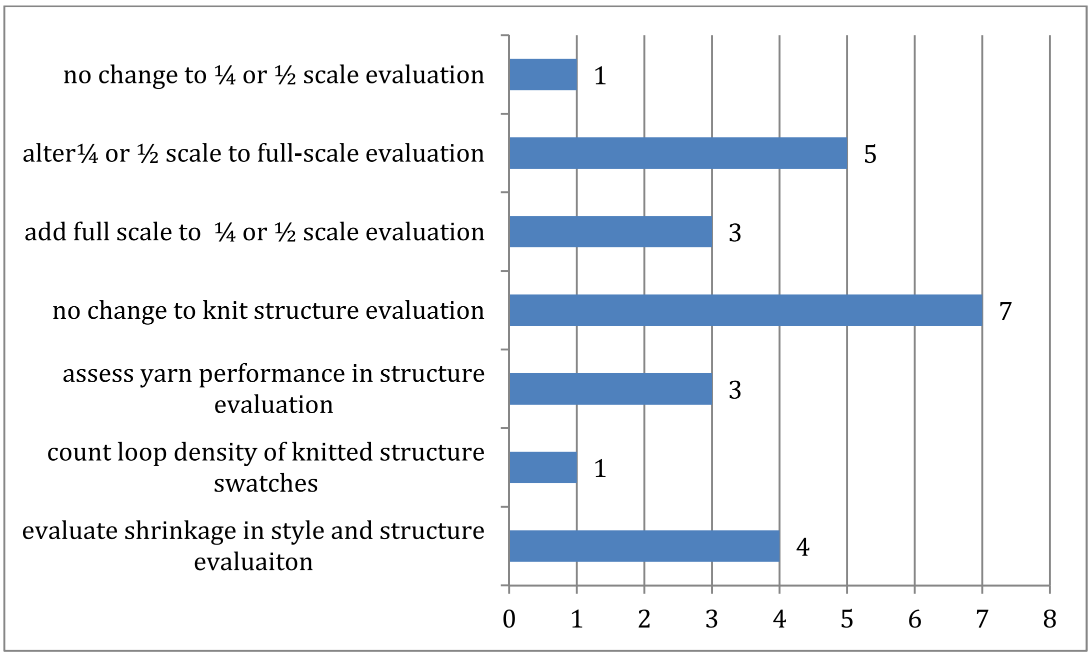


Figure 8.4 Participants' responses to question six

The following question, interview question seven, assisted in validating components in evaluation of full-scale prototypes and shrinkage. Responses of six participants revealed that evaluation components in prototype production were both necessary and sufficient, so that no change was needed in this phase. However, four experts thought those evaluation processes were necessary but not sufficient. Of the four experts, two presented a concept called “mending”. One participant stated that, “Mending is checking to see if there is any dropped needle on the garment after production, and it is part of quality control. Sometimes you can fix these dropped stitches, but sometimes you have to knit the garment all over again.” Another participant specified that, “Mending dropped stitches or hiding knots is to improve knitting quality in production, but serious dropped stitches or damages can’t be mended.” The concept of mending mentioned in this question is a method to repair dropped stitches that are not serious and repairable, so mending can be counted as a post-knitting procedure. Further, four out of the ten participants pointed out that customer evaluation might be needed after prototype production. For example, one participant stated, “A prototype knitted without damages or dropped stitches must be evaluated by customers in terms of design, size, knitting time, cost and quality. Only when the prototype was approved by customers, it could be sent to the factory for manufacturing.” This comment was similar to another comment about adding cost reduction and production efficiency improvement as an additional step in interview question two. Adoption of customer evaluation in the model could not only assess whether or not knitted prototypes meet customer requirements, but also allow designers or technicians and customers to deliberate cost reduction and production efficiency improvement.

The last interview question asked if participant experts thought knowledge building and evaluation components are important to supporting the design and development process in an integrated model. The ten participant experts all said “Yes” to this question. Particularly, 7 of the 10 respondents emphasized that they thought this model integrating the design and development process, evaluation and knowledge needed would be a valuable and useful tool for fully-fashioned and seamless knit garment development. One participant specifically noted: “This flowchart or model depicts necessary steps to create knitted garments, as well as explains how and why to accomplish each step. In particular to seamless knitting, the model could provide a great guide to train fresh knitwear designers."

Overall, most responses from industry experts in the interview were positive; especially, responses to interview question eight proved the significance of this research and that a need existed to establish an integrated model for fully-fashioned and seamless knit garment design and development. Interview results of the first seven questions indicated the preliminary model developed in research stage two was generally valid and reliable. According to comments from participant experts, most steps and components in the model are necessary, but some steps and components could be added or omitted to enhance sufficiency of the model. Also, terminology changes recommended by respondents could contribute to improving readability of the model and making it easy to understand.

8.3 Comparison of results of expert interview and in-depth case studies

Data gathered through the two validation methods in stage three of the research revealed that most results of in-depth case studies corresponded with comments from industry experts in the interview. Table 9.1 presents refinements to the preliminary model obtained from observation in the five in-depth case studies and comments of expert interview.

Table 8.1 Summary of results of model validation

Results \ Validation method	In-depth case study	Expert interview
Process steps	• Add alternative step for 3-piece knitting before sizing and shapes • Reverse steps for style design and knitted structure design • Repeat steps for design modification and prototype production • Require linking/sewing in fully-fashioned garment development	• Add concept generation before style development • Add linking/sewing after prototype production in fully-fashioned knitting • Change structure selection to structure design • Present possible finishing processes and decoration methods • Change preproduction to prototype production
Knowledge building	• Knowledge of shaping methods and limitations in fully-fashioned and seamless knitting • In addition to adjusting machine settings, CAM training includes threading up yarns, adjusting top and side tension on yarns and solving simple mechanical problems • Understanding of garment formation procedures on the machine	• Understanding of shaping methods • Comprehend the influence of fabric width on loop density • Knowledge of linking and sewing in fully-fashioned garment formation • Yarn set up before knitting • Understand knitting procedures on the machine • Alternative knowledge of machine maintenance and bad quality repair
Evaluation	• 1/4 or 1/2 scale evaluation not needed in most cases • Add full-scale test piece evaluation • Assess shrinkage in finishing after yarn selection, style design, knitted structure design and prototype production • Assess yarn performance in knitted structure evaluation	• Change yarn evaluation to test swatches evaluation • Alter 1/4 or 1/2 scale to full-scale evaluation • Keep 1/4 or 1/2 scale and add full-scale evaluation • Assess yarn performance in knitted structure evaluation • Consider loop density of fabrics knitted with novelty structures • Add customer evaluation

