

## **ABSTRACT**

CHOI, WONSEOK. The Development of Specialized Knitted Structures in the Creation of Resist Dyed Fabrics and Garments. (Under the direction of Professor Nancy Powell (Co-chair) and Professor William Oxenham (Co-chair)).

It is critical in developing innovative new products to effectively combine and build upon advancing technologies through creative exploration to sustain competitiveness in the global textile industry. Seamless knitting proposes to offer numerous advantages to consumers and producers including better fit, quick turn around time, improved performance characteristics, reduced system costs, reduced labor costs and consistent quality. The investment in and adoption of this new technology does not preclude looking at innovative methods of delivering color in patterns to the knitted garment through a translation of traditional hand dyeing methods to industrial machines. This research focused on exploring and developing resist-dyed structures on knitted fabrics or garments created by computerized seamless-knitting technology. The purpose of this research was to incorporate the advanced technology of electronic knitting to newly interpret traditional resist dyeing effects.

McIntyre and Daniels defined resist as “a substance applied to a substrate to prevent the uptake or fixation of a dye in a subsequent operation” (1997, p. 276). Resist dyeing techniques have been traditionally created by numerous ways around the world, such as wax resist, tied resist and pattern-dyed indigo. This research examined a variety of three-dimensional knitted structures for resist designs duplicating traditional methods of stitching, binding, or folding to gather or pleat the fabric through electronic knitting systems. The research resulted in the discovery that different knit structure variables including float length, course distance, and placement of gathering threads have a

significant relationship with the resist dyed image. In addition, the research studies found that different types of yarn applications resulted in various knitted resist patterns. This research also explored the possibilities of various complex three-dimensional structures created by computerized flat V-bed knitting machines that affected the resist-dyed images. The ability to control multi-colored patterns in simple and complex knitted fabrics and garments through knitted resist structures and piece dyeing will be of interest to industry, academicians, and designers.

**THE DEVELOPMENT OF SPECIALIZED KNITTED STRUCTURES  
IN THE CREATION OF RESIST-DYED FABRICS AND GARMENTS**

**BY  
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# DEDICATION

*To my parents and three sisters  
for all their faith, support and encouragement*

# **BIOGRAPHY**

Wonseok Choi was born in Daegu, South Korea on April 23, 1972. He spent most of his life in Korea before he went to study in the US. He received his bachelor of the Textile Engineering at SungKyunKwan University, in Korea in 1997. Then, he transferred to Iowa State University and completed another bachelor of Apparel Merchandising in College of Human Sciences, at Iowa State University in 1999. Wonseok continued his studies and finished Master's degree of Textile Design, in School of Engineering & Textiles, at Philadelphia University in 2002. In 2003, he started his Doctoral degree in Textile Technology Management, at North Carolina State University.

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# Chapter 1. INTRODUCTION

In order to sustain competitiveness in the textile and apparel industry, it is critical to develop innovative products which effectively combine and build upon advancing technologies through creative exploration. It is reported by the industry that seamless knitting, as a new process, has been developed and continuously improved since it provides numerous advantages such as higher productivity and lower costs to manufacturers and higher benefits to customers. Seamless production has gradually become a key issue in the current textile and apparel industry.

A seam, according to Glock and Kunz (2000), is a series of stitches utilized to join two or more pieces of fabric together. Seams play an important role in producing a garment since they determine garment quality, performance, and costs (Glock & Kunz, 2000). Sewing is the most dominant process for making seams. The increasing speed of sewing a garment and its contribution or relationship to lower costs is a critical issue in the textile and apparel industry. However, eliminating the cutting and sewing step in the assembling process has the potential for improvements in time to market, costs and fit (Birnbaum, 2000). Hence, the desire for “seamless” is increasingly being fulfilled in the textile and apparel industry. Anderson (2004) mentioned five reasons for minimizing or eliminating stitches:

- Cutting and sewing is the most labor intensive step in the formation of a product.
- There is a concentration of stress at seam locations, which jeopardizes performance properties and ultimately results in premature product failure.
- Cutting and sewing are performed manually introducing the potential for human error.
- The sewing process can create small holes in the fabric as well as damage the yarn.
- Fabric scraps produced from the cutting-and-sew process are discarded resulting in fabric waste.

Source: Issacs, M. (2005). Seamless: Eliminating Stitches-More than a Buzzword. *AATCC Review*, 5(11), p. 16-19.

- Seam allowance, which is the distance from the seam edge to the needle hole (Solinger, 1980), requires additional fabric. Seam allowance also may need to be serged or overlocked which may increase production costs.

Several technologies eliminating stitches involve the use of adhesives, seamless garment knitting, braiding to shape, and weaving to shape (Issacs, 2005). Seamless garment knitting, which creates a complete garment with minimal or no cutting and sewing processes, is considered to be one of the most vital techniques in the current knitting industry providing several advantages. Numerous manufacturers have produced seamless garment knitting machinery, including weft and warp knitting machines. Furthermore, more apparel and textile companies have endeavored to apply the new advanced techniques to reduce production time and costs.

Most knitted garments are colored to meet customers' preferences for the latest fashion trends. The coloration of knitted garments can be created through yarn dyeing or

piece/garment dyeing. In order to make multi-colored patterns on knitted garments, various techniques can be used such as knitting with several different colored yarns, multi-colored garment printing, or multi-colored piece/garment dyeing. However, the multi-colored patterning created on knitting machinery has structural limitations including the number of colors and type of patterning. A printing or dyeing technique may be a solution to enhance or extend beyond the knitted structural limitations.

Resist dyeing, a specialist dyeing method, has been recognized as a unique design technique. Resist dyeing can be defined as using “a substance applied to a substrate to prevent the uptake or fixation of a dye in a subsequent operation” (McIntyre & Daniels, 1997, p. 276). Resist dyeing has been historically created in many ways throughout the world, such as wax resist, tied resist, pattern-dyed indigo and shibori (Bosence, 1985). Shibori is the Japanese term for varied methods of embellishing textiles by shaping a fabric and securing it before dyeing (Wada, Rice & Barton, 1999). Shibori is utilized to create a variety of color patterns on a fabric by means of a resist-dyed technique. However, most shibori techniques have been created on woven fabrics; and gathering yarns, required to pull up the fabric for resist dyeing, have been sewn into the fabric and manipulated by hand. This research focuses on exploring the resist-dyed (shibori) patterns using structures in single-jersey knitted fabrics created by computerized seamless knitting technology.

This research into the combining of the resist-dyed technique and seamless knitting is initiated by examining the traditional methods and looking at the possibilities of appropriate knit structures and yarn applications required for resist dyeing. It also evaluates color penetration and surface texture in different shibori-knitted structures. By

use of the advanced knitting technology, a production of a seamless-knitted and resist-dyed whole garment also can be considered. Furthermore, a new product development process for seamless-knitted and resist-dyed technique as a new product or a new method is explained. Thus, the objective of this research is to give a new interpretation to traditional resist dyeing methods by incorporating seamless knitting technology.

## **1.1. Objectives**

The objectives of this research are to:

1. explore current seamless knitting technology on flat V-bed machines and evaluate a new possibility for this advanced technology; and
2. review traditional resist dyeing methods and combine resist dyeing procedures with seamless knitting technology. These include:
  - a. evaluation of the possibilities of knit structures appropriate for resist dyeing, and
  - b. analysis of the color entropy (randomness), color contrast and color coverage in different knitted resist structures, and
  - c. examination of different types of yarn applications to create knitted resist-dyed patterns, and
  - d. exploration of more complicated resist textural patterns created on flat V-bed knitting machines, and
3. consider the possibility of shibori knitting for complete garments.

This research has implications for researchers, designers and industrial personnel, who require information on three-dimensional knitting technology, resist dyeing technique and its application as a new product development (NPD) process in the textile and apparel field.

## **Chapter 2. LITERATURE REVIEW**

### **2.1. Three-Dimensional Seamless Knitting**

#### **2.1.1. Definition**

Knitting, defined by Brown (1973), is the process of forming a fabric by the intermeshing of loops of yarn. Knitting accounts for more than 30% of total fabric production worldwide (Millington, 1996). The end uses of knitted fabrics, created either in tubular or flat form, include apparel and other products such as sweaters, outerwear, underwear, hosiery, lace, socks, stockings, curtains and automotive seat covers.

Knitting is classified into two general types, weft knitting and warp knitting. In weft knitting, loops are formed in a horizontal direction whereas in warp knitting, loop formation takes place in a vertical direction (Wilson, 2001, see Figures 2.1 and 2.2). Weft knitting is more resilient and more open compared to warp knitting. Conversely, warp knitting has less resilience, more coverage and lighter weight. Weft knitting can be also divided into circular knitting and flat knitting according to the type of fabric, type of needle, and form of needle bed. In a circular knitting machine, needles are set radially or parallel in one or more circular beds. On the other hand, a flat knitting machine employs straight needle beds carrying independently operated needles, which are typically of the latch type (Denton & Daniels, 2002).

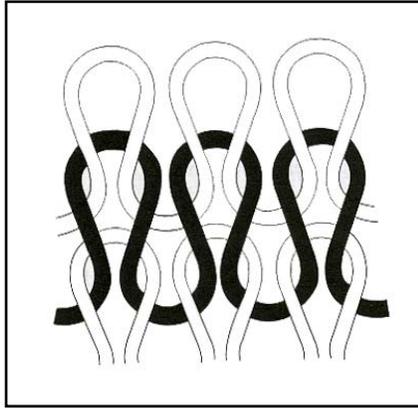


Figure 2.1 Weft knitting.

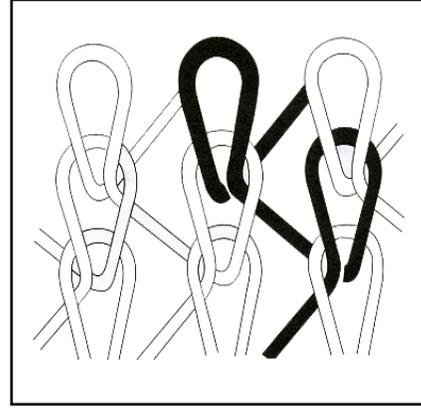


Figure 2.2 Warp knitting.

Source : Wilson, J. (2001). *Handbook of Textile Design*. Cambridge: Woodhead Publishing Limited, p. 93-94.

Compared to flat weft knitting machines, circular weft knitting machines provide higher productivity. However, flat knitting machines have greater versatility in loop structure combinations and patterning since their machine cams can be changed after every course (even every loop) and they are able to knit one or both beds easily (Young, 1985). It should also be noted that electronic circular machines, which employ a computer-controlled electronic needle selection system, have the same capability.

Flat bed machines have four different classes; (i) *V-bed machines* which have two inverted V-formed needle beds; (ii) *Purl machines* which have double ended needles; (iii) machines that have *a single bed* of needles which include most domestic models and a few hand manipulated Intarsia<sup>1</sup> machines; and (iv) *the uni-directional multi-carriage machines* (Spencer, 1989). Category (ii) and (iv) should be regarded as specialist or minority usage. Figure 2.3 depicts a knitting classification diagram for machinery, and Table 2.1 describes a comparison of the major knitting machinery. This research focuses on knitting (especially, seamless garment knitting) on flat V-bed machines, which offer diverse knitting structural possibilities by use of electronic selection systems.

<sup>1</sup> Intarsia: Intarsia is a technique of producing flat knit fabric with patterns knitted in solid colors (or textures), so that both sides of the intarsia fabric are equal (Tortora & Merkel, 1996).

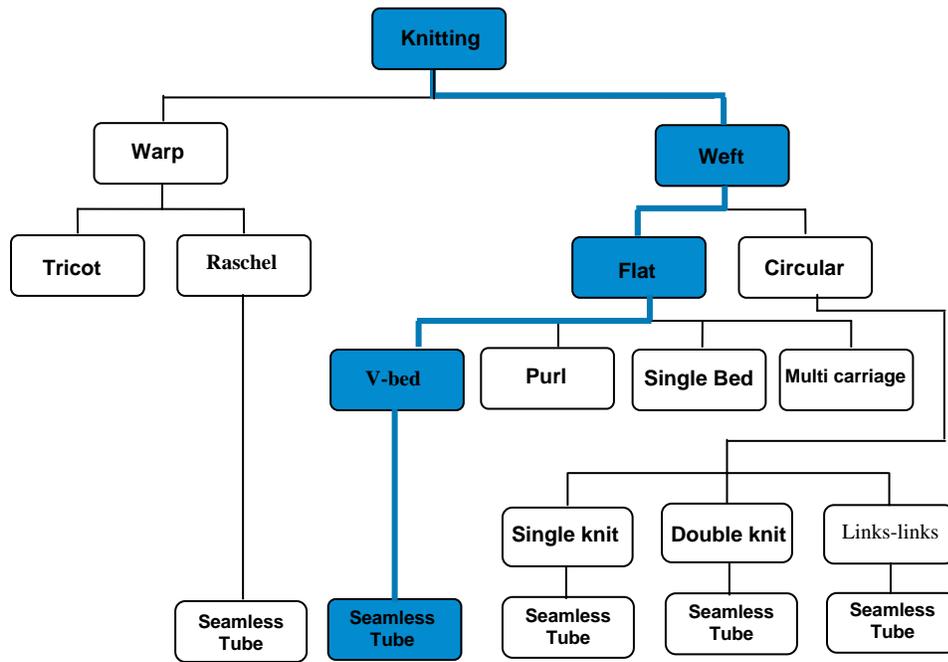


Figure 2.3 A knitting classification diagram for machinery type.

Table 2.1 Comparison of knitting machinery

Knitting classification for machines	Knitting						
	Weft knitting					Warp knitting	
	Flat		Circular			Tricot	Raschel
	V-bed	Single bed	Single knit	Double knit	Links-links <sup>2</sup>		
Format	Open width or tubular	Open width	Tubular	Tubular	Tubular	Open width	Open width or tubular
Needles	Latch or compound	Latch	Latch	Latch	Double sided latch	Bearded or compound	Latch or compound
Sets of needles	Two sets (Front and back beds)	One set	One set	Two sets (Cylinder and Dial)	Two sets (Two cylinders)	One set	One set or two sets
Yarn feed	Individual package	Individual package	Individual package	Individual package	Individual package	Beam	Beam
Movement of needles	Sequential	Sequential	Sequential	Sequential	Sequential	Together	Together
Approximate range of gauge used in the industry	3-18	-	4-54	4-32	5-12	8-44	1-56
Fabric formation	Horizontal direction	Horizontal direction	Horizontal direction	Horizontal direction	Horizontal direction	Vertical direction	Vertical direction
Yarns utilized	Spun or filament	Spun or filament	Spun, filament or spandex	Spun, filament or spandex	Spun, filament or spandex	Filament, usually spandex	Spun, filament or spandex
Typical end uses	Sweaters	Apparel	Hosiery	Fleece	Swimwear, lady's innerwear	Underwear, swimwear, lingerie	Lace, curtains, automotives, medical textile

Source used :

Tou, N. (2005). *An Investigation of Arcing in Two Structure Weft Knit Fabrics*. Personal Communication with Smith, G. Masters Thesis, North Carolina State University, p. 13.

<sup>2</sup>Links-links: Links-links structure is basically composed of front loops and rear loops in different courses. Thus, it is applied to purl structures.

### 2.1.2. Weft Knit Fabric Notations

Table 2.2 demonstrates the basic loop notations for weft knit fabrics. The fundamental loops for weft knitting are composed of three types of loop formation, which are knit loop, tuck loop, and float loop (see Figure 2.4). A knit loop is formed when a needle receives a new yarn and knocks over<sup>3</sup> the old loop. A tuck loop is produced when a needle receives a new yarn, but does not knock over the old yarn which forms a held loop. A float loop is accomplished when a needle is presented a yarn but does not grasp it, thus it displays the missed yarn as a float on the back side of the held loop.

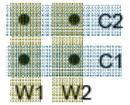
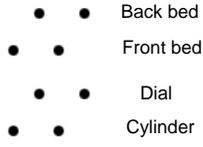
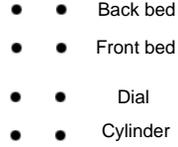
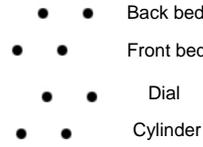
A course is a horizontal row of loops produced by adjoining needles in one needle bed. On the other hand, a wale is a vertical column of loops created by each needle (Spencer, 2001).

In weft knitting machinery, the single jersey machine produces a single jersey fabric on one needle bed such as a latch needle cylinder on circular knitting machines. On the other hand, a rib machine can produce more diverse knit fabrics by the use of two needle beds such as a dial and a cylinder on circular knitting machines or a front bed and back bed of needles on a V-bed machine. Needles may be aligned with the needles in the opposite bed. Machines can use two different gaiting systems; interlock gaiting and rib gaiting. In interlock gaiting, the needles are positioned in two beds exactly opposite each other. In rib gaiting, “the alternate alignment of one set of needles with the other on a machine is equipped with two sets of needles arranged to knit rib fabrics” (Tubbs & Daniels, 1991, p. 133) and needles are offset.

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<sup>3</sup>Knock-over: “The action of casting off the previously formed loop over the head of the needle to mesh with the newly formed loop” (Denton & Daniels, 2002, p. 186).

Table 2.2 Weft knit fabric notations

Loop notation	Term	Loop notation	Term
	Knit loop (face)		Knit loop (rear)
	Tuck loop (face)		Tuck loop (rear)
	Float loop (face)		Float loop (rear)
	Courses :  Wales : 		
	Single jersey machines		Rib machines
	Interlock gaiting		Rib gaiting

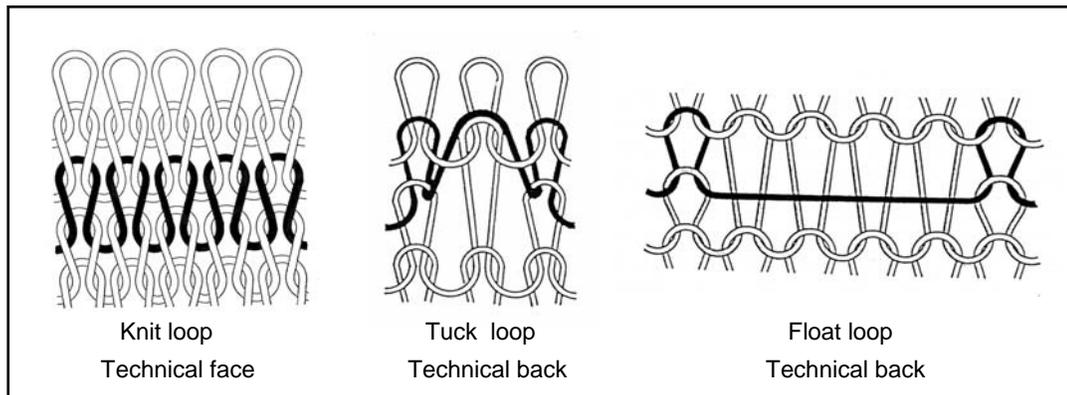


Figure 2.4 Knit, tuck and float loop.

Source: Spencer, D. (2001). *Knitting Technology, a Comprehensive Handbook and Practical Guide* (3rd ed.). Cambridge: Woodhead Publishing Limited, p. 95, p. 97.

### 2.1.3. Knitting Systems on V-bed Machines

To create a tubular knit fabric on a flat knitting machine, two sets of needle beds in a “V” formation are required. It is necessary to understand fundamental knitting systems on V-bed machines to comprehend complete garment knitting systems. In this section, several crucial knitting systems on V-bed machines are introduced. Spencer (1989) defined cams as “the devices which convert the rotary machine drive into suitable reciprocating action for the needles” (p. 26). Figure 2.5 shows the knitting action of latch needles for the cam track on a V-bed knitting machine. According to the position of needle butts moving up and down through the cam system, the loop can be formed sequentially (Raz, 1991).

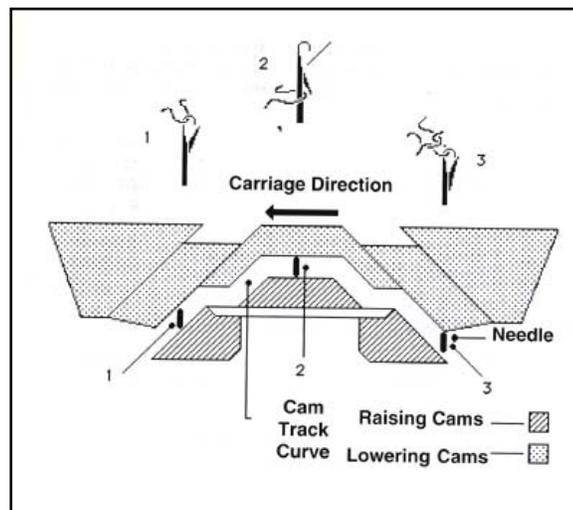


Figure 2.5 Knitting action of latch needle through cam track.

Source: Raz, S. (1991). *Flat Knitting : The New Generation*. Germany: Meisenbach Bamberg, p. 35.

Figures 2.6 and 2.7 illustrate the basic knitting machine parts on a flat bed machine including a carriage, latch needles, sinkers, brushes, yarn carriers and take down rollers. A carriage that has cam boxes travels along the beds forcing the needle butts in its way to follow the curved shape of the cam (Raz, 1991).

The latch needle, the most widely used needle in weft knitting, is mainly composed of a needle hook, a latch, and a needle stem (see Figure 2.8). The major advantage of the latch needle is that it self acts or controls the loop so that individual movement and control of the needle permits loop selection to be accomplished (Spencer, 1989). The sinker is another primary element in knitting. The main purposes of the sinkers are loop formation, holding down, and knocking-over (Spencer, 1989). However, the role of sinkers on a V-bed knitting machine with latch needles is predominantly a holding down function. Thus, holding down sinkers are capable of tighter fabric structures with an improved appearance. The purpose of the brushes is to open the latches at the first course when the machine starts to knit and to avoid any closing of the latches (Maison, 1979). The yarn carrier or yarn feeder is pulled along the needle bed by the carriage and both introduce and feed yarns required for knitting. The yarn carrier is assembled on a dovetail profiled rail (Raz, 1991). Take down rollers are needed to prevent the previous loop, which is located in the hook enclosure, from riding up with the needle ascension. This is critical for loop formation because the previous loop will not slide under the latches and new loops will not be formed without the operation of the take down rollers (Raz, 1991).

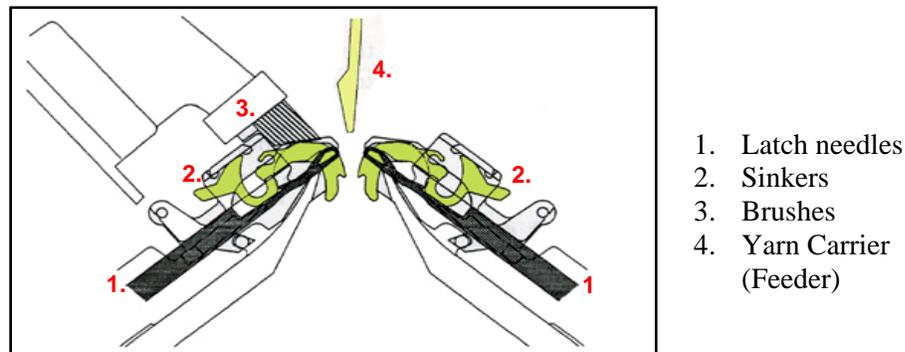


Figure 2.6 Knitting machine systems on flat V-bed machine.

Source: Shima Seiki. (2004). *Shima Seiki Instruction Manual – Shimatronic WholeGarment® Machine SWG-V*. Wakayama, Japan, p. 1-4.

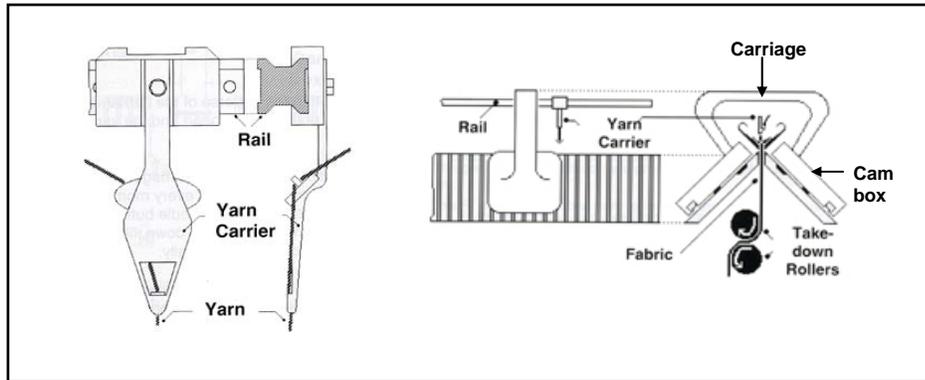


Figure 2.7 Yarn carriers, carriage and take-down rollers.

Source: Raz, S. (1991). *Flat Knitting : The New Generation*. Germany: Meisenbach Bamberg, p. 36-37.

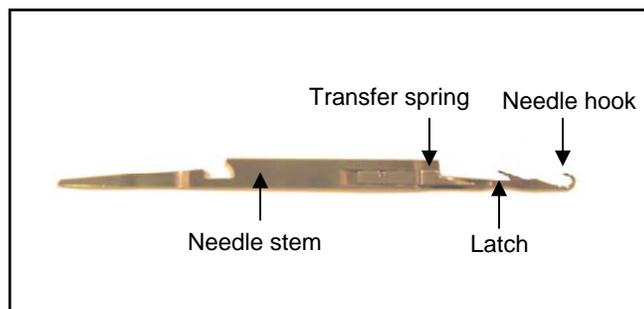


Figure 2.8 A latch needle on Shima Seiki machine.

#### 2.1.4. Historical Events Contributing to the Development of Seamless Knitting

Kadolph and Langford (1998) explained that historical remnants of knit fabrics have been dated from A.D. 250 in the Palestine area. Knitting was accomplished by a hand process until 1589, when William Lee in England invented the first flat-bed weft knitting machine to create hosiery (Shinn, 1976). Interestingly, the fundamental technology of the current knitting machinery is comparable to Lee's machine (Shaikh, 2005). The first operational V-bed flat knitting machine using latch needles was invented in 1863 by Issac W. Lamb (Raz, 1991). William Cotton of Loughborough obtained a patent between 1846 and 1864 for his rotary-driven machine that used a flat bed to

produce fully-fashioned knitted flat pieces (Spencer, 2001). According to Hunter (2004c), in the 1800's, the flat knitting machine was fitted with sinkers which controlled loops in order to knit single jersey tubular articles such as gloves, socks and berets. In 1940, the manufacture of shaped knitted skirts was patented in the USA. This permitted darting on knitted skirts using a technique called "Flechage", which conducts two or three dimensional course-shaping knitting (see Figure 2.9). The flechage technique not only improved drape and fit, but cut production cost by shaping knitting. In 1955, the Hosiery Trade Journal reported on the automatic knitting of traditional berets through the shaping of components.



Figure 2.9 A beret created by shaping knitting.



Figure 2.10 A seamless glove created on the Shima Seiki machine at Polygenex Inc. (2004).

Source: Simmons, J. L. (1998). *French Beret*. Retrieved February 18, 2006, from [http://www2.datasync.com/orion/french\\_beret.htm](http://www2.datasync.com/orion/french_beret.htm) (for Figure 2.9).

In the 1960's, the Shima Seiki Company further explored the tubular-type knitting principle on flat bed machines commercially to produce gloves (see Figure 2.10). By using a flat knitting device including a pair of front and back needle beds, each finger is knitted in turn from its tip, with its loops then being held until the palm sequence begins

(Spencer, 2001). Also, in the 1960's, engineers at Courtaulds in the UK established British patents for the idea of producing garments by joining tube knitting; however, the method was too advanced to be commercialized at that time. By 1995, Shima Seiki had fully developed shaped seamless knitting (Hunter, 2004c). In the 2000's, by employing more advanced computerized systems, simplified programming was possible, and the computerized systems facilitated the production of more complicated and sophisticated knitted structures and products. The history of seamless knitting can be seen in Table 2.3.

Seamless entire garment knitting was introduced in 1995, at ITMA-E, the International Textile Machinery Association – Exhibition (Millington, 1996). Many researchers (Hunter, 2004; Legner, 2003; Mowbray, 2004) stated that seamless knitting or complete knitting, which produces one complete garment without a sewing or linking process, provided a variety of advantages in knitting production such as savings in cost and time, higher productivity, consistent product quality, quick response production and other advantages. However, it is also noted that seamless knitting has disadvantages such as cost of capital investment, and relatively complex and difficult machine operation including takedown tension compared to fully-fashioned knitting. Seamless knitting can be accomplished both by circular knitting machines and flat (V-bed) knitting machines. It will be important to understand principles, machines, technologies, and characteristics of complete garment knitting on V-bed flat knitting machines to complete this research.

Table 2.3 Events contributing to development of seamless knitting on V-bed machines

Year	Historical Events Contributing to Development of Seamless Knitting
1589	William Lee in England invented the first flat-bed frame to create hosiery.
1863	Issac W. Lamb invented the first operational V-bed flat knitting machine including the latch needles.
1864	William Cotton of Loughborough patented his rotary-driven machine that used a flat bed to produce fully-fashioned garments
1800's	The flat knitting machine was fitted with sinkers which controlled stitches in order to knit single jersey tubular articles such as gloves, socks and berets.
1940	The manufacture of shaped knitted skirts using a "flechage" technique was patented in the USA.
1955	The Hosiery Trade Journal reported on the automatic knitting of traditional berets through shaped sections.
1960's	Shima Seiki company further explored the tubular-type knitting principle to produce gloves commercially.
1960's	Courtaulds established British patents for producing garments by joining tube knitting.
1995	Shima Seiki introduced seamless entire garment knitting at ITMA.

### 2.1.5. Cut and Sew Production to Seamless Garment Knitting

The knitting industry has gradually developed through the ages since William Lee of Calverton successfully converted the actions of hand knitting with two needles into a mechanical process. Lee's work was the first attempt at mechanizing hosiery knitting in 1589. Since the invention of the frame knitting machine, knitting technology has progressed from hand flat machines to complete garment knitting machines. Section 2.1.5 explains the evolution of the knitting process from cut and sew production to seamless knitting. It will also explain how knitwear is produced.