In general, results of both in-depth case studies and expert interview all indicated the established model in stage two of the research could assist designers to complete fully-fashioned or seamless knit garment design and development, but they also provided refinements to the model to enhance its versatility and sufficiency. Some comments from experts in the interview depict the same conclusions obtained from observation of the in-depth case studies. For example, linking or sewing was adopted in case studies to create fully-fashioned garments, and results of expert interview clarified the necessity of linking and sewing in fully-fashioned garment development. In knowledge building, both results of in-depth case studies and comments from experts verified that an understanding of shaping methods, garment formation procedures and limitations in fully-fashioned and seamless knitting is needed to complete knit garment creation. Detailed information of CAM training observed in the in-depth cases, such as adjusting machine settings, threading yarns, adjusting top and side tension on yarns and solving simple mechanical problems, are consistent with a comment in an expert interview related to yarn set up before knitting. Also, in evaluation, results in both validation methods indicated ¼ or ½ scale may be not necessary in most cases and a full-scale test piece can provide more reliable and useful information for prototyping. Additionally, in the in-depth case studies, the participant designers assessed shrinkage of yarn test swatches after yarn selection, structure swatches after knitted structure design, test pieces after style design, and full-scale prototype after prototype production. This step matched a comment in the interviews on shrinkage in finishing. In knitted structure evaluation, both experts in the interview and participants in the in-depth case studies indicated that performance of yarns could be evaluated again when they were knitted with novelty knitted structures. Furthermore, two of the five in-depth case studies employed 3-piece knitting, which created three tubular fabrics knitted with different widths using the same yarns and machine settings. It was important to implement 3-piece knitting in determining accurate loop density of fabrics with different widths. Although experts did not mention the concept of 3-piece knitting, a comment regarding the influence of fabric width on loop density discussed in the interview represented the knowledge needed in 3-piece knitting.

Even though in-depth case studies and expert interviews point to similar refinements to the preliminary model, some comments from industry experts were not observed in the in-depth case studies, and, conversely, in-depth case studies also provided different results from the interview. For steps of the design and development process, the observer found that style design and knitted structure design could be reversed in actual projects, but this point was not mentioned in expert interviews. In addition, many participant experts talked about terminology changes in the model, such as changing the term “structure selection” to “structure design”, or changing “preproduction” to “prototype production”. Those terms are not incorrect, just the most accurate from an industry expert’s perspective, so they are not noticed in the in-depth case studies. Again, in evaluation, some experts suggested the term “changing yarn evaluation” to “yarn test swatches evaluation” in order to clearly show the purpose of this step. The latter term is consistent with the process in the in-depth case studies, where test swatches were actually used to test selected yarns. For the knowledge building, some experts in the interview thought machine maintenance and bad quality repair could be alternative knowledge for designers. Although this comment was not clarified in the results of in-depth case studies in Table 8.1, machine maintenance such as bad needle replacement or needle inspection was actually done in some case studies. Also, in case studies three and four, some repairable dropped stitches were mended after production. This proved that bad quality repair is needed sometimes. Additional components recommended in the interviews, such as loop density of fabrics knitted with novelty structures and customer evaluation, were not observed in the in-depth case studies, but it doesn’t mean those comments are not valuable.

Results of the in-depth case studies validated that steps and components in the preliminary model were able to guide designers in knit garment design and development processes, and the interviews validated necessity and sufficiency of the model and provided valuable feedback on the model from the experts' perspective. Consequently, both observations in the in-depth case studies and comments from experts are used to develop a refined model.

9 Model refinement

An integrated model for fully-fashioned and seamless knit garment design and development combining earlier findings is developed in this chapter. The preliminary model established in stage two of the research was validated through mapping in in-depth case studies of knit garment development and review of industry experts. Results presented in Chapter 7 and Chapter 8 provided confidence in the importance of knowledge building and evaluation in an integrated model, and in the necessity of model components. Additionally, analysis of data collected through in-depth case studies and expert interviews revealed refinements to the model. In this chapter, the preliminary model is refined based on findings in previous research.

Figure 9.1 provides an overview of the integrated model for shaped knit garment design and development. The model integrates the design and development process, evaluation components, knowledge building, and a reference library. Design and development of fully-fashioned or seamless knit garments is accomplished in three phases: (1) *garment style generation*; (2) *digital design via CAD/CAM*; and (3) *knit garment prototyping*. Process steps in the three phases provide designers or knitwear development teams a guide to create knit garments using advanced fully-fashioned or seamless knitting technology. Evaluations represent decision points, which assist designers to assess a given step and move forward to the next step. In each evaluation process, designers or development teams not only verify whether knitted samples or prototypes meet design and quality requirements, but they also need to identify methods to address the knitting defects. Essential knowledge needed to correct challenges in the evaluations are listed in knowledge building. The knowledge building components also present the knowledge needed to accomplish relevant steps in the design and development process. The other important part of the integrated model is the reference library, which can increase efficiency and effectiveness of completing process steps and making appropriate decisions in evaluation. In the knitwear industry, designers refer to a digital pattern library to find inspiration and create new designs, and technicians may use documented references to adjust machine settings or stitch settings in knit production. Over time, companies build their own reference libraries through design archives. In this research, a reference library was developed, which included physical samples, digital patterns, records of machine settings and findings achieved in fundamental research. Samples and digital patterns of different knitted structures created in research stage one and knitted garments created in case studies of stages two and three were documented in the reference library, which provided inspiration or ideas for other designers. Machine settings used to produce those samples were also recorded in the library. Unlike in the knitting industry, the reference library established in this research also includes findings of fundamental experiments in stage one, which provided a base for designers to understand dimensional changes of fabrics knitted with different structures or stitches and enable them to adjust knit garment size and fit through altering knitted structures. The reference library combining the design and development process, evaluations and knowledge building constructed an integrated model for creating fully-fashioned and seamless knit garments. Figures 9.3, 9.4, 9.5 provide an in-depth explanation of each phase of the design and development process and a detailed description of the knowledge building and evaluation to support the process. A legend of keys used in model interpretation is presented in Figure 9.2.