## 1) Cut and Sew Production

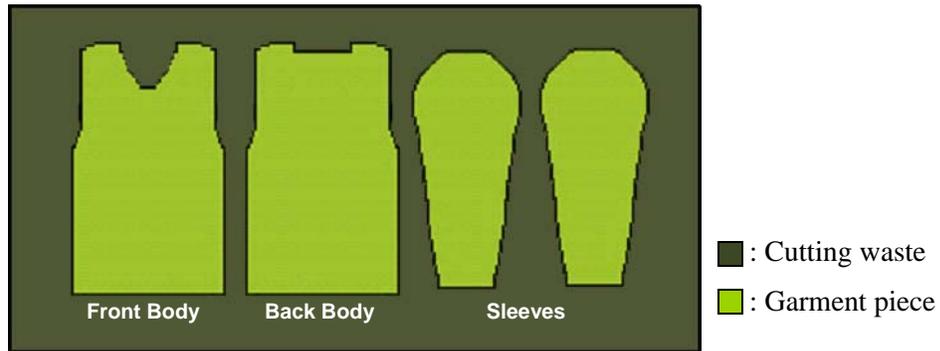


Figure 2.11 Cut and sew production.

Cut and sew production utilizes one entire panel of fabric. Figure 2.11 illustrates the cutting layout for the front and rear body portions and also the sleeve portions required to create a sweater. Through a cutting and sewing process, the garment can be assembled. However, this garment production process requires several post knitting processes beyond cutting and sewing. Moreover, in this process, separately knitted trimmings and pockets need to be attached. According to the Shima Seiki Company (2004), up to 40% of the original fabric can be wasted with a cut and sew process. However, advanced fabric cutting systems including laser cutters and sewing systems have been also developed to shorten the time to market in current industry.

## 2) Fully-Fashioning

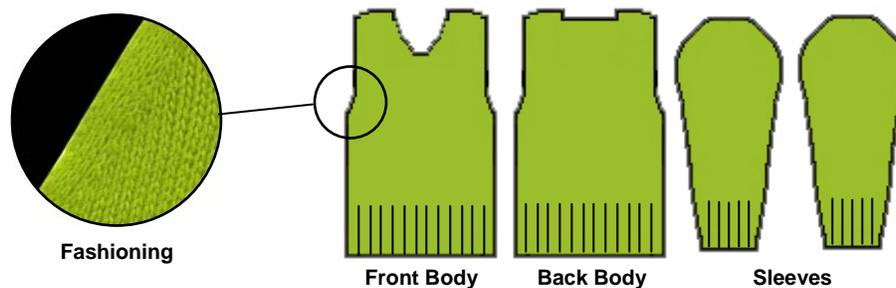
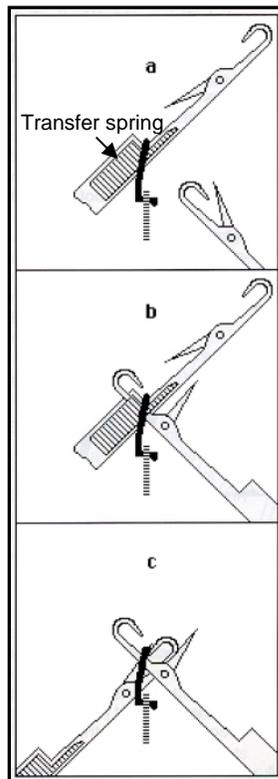


Figure 2.12 Fully-fashioning production.

Fully-fashioned knitting means “shaped wholly or in part by widening or narrowing of piece of fabric by loop transference in order to increase or decrease the number of wales” (Denton et al., 2002, p. 308). Thus, as the number of loops are increased or decreased, the fabric can form shaped areas. To achieve fully-fashioned knitting, loop transference is necessary. The loop transference is the process that moves loops from the needles on which they were made to other needles (Tubbs & Daniels, 1991). Figure 2.13 illustrates the mechanism of loop transference on a V-bed flat knitting machine.



a. The delivering needle is raised by a cam in the carriage. The loop is stretched over the transfer spring.

b. The receiving needle is raised slightly from its needle bed. The receiving needle enters the transfer spring of delivering needle and penetrates the loop that will be transferred.

c. The delivering needle retreats leaving the loop on the receiving needle. The transfer spring opens to permits the receiving needle to move back from its closure. Finally, loop transference is completed.

Figure 2.13 Mechanism of loop transference on V-bed flat knitting machine.

Source: Raz, S. (1991). *Flat Knitting : The New Generation*. Germany: Meisenbach Bamberg, p. 62.

In addition, the loop notation in Figure 2.15 describes how widening or narrowing occurs by loop transference on fully-fashioned machines. The fully-fashioning process allows the separate creation of shaped front and back body parts and sleeve parts by increasing or decreasing the number of loops; this eliminates the cutting operation. However, since all parts of the garment are knitted separately, fully-fashioned knitting still requires a post sewing or linking<sup>4</sup> process.

In order to increase the productivity, flat-machine suppliers have introduced multi-piece fully-fashioned knitting (see Figure 2.14). According to Stoll (2004), in the multi-piece knitting, two front pieces, two back pieces, and four sleeve pieces can be sequentially knitted in the necessary sizes. In two piece knitting, the first fabric can be knitted on the left by the two left knitting systems, and the second fabric can be knitted on the right by the two right knitting systems at the same time.



Figure 2.14 Two-piece fully fashioned knitting.

Source: *Knitting International*. (2004e). Stoll Launches Flexible All-Rounder, 111(1321), p. 15.

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<sup>4</sup>Linking: Linking is defined as a process of joining side seams or edges of a piece of fabrics together with a row of knitting on a linking machine (Linda & Leggett, 1990).

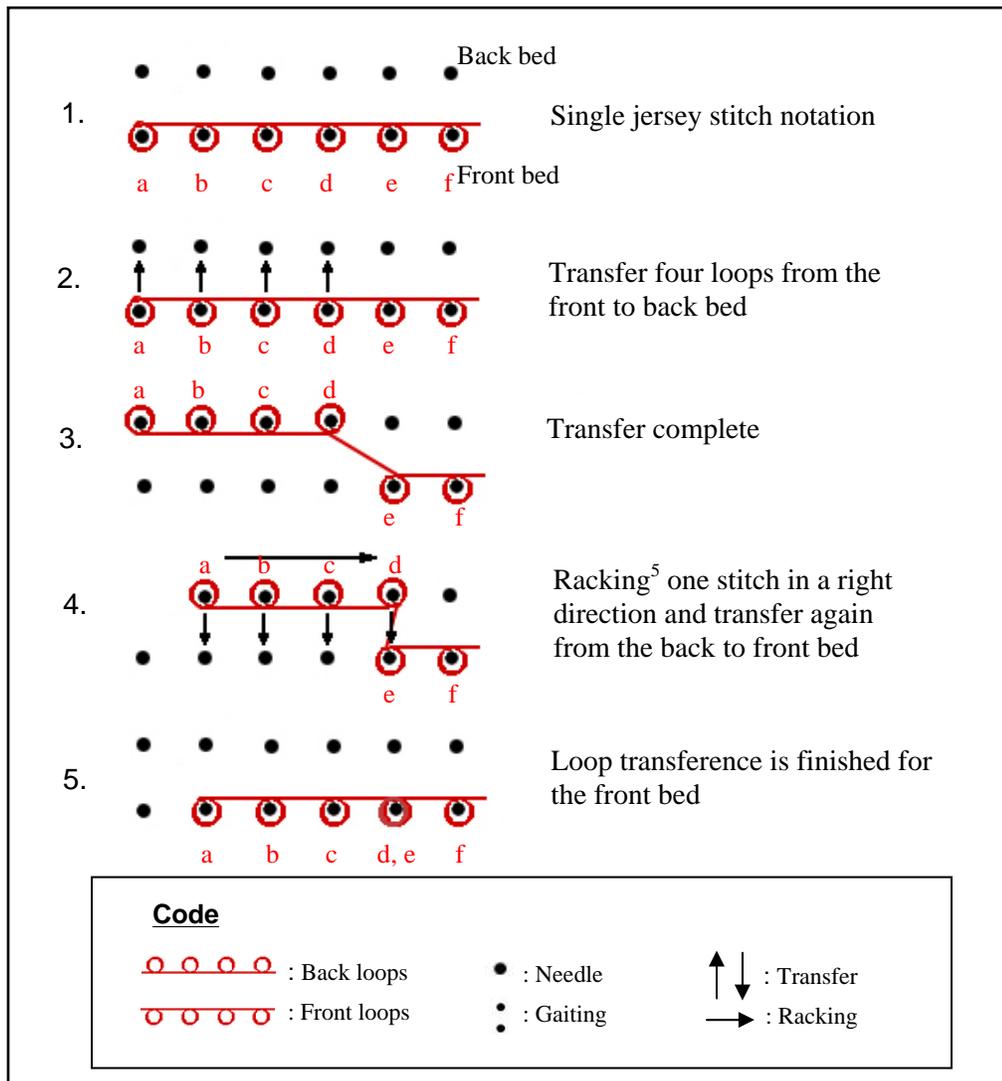


Figure 2.15 Narrowing process by loop transference on flat V-bed machine.

<sup>5</sup>Racking: Racking is the lateral movement of a needle bed.

### 3) Seamless Garment Knitting



Figure 2.16 Seamless garment production by a seamless flat knitting machine.

“Seamless” garment knitting creates a complete garment by several different carriers (feeders) with minimal or no cutting and sewing processes (see Figure 2.16). Therefore, seamless knitting has the capability for a reduction in production time and a cost-saving by removing post knit processes such as the linking or sewing and cutting operation. It also minimizes yarn consumption by reducing the cutting waste and can attain higher total system productivity. Hunter (2004a) explained that yarn consumption can be reduced by seamless garment knitting as well as by effectively analyzing the yarn feed through the computerized system on the machine.

Seamless garment knitting can be achieved either on the circular knitting machine or flat (V-bed) knitting machine. However, seamless circular knitting machines are different from seamless flat knitting machines in that seamless circular machines create only a single tubular type of garment such as those produced on Santoni® machines. Seamless flat knitting machines can create more than one tube and join the tubes together on a machine. The complete garments knitted on circular machines may also need only a minimal cutting operation as seen in Figure 2.17. Moreover, complete garments created

by a circular knitting machine still require minimal seam joining processes on one body tube and two sleeve tubes as well as the finished edges. In addition, seamless circular machines require different diameters of machines to make major changes in garment size, whereas seamless flat machines have the capability to adjust to different garment sizes on the same machine. Consequently, seamless knitting on circular machines is not true seamless knitting. It should be mentioned that knitting on V-bed seamless machines produce truly seamless garment since they do not require any cutting or sewing. In recent years, Santoni has developed a 4-feed single-jersey electronic circular machine, which enables the creation of a shaped garment by reciprocal movement (Santoni, 2006, see Figure 2.18). In Section 2.1.6, the knitting method of multi-tubular knitting techniques created on a V-bed knitting machine will be discussed.

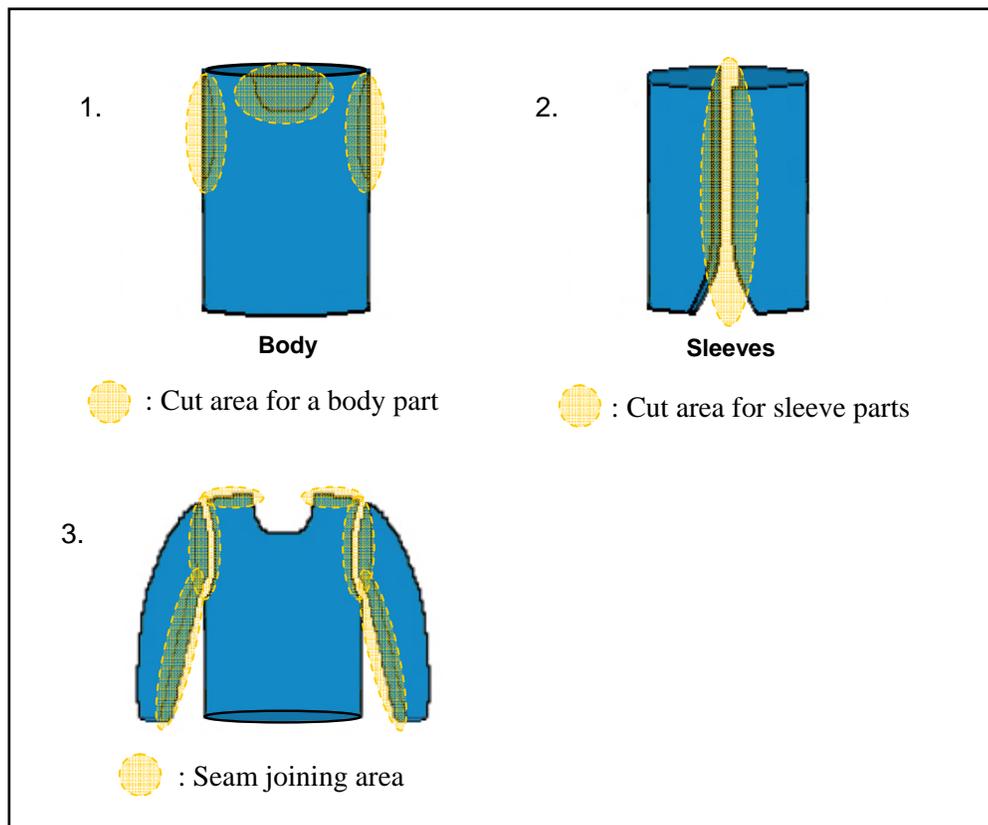


Figure 2.17 Seamless garment production by a seamless circular knitting machine.

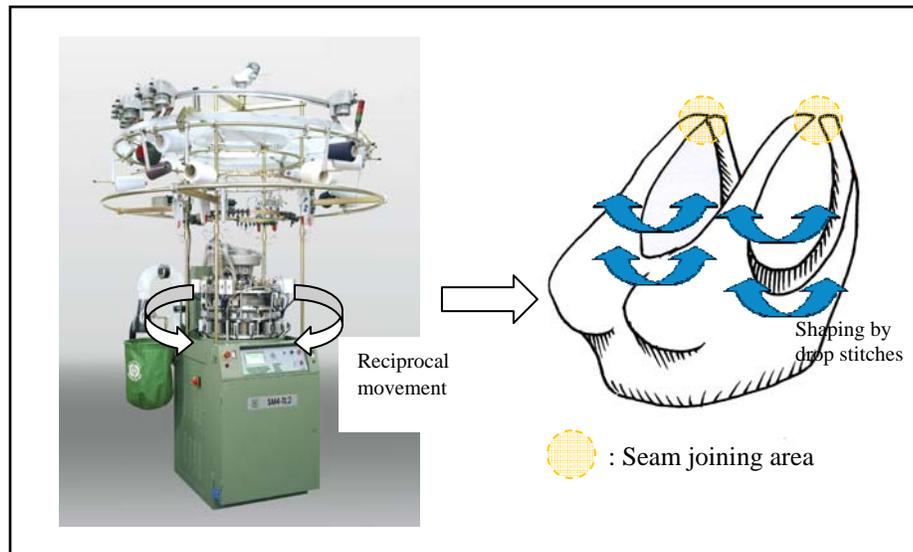


Figure 2.18 Santoni SM4-TL2 machine and its shaped product created by reciprocal movement.

Source: Santoni (2006). Retrieved January 11, 2006, from <http://www.santoni.com>.

### 2.1.6. Knitting Method of Seamless Garments on V-bed Machines

Seamless garments on a flat V-bed machine can be created in three separate tubular forms by knitting one wider tube for the body part and two narrower tubes for the sleeve parts. Tubular knitting is created on both needle beds, but front and back bed knitting are done alternately (Merle, 2003). The continuously alternate knitting of all needles on front and back needle beds creates a single plain tube. Tubular type knitting is not a new technique because since the 1800's, single jersey tubes have been produced on flat machines (Hunter, 2004c). However, seamless garment knitting can be seen as a more advanced technique in that it can connect the three tubes together to create a sweater (Hunter, 2004a) and has the capability to increase and decrease the dimensions of the tubes (Spencer, 2001). In addition, various structures including plain, knit rib and purl can be created within the seamless garment at the same time. The capability of creating

patterns within the complete garment has an important role in producing a shibori (resist) seamless knitted garment in this research.

On the flat machine, the three tubes are knitted on a pair of front and back needle beds. The flat machine knits and transfers loops between the front needle bed and the back needle bed with different yarn carriers for one body tube (Feeder 2) and two sleeve tubes (Feeders 1 and 3) (see Figure 2.19). The three tubular knitting continues to the underarm point. At the underarm point, the two carriers knitting sleeve parts (Feeders 1 and 3) are taken out of the knitting zone. The remaining carrier (Feeder 2) that knitted the main body part knits together the three tubes into one tube (Hunter, 2004d, see Figure 2.20). The tubes are joined at the underarm points, shoulders and neck points. In this manner, seamless garment knitting is accomplished. However, in order to make a loop transference for performing a shaping or design structure, loops should be formed by selecting alternate needles (Kobata et al., 2001, see Figure 2.21).

Figure 2.22 reveals how loop transference occurs on complete garment knitting by using empty needles. By loop transference using the alternate needles, single jersey tubes as well as rib type tubes can be knitted on the complete garment machine. Figure 2.23 describes how the 2X2 rib structure can be created on the complete garment V-bed knitting machine. However, due to the alternate needle selection on seamless machines, the garment tends to be more open and less elastic than a traditional fully-fashioned garment (Mowbray, 2004). This may require the use of more elastic yarns on the seamless knitting machine compared to the other regular V-bed machines such as fully-fashioned machines.

Additionally, the number of tubes knitted on the machine depends on the desired type of knitted product. The complete garment machine does not need to create multiple tubes every time. For instance, to create a sweater, it requires three tubular typed forms. On the other hand, a single shaped tube may be knitted for applications such as an office chair or an automotive seat cover (see Figure 2.24).

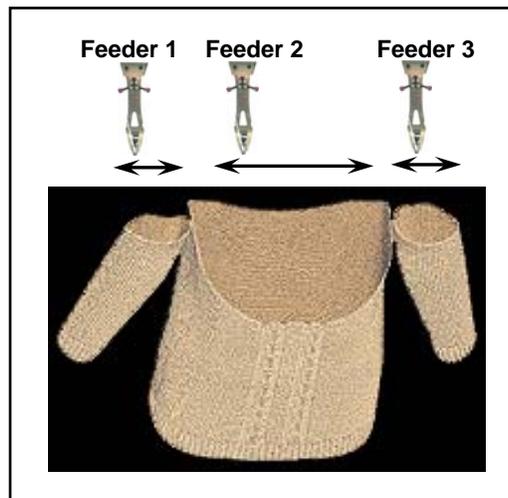


Figure 2.19 Complete garment knitting until underarm point.

Source: Shima Seiki Mfg. (2004). Retrieved September 9, 2004, from <http://www.shimaseiki.co.jp>.

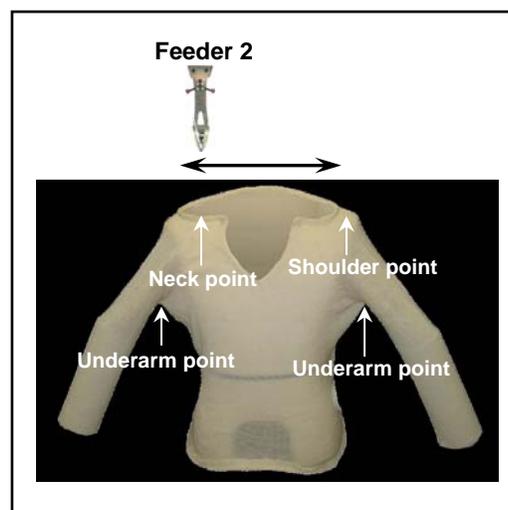


Figure 2.20 Complete garment knitting after underarm point.

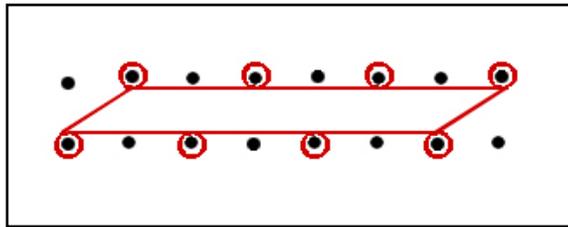


Figure 2.21 Alternate stitch notation in complete garment knitting.

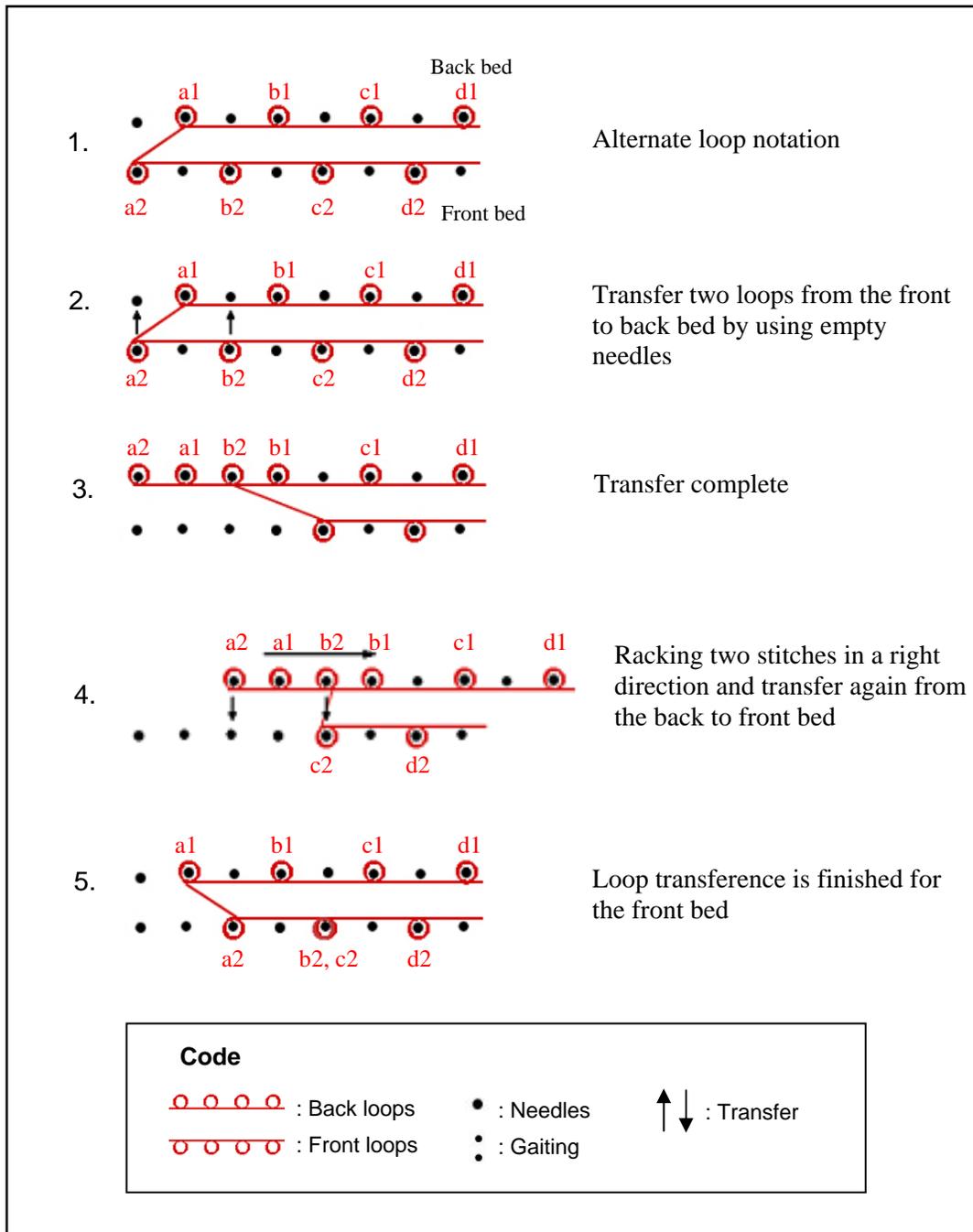
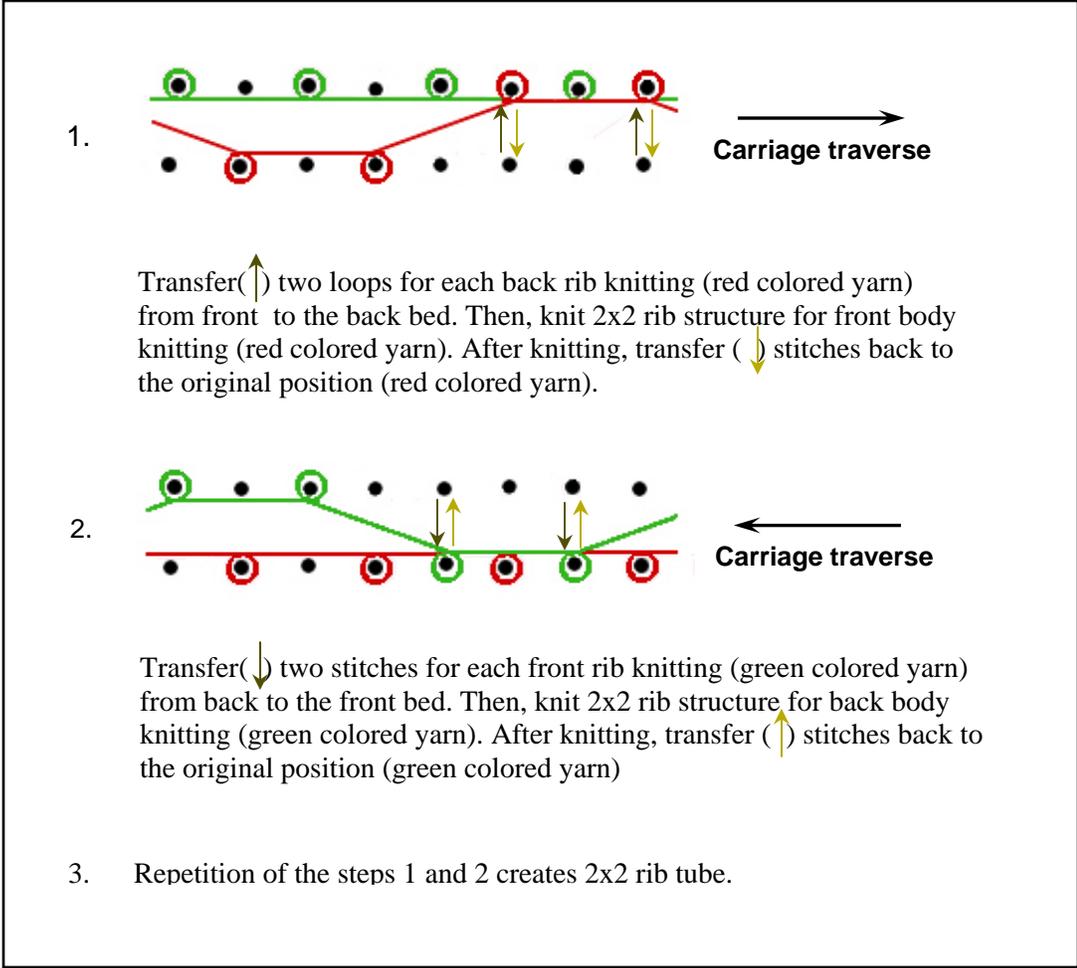


Figure 2.22 Loop transference in complete garment knitting.



\* The upper figures show 2x2 rib tubular type knitting. Green colored yarn and red colored yarn are composed of the same yarn. In order that loop notation can be seen easily, two different colors are utilized in this diagram.

Figure 2.23 Tubular knitting of 2x2 rib on a complete garment machine.



Figure 2.24 Auto seat cover knitted in a tubular form with a 2X2 rib structure on the Shima Seiki SWG-V™ machine.

Source: Powell, N.B. (2003). An auto seat cover knitted by a seamless knitting machine.

### **2.1.7. Seamless Knitting Machines**

In recent years, several companies, including Santoni, Sangiacomo, Orizio and others, have developed seamless or complete garment machines. Santoni is the biggest supplier of the circular knitting machinery and its seamless circular knitting technology is in the forefront of the industry. Santoni, founded in 1919, merged with the Lonati Group, a worldwide leader in the production of machines for the production of men socks and women stockings in 1988 (Santoni, 2004). Now, Santoni, whose customers are major apparel manufacturers, including Nike, Adidas, Sara Lee and others (Powell, 2003), offers several different models of circular knitting machines, from 7 to 32 gauge (needles per inch). The machines produce swimwear, sportswear, outerwear, and underwear. Sangiacomo, which the Lonati Group took over in 2004 (Knitting International, 2004b), and Orizio are other major producers of circular machinery. The Lonati Group's Santoni and Sangiacomo companies focus on a marketing strategy concentrated on global fashion shows and retail customer education. On the other hand, Orizio is perceived as a supplier of economical commodity machines (Powell, 2004).

For seamless flat-bed knitting machines, two suppliers, Shima Seiki and Stoll, are the leaders in machine manufacturing. It is noted that Protti, Steiger, and Universal also have produced machines capable of ready-to-wear garments with a minimal post knitting operation (Henke, 2004). Today, they provide similar knitting machine systems. This research will mainly focus on the Shima Seiki's WholeGarment® knitting system including the CAD (Computer-Aided Design) and machine systems.

## Shima Seiki

The Shima Seiki Company invented the WholeGarment® machine and introduced the commercial complete garment knitting (SWG-V machine) in 1995 at the ITMA-E (International Textile Machinery Association – Exhibition) (Millington, 1996). Since the beginning of WholeGarment® machine production, about 3500 WholeGarment® machines have been manufactured and sold worldwide (Hunter, 2004e). The seamless garment machines of Shima Seiki have a different range of gauges from 3 to 15 gauge and knitting widths ranging from 50 inches to 80 inches. Shima Seiki produces a number of versions of the WHOLEGARMENT® machine that can produce one piece of three-dimensional complete garment with no stitching, linking or sewing process.

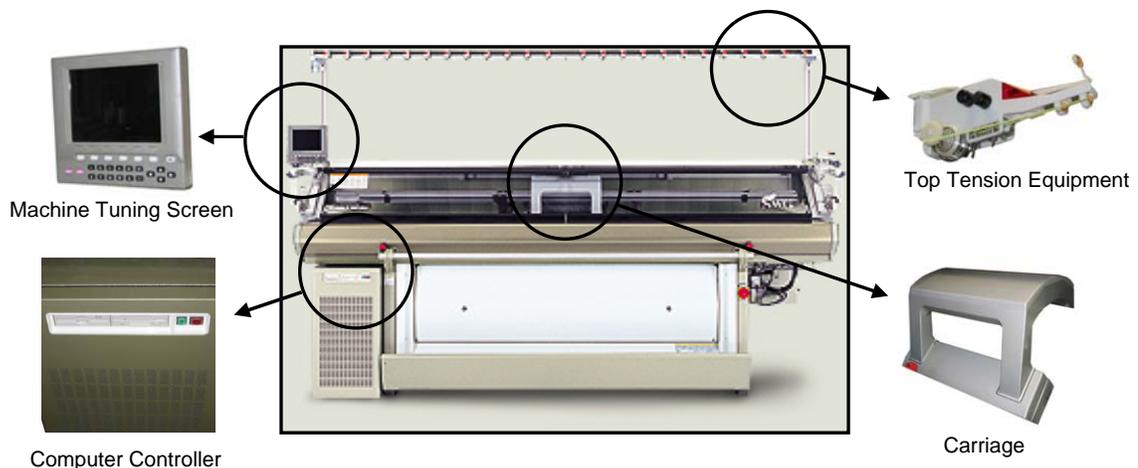


Figure 2.25 SWG-V™ machine.

## 1) Shima Seiki Knitting System and Its Operating Process

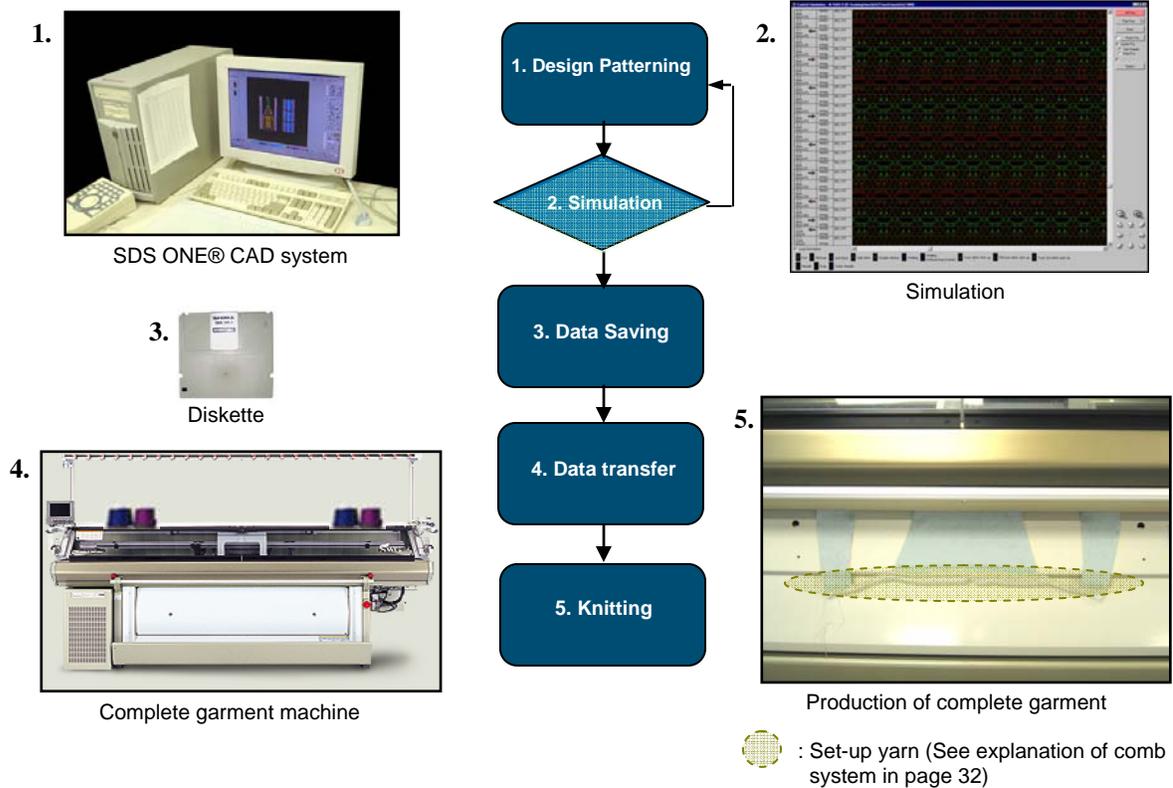


Figure 2.26 Shima Seiki knitting machine system and its operating process.

Figure 2.26 depicts the Shima Seiki knitting machine system and its operating process. In general, knit patterns can be created on the CAD (Computer-Aided Design) system. After a knit pattern is designed on the CAD system, the possibility of knitting on the machine can be evaluated throughout the computerized simulation system. All data for knit structures and garment designs can be saved to a diskette. The saved data can then be transferred to the Shima Seiki knitting machine; and the machine can be operated. Finally, one complete three-dimensional garment can be knitted on the machine.

## 2) Shima Seiki CAD System

The Shima SDS ONE® CAD system is an integrated knit production system that allows all phases of product production including planning, design, evaluation and



The CAD patterning of seamless garment knitting is more complicated than that of the fully fashioned knitting due to alternate needle selection. The bottom figure (Figure 2.28) depicts a single course notation of the tubular-formed knitting. In Figure 2.28, the first row indicates front bed knitting (color number 1) and the second row indicates back bed knitting (color number 2). Accordingly, continuous knitting in a lateral direction between the front and back needle beds forms a tubular-typed fabric. Figure 2.29 shows how loop transference for complete garment knitting can occur and how it can be displayed on the CAD system. The empty needles thus can be used for the loop transference. For the loop transference on complete garment knitting, at least two loops are transferred in a right or a left direction due to alternate needle selection such as Figure 2.29. Note that only even number of loops can be transferred for seamless knitting on V-bed knitting machines.

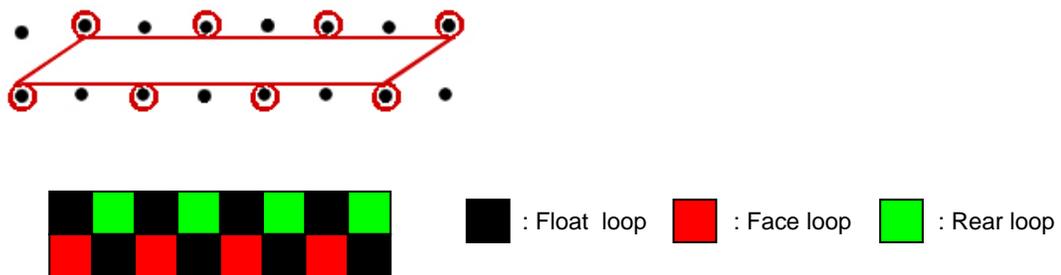


Figure 2.28 Stitch notation for seamless knitting and CAD design on the Shima Seiki CAD system.

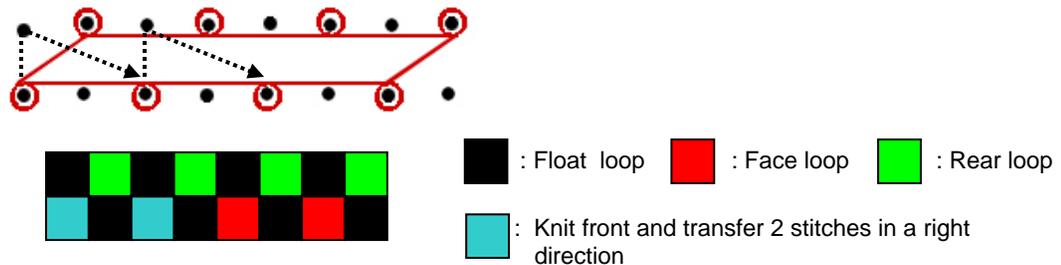


Figure 2.29 Loop transference on the front bed for complete garment knitting.

By means of the principle of the alternate stitch notation, a two-dimensional design can be created on the CAD system as can be seen in Figure 2.30. This represents a three-dimensional tubular typed garment. Figure 2.30 displays a whole garment designed on the Shima Seiki CAD system. In this complete garment design, garment shapes, styles and knit structures can be created and modified. Standard sizes in the Shima Seiki CAD system may be adjusted to fit. Data input from the body scanner can be utilized to adjust the dimensions of the knitted garment. All data for a body size can be input into the CAD system. According to the data for the body sizes, yarn counts for knitting, and machine gauges, dimensions of a garment can be manually or automatically accomplished.

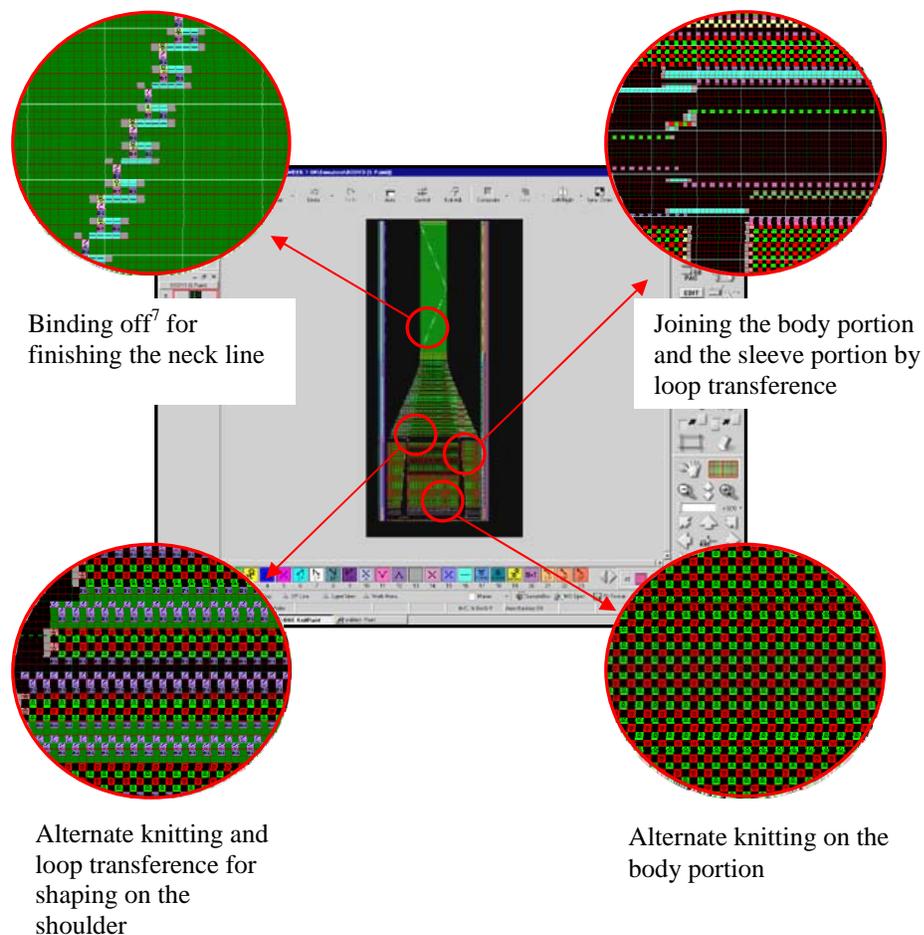


Figure 2.30 Design for a complete garment on Shima Seiki CAD system.

<sup>7</sup>Binding-off : Binding-off is the process that sequentially moves the stitches to the next loop from the edge (Shima Seiki, 2004). This technique is generally utilized to finish edge lines.

### 3) Types of Shima Seiki Seamless Knitting Machines

Shima Seiki offers a number of versions of seamless knitting machines according to range of gauge, range of knitting width, type of needle, and sets of needles or needle beds.

#### SWG-V™

The Shima Seiki's SWG-V™ machine, which comes in 5 gauge and 7 gauge, is the first commercial application of Wholegarment® technology (Shima Seiki, 2004). The SWG-V™ machine uses a latch needle where the latch closes into the hook of needle as it pulls the yarn through a loop to form a new loop (Raul, 1998). The latch needles used in flat bed machines require an additional attachment, a transfer spring, in order to transfer a loop as can be seen in Figure 2.8. However, due to the transfer spring, the needles can not be located in the center of the needle groove which results in a slightly asymmetrical loop formation.

Shima Seiki introduced a new version of the SWG-V™ machine, with its enhanced technical capabilities such as the yarn carrier kickback device and increased memory capacity. The yarn carrier kick back device is used to automatically move a carrier without knitting and ready to knit for the next row. The new version of SWG-V™ machine also uses a special twin gauge needle configuration (Figure 2.31) that includes a pair of needles working together in each needle slot. Complete garment knitting with loop transference needs two sets of needles, for the front and back of the garment, unlike a traditional single jersey tube that has only one set of needles (Hunter, 2004d). Hence, this twin needle configuration allows the needles to more effectively create widening or narrowing as well as diverse knit structures for complete garment knitting.

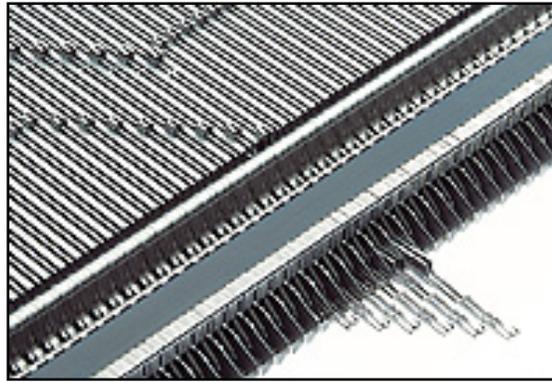


Figure 2.31 Twin gauge needles.

Source: Shima Seiki Mfg. (2004). Retrieved September 9, 2004, from <http://www.shimaseiki.co.jp>.

### SWG-X™

The SWG-X™ machine is used to produce fine gauge knitwear, which is available in 12 or 15 gauge. Fine gauge knitting is produced by the slide compound needle and pull-down device, which independently controls takedown tension for front and back body portions. Specifically, the SWG-X™ is configured for complete garment knitting with four separate needle beds and an additional loop presser bed (Shima Seiki, 2004). This is the reason why the SWG-X™ machine is the only machine that can knit complete garments without alternate needle technique. As can be seen in Figure 2.32, front body knitting can be achieved on needle beds 1 and 2, whereas back body knitting can be done between beds 3 and 4.

In fact, a machine that includes four needle beds and four cam plates is much more expensive to produce than a V-bed machine with two needle beds. The reason Shima Seiki chose the more expensive four-bed route for fine gauge is that if the machine was to take the half-gauge route for the fine gauge, the gauge would be just too fine for flat knitting technology (Hunter, 2004d). The half gauge route on two needle beds for 12

or 15 gauge knitting is too fine to endure rigorous racking or transferring for complete garment knitting. The needle hook is also too small to accept the yarn required for 12 or 15 gauge knitting.

This multi-needle bed configuration permits complete garment production with sufficient stitch density. Moreover, stitch transference can be more easily accomplished to create tubular ribs. In addition, various knit structures can be knitted at the same time with required stitch densities. For instance, complex structures in isolated areas in a garment such as high performance sportswear or medical textiles can be effectively created with required stitch densities.

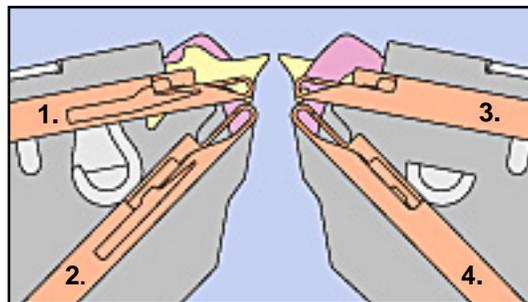


Figure 2.32 Cross section diagram of the SWG-X™ four-needle bed configuration.

Source: Shima Seiki Mfg. (2004). Retrieved September 9, 2004, from <http://www.shimaseiki.co.jp>.

### SES-S.WG™

As with the SWG-V™ machine, the SES-S.WG™ has the capability to knit complete garments with latch needles. However, unlike the SWG-V's twin-needle configuration, the SES-S.WG™ uses the standard latch needles and spring-type sinkers at the same pitch. This enables the machine to knit fine-gauge shaping as well as integral knitting and it also makes possible multiple-gauge knitting. In multiple-gauge knitting, a number of different gauges can be knitted in a single course. Multiple-gauge knitting is

different from fixed gauge knitting in that an assortment of gauge sizes may be knitted in a single garment (Shima Seiki, 2004, see Figure 2.33). The multiple gauges contain a combination of techniques, such as intarsia zoning, half-gauging, using different numbers of yarn ends, and blocks of different gauges of needles each working with its corresponding count of yarn and yarn carriers (Spencer, 2001). Shima Seiki (2004) explains that this capacity can respond to the change of seasons and trends without investing in a machine for every gauge. As a result, it saves time by eliminating the task of gauge conversion from one machine to another machine. Product variety can be enhanced by achieving more sophisticated design patterns.

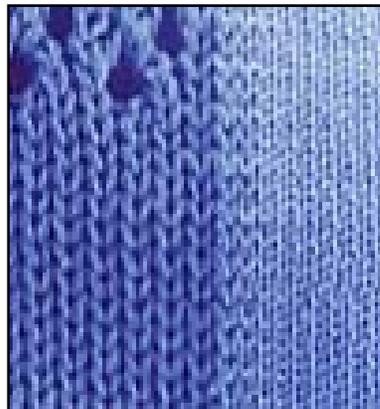


Figure 2.33 A multiple-gauge knitting sample with 12G and 7G mixed side by side.

Source: Shima Seiki Mfg. (2004). Retrieved September 9, 2004, from <http://www.shimaseiki.co.jp>.

### SES-C.WG™

The SES-C.WG™ is a flexible machine since it can achieve quality knitting in a range of production styles. The SES-C.WG™ machine has the capability to perform shaping and integral knitting similar to the other SES-series. In addition, this machine can knit coarser gauge complete knitwear. By using compound needles and a take down system featuring a pull-down device, the SES-C.WG™ can produce a coarse gauge

seamless garment. The compound needle, in which the hook and hook closing portions are separately controlled, is generally used in warp knitting machines (Knit Americas, 2001, see Figure 2.34). However, Shima Seiki applied the concept of compound needles to the flat bed machine for the first time in the world.

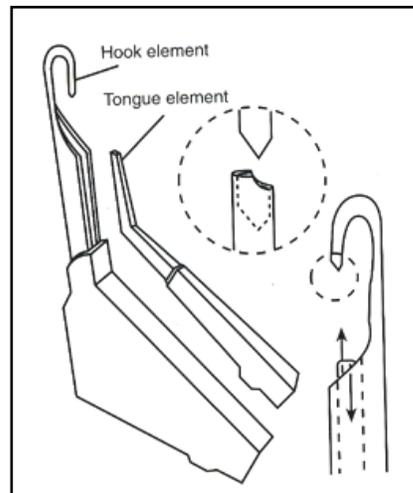


Figure 2.34 A compound needle.

Source: Kadohph, S. J. & Langford, A. L. (1998). *Textiles* (8th ed.). New Jersey: Merrill Prentice Hall, p. 220.

Compared to traditional latch needles, the compound needle is more complex and expensive to manufacture (Spencer, 2001). However, the compound needle gives higher operational stability, which is required for larger needle sizes. According to Shima Seiki (2004), the compound needle offers a significant reduction in needle stroke to allow for similar reductions in needle bed and carriage size. Thus, the short stroke knitting helps reduce space in the carriage and permits a smaller and lighter carriage (Hunter, 2004a). John Ward (2004), a technician at Shima Seiki USA Inc., stated that the compound needle eliminates the necessity for a brush on the carriage since the needle has a slider that opens and closes the hook of the needle unlike a latch needle. The slider moves up

and down by the movement of the cam system, which is timed to work closely with the movement of the needle. This increases the stability of knitting, and there are no brushes to wear out.

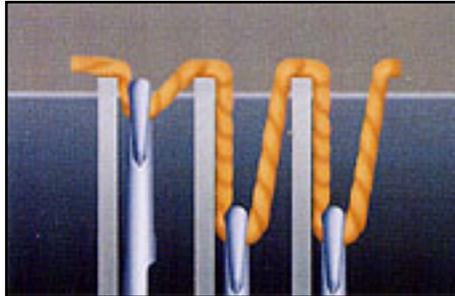
Another feature of the compound needle is that it does not have to be raised as high because there is no latch that must be cleared which increases knitting stability at higher speeds. However, one draw-back of both the latch and the compound needle is that both needles have to be off center in the trick wall to allow for the transfer spring. This puts the needle hook closer to the knock-over bit on one side, resulting in a slightly imbalanced stitch. To solve the problem of imbalance, the Shima Seiki developed the slide compound needle (Ward, 2004).

#### First™

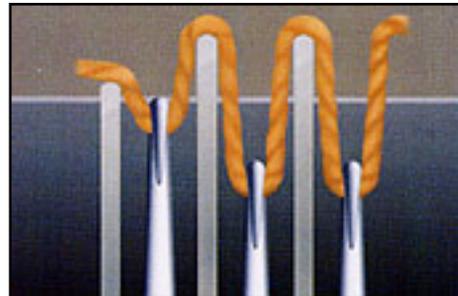
The First™ machine has a gauge range from 12 to 18. This machine executes all types of production from fully fashioning and three-dimensional shaping to seamless production. All this capability is accomplished through the development of the slide compound needle instead of latch needles; this slide compound needle uses a unique two-piece slide mechanism.

Shima Seiki (2004) points out, “a flexible two-piece slide mechanism splits and extends beyond the needle hook for increased potential especially in complex transfers. Using the slider mechanism for transfer effectively eliminates the transfer spring, allowing the needle to be mounted in the center of the needle groove. The slide compound needle thereby achieves perfectly symmetrical loop formation for knitting the highest possible quality fabrics” (see Figure 2.35). An asymmetrical loop formation makes a slightly unbalanced stitch, which gives lower quality for garments compared to

the symmetrical loop formation. Accordingly, by using the slide compound needle, the machine provides better quality and stable knitting as well as higher productivity.



Conventional latch needles offset slots



Slide compound needles centered in slots

Figure 2.35 Comparison of the new slide compound needle with a latch needle.

Source: Spencer, D. (2001). *Knitting Technology, a Comprehensive Handbook and Practical Guide* (3rd ed.). Cambridge: Woodhead Publishing Limited, p. 240.

Another distinctive feature of the First machine™ is its takedown system. “Precision pull down of the garment is independently controlled by tiny pins mounted on front and rear panels which feature adjustable working width through individually controlled 1.5 inch wide sections. This precise control of take-down tension permits 3-dimensional shaping of complete garment items” (Hunter, 2004d, p. 22).

## **2.2. Dyeing and Resist Dyeing**

### **2.2.1. Dyeing**

Tortora and Merkel (1996) described dyeing as the process of applying color to fiber, yarn or fabric with a dye treatment. The dyeing process can be accomplished by fiber dyeing, yarn dyeing, piece dyeing or garment dyeing. Fiber dyeing or stock dyeing is the process of dyeing fibers prior to yarn production. Wool fibers are usually stock dyed. Fiber dyeing makes possible even or level dyeing, which gives a more uniform

appearance in formed materials, with excellent fastness properties (Rilvlin, 1992). However, the main drawback in this process is a high production cost.

Yarn dyeing can be performed before fabric manufacture. Yarns are usually dyed to one solid color, but yarns may be dyed in multiple colored effects by the technique called space dyeing (Tortora, 1992). There are several methods of yarn dyeing such as package dyeing and skein dyeing. Package dyeing uses perforated tubes around which undyed or greige yarns are wound. The dye is pumped and circulated through the tubes. In skein dyeing, slackly wound skeins or hanks of yarns are placed in a container for dyeing (Tortora, 1992). The experiment in this current research utilizes a skein dyer since the skein dyeing machine minimizes agitation and facilitates the dyeing of numerous small samples (see Figure 2.36).

Piece dyeing, used in most dyed fabrics due to the inherent flexibility of this method from an economic standpoint, is the process of dyeing a piece of fabric rather than raw stock or yarn (Linton, 1973). Piece-dyed fabrics are common in solid colors, except where a pattern has been placed on the materials by resist printing, or later removed by discharging printing<sup>8</sup> (Tortora et al., 1996). Anton (2002) indicated that piece dyeing provides fabric value including cover, bulk, tactility, and economical shorter-run operational advantages. According to Hong Kong Polytechnic University (2006), piece-dyeing methods provide the greatest flexibility to manufacturers in terms of controlling inventory for large or small orders and for changing fashion colors. Most materials may be dyed through piece dyeing methods, but quality difficulties can occur, such as fabric distortion, uneven dyeing and comparatively poor penetration, which may result in inferior fastness properties. Pad dyeing can be also considered. Pad dyeing can be applied

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<sup>8</sup>Discharging printing: “Localized chemical removal, decolorization, or discharge, of dye on dyed fabric by transfer of discharging agent from a thickened paste” (Denton et al., 2002).

on open-width pieces, on fabrics that are sensitive to crease and crush marks. Pad dyeing requires reduced water quantities and results in lower energy consumption (Shaikh, 2005). Thus, the advantages of pad-batch methods include greater efficiency, reduced dye costs and savings in water and energy. However, due to less absorption of dye compared to other dyeing processes, it is difficult to get even dyeing, which can be a benefit for resist dyeing (Davis, 2006).



Figure 2.36 THEN@ skein dyer, German.

Garment dyeing, which is an economical dyeing method, is the dyeing of the assembled garment. Garment dyeing has been conventionally utilized for non-tailored garments such as socks, pantyhose, gloves and sweaters (Hatch, 1993). Benefits of garment dyeing include minimum inventory, maximum color ranges, novel pre-washed and worn effects, and quick turn-around time (Cheek, 1987). However, garment dyeing is one of the most difficult processes due to garment distortion, seam puckering and poor penetration of color (Hong Kong Polytechnic University, 2006). The actual cost of garment dyeing is also more expensive than the cost of piece dyeing (Hatch, 1993).

## SIP-100F™ Printer

Of noteworthy mention, the Shima Seiki introduced the SIP-100F™ inkjet printing system for knitwear and knitted fabrics at the IKME, in October 2003 (Knitting International, 2004a). The inkjet printing system has the capability to rapidly print colors on a variety of fabrics including circular-knitted fabrics or flat-knitted fabrics and even finished garments. The printer utilizes reactive or disperse dyes, which provide a complete range of colors, for printing on garments of various fiber content. The printing head may be raised or lowered for printing on fabrics with three-dimensional textures and particularly on complete knitting garments (Knitting International, 2004a). According to Shima Seiki (2006), “The SIP-100F™ can attain a maximum print head speed of 0.7 m/s and uses wide-nozzle, high-speed printing in both directions over a print area of 1600 mm x 1000 mm.” However, one of issues for this machine is that the SIP-100F™ printer can be applied on fabrics or garments available for only reactive or disperse dyes.

In fact, a jacquard or an intarsia structure created on knitting devices has limitations in multiple colors and design patterning. Multi-color patterning especially on a complete garment machine may have more difficulties due to tubular knitting and alternate needle selection. This inkjet print machine could be used to express a variety of colored designs on knitted garments. However, it would be more efficient to use existing knit equipment to develop structures to create multi-colored piece dyeing on existing garment dyeing machines.



Figure 2.37 Shima Seiki SIP-100F™ inkjet printing system and its collection.

Source: Shima Seiki Mfg. (2006). Retrieved January 10, 2006, from <http://www.shimaseiki.co.jp>.

After the dyeing process, a finishing process is necessary. McIntyre et al. (2002) defined finishing as the processes when/where physical or chemical treatments are applied to a substrate to provide desired effects. Fabric finishing may be either chemical, including softeners, wrinkle resistance, and water or oil repellent, or mechanical, including sanding, napping, calendaring. It also may be a combination of the two (Cotton Inc., 2006). Achwal, Praharaj and Thakur (1984) explained that finishing is generally the last phase in processing of fabrics or garments having the following aims:

- to enhance the stability by improving appearance and feel, and
- to impart or enhance certain properties desirable for satisfactory use by consumer, e.g. dimensional stability, wrinkle resistance and flame-proofing, and
- to increase the useful life and utility of the fabric for particular specific use.

Source: Achwal, W. B., Praharaj, M. K. & Thakur, A. S. (1984). *Symposium on Chemical Finishing and Allied Processes – New Techniques in Finishing*. Delhi, India: Indian Institute of Technology, p. 46-67.

For garment finishing, steaming or heat setting can be conducted for shaping and drying. These operations are generally performed for socks, ladies hosiery, medical

hosiery and pantyhose. For the finishing process, several boarding machine makers including Cortese, Technopea, Firsan, and SRA have developed models for socks, hosiery and pantyhose (Knitting International, 2004c). SRA (2006) explained that in a boarding machine, garment loaded forms pass through a steam chamber under pressure and then through a drying area with hot air in circulation and ventilated in selectable directions. The finishing process of bodywear garments is complete when the garments are removed from the boarding frames. Knitting International (2004d) indicated that the boarding systems now focus on fully automatic and robot assisted loading of boarding machines. The Cortese company developed fully electronic boarders for seamless and lingerie items (Knitting International, 2005). SRA (2006) also employs several boarding machines for seamless garments including underwear and bodywear garments in several shapes such as socks and children tights. By 2004, SRA developed a semi-boarding-laser (SBL) machine, which utilizes laser cutting technology in order to minimize handling of the knitted fabrics (Knitting International, 2004d).

### **2.2.2. Definition of Resist Dyeing**

Wada (2002) defined resist dyeing as “a technique or material that creates patterns on cloth by impeding dye or pigment from penetrating fabric” (p. 209). According to Brito (2002), resist dyeing is described as “any process that dyes part of the cloth and deliberately prevents other parts from dyeing” (p. 8). Researchers (Belfer, 1977; Bosence, 1985; Larsen, 1976; Wada, 2002) pointed out that most resist patterns have been created on woven fabrics, but this woven research will be a knowledge base for considering resist dyeing on knitted fabrics. Resist dyeing techniques can be divided into different groups

including batik (wax resist), shibori or plangi (tied fabric resist) and ikat (yarn resist) according to the interpretation of the classification.