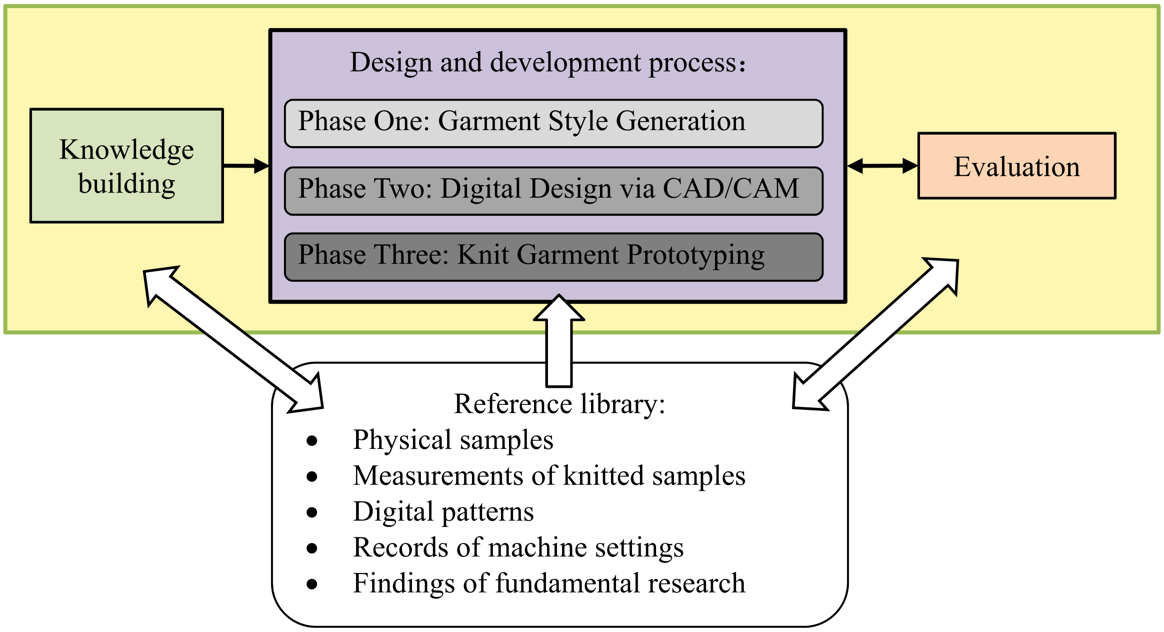


Figure 9.1 Structure of the integrated model

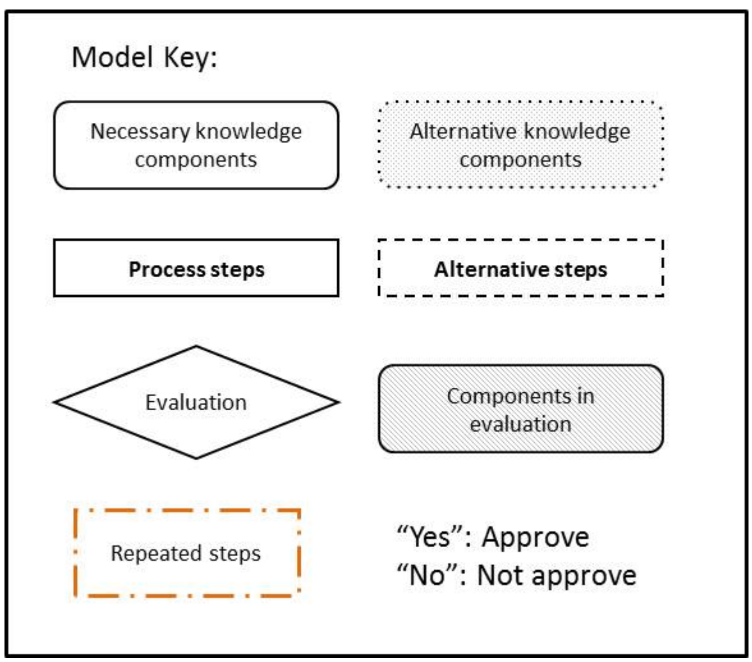


Figure 9.2 Integrated model legend

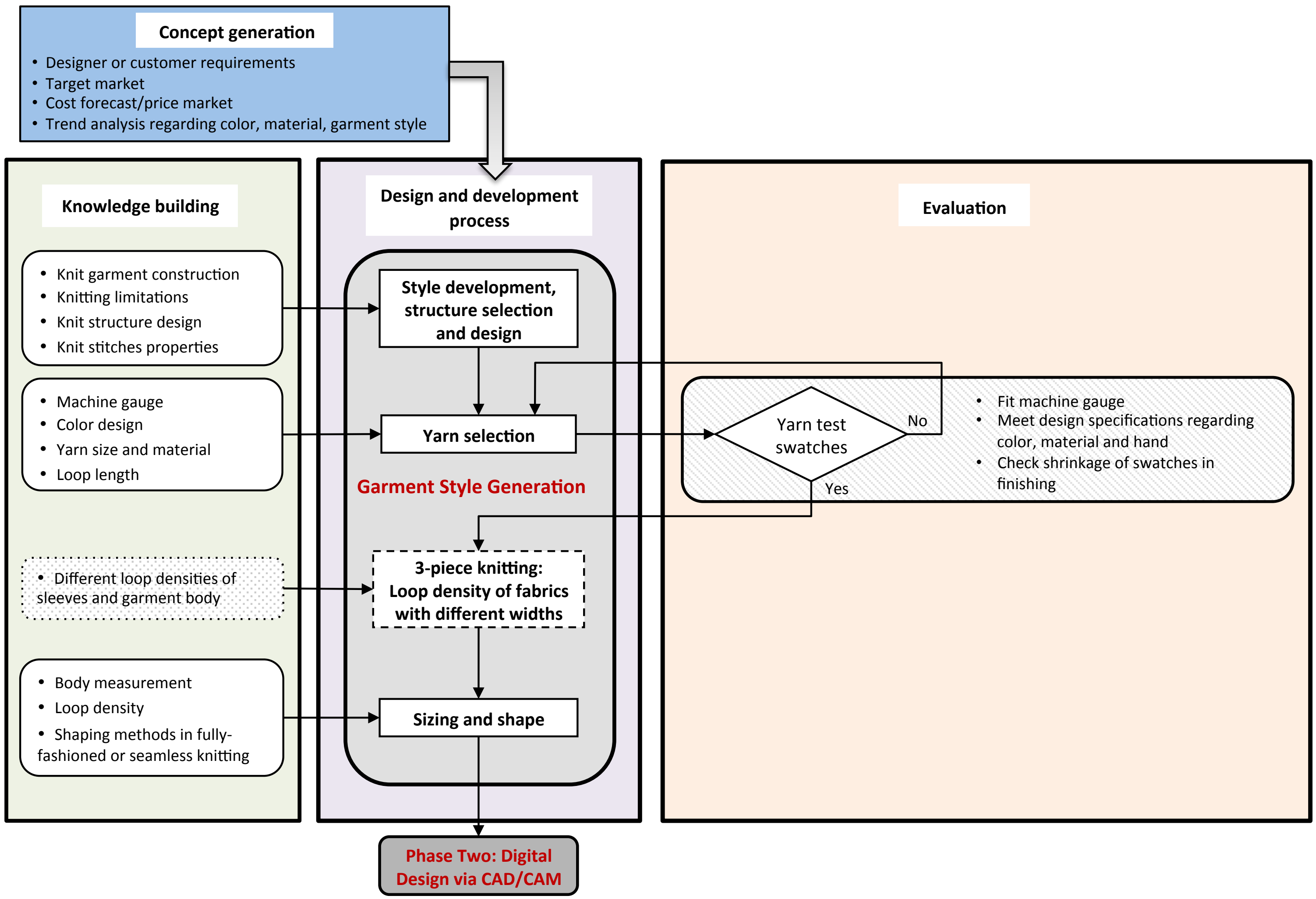


Figure 9.3 Phase one – garment style generation

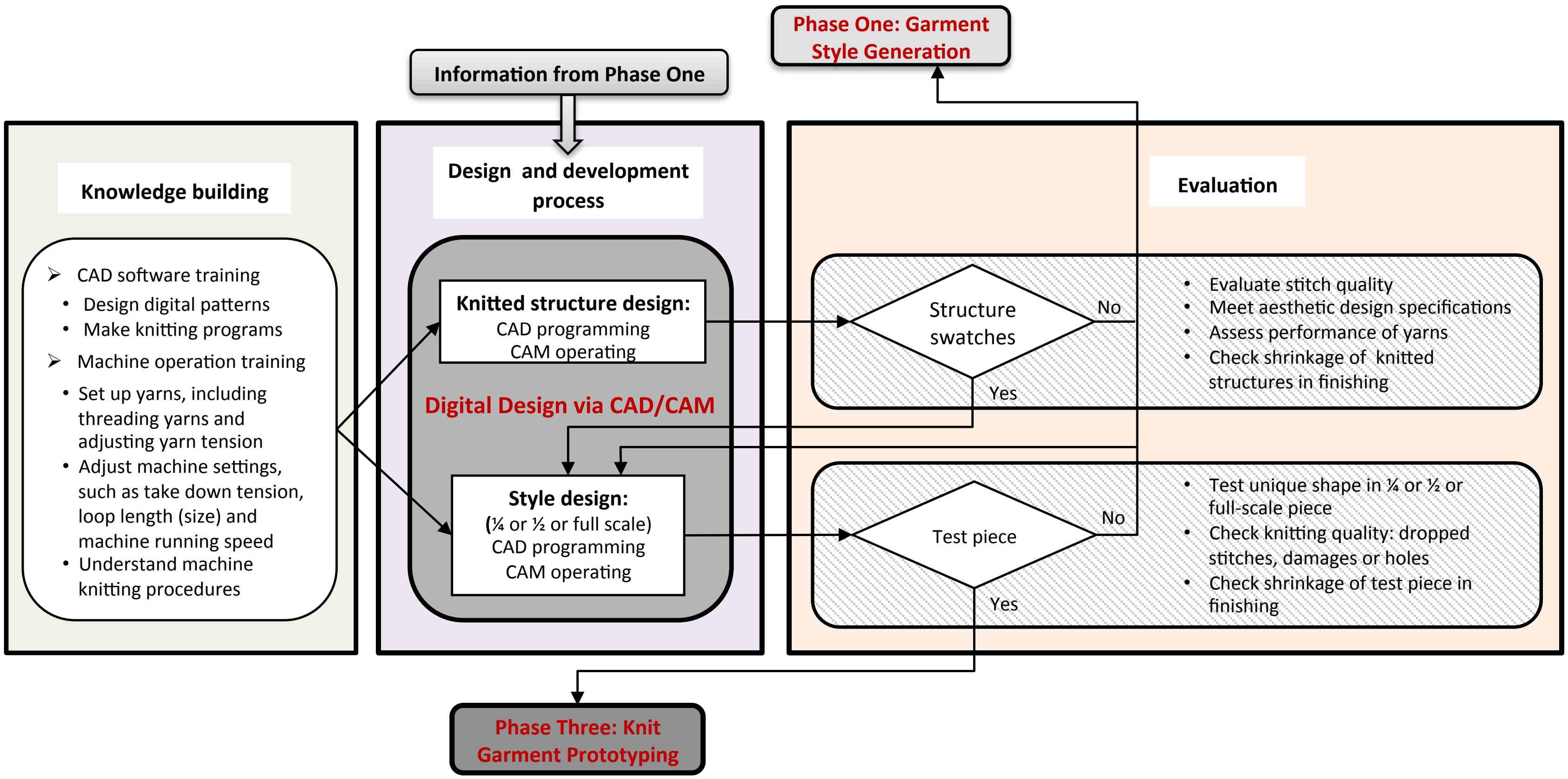


Figure 9.4 Phase two – digital design via CAD/CAM

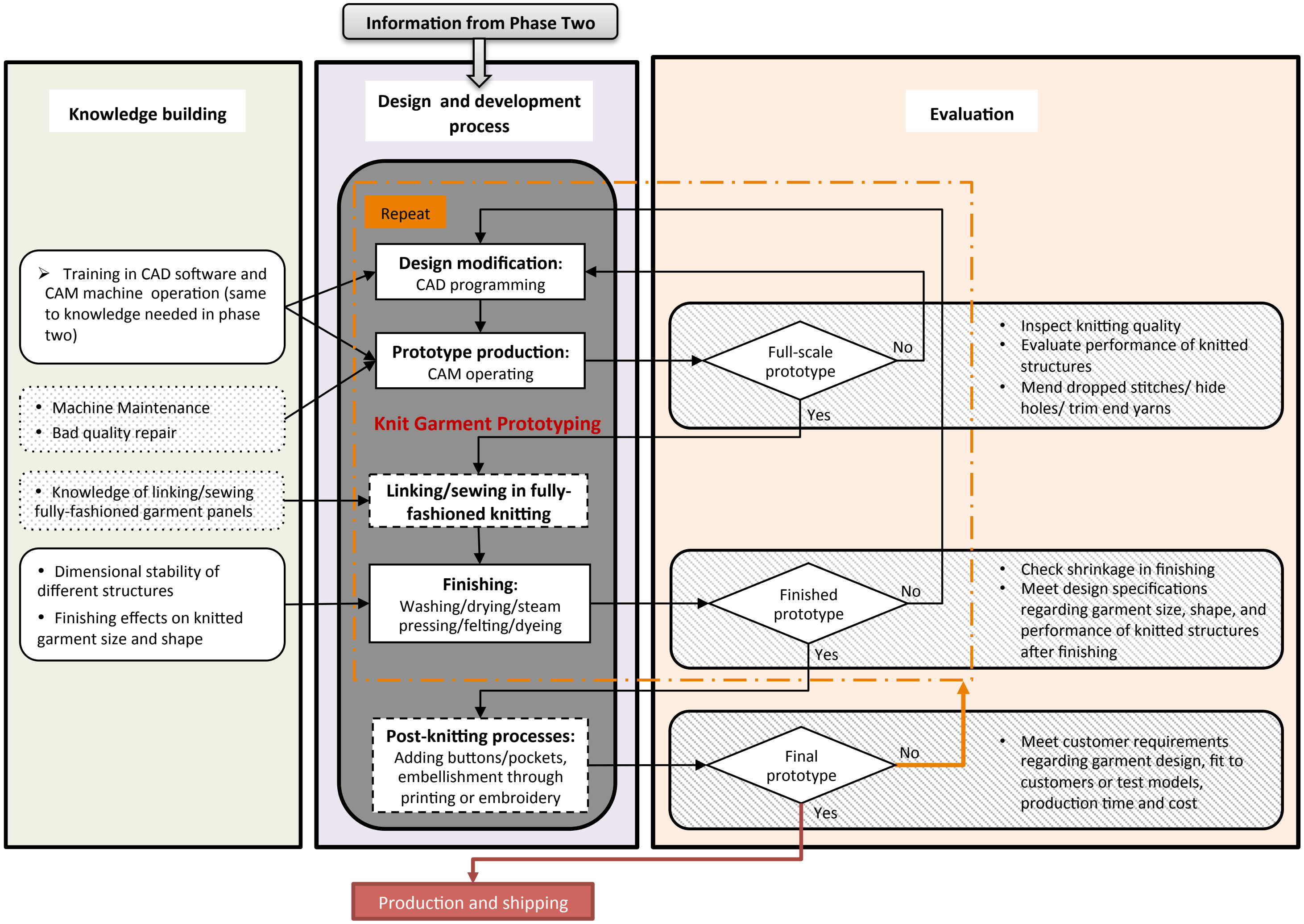


Figure 9.5 Phase three – knit garment prototyping

The model presented in Figures 9.1 – 9.5 incorporates refinements based on the results of model validation work. Those refinements are detailed in the following section.

As shown in Figure 9.3, *concept generation* representing an initiating step prior to design and development of a fully-fashioned or seamless knit garment precedes the model. The addition of *concept generation* was recommended by experts in the interviews to provide visually a context for the model. At this point, the knit garment development team or individual may explore customer requirements, identify target market, forecast cost and price of knit garments and conduct fashion trend analysis to generate initial ideas or concepts of knit garment design, and then move to the first phase of the design and development process.