#### 1) Batik (Wax Resist)

The word, batik, comes from Indonesia and means ‘wax writing’ (Singer & Spyrou, 2000). Dryden (1993) and Gittinger (2005) defined batik as a resist method that involves applying wax onto the surface of a fabric to protect the original colors on the fabric. Hot liquid wax is used to create batik patterns. After application, it quickly cools on the material and solidifies. Since the cool dye liquid cannot penetrate the wax, the area covered by wax keeps its original color after dyeing (Spée, 1982). Researchers (Belfer, 1977; Krishna, 1977) indicated that Batik originated from Egypt approximately 2,000 years ago. Japan, China, India, Central and Southeast Asia, Europe and parts of Africa have also been known for areas of batik culture (Krishna, 1977). Batik throughout Asia has been historically created on silk and cotton, and has been primarily used on garments (Belfer, 1977).

To create batik dyed fabrics, beeswax, paraffin wax, microstalline wax, and batik wax, composed of 50% beeswax and 50% of paraffin wax, are utilized (Singer & Spyrou, 2000). Different types of wax give a slightly different design result (Dryden, 1993). Batik includes several techniques, including hand-drawn wax resist created by a wax pen called tjanting (tulis batik) or carved blocks (tjap batik), and generates a great variety of batik patterns (Larsen, 1977).



Figure 2.38 Wax resist (batik) created by cotton, Indonesia, Java.

Source: Gittinger, M. (2005). *Textiles for This World and Beyond: Treasure from Insular Southeast Asia*. Washington D.C.: Scala Publisher, p. 47.

## 2) Ikat (Yarn Resist)

Larsen (1976) described ikat, a Malay-Indonesian word, as the methods of wrapping-to-pattern, then dyeing, segments of yarn before fabric is constructed. In Central Asia, the ikat silk-weaves are known as abr, which means “cloudlike” (Harvey, 1997). Ikat is different from batik or plangi (shibori) in that ikat binds and dyes yarns prior to weaving process, whereas batik or plangi uses resist techniques on an already woven fabric (Battenfield, 1978). The ikat process therefore requires plenty of meticulous sorting of yarns before and after dyeing, systematic wrapping and unwrapping of areas for resisting or dyeing, and particular care in setting up of warps and wefts on the loom to guarantee that the pre-dyed parts emerge in the right place on the finished fabric (Crill, 1998). Ikat involves three basic methods, which are ‘single ikat’, ‘combined ikat’ and ‘double ikat’. Nawawi (2003) stated that in ‘single ikat’, warp or weft yarns are tied and dyed before weaving. In ‘combined ikat’, warp and weft ikat may coexist in different

portions of the fabric. In the method of ‘double ikat’, “both warp and weft yarns are tied and dyed with such a precision, that when woven, yarns from both axis mesh exactly at certain points to form a complete motif of pattern” (Nawawi, 2003, see Figure 2.39). Battenfield (1978) indicated that cotton and silk have been the most widely utilized as ikat materials, linen and wool less frequently. This type of resist technique has been performed in numerous places around world including Indonesia, India, Japan, Persia, part of Africa and Latin America (Battenfield, 1978).

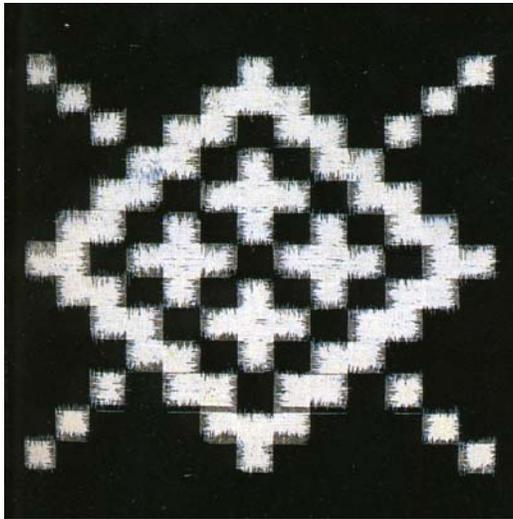


Figure 2.39 Japanese ikat - geometric shape.



Figure 2.40 Workshop for silk ikat.

Sources: Hibi, S. (1989). *Japanese Detail - Fashion*. California: Chronicle Books, p. 43.  
Harvey, J. (1997). *Traditional Textiles of Central Asia*. Hong Kong: Thames and Hudson. p. 101.

### 3) Shibori (Tied Fabric Resist)

Shibori is a process of dyeing to create unique patterns by tying fabric to restrict the penetration of dye before immersion dyeing (McIntyre et. al., 1997). Although tie-dye is described in different terms all over the world (for instance, it is called ‘bandhani’ in India, ‘plangi’ in Indonesia and ‘shibori’ in Japan), the techniques have also been shown in variety of countries such as India, Indonesia, Japan, China, Latin America and part of

Africa. The techniques can be formed in numerous variations, including multiple color applications and diverse pattern repetition.

Shibori does not have a corresponding word in English. However, it can be simply expressed as ‘shaped-resist dyeing’ or ‘tie-dye’. Shibori, as defined by Wada (2002), is a Japanese term that refers to many methods of embellishing textiles by shaping fabric and securing it prior to dyeing. The word, shibori, comes from the Japanese verb root shiboru, “to wring, squeeze, press” (Wada, 2002). Ellis (2005) defined shibori as “a term for shaped-resist dyeing, a process by which a flat piece of cloth is shaped by folding, stitching, tying, or wrapping and then secured before dyeing” (p. 3). Shibori thus covers all ‘physical’ resists (Schoeser, 2003). After the dyeing process, the shaped resist areas can be expressed by various pattern designs (see Figure 2.41). In order to achieve the shibori patterns, it is essential to create a three-dimensional form by folding, crumpling, plaiting, and twisting, rather than treating fabric as a two-dimensional surface (Wada, Rice & Barton, 1999).



Figure 2.41 Woven shibori.

Source: Ellis, C. (2005). *Woven Shibori*. Colorado: Interweave Press, p. 20.

Shibori has the potential to create various shaped and resisted designs. The shibori shaped resist dyeing techniques include “binding or tying the fabric in specific places to resist the dye; clamping the fabric; stitching the fabric to resist dye; and any number of variations on that theme” (Dryden, 1993, p. 97). Wada, Rice and Barton (1999) explained that the particular characteristic of shibori is a soft or blurry-edged pattern, which differs from the clearly defined or sharp-edged resist obtained with stencil, paste, and wax. Changing fabric structures may control the randomness or the repetitiveness of shibori patterns. “With shibori the dyer works in concert with the materials, not in an effort to overcome their limitations but to allow them full expression. And, an element of the unexpected is always present” (Wada et al., 1999, p. 7). Through the diverse body and texture of the fabric, dramatic, interesting, and complicated results can be accomplished. This research will focus on tie-dye (shibori) among the three main resist dyeing techniques.

### **2.2.3. History of Shibori (Tied Fabric Resist)**

Shibori is considered a prehistoric technique. Many different types of tied resist have historically been utilized in numerous cultures including Japan, China, India, Indonesia, Turkey, western Africa and Central and Latin America (Wada, 2002). Terms describing tie-dyeing methods are different in each culture, and the techniques also include variations. In this section, traditional tie-dye techniques in three countries will be discussed.

#### **1) India**

According to Wada (2002), many tie-dyed crafts, dated as early as 4000 B.C., were found in the northwestern region of the Indian subcontinent in the Indus River

basin. One of the oldest examples of the Indian tie-dye techniques is “bandhani”. Bandhani can be seen in the sixth- and seventh- century painting describing the life of Buddha found from Ajanta Cave 1, India. The term, bandhani (Bandhana), derives its name from a Hindi word, Bandhan, which means “to tie up”. The bandhani work was introduced in England in the nineteenth century (Storey, 1974), and a word, “Bandhana”, has been adopted in English for certain forms of the process (Larsen, 1976). The resist technique is created by plucking the fabric with fingernails into many tiny bindings that form a figurative design. Thus, designs are expressed by dots, in which numerous tiny points are tied with threads before dyeing (see Figure 2.42). Bandhani is tied on cotton, silk and rarely on wool fabrics (Larsen, 1976). Primary production of bandhani, which has been mainly utilized as a shawl or head covering, in Jaipur and the Shekavati region on the north, in Rajasthan, and in Ahmedabad and the Saurashtra and Kutch regions to the west, in Gujarat (Wada, 2002).



Figure 2.42 Silk bandhani with silver embroidery, 20<sup>th</sup> c.

Source: Wada, Y. I. (2002). *Memory on Cloth - Shibori Now*. New York: Kodansha America, p. 19.

## 2) Indonesia

The popularity of resist dye techniques in Indonesia has been influenced by India. However, they developed their own unique tie-dye tradition by use of stitching, capping, and binding techniques (Wada, 2002). In particular, plangi, one of popular tie-dye techniques in Indonesia, was made by gathering, binding and dyeing in multiple colors. In Indonesia, the Palembang area of southeast Sumatra, Java, and Bali is well known for tie-dye (plangi) techniques (Wada, 2002). According to Larsen (1976), the plangi cloths predominantly made of tussah or a thin Chinese silk have been used as shawl, skirt, sash, girdle, breast wrap and kerchief apparel.

## 3) Japan

Japan has a long history of shaped-resist dyeing. Wada (2002) estimated that shibori techniques originated from India and influenced China and Japan via the Silk Road. By the 7th century, there were three types of resist-dye fabric, including kokechi (tied and bound resist), rokechi (wax resist), and kyokechi (clamp resist) (Wada et al., 1999). Several of the kokechi, which has been replaced with “shibori” in modern Japanese, resemble shibori found in a tomb in Astana in China, which dates from about A.D. 400 (Wada, 2002). Since shibori techniques were introduced in Japan, various methods were created and developed such as itajime shibori (board-clamp resist dyeing), kumo shibori (spider-web binding, which is created by pulling up a spot of fabric from the center and binding it with string (Brito, 2002)), miura shibori (looped binding), tesuji shibori (hand pleating) and arashi shibori (pole-wrap resist). In the 1900s, shibori began being exported from Japan to Korea, Taiwan, Singapore, and even Africa (Wada et al., 1999).

#### 2.2.4. Techniques of Shibori

The fundamental technique of shibori is based on fabric that is given a three dimensional form. After dyeing, the fabric may be returned to its two dimensional shape. Wada, Rice and Barton (1999) pointed out that the design that appears on the fabric is the result of the three-dimensional shape of the fabric. The fabric delicately records both the shape and pressure of the binding or other resist methods, which are the essence of shibori. The major groups of tie-dye techniques are composed of binding, stitching, folding, and pole-wrapping (see Figure 2.43).

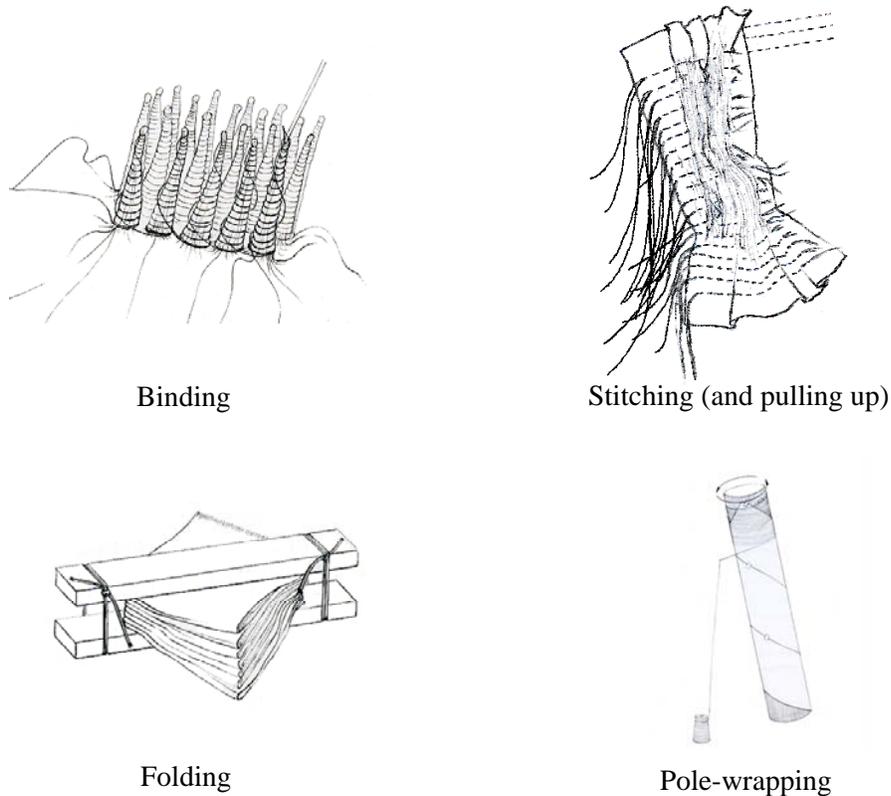


Figure 2.43 Major group of tie-dye techniques.

Source: Wada, Y. I., Rice, M. K. & Barton, J. (1999). *Shibori – The Inventive Art of Japanese Shaped Resist Dyeing*. New York: Kodansha America, p. 69, p. 75, p. 118, p. 125.

## 1) Binding

According to Wada et al. (1999), the nature of the binding method restricts the type of pattern to circles and modified squares (see Figure 2.44). They quoted, “The shape of the cloth, the tension of thread, and the resisting action of the thread determine the configuration of each unit, while the placement, spacing, and amount of thread affect the way of dye penetrates” (p. 55). A specific portion of fabric is drawn up by the fingers or a small hook and held while a yarn is bound around it. Thus, bound sections of the fabric are undyed across the entire finished fabric (Larsen, 1977). This technique is comprised of ring shibori and dots, spiral and shell shibori, spiderweb<sup>9</sup> shibori, looped binding shibori, and crisscross binding (Wada et al., 1999). It is also a common technique in traditional Indian bandhani, African resist dyeing, American tie-dye, and ancient Andean textiles (Brito, 2002)

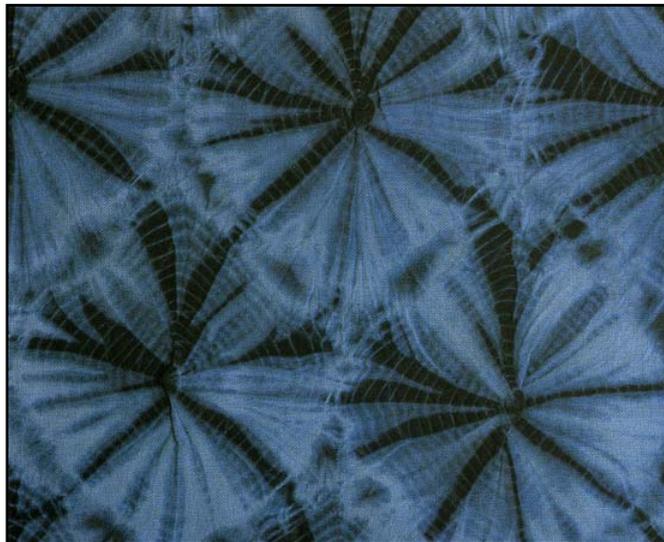


Figure 2.44 Spiderweb (kumo) shibori.

Source: Wada, Y. I., Rice, M. K. & Barton, J. (1999). *Shibori – The Inventive Art of Japanese Shaped Resist Dyeing*. New York: Kodansha America, p. 50.

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<sup>9</sup>Spiderweb : Spiderweb has “a roughly circular area with a dark spot in the center (the spider) and dark spokes radiating out, broken by thread lines” (Brito, 2002, p. 82, see Figure 2.41).

## 2) Stitching

Stitching for shibori is usually accomplished by hand. This method depends on a needle technique of stitching on the fabric. The effects of stitched shibori are different according to the type of stitches and arrangement of stitches such as straight, curved, parallel and shape of enclosed area. When the fabric is stitched as a form of resist, the yarns are pulled up, and the fabric is gathered up along the stitched yarn and secured by knotting. Stitched shibori requires a tightly stitched fabric in order that the fabric in the gathers should resist the dye (Brito, 2002). This is the reason why the gathering yarns or cords utilized in the stitching process are required to be strong enough to endure the tension of the pulling up of fabric (Dryden, 1993). Finally, the gathered fabric is dyed. This technique includes wood grain shibori, which uses parallel lines of stitching, ori-nui shibori, which has undulating patterns, Japanese larch shibori and chevron stripes shibori (Wada et al., 1999). This research focuses on wood grain shibori by computerized knitting equipment. Figure 2.45 illustrates shibori patterns created by hand stitching.



Figure 2.45 Hand stitched shibori patterns on a woven fabric.

Source: Brito, K. K. (2002). *Shibori – Creating Color & Texture on Silk*. New York: Watson-Guption Publications, p.86.

## Woven Shibori

Since 1995, Catherine Ellis (2005) has developed new approaches to shibori fabrics. Ellis supplemented the weft floats and also the warp ends in weaving, which are used to create shaped-resist dyeing, including numerous woven structures, such as monk's belt, overshot, twills and laces. In achieving successful woven shibori, Ellis (2005) pointed out that two-end floats for gathering yarns are generally not enough to get distinct pleat images, but three- or four-end floats will obtain clear resist images. Ellis (2005) also mentioned that when gathering yarns are removed, they leave small holes and spaces, which are characteristics of the process and not to be avoided in a fabric. In addition, longer floats are easier to pull up due to less resistance as well as result in bolder patterns. On the other hand, shorter floats bring less detail to the pattern. Figure 2.46 shows results of resist dyeing according to different stitching methods. Based on these woven structures a consideration of appropriate knit structures for gathering pleats could be explored.

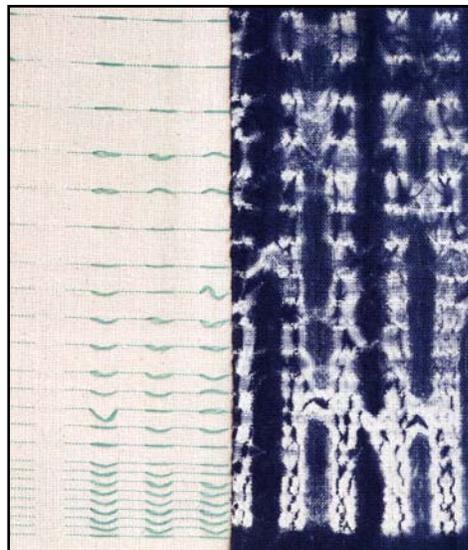


Figure 2.46 Dyeing results according to different stitching methods.

Source: Ellis, C. (2005). *Woven Shibori*. Colorado: Interweave Press. p. 17.

### 3) Folding

Fold resist dyeing is created by pleating or by folding fabric so compactly to resist absorption of the dye (Larsen, 1976). Dye reaches the uncompressed parts outside, but may not penetrate to the inside. According to folding positions and methods, diverse techniques are applied such as hand pleating, machine pleating, stitched pleating, double pleating, stripes and dyed band, triangles, tortoiseshell, and lattice (Wada et al., 1999), and numerous geometric patterns are accomplished.

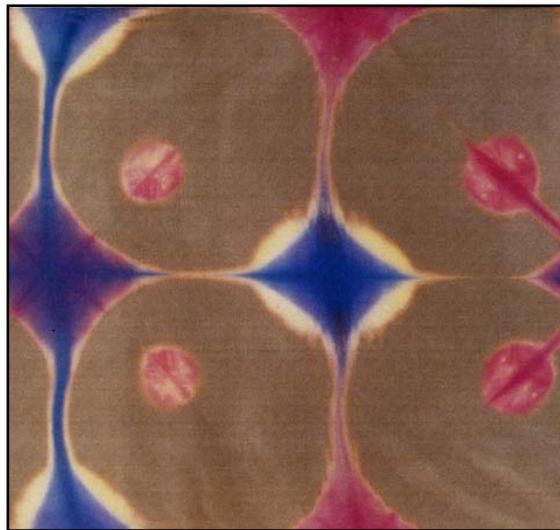


Figure 2.47 Itajime, folded into triangles, clamped with a semi-circular shape.

Source: Brito, K. K. (2002). *Shibori – Creating Color & Texture on Silk*. New York: Watson-Guption Publications, p. 80.

### 4) Pole-Wrapping

Arashi, which means “storm” in Japan, was developed at the beginning of the nineteenth century in Japan (Möller, 2000). This technique is achieved by the process of wrapping a fabric around pole, winding a yarn, compressing it into folds, and finally dyeing it (Wada et al., 1999). Through the techniques, various patterns can be achieved in vertical, horizontal, and diagonal directions.

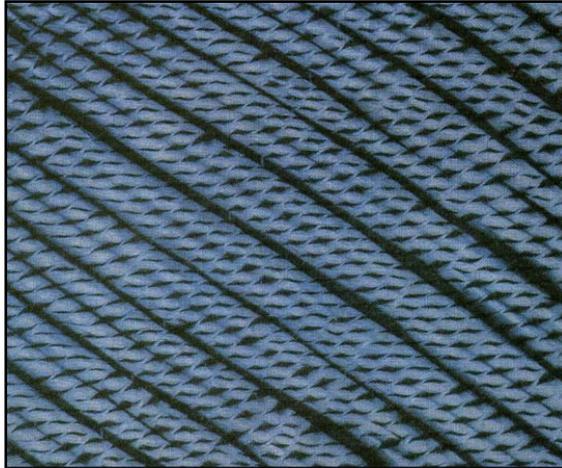


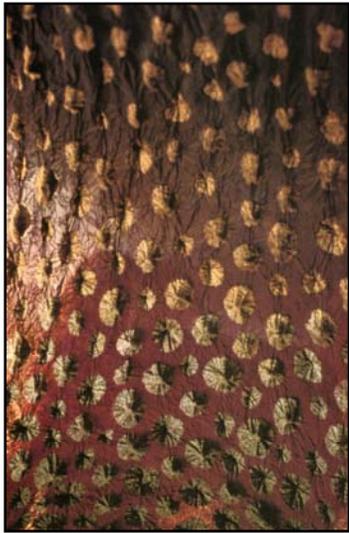
Figure 2.48 Pole-wrapping (arashi).

Source: Wada, Y. I., Rice, M. K. & Barton, J. (1999). *Shibori – The Inventive Art of Japanese Shaped Resist Dyeing*. New York: Kodansha America, p. 51.

### **2.2.5. Contemporary Shibori**

Since the 1990's, tied fabric dyeing has been advanced by incorporating modern technology such as electronic jacquard weaving, heat-setting, steaming, chemical treatment and innovative fiber applications. The development of richer colors and three dimensionality of fabrics gives complex visual effects. Indeed, shibori has gradually become a unique fabric design technique in the development of high fashion and wearable art (Wada, 2002).

The following images illustrate contemporary shibori design works. As discussed in the previous section (Woven Shibori, p. 57), Ellis explored a new stitching and gathering technique on hand woven fabric. Plume has implemented new methods of shibori dyeing by creating images through jacquard weaving. Current sophisticated computerized knitting systems may permit creation of diverse three-dimensional effects including pleated or bound fabrics for shaped-resist dyeing. Thus, traditional shibori structures can be newly explored through advanced knitting technology.



Jurgen Lehl



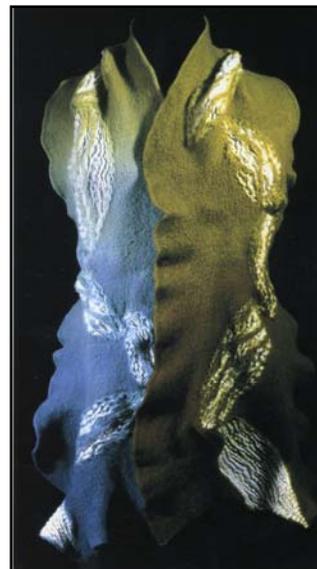
Catherine Ellis



Vita Plume



Masha Mioni



Jeung-Hwa Park

Figure 2.49 Contemporary shibori design works.

Sources: Ellis, C. (2005). *Woven Shibori*. Colorado: Interweave Press, p. 52, p.91.  
Wada, Y. I. (2002). *Memory on Cloth - Shibori Now*. New York: Kodansha America, p. 62, p. 75, p. 110.

## **2.3. The Use of Seamless Knitting Technology to Develop a New Product**

### **2.3.1. Introduction**

Today, the world is characterized by macro and micro-environmental influences. These influences involve the rapid evolution of socio-cultural patterns and life styles, self-awareness and decisional autonomy of consumers, a rising significance of mass production and distribution systems, an incessant introduction of technological and managerial innovations, increasing levels of competition and globalization dynamics (Ciappei & Simoni, 2005). These influences are impacting the textile and apparel industry including knitting production and business, creating diverse marketplace opportunities and challenges.

In order for companies to effectively build and sustain competitiveness in the global textile and apparel industry, they are implementing several strategies. One key strategy is to develop capabilities in product innovation and new product development (NPD). It is also evident that companies require a clearly defined and effective new product development process to compete in the global industry.

This chapter defines new product development (NPD) and reviews key NPD functions. Required conditions for successful new product management are also mentioned. As it relates to main topic of this research, a NPD process in seamless-knitted and resist-dyeing production is discussed.

### **2.3.2. New Product and New Product Development**

A new product concept, as defined by Crawford and Di Benedetto (2003), is “a statement about anticipated product features (form or technology) that will yield selected benefits relative to other products or problem solutions already available” (p. 184).

According to Belliveau, Griffin and Somermeyer (2002), a new product is defined as “a product (either a good or service) new to the firm marketing it. It excludes products that are only changed in promotion” (p. 450). New product development is essential for exceptional corporate performance, and research about what leads to new product success and failure has been carried out for both goods and services (Brentani, 2001). Ulrich and Eppinger (2004) described New Product Development (NPD) as “the set of activities beginning with the perception of market opportunity and ending in the production, sale, and delivery of a product” (p. 2).

It is important to develop innovative products based on customers’ requirements by effectively integrating advancing technologies. Despite seamless knitting technology having been introduced in 1995, it can be considered a new product in that the technology has been continuously improving and is yielding additional benefits. Moreover, as one type of new product categories the technology offers enhanced performance and greater perceived value over the conventional knitting production. Thus, seamless knitting technology can belong to the product improvement category among new product categories. The combination of seamless-knitted and resist-dying techniques as a new product considered in this research is specifically expected to give many technical as well as marketing advantages in the knitting market.

### **2.3.3. Key NPD Functions**

Development of new products is an interdisciplinary activity requiring contribution from nearly all the functions of a company (Ulrich et al., 2004). To produce seamless-knitted shibori garments, it also needs cross-functional activities of the

following key NPD functions. The following functions are consistently essential to new product development projects:

#### 1) Marketing

The functions of marketing mediate the interactions between the firm and its customers. Marketing facilitates the recognition of product opportunities, the definition of market segments, and the identification of customers' needs (Ulrich et al., 2004). Marketing also arranges for communication between the firm and its customers, sets target prices, and oversees the launch and promotion of the product (Ulrich et al., 2004).

The latest market research has been recognized as being important to the success of new product development. It is important to identify early market requirements and to understand the market place. Marketing is related to all stages of the new product development process, from product planning, screening, and testing through launch (Bruce & Biemans, 1995).

As consumers' requirements for apparel, such as style, fit and comfort, have increased, investment in innovative seamless knitting technology has grown in the knitting industry. Knit Americas (2005) pointed out that the number of seamless knitting machines has been incessantly increasing, and the seamless market also has become more diverse (see Table 2.4 and Figure 2.50). It is because the new technology satisfies the contemporary market needs such as quick response and 'just in time' production. It also permits cost reduction in production. However, one of the challenges in the current seamless market is that most customers usually do not realize that the garment is actually seamless and are not even aware of the benefits of seamless garments (Legwear Trends, 2006). Thus, education for seamless knitting to customers may be required. Gayle

Pierson, intimate apparel buyer for Belk stores, suggested that use of hangtags for seamless garments can be one of the best ways to indicate that the garment is seamless (Legwear Trends, 2006). Current textile and apparel markets require more specialized as well as engineered textiles. By combining seamless knitting technology with traditional resist dyeing techniques, a unique product for a high-end apparel niche market may be created.

Table 2.4 Trends in the seamless market by end use

Application	2005	2007 (Forecast)
Underwear	73 %	60%
Sportswear/Outerwear	24 %	35%
Swimwear	2 %	3%
Medical	1 %	2%

Sources: *Knit Americas*. (2005). What Next for Seamless Body Size Clothing? Fall, p.20  
 Santoni. (April 4, 2006). Seamless Apparel Symposium. Greensboro, NC.

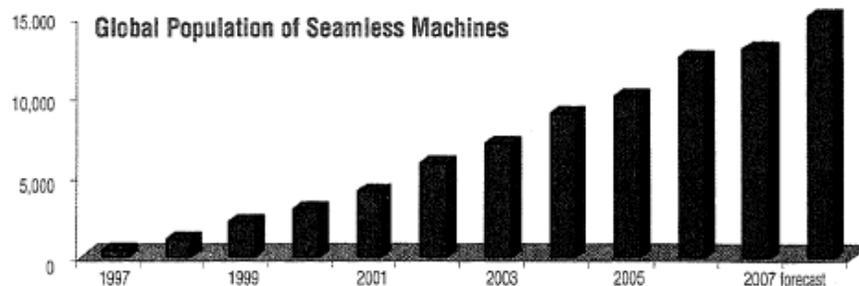


Figure 2.50 Global population of seamless machines.

Source: *Knit Americas*. (2005). What Next for Seamless Body Size Clothing? Fall, p. 20

- Santoni and Sangiacomo have sold the approximate 8,500 seamless circular knitting machines worldwide until 2006.

Source: Santoni. (April 4, 2006). Seamless Apparel Symposium. Greensboro, NC.

## 2) Design

The design function also plays a pivotal role in defining the physical form of the product to satisfy customers' needs. The design function includes engineering design such as mechanical, electrical, software, and industrial design such as aesthetics, ergonomics, and user interfaces (Ulrich et al., 2004).

In marketing, industrial design has become a key factor in differentiating products from their competitors by providing them a coherent identity or higher levels of perceived value (Bruce et al., 1995). Engineering design has a critical role in the development of products in the manufacturing industry, solving technical problems using available technology in the most efficient method, and integrating product development with the requirements of effective production (Rothwell & Gariner, 1984).