Phase one, *garment style generation*, is presented in detail in Figure 9.3. The knit garment design and development process begins as designers or development teams accomplish *style development* and *knitted structure selection and design*. According to results of case studies in stages two and three of the research, two tasks are essential in this step: one is to create a draft of garment style, and another task is to create knitted structure design. Style development of fully-fashioned or seamless knit garments differs from cut and sewn apparel design because garment shape is formed on the machine and cannot be changed after production. For this reason, designers need to be familiar with knit garment construction methods and limitations of fully-fashioned and seamless knitting in order to create knittable garment styles. Knitting limitations shown in knowledge building were not identified in the preliminary model, but results of in-depth case studies and expert interviews indicated that they are important knowledge components in supporting the step of style development. Therefore, understanding limitations of fully-fashioned and seamless knitting should be added to knowledge building in the refined model. In knitted structure creation, many designers select existing knitted structures from a reference library, and then alter knitted stitches to generate new structures. *Structure selection and design* seems to be an easy step, but observation of case studies revealed that this step requires skilled designers to know knitting properties of knitted stitches and combination methods in designing novelty structures and their effects on garment shape. *Yarn selection* is important in *garment style generation* because yarn color and material directly determine color, look, and hand of the finished knit garment. The yarn size must fit the machine gauge to meet technical requirements as well. Thus, an understanding of color design, yarn material and yarn size is essential in yarn selection. The selected yarn is evaluated through test swatches knitted with different stitch settings for loop length. In the evaluation, designers verify whether or not the selected yarns fit the machine gauge and meet design specifications. They also assess shrinkage of the test swatches in finishing. Loop length is an important knowledge component that supports designers in evaluating selected yarns. According to results of case studies in stages two and three, designers should know impacts of loop length on look, hand and dimensions of knitted fabrics, so that they can set proper loop length range for yarn swatch knitting and identify an optimal loop length for their design. Additionally, loop density is another essential component in knowledge building in the first phase. According to results of case studies in previous research, loop density of the swatch with preferred knitting results in yarn evaluation is calculated and later applied in the next step of garment *sizing and shape*, but the initial loop density may need to be revised after *knitted structure evaluation* in phase two. Moreover, in seamless knit garment design, loop density calculated in yarn swatch evaluation may be not accurate enough to achieve correct sizing and shape. As explained in the in-depth case studies two and four, the optimal loop density of sleeves and garment body might be different because of varied knitting widths. To improve precision in garment size calculation, *3-piece knitting* can be accomplished before the step of *sizing and shape*, providing accurate loop densities for sleeves and body knitting. Therefore, in the integrated model, an additional step of *3-piece knitting* and the knowledge needed to support it are illustrated with dotted lines. Not all development processes require this step but it can be done when necessary. The last step in phase one is *sizing and shape*. In

CAD knitting systems, garment sizing can be automatically completed through inputting loop density calculated from the previous step and body measurements. Erskine (2012, pp.81) stated in her research, “The user should understand how to accurately specify fabric density and input the number of course and wales per inch into the software.” For garment shapes, designers are able to visually choose a garment shape from the digital pattern library existing in the CAD system, but sometimes designers may want to create unique shapes. At this point, a comprehension of shaping methods in fully-fashioned and seamless knitting is required. Responses of experts in the interview and the results of in-depth case studies demonstrated understanding shaping methods was necessary in supporting accomplishment of garment sizing and shape, so shaping methods in fully-fashioned and seamless knitting are added to the refined model as needed knowledge components.

Phase two as shown in Figure 9.4, translates ideas of knitted structure design and garment style design generated in phase one to digital patterns in CAD systems and then to actual samples. The main purposes of this phase are to assess designed knitted structures and garment style in knitting practice and to prepare reliable digital patterns and knitting information for prototyping in the next phase. Compared to the preliminary model, several additions and modifications are made in the refined model. First, the steps of *knitted structure design* and *style design* are reversed. According to observation of the design and development process in in-depth cases in stage three of the research, accomplishment of *knitted structure design and evaluation* before *garment style design* reduces design time and enhances efficiency, though the steps can be accomplished in either order. Especially when novel knit structures are used; and the design and the garment style are pulled from the pattern library in the CAD system, it is better to evaluate novel structures first and then apply the approved structures in the garment style pattern. In this case, the evaluation of the test garment knitted with novel structures can provide more significant results than a test garment knitted with plain structures. However, when a garment is designed with a special style or shape, possibility of knitting the unique style will be the main concern in the style evaluation, so the test garment can be knitted with plain structures and evaluated separately from a knitted structure design. Another refinement in the integrated model is a loop added between the style design and test piece evaluation. Results of in-depth case studies indicated that a quarter-scale or half-scale test garment was not necessary in most case unless the garment style was very unique or materials used were expensive. Some experts in the interviews also commented on removing ¼ or ½ scale evaluation and adding full-scale evaluation. Hence, in the refined model, the size of test piece knitting for the garment style evaluation can vary among quarter scale, half scale and full scale depending on customer and designer requirements and cost estimation. In most situations, more than one test piece with corrections is knitted until the quarter scale, or half scale or full scale is approved in the evaluation. It is important to note that machine settings and garment size information gathered in style design apply only when knitting a full-scale test piece. This is because machine settings and digital patterns for the full-scale garment significantly differ from smaller scale knitting. For evaluations in phase two, components in the refined model remain almost the same as the preliminary model. The main evaluation components include testing the possibility of knitting novelty structures and unique garment styles, and verifying whether structure samples and style test pieces meet aesthetic and quality requirements. In addition to these, the evaluation quantifies shrinkage in finishing providing useful information for the next phase. Also, in knitted structure evaluation, performance of the yarn selected in the last phase can be assessed again for knitting special knitted structures. According to results of previous research, evaluations occur to determine whether the design moves forward or requires additional work at the previous steps. Designers not only need to identify knitting defects such as dropped stitches, broken needles, improper design or shape, but sufficient knowledge is also required to address these problems. For example, dropped stitches in a test garment often the resulted from the failure to transfer stitches during shaping. An understanding of garment shaping procedures on the machine enables designers or technicians to correct machine settings or adjust the digital pattern in improving knitting quality. This point was not provided in the preliminary model, but the knowledge of machine knitting procedures is indeed necessary, so it is added to the refined model in the knowledge building section. The other refinement in the integrated model is about the knowledge components of CAD/CAM training. Results of case studies in stage two of the research demonstrated that execution of steps in this phase required training in CAD software and CAM machine operation and some knowledge of machine settings. Components of detailed knowledge needed in CAD/CAM training were explored in the in-depth case studies. Results of in-depth case studies indicated that necessary components in CAD software training and machine operation training included digital pattern design, knitting programs, yarn set up and machine settings. These detailed components are consistent with contents of basic training conducted prior to starting knit garment development in each in-depth case study (see section 5.3 in Chapter 5). A need for CAD/CAM training exits as an effective method to get required knowledge, while, the detailed components clarify what knowledge must actually be achieved in training. The refined knowledge components of phase two are shown in Figure 9.4.

Phase three, *knit garment prototyping*, is a process for the first qualified prototype production. In this phase, modifications of the garment pattern are made according to results of evaluations in phase two; then, the modified pattern is knitted into a full-scale prototype. *Prototype evaluation* after knitting the prototype on the machine focuses on knitting quality and whether performance of knitted structures in the full-scale garment meet design requirements. In addition, results of the in-depth case studies and expert interviews specified that a few repairable dropped stitches or small knots could be accepted in the evaluation, but should be mended before moving to the next step. Another refinement in the integrated model is addition of *linking or sewing*. As shown in Figure 9.5, *linking or sewing* is added in the process as an alternative step because this step is only required in developing fully-fashioned knit garments. The next step is *finishing*, which includes washing, drying, and steam pressing, felting of wool, or dyeing when necessary. *Finished prototype evaluation* after finishing is extremely important because it is the last chance to adjust the design before moving to production in the factory. Components of *finished prototype evaluation* include shrinkage in finishing and design requirements regarding garment size, shape and performance of knitted structures after finishing. If the finished prototype doesn't pass this evaluation, it requires revisions to the original design in the step for design modification. Results of case studies in stages two and three of the research demonstrated that several prototypes with corrections were knitted until the last one had no flaws and met all design specifications. Thus, the refined model represents the potential repeat of steps among *design modification*, *prototype production, prototype evaluation, finishing,* and *finished prototype evaluation*. The next step is *post-knitting processes*, which is a new term used to replace the step of *decoration* in the preliminary model. Some *post-knitting processes* noted in expert interviews and observed in case studies are illustrated in the model, such as adding buttons or pockets, and embellishment through printing and embroidery, but they are optional based on designers' requirements. Finally, customers or designers evaluate the production-ready prototype before sending it to manufacturing. Experts in the interviews pointed out that customer or designer evaluations of the final prototype were necessary in determining garment fit, assessing customer requirements and forecasting production cost and time. So the model is modified with an additional step of *final prototype evaluation*. When customers or designers finally approve the prototype, the design and its knitting information can be sent to factories for manufacturing. According to comments from experts in the interviews, additional steps such as *production, labeling, packaging and shipping* will be completed after design and development.

Along with additions and refinements of process steps and components, some terminology changes recommended by experts in the interviews are shown in the refined model. For example, in phase one, the term used to describe yarn evaluation is changed to "yarn test swatches" in order to show directly the purpose of this step and methods of yarn evaluation. Also, in phase three, prototype production is used to replace the step of pre-production in the preliminary model. These terminology refinements do not influence any steps in the development process and will not change the meaning of each component, but they clarify the model and enhance breadth of its application.

10 Summary, conclusions and recommendations

The current research was undertaken to provide guidance to designers or development teams in knitwear design and development using fully-fashioned or seamless knitting technology. A model has been developed that integrates the design and development process with the associated knowledge building and evaluation components, and documents the value of a reference library. This integrated model not only illustrates the process steps from idea generation through garment prototyping, but it also reveals the knowledge needed to support each step and explains evaluation components to correct problems during knitting.

10.1 Summary

The literature review in Chapter 2 revealed that the lack of well-defined knowledge building requirements and inadequate understanding of the development process inhibit implementation of fully-fashioned and seamless knitting technologies in unique knit garment design and development. Insight into these issues was achieved as a result of this research. The preliminary objective of the research was to explore in detail the design and development process for fully-fashioned and seamless knit garments.

The objective was achieved by conducting a three-stage research. Stage one involved fundamental research comprising an understanding of effects of different knitted structures, knitted stitches and course shaping techniques on the shape and dimensions of knitted fabrics or knitted garments. Findings from these fundamental experiments provide a theoretical basis for designers to execute steps of the design and development process, such as knitted structure design, garment sizing and finishing. For example, results obtained in the experiment relating to effects of different knitted structures on knit garment panel size could be further applied to improving knit garment fit and shape.

In stage two of the research, four cases were studied to explore the knit garment development process through participation observation. A result of this investigation was a preliminary model for shaped knit garment design and development that utilized a reference library, and contained knowledge building, design and development process and evaluation components. Findings obtained in stage one of this research, and knitted samples and knitting information collected in stages two and three were organized into a reference library. In the knitting industry, companies build over time their own reference libraries through design archives. Results of case studies in this research indicated that the reference library could provide necessary references for designers to implement design and development. In the model, knowledge needed to support a relevant step was listed in knowledge building, and information needed to make process related decisions was reflected in the evaluation components. Therefore, the integrated model not only described the knit garment design and development process conceptually, but it also discussed in-detail the knowledge needed to complete each stage in the process. Additionally, information gained in the case studies expanded the reference library to support further researchers and designers working in shaped knit garment design and development.

Results of stage three assisted in validating the preliminary through model mapping in five in-depth case studies and interviews with experts in fully-fashioned and seamless knitting. In those in-depth case studies, the researcher, an observer with limited participation, examined whether or not designers were able to complete their knit garments following process steps in the preliminary model. The process steps and knowledge needed in the in-depth level cases were compared with the preliminary model, revealing their similarities and differences so as to validate and modify the established model and identify any opportunities for model refinement. Additionally, results of interviews validated the preliminary model form experts' perspective. Comments from experts and results of the in-depth case studies indicated that the preliminary model generally worked well, but some refinements could enhance the model and broaden its applicability. Participant experts in the interview also expressed opinions that some terms used in the model could be altered to clarify the model. Finally, according to results of stage three in the research, the preliminary model developed in stage two was refined into a comprehensive design and development model.

In summary, much progress has been made in establishing a valid and reliable model and investigating detailed information in the design and development process. Consequently, an integrated model for fully-fashioned and seamless knit garment design and development has been established that encompasses use of a the reference library, knowledge building and evaluation in the context of the detailed fully-fashioned and seamless knit garment design and development process.

10.2 Conclusions

The results of this research contributed to the shaped knit garment design and development knowledge base. The integrated model presented in Chapter 9 provides detailed descriptions of the fully-fashioned or seamless knit garment development process and knowledge building required for executing seamless and fully-fashioned knit garment development. Implementation of this research benefits researchers, individual designers, knitwear development teams and also knitwear companies.

1) Researchers or designers, who are studying or working on fully-fashioned and seamless knit garment development, might be interested in this research. Fundamental knowledge explored in the research and detailed description of the development process can assist designers or researchers in learning advanced fully-fashioned and seamless knitting technology.
2) This model provides a theoretical understanding of shaped knit garment design and development, and clarifies how to accomplish each step and what knowledge is needed in the process. The model allows researchers or designers to visualize the necessary steps and identify challenges and opportunities in design and development.
3) In knitting practice, this model has implications for individual designers and knitwear companies. Because the integrated model contains the design and development steps, as well

as knowledge building and evaluation components, it can be a useful tool in training designers or introducing the knit garment development process.

4) Integration of the process and evaluation steps with knowledge building and a reference library enables one person to complete the entire design and development process. This will overcome communication challenges between aesthetic designers and technicians in knitwear companies. Even when aesthetic design and technical design are undertaken by two different development departments, involvement of knowledge and evaluation components in the model will facilitate communication and collaboration between aesthetic designs and technical designers.

5) This research demonstrates the use and value of an organized and thoroughly documented reference library. In the current research, the reference library not only allowed designers to accomplish efficiently each process step, but it also assisted in learning basic knitting knowledge of fully-fashioned and seamless techniques. In the industry, companies can build their own reference libraries to facilitate their design and product development processes through sample archives developed over time.