In seamless garment product development, design would be one of the most critical functions. Companies need to consider both industrial design and engineering design for seamless production in order to satisfy customer preferences. The industrial design relevant to knitwear includes styles, decorative patterns, colors and knit/fashion design. On the other hand, engineering design related to knitwear performance in knitability/productivity involves knit structures, garment structural design on CAD systems and technical notations. Recent computerized knitting machines provide technically as well as aesthetically more advanced design possibilities to create garments. Figure 2.51 shows a multi-color dyed complete garment created on computerized knitting machines. Through the computer-controlled systems, designs can be rapidly changed using the Computer-Aided Design (CAD) system linked to the machine (Hunter, 2005), and a higher design structure capability can be achieved (Knit Americas, 2005). Indeed,

current sophisticated CAD knitting systems provide high speed, low cost and large volume textile production (Kamiya, Cheeseman, Popper & Chou, 2000). In this research, a variety of experiments to create resist dyeing patterns are explored and evaluated by use of computerized systems, including CAD systems, knitting machines and scanners.



Figure 2.51 A multi-color dyed complete garment.

Source: Hishinuma, Y. (2005). 3D-Knit. Japan: Yobisha Co., Ltd., p. 38.

### 3) Manufacturing

Manufacturing is responsible for creating and operating production systems in order to produce new products in volume at an acceptable quality and cost. However, broadly defined, the manufacturing function also often involves purchasing, distribution, and installation (Ulrich et al., 2004). Manufacturing capability can be one technical success factor, and it relates to whether the company has internal or external capability to manufacture higher quality products to satisfy the customer demand (Crawford et al., 2003).

To get a higher quality knitted garment, it is crucial to control the manufacturing functions. In particular, it is critical to effectively communicate between designers and manufacturers to create successful new products in the knitting industry. Eckert, Cross and Johnson (2000) argued that communication between the different team members in the knitwear production is a disreputably difficult problem, since they are involved in different stages of concept creation, embodiment and detail design, fabrication and production. For example, designers complain that the designs that they specified are not accurately created, while technicians complain that the designers do not understand the technical problems in knitting feasibility. They proposed that one solution to overcome the communication problem between designers and technicians would be the use of intelligent CAD systems. The CAD system gives designers and manufacturers the opportunity to specify and evaluate their design more precisely without requiring great time investment and technical expertise. Diverse computer-controlled systems including CAD /CAM controlled machines were developed to solve the communication problems. The Stoll Company (2004) offered a new type of CAD system, which uses two different monitors (displays) including a technical window and a design window for designers and manufacturers, who require different information for the same design (see Figure 2.52). The technical window shows the developing design in the form of running yarn notations and technical data, while the design window presents the design as a virtual simulation (Spencer, 2001). It is expected to minimize miscommunication between designers and technicians in the knitting industry.

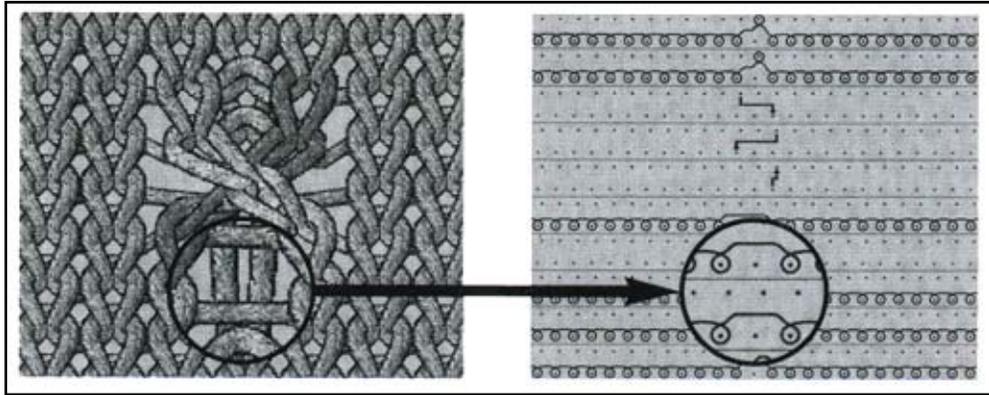


Figure 2.52. Linked windows options of fabric view and technical view.

Source: Spencer, D. (2001). *Knitting Technology, a Comprehensive Handbook and Practical Guide* (3rd ed.). Cambridge: Woodhead Publishing Limited, p. 142.

#### 4) Finance

Another key function that influences the success of the new product development process is financial activity. Projects need to be suitably supported; yet checks on cost, profit margins and return on investment must be part of the process. Many companies utilize phase reviews to keep a check on the progress of the projects, the budget and the authorization to spend (Bruce et al., 1995).

#### **2.3.4. Successful New Product Management and Seamless Technology**

The main issues of new product development relate to the need for interdisciplinary inputs, for quality input, for cost input and for speed in the process (Bruce et al., 1995). The inputs that contribute to the value of new products tend to conflict with each other, but there are synergies (Crawford et al., 2003, see Figure 2.53). These inputs are also critical factors that create a need in the industry for seamless technology.

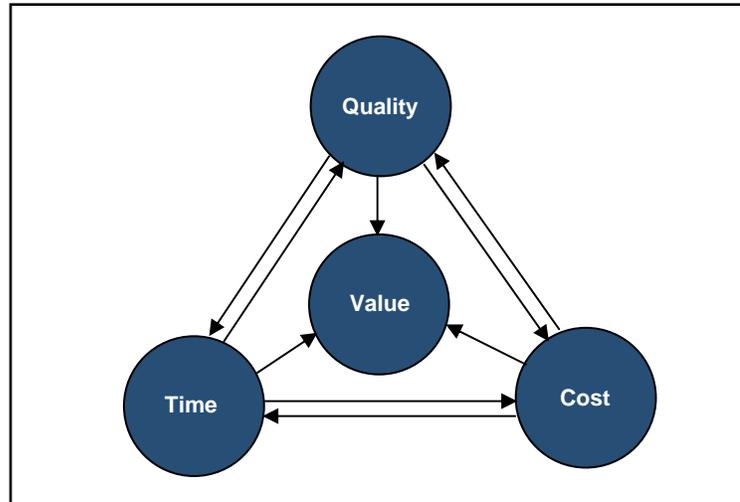


Figure 2.53 Conflicting masters of new products management.

Source : Crawford, M. & Di Benedetto, A. D. (2003). *New Products Management* (7th ed.). New York: McGraw-Hill, p. 15.

### 1) Product Quality

Successful product development depends upon how good the product is, whether the product satisfies customers' needs, and whether the product is robust and reliable. Product quality is ultimately reflected in market share and the price that customers are willing to pay (Ulrich et al., 2004).

At this point, seamless knitting technology provides improved product quality to meet customers' requirements. In garments, seamless knitting technology is purported to give lightness and softness in knitwear since there is no linking or sewing of seams. In addition, there is no bulky and irritating stitches at the underarm points, shoulders and neck lines (Shima Seiki, 2004). For finished edges, the garment can have better trimmed edges through a machine binding-off (knit stitch) process instead of a sewing or linking operation. In addition, a single entire piece production method is claimed to provide more consistent product quality (Legner, 2003). Consequently, seamless knitwear is promoted

to look better, and is believed to provide much more comfort and better fit to customer requirements than cut and sew production or fully-fashioned garments.

## 2) Product and Development Cost

Successful product development also relies on controlling manufacturing cost including spending capital on equipment and tooling as well as the incremental cost of producing each unit of the product. Product cost determines how much profit accrues to the firm for a particular sales volume at a particular sales price (Ulrich et al., 2004). Successful product development also depends on how much the firm has to spend to develop the product. Development cost is usually a critical portion of the investment required to attain profits (Ulrich et al., 2004).

In seamless production, there is no traditional labor intensive cutting and sewing process because of the elimination of seam and seam allowance. Yarn consumption also is decreased or lowered since it does not require a post knitting process. For this reason, the tubular-typed seamless knitting results in potential saving in terms of production cost. However, one drawback for complete garment knitting is that if the garment has a defect such as a hole or unraveling of stitches during knitting, the entire garment is useless and must be discarded. Compared to the cut and sew production and fully-fashioned knitting, in this case there would be more waste, and it may increase production cost when the complete knitted garment has any defect.

## 3) Development Time

How rapidly the new product development team (or firm) completes the product development effort is also an important issue. "Development time determines how responsive the firm can be to competitive forces and to technological development, as

well as how quickly the firm receives the economic returns from the team's efforts" (Ulrich et al., 2004, p. 2-3). McGrath (2004) commented that decreased time-to-market provides numerous benefits such as gaining higher productivity, reducing the costs of many projects, and enabling time-based competition.

In the textile and fashion apparel industry, it is essential to effectively recognize and adapt to quickly changing trends in the market (Keiser & Garner, 2003). Quick response production is possible in seamless knitting technology. The required number of new styled products can be quickly knitted in less time to meet the needs of markets. For instance, according to Legner (2003), in the case of a complete woman's knit sweater, a time saving of about 35% can be achieved with seamless knitting by eliminating cutting and sewing or linking process. According to Peterson (2006), seamless garment technology also enables mass customization<sup>10</sup> to be implemented in the business of high fashion knitted products. In certain markets, seamless garment knitting could be considered for mass customization by rapid design changes according to customers' preferences through computerized knitting systems. Seamless knitting systems also may be utilized for sampling prototype and for niche market and limited production items.

#### 4) Value

The inputs of quality, cost, and time contribute to the value of product. The challenge is to optimize the set of relationships in each new product situation to get higher value in the products (Crawford et al., 2003).

The most significant issue in the success of new product development is to understand the needs (spoken and unspoken) of the customer in terms of perceived requirements and to set up a relationship between the customer input and how products

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<sup>10</sup>Mass customization: "Mass customization is the use of technology and management methods to offer product variety and customization through flexibility and quick response"(Onal, 2003).

are designed, produced, and managed (Urban et al., 1993). Voice of the customer (VOC) has been examined by several researchers (Cooper, 2001; Crawford et al.; 2003; Ulrich et al., 2004; Urban et al., 1993). Products can be sold when customers find them to be superior, of higher value, or unique, and when a firm can deliver the perceived benefits more effectively than competitors.

In the knitting industry, customers often desire multi-colored patterns in knitted fabrics and resulting garments. However, it is not easy to create jacquard or intarsia patterning in multiple colors in seamless-knitted garments as regards to considering knitting time, machine complexity and yarn inventory. Several alternate solutions to make multi-color patterning on knitted fabrics or garments may be multi-colored prints or dyeing operation on seamless-knitted garments. This research considers a seamless-knitted and resist-dyeing process as a new technique to produce multi-color patterns.

### **2.3.5. New Product Development Processes**

A new product development process (NPD Process) is defined as “a disciplined and defined set of tasks and steps that describe the normal means by which a company repetitively converts embryonic ideas into salable products or services” (Belliveau et al., 2002, p. 450). Several researchers have developed new product processes for use with assorted products. Especially, Cooper’s Stage-Gate™ process is widely employed by leading companies to drive their new products to market. For instance, Sara Lee, one of major seamless garment manufacturers, has been utilizing a customized staged review process for their product development practice (Powell, 2006). Table 2.5 shows a summary of the new product development processes developed by several scholars. For organizational purposes as well as illustrating how complex new product development

process have become, Urban and Hauser's process was selected as the first product development process in Table 2.5, and each of the activity categories of other new product development processes are aligned vertically.

Each new product development process model in Table 2.5 consists of different process sequences. For example, Urban and Hauser (1993) described a five step decision process model while Trott's (2002) NPD process is composed of eight steps. Nevertheless, all new product development process (NPD) models have similarities in the key activities and functions. Even though all new product development process models use different step terminologies, the process begins with perception of market opportunities and typically involves identification of customers' needs, design development process, product and market testing, and market launch. In addition, all the processes or activities are multidisciplinary within different company organizations. Based on the new product development processes in Table 2.5, a NPD process in the seamless-knitted and resist-dyeing technology will be introduced in Section 2.3.6.

Table 2.5 New product development processes

	1			2		3	4	5	
Urban and Hauser	Opportunity Identification			Design		Testing	Introduction	Life Cycle Management	
Ulrich and Eppinger	Planning	Concept Development		System-Level Design	Detail Design	Testing and Refinement	Production Ramp-up		
Crawford and Di Benedetto	Opportunity Identification & Selection	Concept Generation	Concept/ Project Evaluation		Development		Launch		
Cooper	Discovery	Scoping		Build Business Case	Development	Testing and validation	Launch	Post Launch Review	
Bruce and Biemans	Idea Generation	Screening	Concept Development	Marketing Strategy	Business Analysis	Product Development	Market Testing	Commercialization	
Trott	Idea Generation	Idea Screening	Concept Testing	Business Analysis		Product Development	Test Marketing	Commercialization	Monitoring and Evaluation

Author : Choi, W. (2005). New Product Development and Its Applications in Textiles, *Journal of Textile and Apparel, Technology and Management*, 4(4).

Sources used :

Urban, G. L. & Hauser, J. R. (1993). *Design and Marketing of New Products* (2nd ed.). New Jersey: Prentice-Hall.

Ulrich, K. T. & Eppinger, S. D. (2004). *Product Design and Development* (3rd ed.). New York: McGraw-Hill.

Crawford, M. & Benedetto, A. D. (2003). *New Products Management* (7th ed.). New York: McGraw-Hill.

Cooper R. G. (2001). *Winning at New Products* (3rd ed.). New York: Addison-Wesley.

Bruce, M. & Biemans, W. G. (1995). *Product Development – Meeting the Challenge of the Design-Marketing Interface*. New York: John Willey & Sons.

Trott, P. (2002). *Innovation Management and New Product Development* (2nd ed.). London: FT Prentice Hall.

### 2.3.6. New Product Development (NPD) Process in Seamless-Knitted Shibori Techniques

Using Urban and Hauser's New-Product-and-Service Development process and Cooper's Stage-Gate™ process, as starting points a new product development process for seamless-knitted and resist-dyed garment production is discussed (see Figure 2.54).

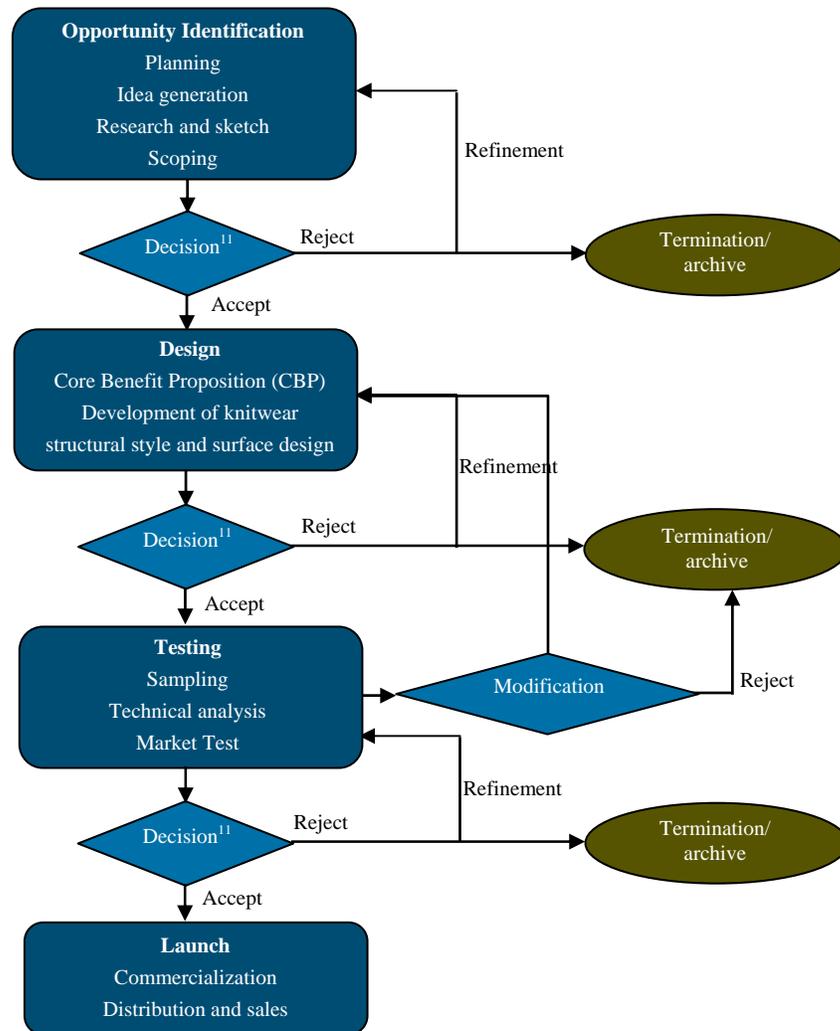


Figure 2.54 A new product development process in the seamless shibori knitting.

Sources used:

Urban, G. L. & Hauser, J. R. (1993). *Design and Marketing of New Products* (2nd ed.). New Jersey: Prentice-Hall.

Cooper R. G. (2001). *Winning at New Products* (3rd ed.). New York: Addison-Wesley.

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

<sup>11</sup>Decision process: Each decision process determines acceptance, termination, or refinement of the project.

## 1) Opportunity Identification

The phase of opportunity identification defines the proper market to enter and discovers creative ideas that generate value for the customers based on the analysis for growth potential, early entry, economic scale, competitive attractiveness, investment, rewards and risk for the new product (Urban et al., 1993). Activities at this stage include primary technical and design research for new possibilities for the market and identification of gaps between the opportunity and real problems in the market (Cooper, 2001). In the scoping process, composed of preliminary market assessment and preliminary technical assessment, a high potential concept can be selected.

The current global textile and apparel market is dominated by China through low priced production costs as well as China's governmental reform and upgrade of industrial systems. In other countries, new product development is required to maintain competitiveness in the textile and apparel industry. Seamless-knitted and resist-dyeing method can be considered an opportunity to enter the global textile and apparel market since it is proposed as a new type of resist dyeing technique using advanced knitting technology. The market for seamless-knitted and resist-dyed production may include sweaters, sportswear, intimate wear, outerwear, medical wear, upholstery, automotive textiles and medical textiles. However, in this research, available equipment including 7 and 8 gauge machines was utilized for experiments which would be more appropriate for fashion outerwear as the proposed market entry.

## 2) Design

The design phase focuses on changing the idea into a physical and psychological entity through engineering, advertising, and marketing and on the development of a Core

Benefit Proposition (CBP) for the product. The Core Benefit Proposition, named by Urban and Hauser (1993), indicates the unique benefits the product not only provides to the customers but also surpasses the competition (Urban et al., 1993). Other significant issues in the design process are how to reduce production cost and to obtain improved performance (Ulrich et al., 2004). This design process encompasses actual detailed design, development of the new product, and the design of the operations or production process based on the Core Benefit Proposition (Cooper, 2001)

Seamless knitting on flat V-bed machines offers assorted advantages to consumers such as better fit and more comfort and consistent quality, and to producers such as improved performance characteristics, quick turn around time, reduced system costs and reduced labor costs. Furthermore, the seamless-knitted and resist-dyed technique gives unique colored patterns on knitted garments. The technique also provides enhanced performance from a seamless garment through more complicated three-dimensional structures by means of knitting machine systems.

### 3) Testing

After an acceptable design is created, the testing process begins. This phase validates the entire feasibility of the project, which involves the product itself, the production process, customer satisfaction, and the economics of the project. A number of activities in this process are lab tests, user or field trial of the product, market testing and revised business and financial analysis (Cooper, 2001). “Testing strategies reduce risk and maximize expected benefits” (Urban et al., 1993, p. 447). The testing activities are crucial since the product must meet customer requirements and expectations (Urban et

al., 1993). This research examined and validated the new possibilities of the seamless-knitted and resist-dyed fabrics and garments through a series of experiments.

#### 4) Launch

If testing is successfully completed, the product can be launched. Launch, or commercialization, has been described as the time or the decision point when firms choose to market a product (Crawford et al., 2003). This launch phase consists of commercialization of the marketing plans and prototypes from the design and development phase and management of the launch program to achieve the goals (Crawford et al., 2003). Marketing and production plans must be aligned, and the timing of launch should be carefully controlled (Urban et al., 1993).

Plant visits and interviews show that Sara Lee and Acme-McCrary, who have already launched seamless knitwear in the market, captured an early market share in their product segment categories such as intimate apparel, sportswear, and others. The companies produce various high quality products, employ diverse trusted brands, and have varied partners, such as Calvin Klein and Nike, to maintain barriers to other competitor's entry. The companies continuously endeavor to repetitively develop innovative products to satisfy the customer needs.

## **Chapter 3. METHODOLOGY**

### **3.1. Objectives**

The objectives of this research are to:

1. explore current seamless knitting technology on flat V-bed machines and evaluate a new possibility for this advanced technology; and
2. review traditional resist dyeing methods and combine resist dyeing procedures with seamless knitting technology. These include:
  - a. evaluation of the possibilities of knit structures appropriate for resist dyeing, and
  - b. analysis of the color entropy (randomness), color contrast and color coverage in different knitted resist structures, and
  - c. examination of different types of yarn applications to create knitted resist-dyed patterns, and
  - d. exploration of more complicated resist textural patterns created on flat V-bed knitting machines, and
3. consider the possibility of shibori knitting for complete garments.

## 3.2. Hypotheses

In order to focus the research objectives, four hypotheses are considered. These are:

- Resist dye patterning can be successfully accomplished on either circular or flat knitting machines through the creation of gathering yarns composed of knit, tuck and float loops, which are utilized to make three-dimensional forms required for resist dyeing.
- Different factors of float length, course distance, and the placement of tuck and float of gathering yarns have a significant relationship to the resist-dyed image.
- The use of each different type of yarn for sample fabrics or gathering yarns can result in different resist effects in color penetration.
- Resist patterns on knitted fabrics can be developed through various complex structures affecting resist-dyed images by computerized flat V-bed knitting machines.

In this research, a variety of three-dimensional knitted structures were explored for resist-dyed patterning. Digitally controlled systems for knitting and dyeing were used to duplicate traditional shibori methods. In addition, numerous different types of resist design knitted patterns were dyed and analyzed through *Grey Level Co-Occurrence Texture Analysis Method (GLCM)* to identify color entropy (randomness), color contrast, and color coverage.

### 3.2.1. Yarns

Two cellulosic fibers, cotton, a natural fiber, and rayon, a manufactured fiber, were utilized to create single jersey fabrics as samples. The two yarns were chosen to

create sample fabrics in this research because cotton and rayon are both cellulosic fibers, thus they can be dyed with the same dyestuffs such as reactive dyes, which obtain reasonable results for each fiber. In addition, it can be recognized how different resist images are achieved according to the use of different types of yarns including a natural and a manufactured fiber.

Cotton has been commonly used to produce knitwear as well as being commonly used in the resist dyeing of woven fabrics. Cotton is a dull fiber with low luster, it has good absorbency, good heat conduction, above-average strength, low resiliency and an elongation of about 3 to 7 percent (Joseph, 1986). Cotton provides soft and comfortable skin contact. However, since cotton is generally harmed by acids, it is required to be scoured after dyeing, but it can withstand strong alkalies (Quinn, 1985). In the initial experiment, one yarn of 8/2 Ne (148 Tex) waxed cotton was utilized to create single jersey fabrics.

Rayon is also a popular choice for knitting because of its drape and luster. Rayon has good absorbency, a higher durability, luster, and a low resiliency (Hollen, Saddler & Langford, 1979). Since rayon has similar chemical properties to cotton, both fibers respond in the same manner to diverse chemical stimuli (Joseph, 1986). Acids also harm rayon more readily than cotton or other cellulosic fibers (Tortora & Collier, 1997). Both cotton and rayon were dyed using fiber reactive dyes in this research. One yarn of 6/1 Ne (99 Tex) ring spun rayon was utilized for the single jersey fabrics. Table 3.1 introduces properties of cotton and rayon.

Table 3.1 Properties of cotton and rayon

Fiber Type	Cotton	Rayon
Molecular structure	Cellulose	Cellulose
Length	0.3 to 5.5 cm	Produced in both filament and staple length
Cross-section	Kidney-shaped	Highly-irregular; serrated edges to almost round
Color	Generally white, may be cream-colored or brown	White
Light reflection	Low luster, dull appearance	Can be produced in dull, semi-dull and bright
Tenacity	3.0 to 5.0 (dry), 3.6 to 6.0 (wet)	Depends on type of rayon. Regular: 2. High-wet-modulus (HWM): 4.5
Stretch and elasticity	3 to 7% elongation at break	Varied with production methods
Resiliency	Low	Low
Abrasion resistance	Fair to good	Low
Dimensional stability	Fabrics may shrink during laundering	Fabrics will relax during laundering, stretch easily during yarn and fabric manufacturing
Effects of bleaches	Highly resistant to all bleaches	Can withstand both oxidizing and reducing bleaches. Attacked by strong oxidizing bleaches
Acids and alkalies	Highly resistant to alkalies. Strong acids or hot dilute acids will cause disintegration.	Easily damaged by strong acids. Hot dilute mineral acid will disintegrate fibers. Concentrated alkalies will cause swelling and reduced strength.
Resistance to stains	Poor resistance to water-borne stains	Poor resistance to water-borne stains
Dyeability	Good affinity for dyes. Dyed with reactive and vat dyes.	Better affinity for dye than cotton. Dyed with reactive and vat dyes.

Source: Smith, B. F. & Block, I. (1982). *Textiles in Perspective*. New Jersey: Prentice-Hall, Inc., p. 75, p. 111.

For a gathering yarn, three different types of yarns were used including spun polyester, shrink polyester and Spandex Lycra®. A gathering yarn in knit shibori requires that it not only needs to be strong enough to be pulled up and easily removed if required but also to have flexibility to be knitted. Polyester composed of any long chain systematic polymer is one of the least absorbent and fairly strong textile fibers. It has good abrasion resistance, fairly good drape, good resistance to wrinkling, and low elasticity (Quinn,

1985). In this research, two polyester yarns, which are 90 Tex spun polyester with the addition of twist and a 768.5 denier (86 Tex) shrink filament polyester with 33 percent elongation and 27 percent shrinkage, were chosen in this research. Spandex Lycra®, a registered trademark for the INVISTA brand, is a synthetic elastic fiber with the highest extension. Spandex Lycra® was selected as one of gathering yarns due to the high elongation. One yarn of 1/840 Dupont’s Spandex Lycra® with 280 percent elongation was used in this experiment. Both shrink polyester and Spandex Lycra® were utilized to create and maintain three-dimensional shapes, and may not be removed. Table 3.2 illustrates the yarn specifications utilized in this experiment.

Table 3.2 Yarn specifications

Use	Fiber Type	Yarn Type	Tex
Fabric samples	Cotton	Spun	148 (8/2 Ne)
	Rayon	Spun	99 (6/1 Ne)
Gathering yarns	Spun polyester	Spun	90
	Shrink polyester	Filament	86
	Spandex Lycra®	covered	94 (with 1/100/34 twist polyester)

According to Spencer (2001), an approximate suitable count for a flat knitting machine may be calculated by the following formula:

$$\text{Worsted count (NeK)} = \text{gauge}^2 / 9 \quad (3.1)$$

(By use of the following formula as; Tex = 885.8 / Worsted count)

Therefore, approximately 163 Tex yarns should be used for the 7 gauge machines. However, in this research, no exact 163 Tex yarns were available to be utilized on the 7 gauge machine.

### 3.2.2. Knitting Machines

A Shima Seiki SES 124-S flat knitting machine and a Shima Seiki SWG-V WholeGarment® flat knitting machine were used in this research. V-bed knitting machines have greater flexibility in loop structure combinations and patterning by means of individual needle selection. A Shima Seiki SES 124-S machine was utilized to conduct multiple sample experiments. A Shima Seiki SWG-V WholeGarment® machine was used to create a final garment based on the sample experiments. Both machines are 7-gauge V-bed flat knitting machines, which employ latch needles with transfer springs. To prove the possibility of resist-dyeing of fabrics knitted on circular knitting machines, an 8-gauge Fukuhara Monarch machine, which employs latch needles, was also utilized. Table 3.3 describes specifications for the two Shima Seiki V-bed flat knitting machines and the one Fukuhara Monarch circular knitting machine.

Table 3.3 Specifications of knitting machines

Machine manufacturer	Shima Seiki	Shima Seiki	Fukuhara
Machine type	Computerized V-bed flat knitting machine	Computerized V-bed flat knitting machine	Circular knitting machine
Machine model	SES 124-S fully-fashioned	SWG-V WholeGarment®	Monarch single knit
Machine gauge	7	7	8
Needle type	Latch needle with transfer spring	Latch needle with transfer spring	Latch needle
Knitting speed	Up to 1.00 meter per second	Up to 1.30 meters per second	Up to 18 rpm
Knitting Width	About 47 inches (120 cm)	About 72 inches (183 cm)	26 inch diameter

### 3.2.3. Tightness Factor

The number of the tightness factor (TF) indicates the extent to which the area of a knitted fabric is covered by the yarn. It is also used to identify the relative tightness or looseness of the plain weft knitted structure (McIntyre et al., 1997). Munden defined the tightness factor as the ratio of the area covered by the yarn in one loop to the area occupied by the loop (Spencer, 2001, see Equation 3.2).

$$\text{Tightness Factor (TF)} = \frac{\sqrt{\text{Tex}}}{\text{Loop length (cm)}} \quad (3.2)$$

In this research, to identify the relationship between tightness factor for weft knitted fabrics and the clarity of the resist-dyed pattern image, three different loop lengths (tight, medium and loose), were evaluated for each hypothesis as can be seen as Tables 3.4 and 3.5. Yarns used to knit the single jersey samples were cotton and rayon, which were 148 and 99 Tex respectively. A total of 120 courses and 120 wales were knitted for each sample fabric.

#### Factor 1.

Table 3.4 Tightness factors for 8/2 Ne cotton (148 Tex) according to different loop lengths

Single Jersey							
Loop length (Shima Seiki)	Sample width (inches)	Sample length (inches)	Weight (grams)	Course per inch	Wales per inch	Loop length (cm)	Tightness Factor (TF)
Tight (7)	12.75	8.25	18.8	16	11	0.9	13.52
Medium (9.5)	18.25	15.00	25.5	8.5	10	1.2	10.14
Loose (12)	22.50	21.25	31.8	7	8	1.5	8.11

( ): Variables for the loop lengths provided from Shima Seiki.