6) Analysis of experts' responses was used to validate the model. In addition to validating model steps and scope, experts in the interviews also provided valuable comments for model refinement. Therefore, results of expert interviews demonstrate that interviews with open-ended questions can be an effective method to refine a newly developed model, because participants can bring their personal professional perspectives and expertise to the questions and express their own thoughts without restrictions.

7) In stage three of the research, both responses of experts in the interviews and results of in-depth case studies indicated much of the same information for model validation and refinement. The use of interviews and case study approach together not only increased

confidence that information gathered was reliable, but also each method of model validation brought additional unique perspectives.

10.3 Recommendations for further research

Due to limited time, funding and resources, case study validation of the integrated model developed in the present research was limited to academic projects that were conducted in the academic environment, rather than in industrial practice. Thus, an extension of this research could apply the model to examining validity and usefulness of process steps and model components in knitwear companies. Additionally, the integrated model enables designers or development teams to produce an approved prototype in an effective and efficient process. The advanced seamless knitting technology that creates a complete garment on the machine allows for fast fashion. This means the model for seamless knit garment development could not only be implemented to manufacture mass produced knitwear, but it could also facilitate mass customization in knitwear development. Further research could investigate the application of the integrated model in customized knit garment design and development.

Another opportunity for further research could be implementation of the model developed in the current research for not only knit garments but for creating other types of knitted products using fully-fashioned or seamless knitting technology. The investigators in further research could explore the process steps and knowledge needed in development of other fully-fashioned or seamless knitted textiles based on the integrated model developed in this research. Determining the most efficient components and steps would enhance design and development of other shaped knitted products and facilitate the use of fully-fashioned and seamless technology in the knitting industry.

Furthermore, advanced technologies such as 3D body scanning and 3D virtual simulations have been used to improve garment fit in apparel development, but they are not fully explored in knitwear design. Investigation of using these technologies in fully-fashioned and seamless knit garment design and development would be meaningful and could improve the development process.

Additionally, fundamental experiments conducted in stage one of this research have revealed significant influences of different shaping techniques on knit garment dimensions and shapes, providing a reference for knit garment design and development. However, because of limited time and resources, many potential shaping techniques were not investigated. Additional research is needed to examine the best methods to use those shaping techniques in knit garment sizing and shaping, and further applications of the shaping techniques in creation of other shaped knitted products.

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APPENDICES

Appendix A. Pilot study of yarns

Cotton Yarn	Structures	Loop Length (mm)	Dry Relaxed State		Relaxed State after One Home Laundering Cycle	
			Courses/inch	Wales/inch	Courses/inch	Wales/inch
3 Ends of 14/1 C.C. cotton yarn	Single Jersey	9.50	13.5	10.5	17.0	12.0
		10.00	12.0	10.5	16.0	11.5
		10.50	11.0	10.0	15.0	11.0
	Interlock	9.50	11.5	21.0	14.5	17.0
		10.00	10.5	20.0	13.0	14.0
		10.50	10	19.5	13	13
	2×2 Rib	9.50	18.0	9.5	26.0	7.5
		10.00	16.0	9.0	24.0	6.5
		10.50	15.5	8.5	23	6.5
3 Ends of 16/2 C.C. cotton yarn	Single Jersey	10.50	13.0	9.5	14.0	10.0
		11.00	12.0	9.5	13.5	10.0
		11.50	11.0	9.0	13.0	9.5
	Interlock	10.00	12.0	21.0	13.0	17.0
		10.50	11.0	22.0	12.0	17.0
		11.00	10.5	19.0	12.0	14.0
	2×2 Rib	8.50	16.0	9.5	22.0	8.0
		9.00	16.0	9.0	21.0	7.5
		9.50	16.0	8.5	20.0	7.0
3 Ends of 20/2 C.C. cotton yarn	Single Jersey	10.00	14.0	10.0	16.0	11.0
		10.50	12.5	10.0	15.0	10.0
		11.00	12.0	9.5	14.0	9.5
	Interlock	10.00	12.0	18.0	13.0	16.0
		10.50	11.0	17.5	13.0	15.0
		11.00	10.0	17.5	12.0	14.0
	2×2 Rib	8.00	21.0	8.5	26.0	7.5
		8.50	20.0	8.5	24.0	7.0
		9.00	18.0	8.0	24.0	6.5
	Single Jersey	9.50	13.0	10.0	16.0	11.0
		10.00	12.0	10.0	15.0	10.5
		10.50	11.0	9.5	14.0	10.0
	Interlock	10.00	11.0	21.0	13.0	18.0
		10.50	10.0	21.0	13.0	18.0
		11.00	9.0	20.0	12.5	18.5
	2×2 Rib	9.0	16.0	9.5	20.0	8.0
		9.5	16.0	9.5	20.0	7.5
		10.0	16.0	9.0	20.0	7.0

Appendix B. IRB approval letter for case studies

From: Jennifer Ofstein, IRB Coordinator
North Carolina State University
Institutional Review Board

Date: March 12, 2013

Title: An Integrated Model for Shaped Knit Garment Design and Development

IRB#: 3155

Dear Yanxue,

The research proposal named above has received administrative review and has been approved as exempt from the policy as outlined in the Code of Federal Regulations (Exemption: 46.101. b.2). Provided that the only participation of the subjects is as described in the proposal narrative, this project is exempt from further review.

NOTE:

1. This committee complies with requirements found in Title 45 part 46 of The Code of Federal Regulations. For NCSU projects, the Assurance Number is: FWA00003429.

2. Any changes to the research must be submitted and approved by the IRB prior to implementation.

3. If any unanticipated problems occur, they must be reported to the IRB office within 5 business days.

Please forward a copy of this letter to your faculty sponsor, if applicable.
Thank you.

Sincerely,

Jennifer Ofstein

Jennifer Ofstein
NC State IRB

Appendix C. IRB approval letter for interviews

From: Jennifer Ofstein, IRB Coordinator
North Carolina State University
Institutional Review Board

Date: March 12, 2013

Title: An Integrated Model for Shaped Knit Garment Design and Development

IRB#: 3203

Dear Yanxue,

The research proposal named above has received administrative review and has been approved as exempt from the policy as outlined in the Code of Federal Regulations (Exemption: 46.101. b.2). Provided that the only participation of the subjects is as described in the proposal narrative, this project is exempt from further review.

NOTE:

4. This committee complies with requirements found in Title 45 part 46 of The Code of Federal Regulations. For NCSU projects, the Assurance Number is: FWA00003429.

5. Any changes to the research must be submitted and approved by the IRB prior to implementation.

6. If any unanticipated problems occur, they must be reported to the IRB office within 5 business days.

Please forward a copy of this letter to your faculty sponsor, if applicable.
Thank you.

Sincerely,

Jennifer Ofstein
NC State IRB

Appendix D. Interview instrument

1. Email to request consent for participation

The purpose of this research is to establish an integrated model for creating fully-fashioned or seamless knit garments that incorporates knowledge building, design and development and evaluation. Experts in knitwear design and production, such as yourself, are being asked to assist in validating the model by completing this interview. Results of the interview will become a part of the published dissertation research conducted by Yanxue Ma.