Table 3.5 Tightness factors for 6/1 Ne rayon (99 Tex) according to different loop lengths

Single Jersey							
Loop length (Shima Seiki)	Sample width (inches)	Sample length (inches)	Weight (oz)	Course per inch	Wales per inch .	loop length (cm)	Tightness Factor (TF)
Tight (7)	14.25	9.50	12.4	14	10	0.85	11.71
Medium (9.5)	18.50	16.25	16.8	10.5	8.5	1.2	8.29
Loose (12)	26.25	23.00	20.6	7.5	7.5	1.5	6.63

### 3.2.4. Process

Each sample composed of different structures was knitted for a total of 120 courses by 120 wales. After knitting, following the Dystar™ dyeing standard Ramazol® dyes (see Table 3.6), the samples were dyed for 30 minutes in the skein dyer with 3 percent dye, 60 grams per liter of salt for cotton (50 grams per liter of salt for rayon) and 5 grams per liter of soda ash at a temperature of 140 Fahrenheit.

Table 3.6 Dye, salt and alkali recommendations for Ramazol® dyeing process at 140 Fahrenheit

Liquor ratio = 10:1								
Dye	%	< 0.1	0.5	1	2	<b>3</b>	5	7
Salt for cotton	g/l	20	30	40	50	<b>60</b>	70	80
Salt for mercerized cotton and rayon	g/l	10	30	30	40	<b>50</b>	50	50
Soda ash	g/l	5	5	5	5	<b>5</b>	5	5

Source: Dystar. (2006). *Dyeing with Levafix® and Remazol® Dyes*. NC: Dystar L.P., p. 12.

After the dyeing process, the fabric samples can be washed and rinsed using either synthetic detergents or natural soaps as a finishing process. The knitted and resist-dyed

samples were evaluated for each hypothesis. The Epson™ Perfection 3200 Photo flat scanner was used to scan the images of each sample fabric. The center point of the knitted and dyed sample was located, then a six inch (width) by six inch (height) centered square was scanned at 300 dpi (dot per inch) resolution. The data for the color contrast, color randomness and color coverage of the images in the knitted and dyed fabric samples were calculated using the ImageJ, which is a public domain Java image processing and analyzing program. The data were based on the *Grey Level Co-Occurrence Texture Analysis Method (GLCM)*, developed by Harallick et al. (1973). According to Jaganathan (2005), the model defines a variety of texture properties of the image based on the Grey-Tone Spatial Dependence Matrices. If a rectangular image, which has  $N_x$  cells in the horizontal direction and  $N_y$  cells in the vertical direction, is considered, they have a discrete gray tone value  $N_g$ . A relative frequency  $P_{ij}$  with two neighboring resolution cells separated by distance  $d$  can be defined. One with gray tone  $i$  and other gray tone  $j$ . Through the variables, the following equations can be achieved:

$$\text{Entropy} = -\sum \sum P_{ij} \log(P_{ij}) \quad (3.3)$$

$$\text{Contrast} = \sum_{n=0 \text{ to } N_g} n^2 \left\{ \sum \sum P_{ij} \right\} \quad (3.4)$$

Color randomness can be calculated by entropy (Equation 3.3) of intensity of an image for a sample. Variables of contrast are achieved by the Equation 3.4. Additionally, the percentage of black and white pixels in the image is measured through the ImageJ software. The variables for color contrast, randomness and coverage are calculated through the ImageJ software.

In this research, to measure color contrast, color randomness and color coverage in Hypotheses 2 and 3, scanned images were opened as 8-bit gray tone in the ImageJ software (see Figure 3.1a). After the process, it is required to open the “Plugins” and to click the “GLCM Texture” to get numeric results for color contrast and color randomness of the scanned image (see Figure 3.1b). Through the automatic calculation through the ImageJ program, the results for the color contrast and color randomness can be achieved (see Figure 3.2). In order to get numeric results for color coverage, it is needed to open the “Analyze” and click the “Histogram” in the ImageJ software (see Figure 3.3a), then the results can be obtained (see Figure 3.3b).

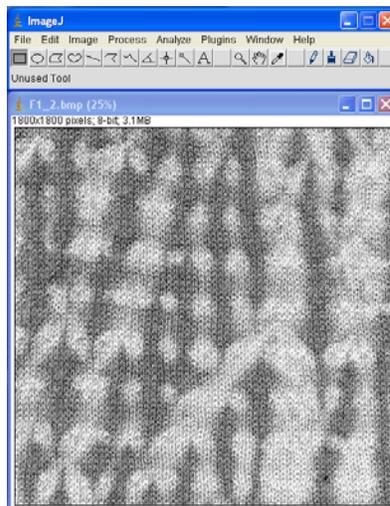


Figure 3.1a An ImageJ software.

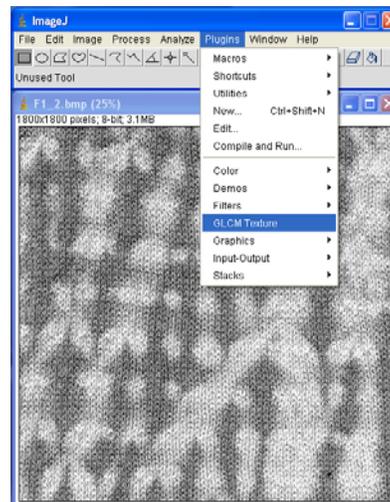


Figure 3.2b Selection of the “GLCM Texture”.

Figure 3.1 ImageJ software program to get numeric results for color contrast and randomness.

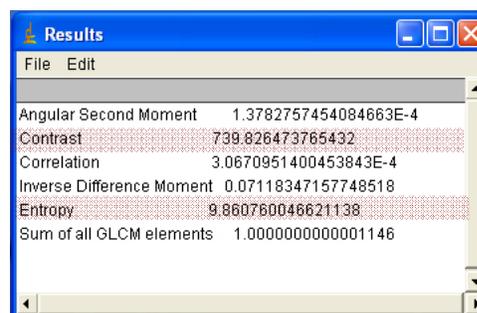


Figure 3.2 Results for color contrast and randomness in ImageJ software.

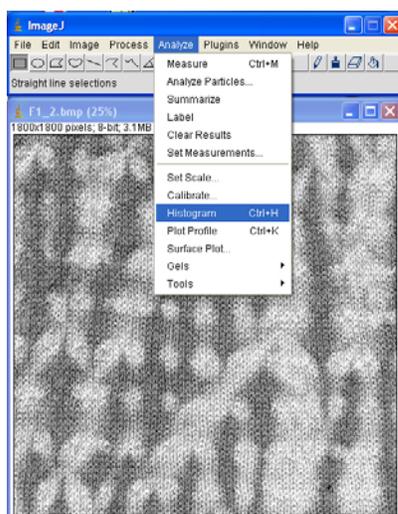


Figure 3.3a Selection of the “Histogram”.

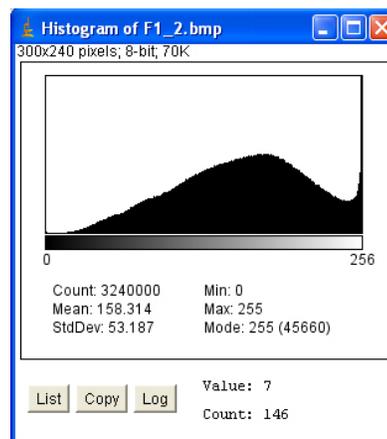


Figure 3.3b Results for color coverage in ImageJ software.

Figure 3.3 Numeric results for color coverage in ImageJ software.

However, it is noted that in this research, all knitted samples except those used to validate Hypothesis 4 were limited to single jersey constructions and focused on the stitched-resist structures by using gathering yarns. Only one color dyestuff (DyStar™ Remazor® reactive blue 19) was utilized in this series of samples, but multiple dyeings may be applied for a multi-colored final garment. The Remazor® reactive blue 19 has a documented record of uneven dyeing or unlevel dyeing. In this research, the objective was to intentionally seek an unlevel dye penetration and as such this particular Remazor® dyestuff was selected.

### 3.3. Application of Methodology for Verification of Hypotheses

As indicated earlier, this section examined utilization of the previous approaches and instruments to test the hypothesis.

### 3.3.1. Hypothesis 1

- **Resist dye patterning can be successfully accomplished on either circular or flat knitting machines through the creation of gathering yarns composed of knit, tuck and float loops, which are utilized to make the three-dimensional forms required for resist dyeing.**

Most resist patterning has been traditionally created on woven fabrics or garments and has generally been sewn or manipulated by hand. A major purpose of this hypothesis was to identify the possibilities of seamless-knitted and resist-dyed fabrics or garments created on circular or flat knitting machines. To achieve this hypothesis, there is a need to introduce the fundamental principle of the knitting structures required to create resist patterns. The principles underlying the knitted resist patterns depends on gathering yarns, which are used to gather up a fabric by pulling up the yarns for resist dyeing. On knitting machines, through floating and tucking processes, pleated or gathered structures can be created for resist dyeing. It is noted that in order to permanently secure gathering yarns, float jacquard structures, composed of knit, tuck and float loops, also can be considered. The following steps describe a resist (shibori) knitting process to pleat or gather up a sample fabric using electronic knitting equipment:

1. Create a single-jersey knitted sample or a seamless tubular knitted garment on circular or flat knitting machines incorporating the placement of gathering yarns;
2. Float with a tuck loop on a selected needle for the next row to create gathering yarns, which can make a “shibori” effect when pulled up and dyed. Gathering yarns for shibori effects can be also achieved by use of float jacquard structures, composed of knit, tuck and float loops;

3. Effectively repeat step 1 and step 2 to create the “shibori” structures;
4. Pull up the gathering yarns on the sample fabric;
5. Dye the samples, one or more times;
6. Remove gathering yarns or permanently secure yarns in the fabric structure.

Figures 3.4 to 3.5 illustrate loop notations for the process to create gathering yarns for a single jersey fabric and a seamless tubular knitted garment. Gathering yarns created by use of tuck and float loops can be removed after the dyeing process (see Figures 3.4 and 3.5). On the other hand, gathering yarns consisting of a float jacquard structure should be permanently secured in the fabric structure after the dyeing operation (see Figures 3.6 and 3.7). A knitted fabric with gathering yarns consisting of a float jacquard structure will have major holes when the gathering yarns are removed. A 7-gauge Shima Seiki V-bed flat knitting machine and an 8-gauge Fukuhara Monarch single-knit circular machine were utilized to evaluate this hypothesis.

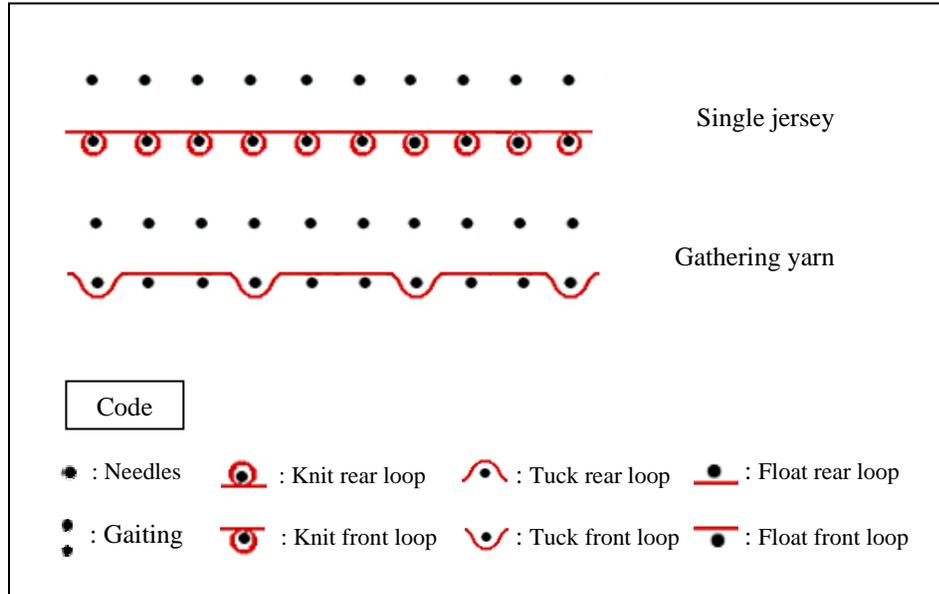


Figure 3.4 Loop notation for the process of creating gathering yarns consisting of tuck and float loops for a single jersey fabric on the flat bed machine.

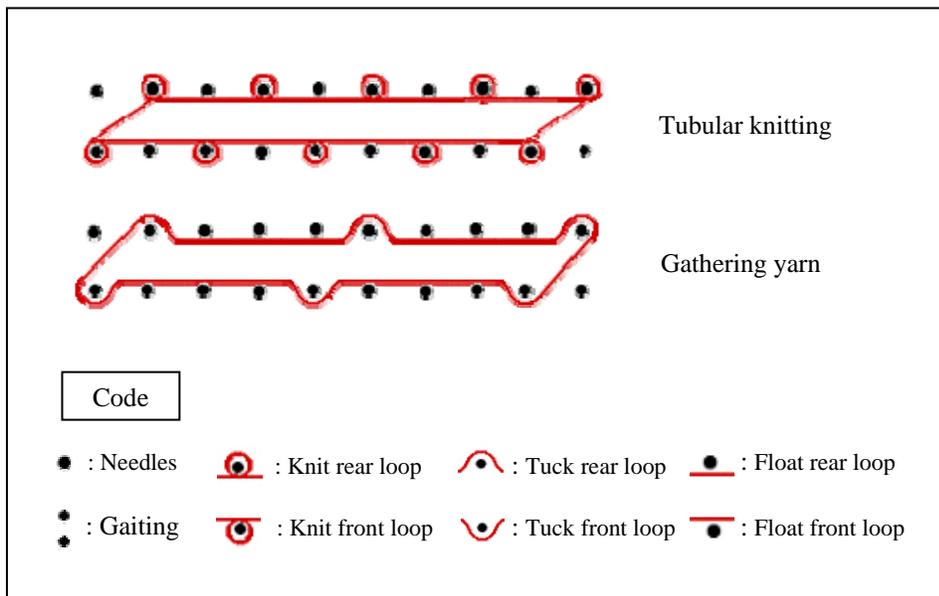


Figure 3.5 Loop notation for the process of creating gathering yarns consisting of tuck and float loops for a seamless tubular knitted garment on the flat bed machine.

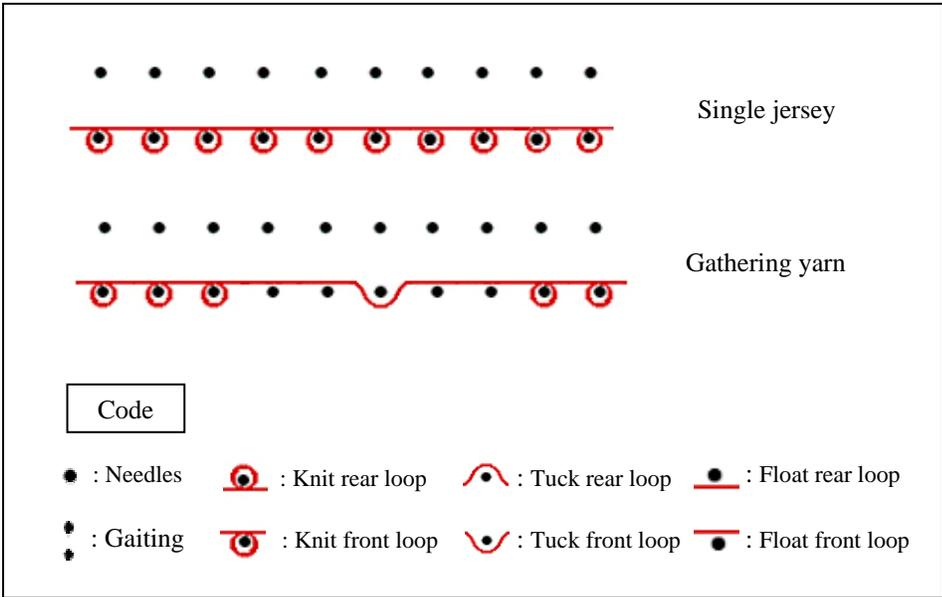


Figure 3.6 Loop notation for the process of creating gathering yarns consisting of a float jacquard structure for a single jersey fabric on the flat bed machine.

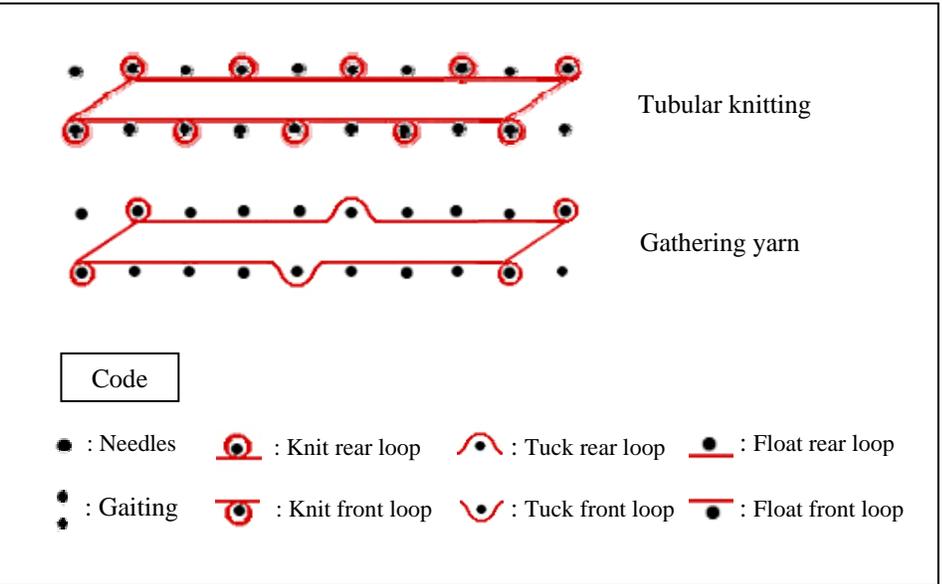


Figure 3.7 Loop notation for the process of creating gathering yarns consisting of a float jacquard structure for a seamless tubular knitted garment on the flat bed machine.

### 3.3.2. Hypothesis 2

- **Different factors of float length, course distance, and the placement of tuck and float of gathering yarns have a significant relationship to the resist-dyed image.**

This hypothesis observed the relationship between the different factors and resist dyed image, related to color contrast, color randomness and color coverage. It also studied the interrelations between the different factors. In Hypothesis 2, 100% 8/2 Ne (148 Tex) cotton was chosen as the sample fabric, and 100% 90 Tex polyester was used for the gathering yarns. Four different factors, including three different tightness factors (Factor 1, see Tables 3.4), three different float loop lengths in a gathering yarn (Factor 2), three different course distances for each gathering yarn (Factor 3) and three different placements of tuck and float loops (Factor 4) were included in the experiment (see Figures 3.8, 3.9 and 3.10). Also, 2 samples for each factor were examined. Hence, a total of 162 samples (i.e., 2 samples \* 3 different loop lengths \* 3 different float loops \* 3 different gathering yarn distances \* 3 different placements of tuck and float loops) were randomly selected, knitted, dyed and evaluated. However, in this hypothesis, only a tuck & float loop structure was explored as a gathering yarn. In future research, a float jacquard structure could also be expected to be analyzed.

**Factor 2.**

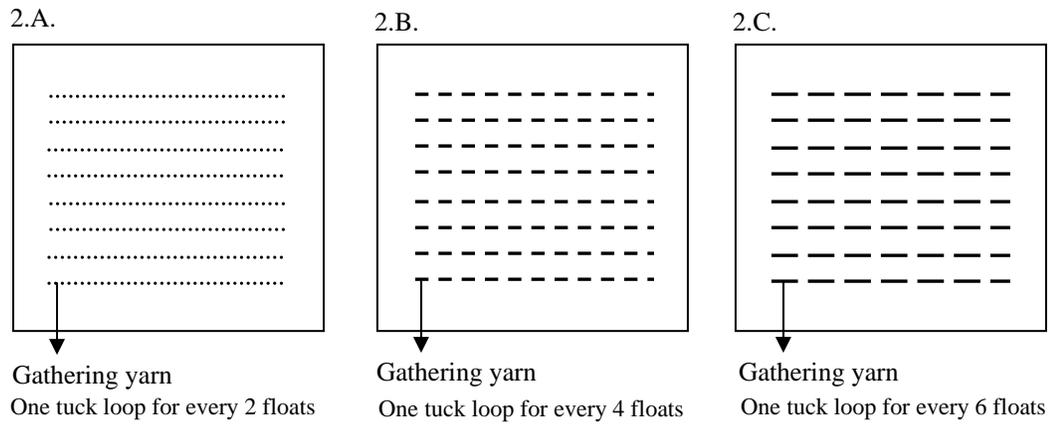


Figure 3.8 Knit samples with three different float loops of gathering yarns.

**Factor 3.**

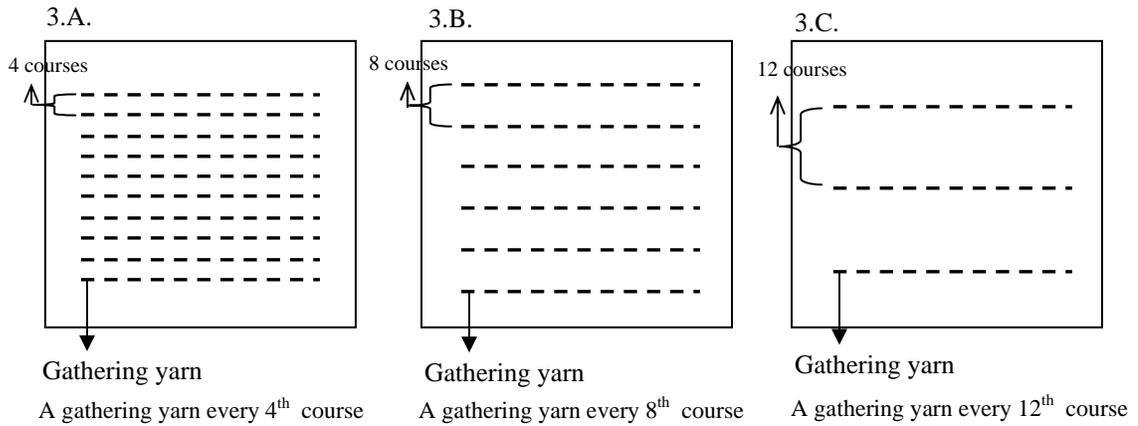


Figure 3.9 Knit samples with three different gathering yarn distances.

**Factor 4.**

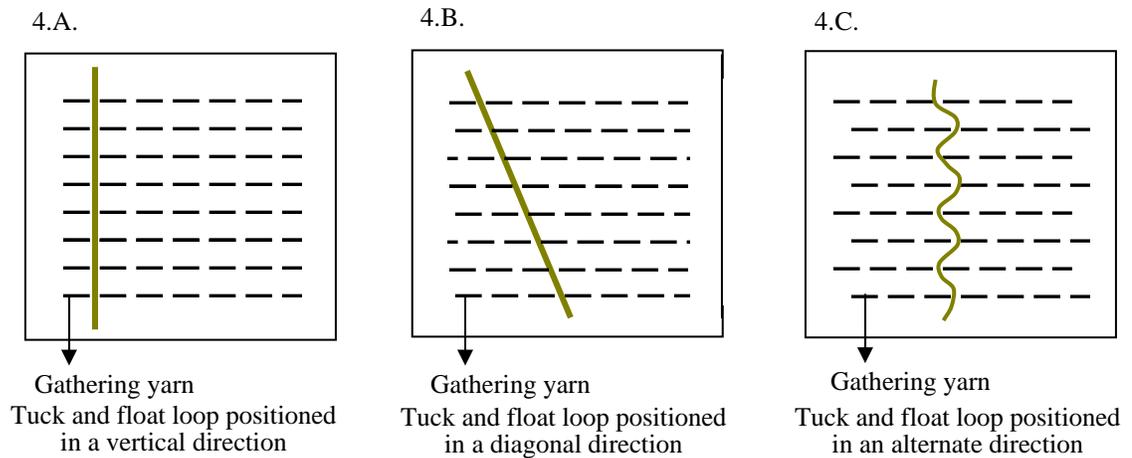


Figure 3.10 Knit samples with three different placements of tuck and float loops.

### 3.3.3. Hypothesis 3

- **The use of each different type of yarn for sample fabrics or gathering yarns can result in different resist effects in color penetration.**

Gathering yarns may be removed or permanently secured in the fabric structure after immersion dyeing. Therefore, it is necessary to choose appropriate yarns as the gathering yarns should create effective resist-dyed structures through the pleating of fabrics as well as pull out easily. In this section, three different gathering yarns including spun polyester, shrink filament polyester and Spandex Lycra® as an elastomeric yarn were assessed. According to shrinkage of yarns including shrink polyester and Lycra® compared to non-shrink polyester, it was evaluated how the shrinkage of gathering yarns affects resist-dyed images. Fiber content of the knitted sample fabrics, cotton or rayon in this experiment, also impacted resist-dyed patterns. According to the shrinkage, density, flexibility, light reflection, softness and dyeability of the sample fabric, resist-dyed patterns may have different results. In this hypothesis, cotton, a natural fiber, and rayon, a manufactured cellulosic fiber, were evaluated in the sample fabrics. Three factors, including two different yarns used in the base sample fabrics (Factor 1), three different yarns used as gathering yarns (Factor 2) and two different gathering yarn structures (Factor 3), were analyzed (see Table 3.7). Two samples for each factor were also evaluated. Thus, a total 24 samples (i.e., 2 samples \* 2 gathering yarn types \* 2 yarns used as sample fabrics \* 3 yarns used as gathering yarns) were randomly selected, knitted, dyed and evaluated. It is noted that the experiment in Hypothesis 3 was conducted for the optimum situation of the knitted structures for Hypothesis 2.

Table 3.7 Resist dyeing test in different yarn structures of sample fabrics and gathering yarns

Sample fabrics Gathering yarns	Single jersey				Factors
	Cotton		Rayon		Factor 1
	Float jacquard	Tuck & float	Float jacquard	Tuck & float	Factor 3
Spun polyester					Factor 2
Shrink filament polyester					
Elastomeric (Lycra®)					

To test Hypothesis 3, ANOVA (Analysis of Variance) was utilized. According to Ott and Longnecker (2001), in ANOVA, “All differences in sample means are judged statistically significant (or not) by comparing them to the variation within samples” (p. 384). Through ANOVA, significant relationships between each factor in Hypothesis 3 were evaluated. It is noted that the statistical results in Hypothesis 3 were calculated and analyzed through the SAS® software, which performs a statistical calculation.

#### 3.3.4. Hypothesis 4

- **Resist patterns on knitted fabrics can be developed through various complex structures affecting resist-dyed images by computerized flat V-bed knitting machines.**

Through varied knitting techniques including flechage, loop transference, purl structures, intarsia knitting or held loop structures, more complicated resist-dyed patterns were explored. In this experiment, cotton and wool (to make use of shrink/felting of the wool yarns) were used as fabric fiber/yarn, and spun polyester was used as the gathering yarns. Three different sections of advanced techniques are introduced.

## 1) Float Patterning

By use of techniques such as flechage or loop transference, diagonal resist patterns, undulating patterns, or diamond motifs were explored.

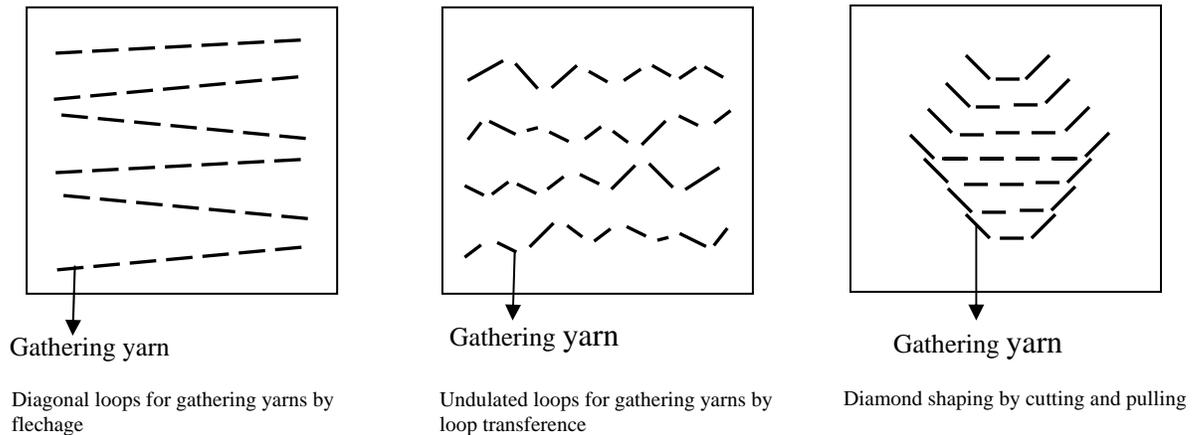


Figure 3.11 Knit samples with diagonal, undulating (irregular), or diamond resist patterns for gathering yarns.

A flechage technique could be utilized to produce diagonal loops for gathering yarns (see Figure 3.11). Flechage is a technique which is executed with variable row knitting. Each row of stitches can be connected by tuck loops. Thus, a course for a gathering yarn can be knitted between diagonal rows.

One of the methods of creating undulated design structures can be achieved by loop transference. One area where all loop transferences occur in one direction and another area where all loop transferences occur in the opposite direction will build undulating knit structures. Through this knitting method, gathering yarns with undulating patterns can be achieved. A diamond shaped gathering structure by diagonally cutting the gathering yarns also can be created (see Figure 3.11). Gathering yarns knitted in a horizontal direction can be selectively cut in various geometric shapes and gathered up. Then, it can be resist-dyed.

## 2) Three-dimensional Knit Binding

By the use of specific techniques such as purl/rib or intarsia knitting, many types of three-dimensional structures can be knitted. The patterns can be utilized to conduct tie-dyeing by a binding process (see Figure 3.12).

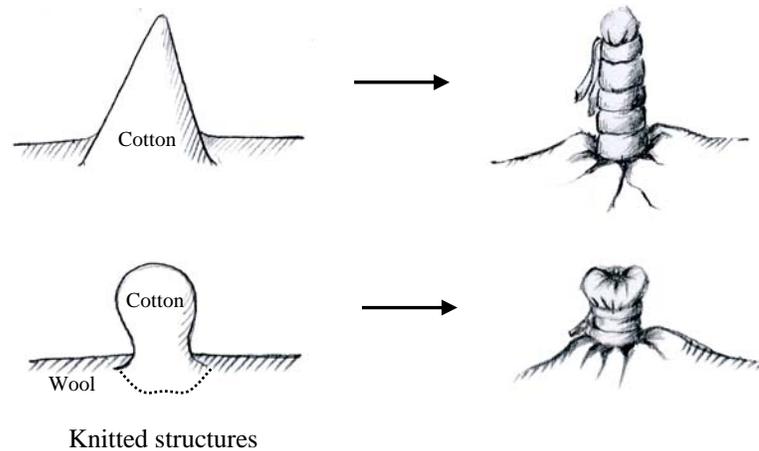


Figure 3.12 Knit samples with three-dimensional structures for bound dyeing.