Your participation in this interview is voluntary, and you may end your participation at any time. The information in the interview records will be kept strictly confidential and no reference will be made in published work which will link you to the research.

There is no monetary compensation awarded for participations in this study. However, one benefit of participating in this survey is you will contribute your expertise and experience to an academic work. Additionally, there are no foreseeable risks associated with completing this survey.

If at any time you have questions about your participation, do not hesitate to contact the researchers Yanxue Ma or Traci Lamar at the College of Textiles, Box 8301, NCSU, Raleigh, NC 919-649-0664.

Please reply to this email to confirm that you understand the above and agree to participate in the study.

If you feel you have not been treated according to the descriptions in this email, or your rights as a participant in research have been violated during the course of this project, you may contact Deb Paxton, Regulatory Compliance Administrator, Box 7514, NCSU Campus (919/515-4514).

2. A brief script for phone call and asking permission to record the interview

Hi, I am Yanxue Ma, a graduate student in North Carolina State University. Thank you for participating in the study. In this interview, your basic information and your comments about the attached integrated model will be asked. Could I record our conversation?

3. Basic information

1) Please provide the following contact information. This information will not be viewed by a third party and your private information will be kept confidential.

   Name:

   Company:

   Email Address:

   Phone Number:

2) What is your job title?

3) What are your main responsibilities in your current position?

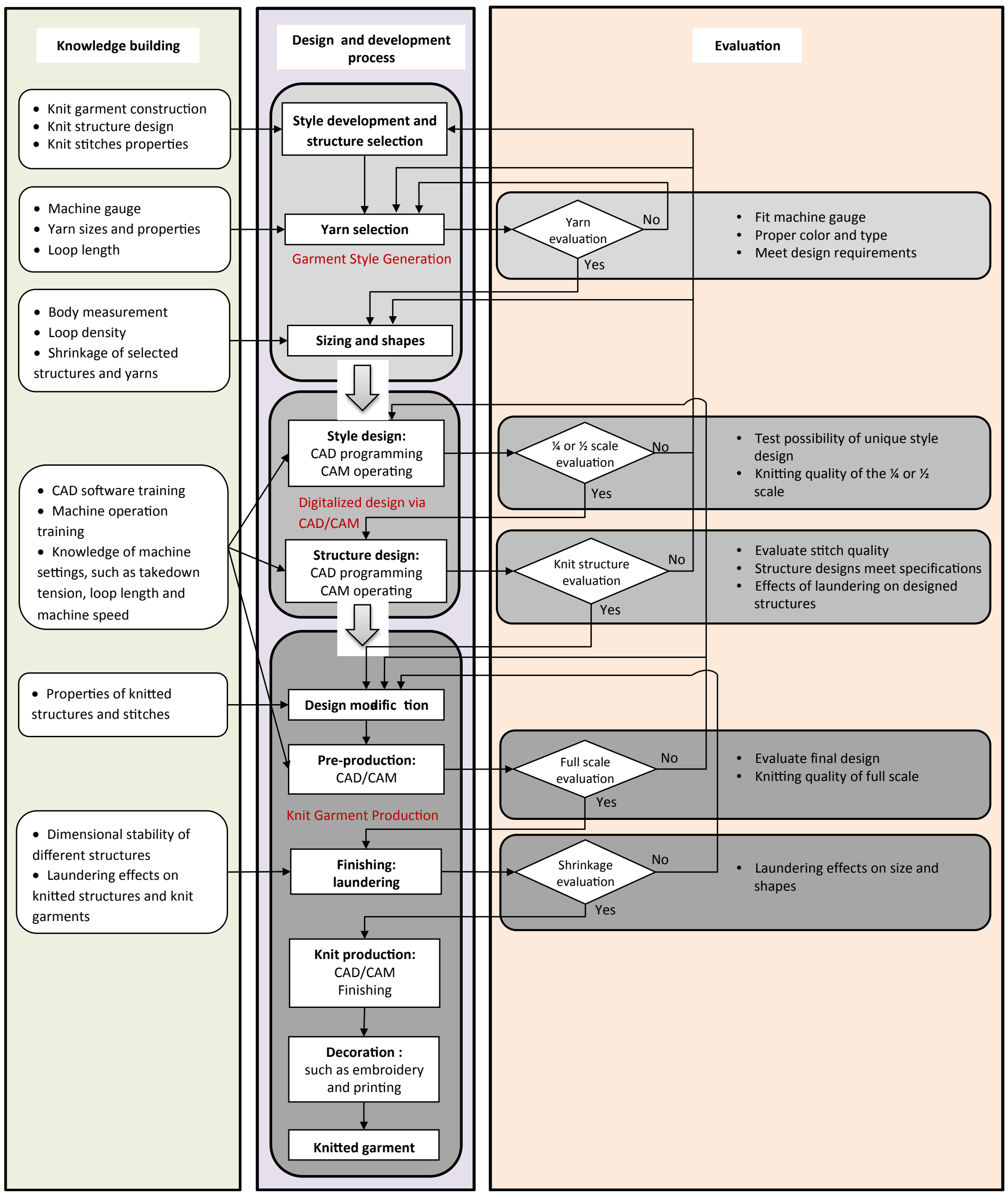
4) What types of knitted products do you design and produce?

5) How many years of experience do you have in knitting or knitted product development?

6) How many hours do you work on knitting or knitted product development per week?

4. Description of the integrated model for shaped knit garment design and development

Researchers established this model via participant observation in design, development and production of knit garments in a multiple case study approach. The integrated model is organized around the design and development process found in the center of the model. Knowledge building and evaluation support each step of the process. Following the steps in the model enables a designer or a product development team to accomplish the entire knitwear development process from style development through production.



5. The objective of this short interview is to validate the attached fully-fashioned or seamless knit garment design and development model. One part of addressing this objective is to verify whether the components in the model are both necessary and sufficient to create fully-fashioned or seamless knit garments.

1) Do you think that the ***design and development process*** captures the steps necessary to design and develop a fully-fashioned or seamless knit garment? If not, please list what additional steps are required or which steps could be omitted.

2) In phase one of the design and development process – garment style generation, do you think the components in ***knowledge building*** are necessary and sufficient to support knit garment development? If not, please list what additional knowledge is required or which components could be omitted.

3) In phase two of the design and development process – digitized design via CAD/CAM, do you think the components in ***knowledge building*** are necessary and sufficient to support knit garment development? If not, please list what additional knowledge is required or which components could be omitted.

4) In phase three of the design and development process – knit garment production, do you think the components in ***knowledge building*** are necessary and sufficient to support knit garment development? If not, please list what additional knowledge is required or which components could be omitted.

5) In phase one of the design and development process – garment style generation, do you think the components in ***evaluation*** are necessary and sufficient to support knit garment development? If not, please list what additional knowledge is required or which components could be omitted.

6) In phase two of the design and development process – digitized design via CAD/CAM, do you think the components in ***evaluation*** are necessary and sufficient to support knit garment development? If not, please list what additional knowledge is required or which components could be omitted.

7) In phase three of the design and development process – knit garment production, do you think the components in evaluation are necessary and sufficient to support knit garment development? If not, please list what additional knowledge is required or which components could be omitted.

8) Do you think knowledge building and evaluation are important to supporting the knit garment design and development process?