\* Gathering yarns are not utilized in these techniques.

In fact, by knitting together the two structures, a jersey (face loop only) and a reverse jersey (rear loop only), interesting knit-structural effects can be achieved. On the vertical lines, a face loop is raised, and a rear loop is lowered. This creates a rib structure. On the horizontal lines, a rear loop is raised and a face loop is lowered. This creates a purl structure (see Figure 3.13). As a result, various three-dimensional structures can be created by effectively using the two structures. After creating a three-dimensional fabric, a binding process is applied to produce tie-dye fabrics. It is noted that the binding process is performed by hand.

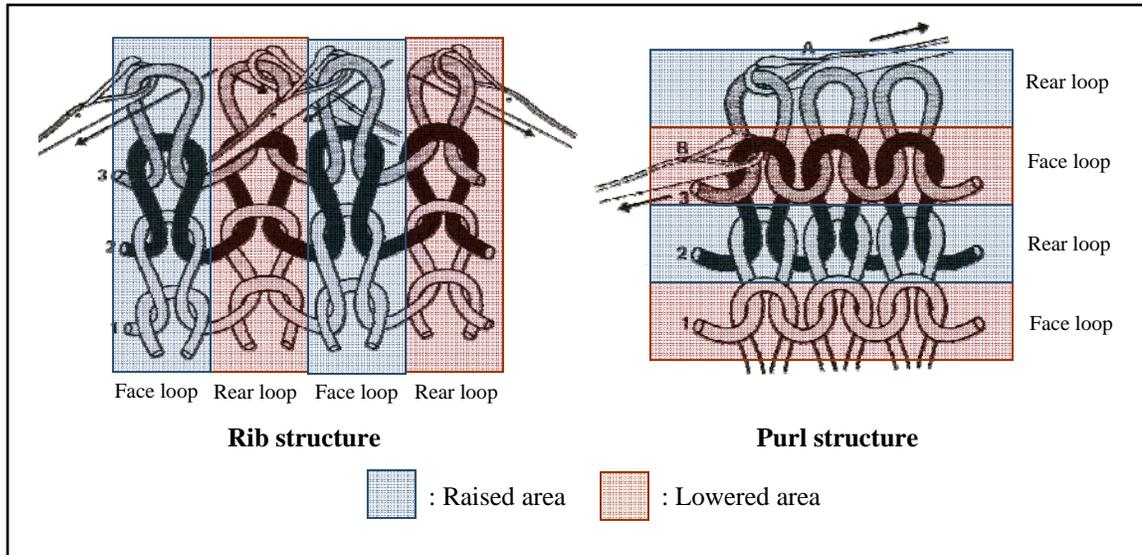


Figure 3.13 Rib and purl structures.

Source: Spencer, D. (2001). *Knitting Technology, a Comprehensive Handbook and Practical Guide* (3rd ed.). Cambridge: Woodhead Publishing Limited, p. 69, p. 77.

Two different types of yarns, which have a high shrinkage (wool) and a low shrinkage (cotton) characteristic, can be also utilized to make a three-dimensional structure (see Figure 3.14). When wool, made of protein, absorbs water under pressure, it is chemically entangled and bonded. When wool fiber has fully bonded, it forms a rigid felt fabric (Vickrey, 1997). However, cotton does not have felting characteristics. After the felting of the intarsia fabric constructed of wool and cotton, the shrunken area of felted wools forces to non-felted cotton fabric to rise. This cotton fabric protrusion can be bound to create a shibori fabric. Thus, the two different characteristics of the two yarns create a three-dimensional structure.

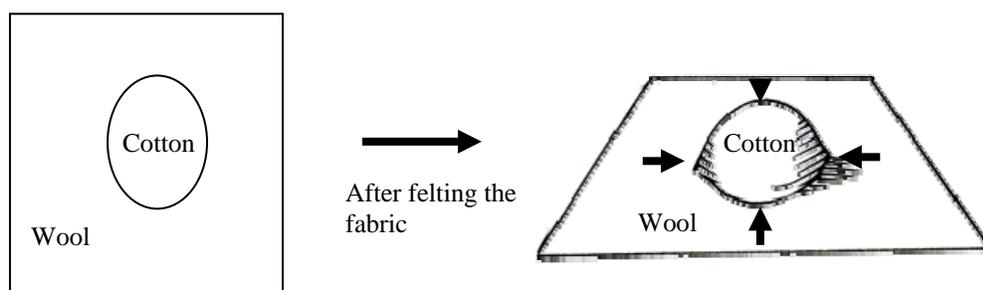


Figure 3.14 Three-dimensional structure created through different yarn characteristics.

### 3) Folding

By the use of techniques such as rib or held loops, folded or pleated structures can be developed. By rib and jersey/reverse jersey structures, a pleated fabric can be created. A shibori fabric can be achieved by a clamping process after creating the permanent pleated fabric (Sample 1 in Figure 3.15). The horizontal tubular pattern created by held loop structures was used for resist dyeing by gathering yarns (Sample 2 in Figure 3.15).

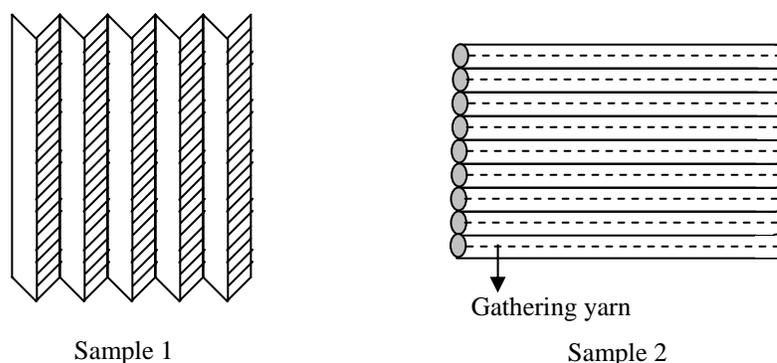


Figure 3.15 Knit samples with three-dimensional structures for fold dyeing.

For Sample 1, in Figure 3.15, according to the changes of positions for jersey or reverse jersey on the all needle knitting (rib) structure, various types of pleated knit structures can be achieved (See Figure 4.31). Also, for Sample 2, in Figure 3.15, by use

of jersey on all needle knitting (rib) structure, a pleated knit fabric by held loop structures can be created (See Figure 4.34). After knitting, the folded or pleated areas can be selectively controlled or stabilized in place during dyeing by means of yarns, cords, clips, wooden strips or plastic wrap. All knitting and dyeing processes for Hypothesis 4 are explained in Chapter 4 in a more detail.

## **Chapter 4. RESULTS AND DISCUSSION**

### **4.1. Hypothesis 1: Resist-Dyed Patterning Created on Circular or Flat Machines**

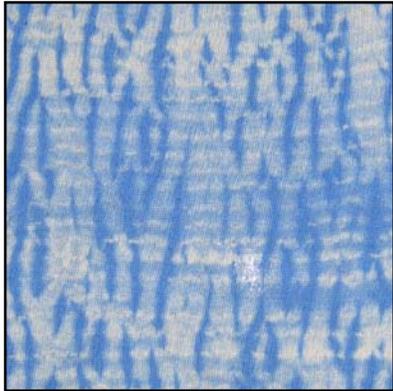
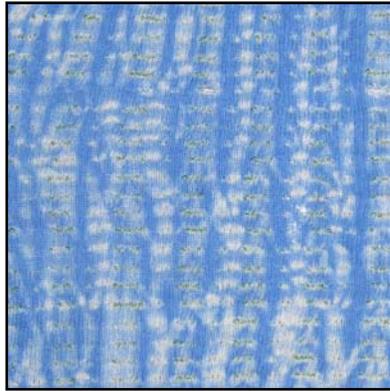
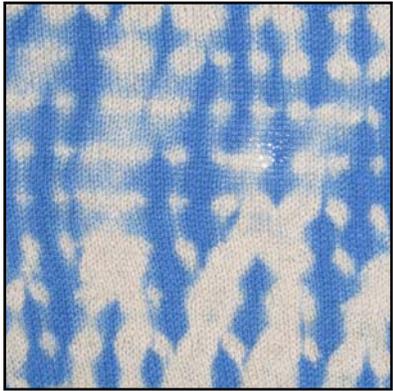
- **Resist dye patterning can be successfully accomplished on either circular or flat knitting machines through the creation of gathering yarns composed of knit, tuck and float loops, which are utilized to make the three-dimensional forms required for resist dyeing.**

In Hypothesis 1, six different possibilities of resist-dyed patterning on a circular knitting machine and two flat knitting machines, including a fully-fashioned flat machine and a complete garment flat machine, were examined. Table 4.1 shows the dyed images for the each different knitted pattern. For samples created on circular knitting machines, because of the different needle gauge (8 gauge), 100% 10/1 Ne (59 Tex) cotton was used to create sample fabrics, and 50 Tex cotton-covered<sup>12</sup> polyester, used for serging or overlocking raw edges, was used to create gathering yarns.

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<sup>12</sup> Covered yarns: “Covered yarns consist of a readily separable core surrounded by wrap or cover formed by one or more spun or filament yarns” (Hatch, 1993, p. 300).

Table 4.1 Resist dyed patterns created on circular and flat knitting machines

		Gathering Structure	
		Tuck & float	Float jacquard
Machine	Monarch 8 gauge circular knitting machine		
	Shima Seiki SES- 124S 7 gauge fully fashioned flat knitting machine		
	Shima Seiki SWG-V 7 gauge whole garment flat knitting machine		

As can be seen in Table 4.1, all experiments for six different possibilities of resist dye patterning on circular and flat knitting machines were successfully achieved. In addition, Table 4.1 shows that both tuck & float structures and float jacquard structures have the capability to create resist patterns. Tuck & float structures as a gathering structure are composed of tuck and float loops. They are used to gather up knitted fabric for resist dyeing. After resist dyeing, in a fabric with tuck & float structures in the gathering yarns, the gathering yarns can be taken out of the sample fabric. On the other hand, float jacquard structures are typically utilized to create accordion fabrics<sup>13</sup>. However, in this research, float jacquard structures were used to create gathering yarns to gather or pleat a fabric for resist dyeing. After resist dyeing, float jacquard structures are permanently secured in the sample fabric. Attempting to remove these gathering yarns would result in damaged fabric.

Additionally, in Table 4.1, it can be recognized that the resist-dyed patterns created on the circular knitting machine are smaller in scale than the patterns created on the V-bed flat knitting machine. It is because the gauge (8 gauge) of circular knitting machine used in this experiment is finer than the gauge (7 gauge) of V-bed flat knitting machines. Due to the difference in knitting machines, the yarn sizes utilized on the circular knitting machine were also finer compared to those utilized on the flat knitting machines. The patterns on each knitted structure for gathering yarns were comparable even though they have a difference in pattern dimensions. It is important to identify that patterns can be changed according to each knitted structures for sample fabrics or gathering yarns.

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<sup>13</sup>Accordion fabric: “Accordion fabric is single jersey with the long floats held in place on the technical back by tuck stitches” (Spencer, 2001, p. 107). The accordion structure is composed of knit, tuck and float loops.

Figure 4.1 depicts a three-dimensional seamless-knitted and resist-dyed sample for the tuck & float structure created on the Shima Seiki SWG-V WholeGarment® machine. The figure illustrates the resist-dyed patterns in four different directions. As can be seen in Figure 4.1, the patterns do not show up exactly the same. However, each pattern viewed from four different viewpoints around the tube still has comparable or related patterns. By evaluating scans of these images, percentage of color coverage suggests similar levels of dyed resist and penetration.

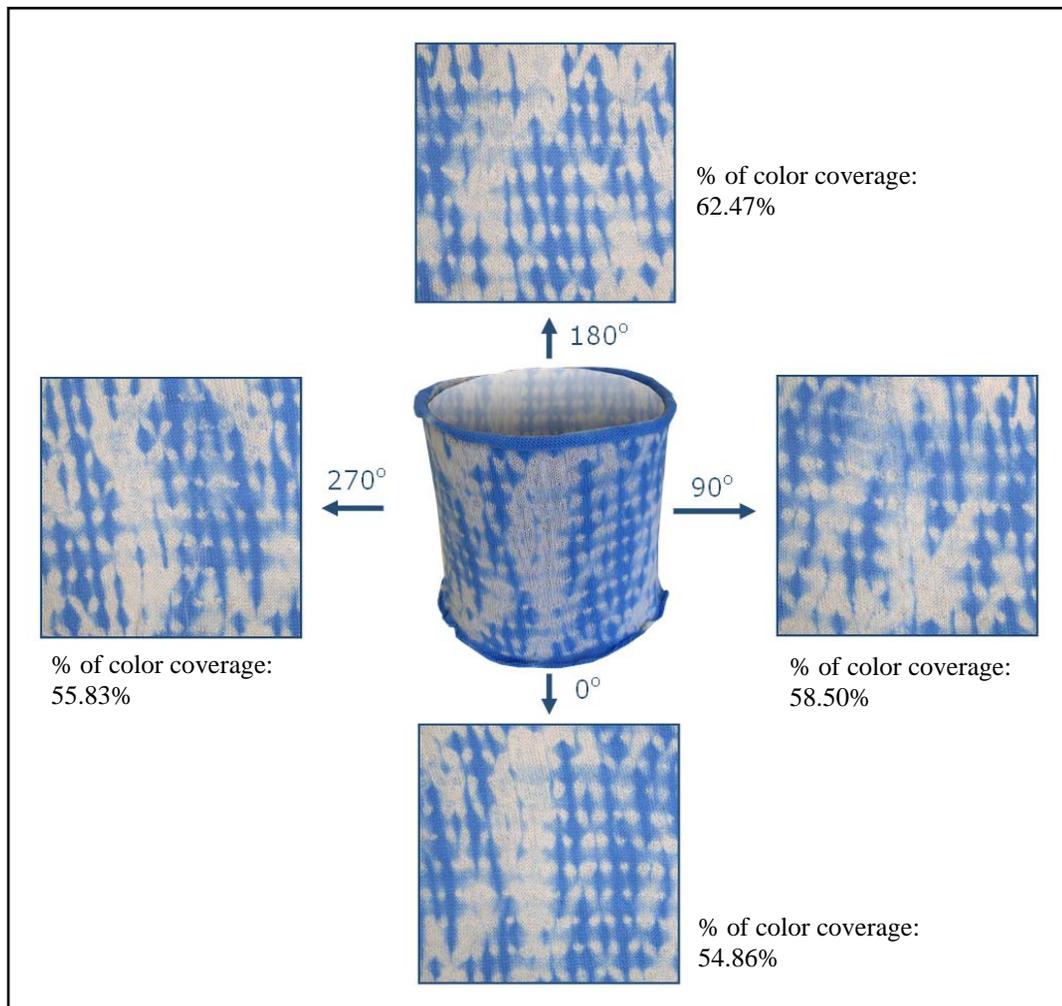


Figure 4.1 A three-dimensional seamless knitted and resist-dyed sample.

As a result, Hypothesis 1, which evaluated resist dye patterning created on circular or flat machines, was accepted. The result shows that resist dye structures can be created on weft knitting machinery, including either circular or flat V-bed knitting machines.

#### **4.2. Hypothesis 2: Resist-Dyed Patterning according to the Different Knitted Structures**

- **Different factors of float length, course distance, and the placement of tuck and float of gathering yarns have a significant relationship to the resist-dyed image.**

The purpose of Hypothesis 2 was to identify the relationship for resist dyed images according to the four different situations of knitted structures. 162 samples including the four different factors were randomly knitted on the Shima Seiki SES-124S fully fashioned machine, and all knitted and gathered-up samples were dyed in the Then® skein dyer with the same dyestuff (3% of Ramazol® blue 19) at the same time. However, after all samples were simultaneously dyed, it was recognized that the all samples were not evenly dyed according to the following sample positions in the skein dyer as can be seen as the Figure 4.2. Among all dyed samples, samples that have over 50% resist patterns totaled 54 samples, samples that have 20-50% resist patterns included 34 samples, and the rest of them, samples that have under 20% resist patterns numbered 74 samples.

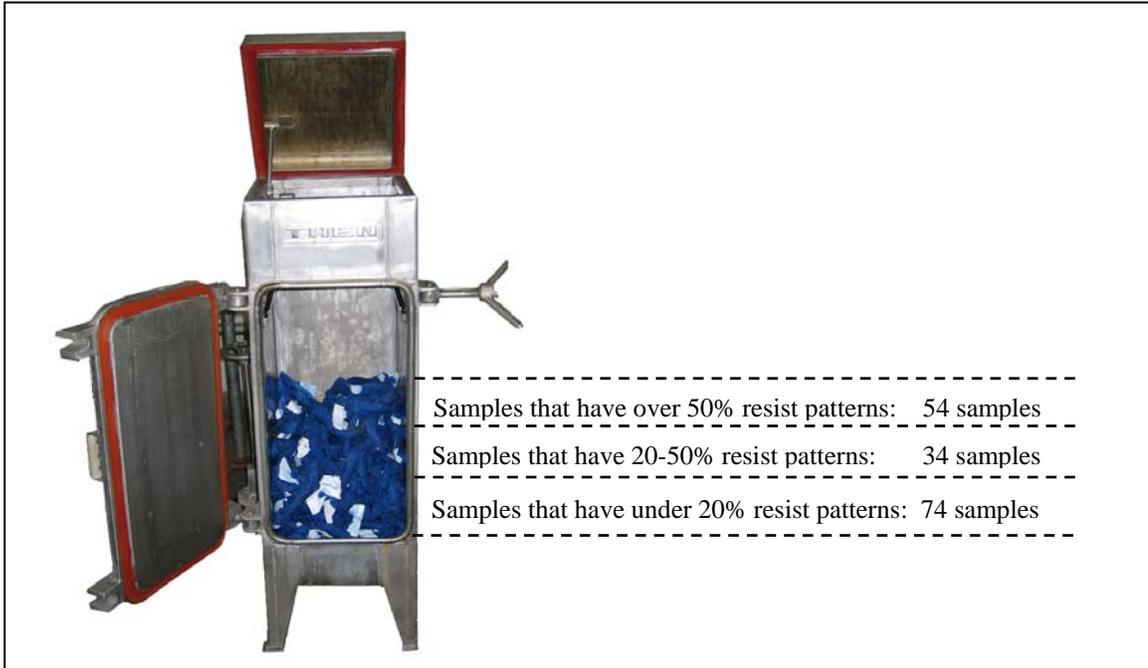


Figure 4.2 Samples in the Then® skein dyer after resist dyeing.

Tables 4.2 to 4.4 demonstrate numeric results about color contrast, color randomness and color coverage for the samples that have over 50% resist-dyed patterns measured by the ImageJ software.

However, as can be seen in Tables 4.2 to 4.4, the variables for each factor do not have a statistical relationship. Even though the sample fabrics had the same knitted structures, after dyeing the numeric results for the dyeing absorption of the resist patterning created were too different. The samples were also dissimilar in appearance. This means that even if the same knitted structures were simultaneously dyed in the same skein dyer, according to the position of the knitted samples in the skein dyer, dye penetration was differently conducted.

\* A higher number means that it has a higher contrast. (The results for the first sample/the results for the second sample)

Table 4.2 Numeric results for the color contrast for samples that have over 50% resist patterns

Float loops	Course distances	Placement of tuck & float	Tightness Factor (TF)		
			Tight	Medium	Loose
2 floats	4 courses	Vertical	647.957	748.537	-
		Diagonal	602.478	632.191	-
		Alternate	-	-	530.875/600.625
	8 courses	Vertical	530.000	601.344	720.706/460.642
		Diagonal	-	506.258	-
		Alternate	512.132	536.841	-
	12 courses	Vertical	802.588	-	463.385
		Diagonal	-	-	-
		Alternate	455.626	-	-
4 floats	4 courses	Vertical	498.314	483.071	400.682
		Diagonal	558.853	529.048/684.505	641.170/534.586
		Alternate	-	-	708.828
	8 courses	Vertical	473.01	-	427.381
		Diagonal	-	-	457.641
		Alternate	565.276	-	558.082
	12 courses	Vertical	493.756	963.125/793.431	565.944
		Diagonal	563.430	-	-
		Alternate	-	402.019	464.888
6 floats	4 courses	Vertical	492.775	932.559	341.340
		Diagonal	538.578	812.191/959.999	761.688
		Alternate	553.302	-	-
	8 courses	Vertical	534.807	-	-
		Diagonal	433.160	561.781/815.731	-
		Alternate	456.641	536.753	-
	12 courses	Vertical	542.643	-	-
		Diagonal	-	-	-
		Alternate	528.185	557.608	-

\* A higher number means that it has a higher randomness. (The results for the first sample/the results for the second sample)

Table 4.3 Numeric results for the color randomness for samples that have over 50% resist patterns

Float loops	Course distances	Placement of tuck & float	Tightness Factor (TF)		
			Tight	Medium	Loose
2 floats	4 courses	Vertical	9.710	9.622	-
		Diagonal	9.407	9.663	-
		Alternate	-	-	9.607/9.566
	8 courses	Vertical	9.432	9.597	9.760/9.312
		Diagonal	-	9.721	-
		Alternate	9.364	9.592	-
	12 courses	Vertical	9.787	-	9.714
		Diagonal	-	-	-
		Alternate	9.609	-	-
4 floats	4 courses	Vertical	9.379	9.323	9.324
		Diagonal	9.623	9.546/9.720	9.700/9.612
		Alternate	-	-	9.738
	8 courses	Vertical	9.177	-	9.267
		Diagonal	-	-	9.294
		Alternate	9.642	-	9.484
	12 courses	Vertical	9.326	9.945/9.849	9.559
		Diagonal	9.388	-	-
		Alternate	-	9.300	9.613
6 floats	4 courses	Vertical	9.411	9.896	9.041
		Diagonal	9.638	9.922/9.993	9.826
		Alternate	9.652	-	-
	8 courses	Vertical	9.662	-	-
		Diagonal	9.599	9.654	-
		Alternate	9.596	9.670/9.830	-
	12 courses	Vertical	9.409	-	-
		Diagonal	-	-	-
		Alternate	9.385	9.480	-

\* A higher number means that it has a lighter coverage. (0: Pure black, 256: Pure white)

(The results for the first sample/the results for the second sample)

Table 4.4 Numeric results for the color coverage for samples that have over 50% resist patterns

Float loops	Course distances	Placement of tuck & float	Tightness Factor (TF)		
			Tight	Medium	Loose
2 floats	4 courses	Vertical	139.715	110.330	-
		Diagonal	107.197	123.917	-
		Alternate	-	-	155.797/166.423
	8 courses	Vertical	110.126	120.973	143.174/93.222
		Diagonal	-	123.711	-
		Alternate	104.708	105.016	-
	12 courses	Vertical	152.006	-	142.604
		Diagonal	-	-	-
		Alternate	118.132	-	-
4 floats	4 courses	Vertical	97.738	100.832	131.843
		Diagonal	137.298	116.935/143.933	136.637/131.183
		Alternate	-	-	144.142
	8 courses	Vertical	89.141	-	113.511
		Diagonal	-	-	94.394
		Alternate	115.008	-	93.874
	12 courses	Vertical	98.377	146.782/144.986	86.022
		Diagonal	96.775	-	-
		Alternate	--	95.402	101.976
6 floats	4 courses	Vertical	102.756	127.656	94.063
		Diagonal	115.624	143.055/140.059	138.912
		Alternate	119.719	-	-
	8 courses	Vertical	130.920	-	-
		Diagonal	144.096	110.212	-
		Alternate	116.761	111.837/152.349	-
	12 courses	Vertical	107.546	-	-
		Diagonal	-	-	-
		Alternate	103.349	107.929	-

#### 4.2.1. Testimony of the Experiment

Standard industry dyeing procedures have been continuously improved with the objective of obtaining constant level dyeing of fabrics and garments. In preliminary experimentation, level dyeing was achieved on approximately 200 gathered sample bundles in the Then® skein dyer utilizing a different dyestuff, high agitation and longer dwell time. To achieve uneven dyeing or to maximize resist dyeing, a process was developed with shorter dwell time, no or minimum agitation, and an appropriate dyestuff.

To prove the results for different dye penetration according to the position of the knitted samples in the skein dyer in Hypothesis 2, eight samples including a pair of four different samples were randomly selected, knitted, and dyed. In order to make the same situation as the test in Hypothesis 2, the first four samples were suspended in the top position of the skein dyer, while the second set of four samples, with the same knitted structures as the first sample set, were placed on the bottom of skein dyer as can be seen in Figure 4.3. Then, an approximate four kilogram-weight metal basket, the same as the weight of knitted samples in test of Hypothesis 2 in the previous experiment, were placed upon the four samples on the bottom of the skein dyer as can be seen as Figure 4.4.

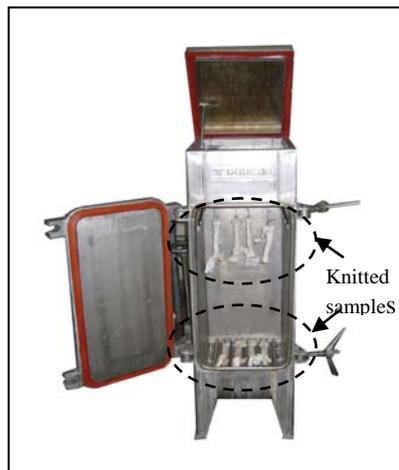


Figure 4.3 Position of a pair of four samples.

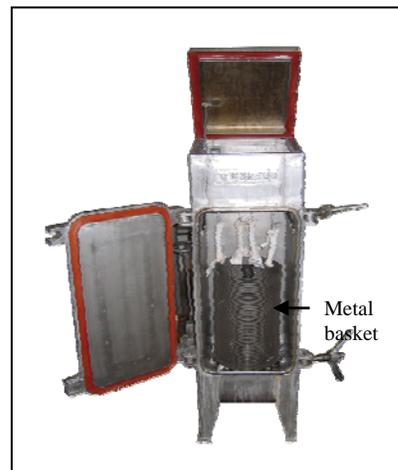
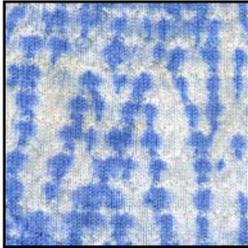
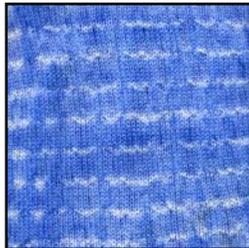
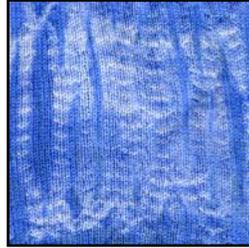
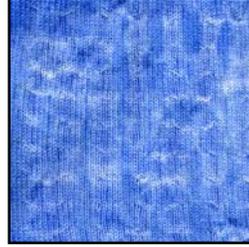
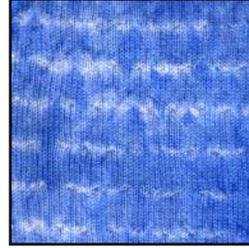


Figure 4.4 Final setting of a pair of four samples.

After positioning the samples in the same situation as the test in Hypothesis 2, according to the Dystar™ dyeing standard Ramazol® dyes, the samples were dyed for 30 minutes in the same skein dyer with 3 percent of dye, 60 grams per liter of salt for cotton and 5 grams per liter of soda ash at the temperature of 140 degrees Fahrenheit. The results of the resist-dyed patterns of the eight samples are shown in Table 4.5.

Table 4.5 Eight resist-dyed samples to verify the experiment of Hypothesis 2

		Sample positions in the skein dyer	
		Top of the skein dyer	Bottom of the skein dyer
<b>Knitted structures</b>	Tight, a tuck loop for every 2 floats, gathering yarns every 8th course, and a diagonal placement of a tuck loop		
	Tight, a tuck loop for every 4 floats, gathering yarns every 4th course, and a vertical placement of a tuck loop		
	Tight, a tuck loop for every 4 floats, gathering yarns every 12th course, and an alternate placement of a tuck loop		
	Tight, a tuck loop for every 6 floats, gathering yarns every 8th course, and a vertical placement of a tuck loop		

In Table 4.5, it can be easily identified that compared to the samples dyed on the top position of the skein dyer, the samples dyed on the bottom position of the skein dyer had more dye absorption. Thus, the samples dyed on the top of the skein dyer show clearer resist patterns. It is inferred that the results are influenced by the sample weight (about 4 kilogram dry weights of sample fabrics), water agitation (specifically, a pumping system for an agitation operation is located in the bottom of Then® skein dyer), and dyeing time. The heavy weight of the samples and the high number of samples in the skein dyer caused uneven dye absorption for each sample fabric according to the different sample positions in the skein dyer. On the other hand, continuous water agitation from the bottom of the skein dyer and longer dyeing time caused the even dye absorption for each sample fabric. Thus, sample fabrics in the bottom position of the skein dyer evenly dyed without any resist patterns. This could result in the same issue with garment dyeing if sample sizes are large and heavy. Chuck Stewart (2006), President of Tumbling Colors Company, mentioned that no water agitation is required for fabric/garment resist dyeing. Stewart also suggested that a spraying process on fabrics or garments may be another option of resist dyeing methods. For future research, it is recommended to consider other dyeing equipment and processes appropriate to create shibori knit fabrics or garments. Based upon this result, to perform experiment Hypothesis 3, the small amount of sample fabrics (24 sample fabrics) were dyed without agitation of the dye liquor.

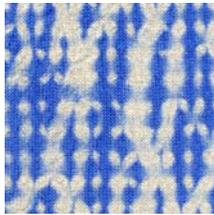
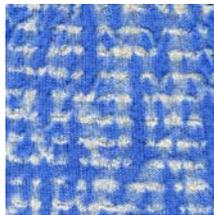
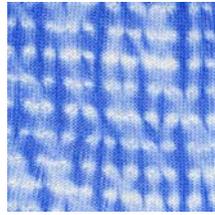
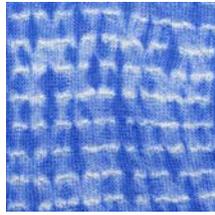
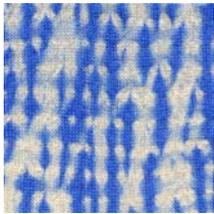
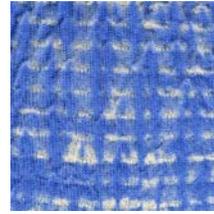
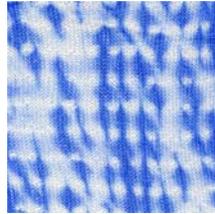
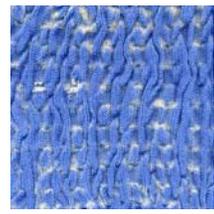
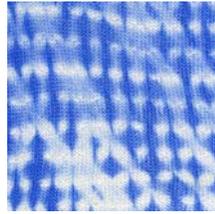
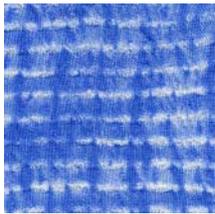
However, from Table 4.5, it is also recognized that according to different knitted structures, resist dyed images showed up differently. This fact extends previous research conducted by Brito (2002), Ellis (2005) and Wada (2002), who have experimented different resist dyed patterns according to different gathering structures on woven fabrics.

### **4.3. Hypothesis 3: Resist-Dyed Patterning according to the Different Yarn Applications**

- **The use of each different type of yarn for sample fabrics or gathering yarns can result in different resist effects in color penetration.**

Hypothesis 3 observed the relationship between the different type of yarns and the resist-dyed image, related to color contrast, color randomness and color coverage. Also, differences in dyed patterns were examined according to the different gathering structures. Table 4.6 represents results of different resist-dyed patterns according to three different factors, and Tables 4.7 to 4.9 show the numeric results for color contrast, color randomness and color coverage by the ImageJ software.

Table 4.6 Results of resist dyeing tests in different yarn structures of sample fabrics and gathering yarns

Sample fabrics Gathering yarns	Single jersey			
	Cotton		Rayon	
	Tuck & float	Float Jacquard	Tuck & float	Float Jacquard
Spun Polyester				
Shrink filament Polyester				
Elastomeric (Lycra®)				

\* A higher number means that it has a higher contrast (The results for the first sample/the results or the second sample).

Table 4.7 Numeric results for color contrast according to three different factors

Sample fabrics Gathering yarns	Single jersey				Factors
	Cotton		Rayon		Factor 1
	Tuck & float	Float jacquard	Tuck & float	Float jacquard	Factor 3
Spun polyester	704.069 / 739.826	963.917 / 943.180	592.129 / 597.835	782.244 / 813.851	Factor 2
Shrink filament polyester	893.846 / 813.008	846.213 / 902.991	542.079 / 544.823	989.500 / 946.213	
Elastomeric (Lycra®)	799.597 / 810.693	728.595 / 682.982	629.104 / 599.808	963.183 / 900.023	

\* A higher number means that it has a higher randomness (The results for the first sample/the results for the second sample).

Table 4.8 Numeric results for color randomness according to three different factors

Sample fabrics Gathering yarns	Single jersey				Factors
	Cotton		Rayon		Factor 1
	Tuck & float	Float jacquard	Tuck & float	Float jacquard	Factor 3
Spun polyester	9.753 / 9.861	9.981 / 9.936	9.502 / 9.503	9.711 / 9.742	Factor 2
Shrink filament polyester	9.922 / 9.886	9.910 / 9.913	9.363 / 9.427	9.896 / 9.844	
Elastomeric (Lycra®)	9.924 / 9.891	9.791 / 9.757	9.514 / 9.376	9.859 / 9.786	

\* 0 is a pure black and 256 is a pure white. The number indicates a mean of the total coverage. Thus, a higher number means it has more white coverage and a lower number means it has more black coverage (First sample / Second sample).

Table 4.9 Numeric results for color coverage according to three different factors

Sample fabrics Gathering yarns	Single jersey				Factors
	Cotton		Rayon		Factor 1
	Tuck & float	Float jacquard	Tuck & float	Float jacquard	Factor 3
Spun polyester	164.080 / 158.314	151.609 / 156.764	171.619 / 174.404	153.640 / 151.345	Factor 2
Shrink filament polyester	158.626 / 160.619	140.943 / 142.377	180.383 / 176.320	144.534 / 146.072	
Elastomeric (Lycra®)	153.894 / 156.651	142.781 / 142.168	172.336 / 181.267	144.888 / 144.118	

## 1) Color Contrast

For each color criteria, the ordered means (model adjusted) are provided in Table 4.10. The “Order” column represents the rank of the means from small values to large values. In column of “Yarns for sample fabric”, number 1 means cotton, and number 2 means rayon. The column of “Gathering yarns” is composed of spun polyester (number 1), shrink polyester (number 2), and elastomeric Lycra® yarn (number 3). In the “Gathering structures” column, the number 1 represents the tuck & float structure, and the number 2 represents the float jacquard structure.

The “LSMEANS” column indicates the model adjusted average of the combinations. According to SAS (2006), the LSMEANS (Least-Squares means) statement is utilized to conduct a multiple comparison on interactions. The following examples show similarity and difference between MEANS and LSMEANS.

### Example 1

This data set has a Factor A with three levels (1, 2, and 3) with 3 reps of each.

### **Factor A**

Table 4.10 The first example to show difference between MEANS and LSMEANS

Rep	1	2	3
1	4	7	4
2	6	3	2
3	2	5	3
$\bar{X}_{ai.}$	12	15	9
$\bar{X}_{a.}$	4	5	3

A MEANS statement easily calculates the overall mean of Factor A by summing all 9 data point and dividing by 9 as the following:

$$\bar{X}_{..} = (\bar{X}_{ai.})/n = (4 + 6 + 2 + 7 + 3 + 5 + 4 + 2 + 3)/9 = 4.0$$

On the other hand, the LSMEANS statement utilizes a linear combination of the estimated Factor A effects, which in this case are the factor A means,  $\bar{X}_a$ ,

$$\bar{X}_{..} = (\bar{X}_a)/n = (4 + 5 + 3)/3 = 4.0$$

Because the data were balanced, the two methods created the same result. However, if a data point is deleted, the results will change. Suppose the data were revised as the followings:

### **Factor B**

Table 4.11 The second example to show difference between MEANS and LSMEANS

Rep	1	2	3
1	4	-	4
2	6	3	2
3	2	5	3
$\bar{X}_{ai}$	12	8	9
$\bar{X}_a$	4	4	3

The MEANS statement gives:

$$\bar{X}_{..} = (\bar{X}_{ai})/n = (4 + 6 + 2 + 3 + 5 + 4 + 2 + 3)/8 = 3.625,$$

whereas the LSMEANS statement provides:

$$\bar{X}_{..} = (\bar{X}_a)/3 = (4 + 4 + 3)/3 = 3.667.$$

Hence, when the data includes missing values, the average of all the data does no longer equal the average of the averages. LSMEANS is the appropriate selection in the case of Factor B since it imposes the treatment structure of factor B on the calculated mean  $\bar{X}_{..}$ . Thus, when covariates are present in the model, the LSMEANS statement produces means which are adjusted for the average value of the specified covariate(s).

Used Source: University of Idaho. (2006). *SAS Workshop PROC GLM*. Retrieved July 20, 2006, from [http://www.uidaho.edu/ag/statprog/sas/workshops/glm/handout2.1\\_glm.pdf](http://www.uidaho.edu/ag/statprog/sas/workshops/glm/handout2.1_glm.pdf).

LSMEANS in this section are the adjusted averages for the color contrast, but it is also to be noted that LSMEANS for color contrast is the same as MEANS for color contrast in this section. The “STDEER” column denotes the standard error. The numbers in parentheses in the “Observation” column designate each experiment situation according to three different factors. Finally, in Table 4.13, cells with the same capital letters show that they do not have significant differences and can be grouped together. The same group information is also provided in Table 4.12 at the column of “Groups by pairwise comparisons”.

Table 4.12 Sorted means of color contrast

Order	Yarns for sample fabric	Gathering yarns	Gathering structures	LSMEANS	STDERR	Observation	Groups by pairwise comparisons				
1	2	2	1	543.451	21.1301	(5)	A				
2	2	1	1	594.982	21.1301	(4)	A	B			
3	2	3	1	614.456	21.1301	(6)	A	B			
4	1	3	2	705.789	21.1301	(9)		B	C		
5	1	1	1	721.948	21.1301	(1)			C		
6	2	1	2	798.048	21.1301	(10)			C	D	
7	1	3	1	805.145	21.1301	(3)			C	D	
8	1	2	1	853.427	21.1301	(2)				D	E
9	1	2	2	874.602	21.1301	(8)				D	E
10	2	3	2	931.603	21.1301	(12)					E
11	1	1	2	953.549	21.1301	(7)					E
12	2	2	2	967.857	21.1301	(11)					E

Table 4.13 Grouped means of color contrast

Gathering yarns	Sample fabrics	Single jersey				Factors
		Cotton		Rayon		Factor 1
		Tuck & float	Float jacquard	Tuck & float	Float jacquard	Factor 3
Spun polyester		C (1)	E (7)	A B (4)	C D (10)	Factor 2
Shrink filament polyester		D E (2)	D E (8)	A (5)	E (11)	
Elastomeric (Lycra®)		C D (3)	B C (9)	A B (6)	E (12)	

Table 4.14 Pairwise comparisons of all LSMEANS for color contrast

Pr >  t  for H0: LSMean(i)=LSMean(j)						
Dependent Variable: random						
i/j	1	2	3	4	5	6
1		0.0253	0.2922	0.0322	0.0023	0.0896
2	0.0253		0.8740	<.0001	<.0001	0.0001
3	0.2922	0.8740		0.0005	<.0001	0.0013
4	0.0322	<.0001	0.0005		0.8282	0.9999
5	0.0023	<.0001	<.0001	0.8282		0.4802
6	0.0896	0.0001	0.0013	0.9999	0.4802	
7	0.0002	0.1304	0.0104	<.0001	<.0001	<.0001
8	0.0083	0.9997	0.5078	<.0001	<.0001	<.0001
9	1.0000	0.0108	0.1356	0.0754	0.0051	0.2008
10	0.3947	0.7659	1.0000	0.0007	<.0001	0.0018
11	0.0001	0.0624	0.0050	<.0001	<.0001	<.0001
12	0.0005	0.3626	0.0331	<.0001	<.0001	<.0001
i/j	7	8	9	10	11	12
1	0.0002	0.0083	1.0000	0.3947	0.0001	0.0005
2	0.1304	0.9997	0.0108	0.7659	0.0624	0.3626
3	0.0104	0.5078	0.1356	1.0000	0.0050	0.0331
4	<.0001	<.0001	0.0754	0.0007	<.0001	<.0001
5	<.0001	<.0001	0.0051	<.0001	<.0001	<.0001
6	<.0001	<.0001	0.2008	0.0018	<.0001	<.0001
7		0.3511	0.0001	0.0072	1.0000	0.9996
8	0.3511		0.0037	0.3875	0.1831	0.7376
9	0.0001	0.0037		0.1921	<.0001	0.0003
10	0.0072	0.3875	0.1921		0.0035	0.0227
11	1.0000	0.1831	<.0001	0.0035		0.9770
12	0.9996	0.7376	0.0003	0.0227	0.9770	

Each group in the column of “Groups by pairwise comparisons” was grouped based on the result (p-value) for the all pairwise comparisons using t-tests in Table 4.14. Pairwise comparisons commonly indicate a process of examining means in pairs to estimate which of each pair is preferred (Toothaker, 1993). This method enables the determination of the relative order of a group of items (Salustri, 2005). According to Rice University (2006), in order to test pairwise comparisons among mean, Tukey Honestly Significant Difference test or *Tukey HSD* method is usually utilized as the following formula (see Equation 4.1);

$$t_s = \frac{M_i - M_j}{\sqrt{\frac{MSE}{n_h}}} \quad (4.1)$$

where  $M_i - M_j$  is the difference between the  $i$ th and  $j$ th means, MSE is the mean square error from the ANOVA, and  $n_h$  is the harmonic mean of the sample sizes of groups  $i$  and  $j$  (Tukey, 1953). The Tukey HSD is based on a variation of the  $t$  distribution that takes into account the number of means being compared. This distribution is called the studentized range distribution.

From the data in the Tables, the graphs of correlation for the three different factors, including sample fabrics, gathering yarns and gathering structures, were achieved as seen in Figures 4.5 to 4.7. Also, Table 4.15 shows the ANOVA (Analysis of Variance) results of the color contrast for the three different factors.

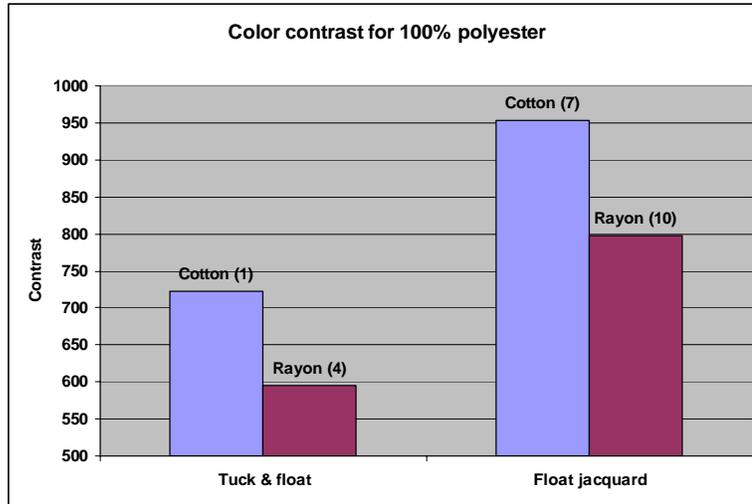


Figure 4.5 Color contrast for spun polyester.

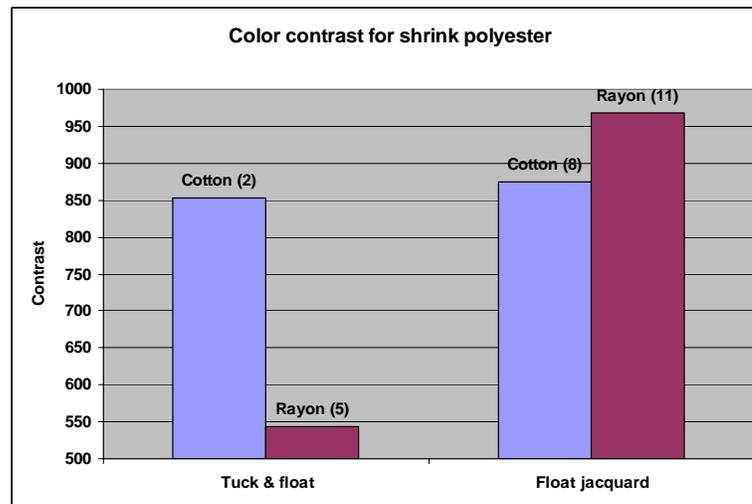


Figure 4.6 Color contrast for shrink filament polyester.

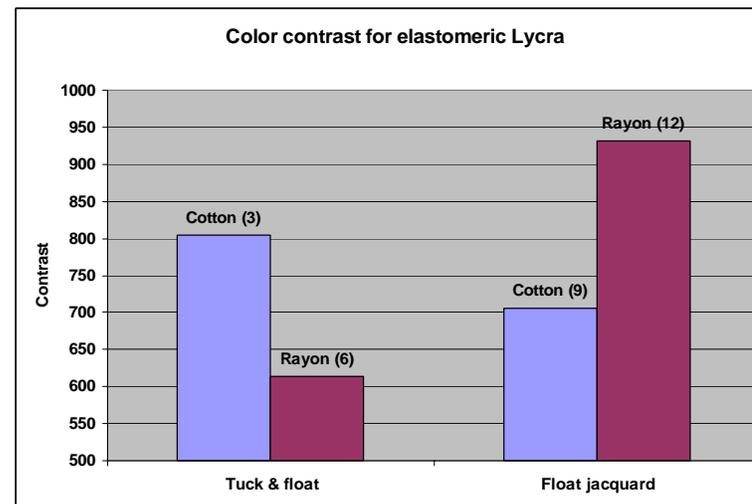


Figure 4.7 Color contrast for elastomeric Lycra® yarn.

Table 4.15 ANOVA Table for color contrast

Source	DF	Type III SS	Mean Square	F Value	Pr > F
Gathering structures (JT)	1	200947.7252	200947.7252	225.04	<.0001
Yarns for sample fabrics (Y)	1	35892.3340	35892.3340	40.19	<.0001
JT*Y	1	104332.511	104332.511	116.84	<.0001
Gathering yarns (G)	2	10426.4570	5213.2285	5.84	0.017
JT*G	2	16507.0998	8253.5499	9.24	0.0037
Y*G	2	28102.3325	14051.1662	15.74	0.0004
JT*Y*G	2	64109.6271	32054.8136	35.90	<.0001

The results for the color contrast for the three factors were achieved as the followings:

1. The three-way interaction of the factors is significant (P-value <.0001). It means that for different gathering yarns, the relationship between yarns for sample fabrics (Cotton and Rayon) and gathering structures (tuck & float and float jacquard) are different (see Table 4.15).
2. The interaction between these three factors is more dramatic for contrast than for randomness (see Tables 4.12 and 4.16). When the gathering yarn is created by spun polyester, sample fabrics created by cotton have higher contrast than fabrics created by rayon. Also, when the sample fabrics are created by either cotton or rayon with gathering yarns created by spun polyester, the sample fabrics gathered as float jacquard structures have higher contrast than the sample fabrics gathered as tuck & float structures (see Figure 4.5).
3. When a shrink filament polyester is used as the gathering yarn using the tuck & float structure, the sample fabrics created with cotton yarn have higher contrast than the sample fabrics created with rayon. In the float jacquard structure, it can be noted that

the sample fabrics created by both cotton and rayon have the same contrast (see Figures 4.6 and Table 4.13).

4. When the gathering yarn chosen is the elastometric Lycra®, in tuck & float structures, the sample fabrics created by cotton have higher contrast than the sample fabrics created by rayon. On the other hand, in float jacquard structures, the sample fabrics created by rayon have higher contrast than the sample fabric created by cotton (see Figure 4.7).

## 2) Color Randomness

All data for color randomness were acquired in the same way as data for color contrast. The “LSMEANS” column shows the adjusted means for color randomness of each sample fabric. The each LSMEAN for color randomness was grouped by pairwise comparisons. Table 4.16 shows the results for the model adjusted average of the combinations for the color randomness. It also includes groups by pairwise comparisons for color randomness. Table 4.16 depicts the grouped means of color randomness for each factor. The groups in Tables 4.16 and 4.17 were also derived from the results of Table 4.18.

Table 4.16 Sorted means of color randomness

Order	Yarns for sample fabric	Gathering yarns	Gathering structure	LSMEANS	STDERR	Observation	Groups by pairwise comparisons		
1	2	2	1	9.395	0.032072	(5)	A		
2	2	3	1	9.445	0.032072	(6)	A		
3	2	1	1	9.5025	0.032072	(4)	A		
4	2	1	2	9.7265	0.032072	(10)		B	
5	1	3	2	9.774	0.032072	(9)		B	C
6	1	1	1	9.807	0.032072	(1)		B	C
7	2	3	2	9.8225	0.032072	(12)		B	C
8	2	2	2	9.87	0.032072	(11)		B	C
9	1	2	1	9.904	0.032072	(2)		B	C
10	1	3	1	9.9075	0.032072	(3)			C
11	1	2	2	9.9115	0.032072	(8)			C
12	1	1	2	9.9585	0.032072	(7)			C

Table 4.17 Grouped means of color randomness

Gathering yarns	Sample fabrics	Single jersey				Factors
		Cotton		Rayon		Factor 1
		Tuck & float	Float jacquard	Tuck & float	Float jacquard	Factor 3
Spun polyester		B C (1)	C (7)	A (4)	B (10)	Factor 2
Shrink filament polyester		B C (2)	C (8)	A (5)	B C (11)	
Elastomeric (Lycra®)		C (3)	B C (9)	A (6)	B C (12)	

Table 4.18 Pairwise comparisons of all LSMEANS for color randomness

Pr >  t  for H0: LSMean(i)=LSMean(j)						
Dependent Variable: random						
i/j	1	2	3	4	5	6
1		0.6103	0.5672	0.0008	<.0001	0.0001
2	0.6103		1.0000	<.0001	<.0001	<.0001
3	0.5672	1.0000		<.0001	<.0001	<.0001
4	0.0008	<.0001	<.0001		0.4834	0.9691
5	<.0001	<.0001	<.0001	0.4834		0.9883
6	0.0001	<.0001	<.0001	0.9691	0.9883	
7	0.1325	0.9784	0.9865	<.0001	<.0001	<.0001
8	0.5188	1.0000	1.0000	<.0001	<.0001	<.0001
9	0.9996	0.2618	0.2355	0.0022	<.0001	0.0004
10	0.8047	0.0547	0.0484	0.0109	0.0004	0.0016
11	0.9451	0.9995	0.9988	0.0001	<.0001	<.0001
12	1.0000	0.7941	0.7552	0.0005	<.0001	<.0001
i/j	7	8	9	10	11	12
1	0.1325	0.5188	0.9996	0.8047	0.9451	1.0000
2	0.9784	1.0000	0.2618	0.0547	0.9995	0.7941
3	0.9865	1.0000	0.2355	0.0484	0.9988	0.7552
4	<.0001	<.0001	0.0022	0.0109	0.0001	0.0005
5	<.0001	<.0001	<.0001	0.0004	<.0001	<.0001
6	<.0001	<.0001	0.0004	0.0016	<.0001	<.0001
7		0.9927	0.0429	0.0083	0.7142	0.2180
8	0.9927		0.2081	0.0421	0.9973	0.7083
9	0.0429	0.2081		0.9920	0.6227	0.9907
10	0.0083	0.0421	0.9920		0.1720	0.6227
11	0.7142	0.9973	0.6227	0.1720		0.9920
12	0.2180	0.7083	0.9907	0.6227	0.9920	

Based on the data in the upper tables, the following graphic results were achieved as can be seen in Figures 4.8 to 4.10. Also, Table 4.19 demonstrates the results of ANOVA for the color randomness for the three different factors.

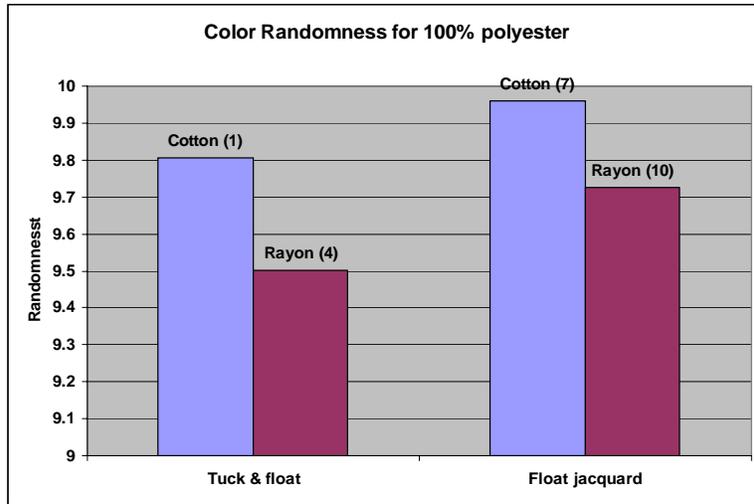


Figure 4.8 Color randomness for spun polyester.

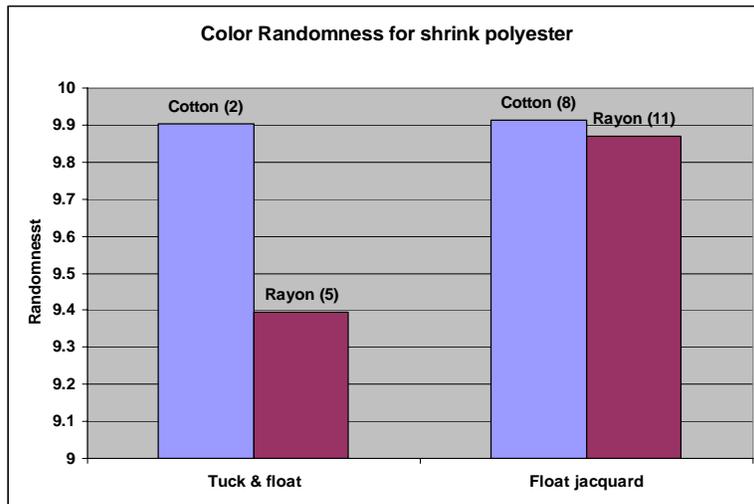


Figure 4.9 Color randomness for shrink filament polyester.

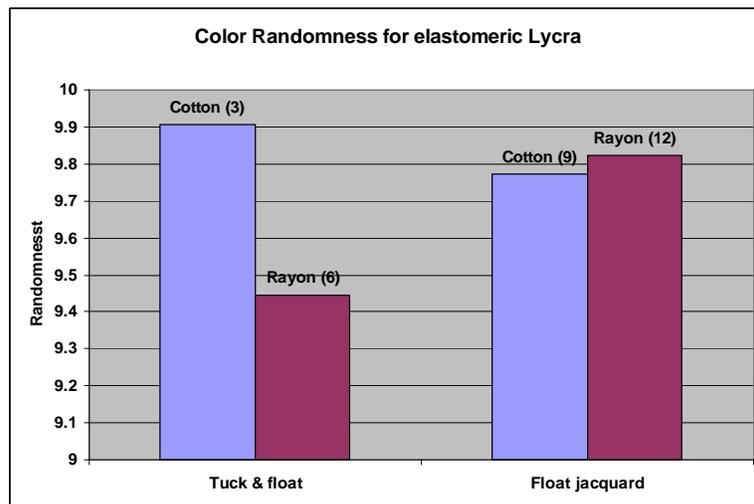


Figure 4.10 Color randomness for elastomeric Lycra® yarn.

Table 4.19 ANOVA Table for color randomness

Source	DF	Type I SS	Mean Square	F Value	Pr > F
Gathering structures (JT)	1	0.20240067	0.20240067	98.38	<.0001
Yarns for sample fabrics (Y)	1	0.37550017	0.37550017	182.53	<.0001
JT*Y	1	0.18410017	0.18410017	89.49	<.0001
Gathering yarns (G)	2	0.00445975	0.00222988	1.08	0.3692
JT*G	2	0.01427058	0.00713529	3.47	0.0648
Y*G	2	0.00563908	0.00281954	1.37	0.2910
JT*Y*G	2	0.05836658	0.02918329	14.19	0.0007

As a result for color randomness, it can be recognized as the followings;

1. The three-way interaction of the three factors is significant (P-value .0007), which means that for different gathering yarns, the relationship between yarns (cotton and rayon) utilized as sample fabrics and gathering structures (tuck & float and float jacquard structures) are different (see Table 4.19).
2. When spun polyester is selected as a gathering yarn, the color randomness of sample fabrics created by cotton are higher than that of the samples created by rayon no matter which techniques are used as gathering structures including tuck & float or float jacquard. Also, the sample fabrics gathered as float jacquard structures have a higher randomness than the sample fabrics gathered as tuck & float structures on sample fabrics created by rayon (see Table 4.17 and Figure 4.8).
3. When shrink polyester and elastomeric Lycra® are selected as the gathering yarns and the gathering structure is tuck & float, the sample fabrics created by cotton have a higher randomness than the sample fabrics created by rayon. When float jacquard is chosen as the gathering structure, the sample fabrics created by both cotton and rayon have the same randomness (see Table 4.17 and Figures 4.9 and 4.10).

### 3) Color Coverage

In the same methods as the previous ones, the following results were accomplished. Table 4.20 shows the results for “LSEMEANS” and groups by pairwise comparison. In the order column of this table, a higher number means that it has a more white coverage, while a small number means that it has a more black coverage.

Table 4.20 Sorted means of color coverage

Order	Yarns for sample fabric	Gathering yarns	Gathering structure	LSMEANS	STDERR	Observation	Groups by pairwise comparisons			
1	1	2	2	141.660	1.96892	(8)	A			
2	1	3	2	142.475	1.96892	(9)	A			
3	2	3	2	144.503	1.96892	(12)	A	B		
4	2	2	2	145.303	1.96892	(11)	A	B		
5	2	1	2	152.493	1.96892	(10)	A	B	C	
6	1	1	2	154.187	1.96892	(7)		B	C	
7	1	3	1	155.273	1.96892	(3)		B	C	
8	1	2	1	159.623	1.96892	(2)			C	
9	1	1	1	161.197	1.96892	(1)			C	
10	2	1	1	173.012	1.96892	(4)				D
11	2	3	1	176.802	1.96892	(6)				D
12	2	2	1	178.352	1.96892	(5)				D

Table 4.21 Grouped means of color coverage

Sample fabrics Gathering yarns	Single jersey				Factors
	Cotton		Rayon		Factor 1
	Tuck & float	Float Jacquard	Tuck & float	Float Jacquard	Factor 3
Spun polyester	C (1)	B C (7)	D (4)	A B C (10)	Factor 2
Shrink filament polyester	C (2)	A (8)	D (5)	A B (11)	
Elastomeric (Lycra®)	B C (3)	A (9)	D (6)	A B (12)	

Table 4.22 Pairwise comparisons of all LSMEANS for color coverage

Pr >  t  for H0: LSMean(i)=LSMean(j)						
Dependent Variable: random						
i/j	1	2	3	4	5	6
1		1.0000	0.6164	0.0325	0.0017	0.0039
2	1.0000		0.8939	0.0133	0.0008	0.0017
3	0.6164	0.8939		0.0013	0.0001	0.0002
4	0.0325	0.0133	0.0013		0.7322	0.9515
5	0.0017	0.0008	0.0001	0.7322		1.0000
6	0.0039	0.0017	0.0002	0.9515	1.0000	
7	0.4085	0.7137	1.0000	0.0007	<.0001	0.0001
8	0.0005	0.0011	0.0117	<.0001	<.0001	<.0001
9	0.0008	0.0017	0.0186	<.0001	<.0001	<.0001
10	0.1817	0.3881	0.9945	0.0003	<.0001	<.0001
11	0.0034	0.0079	0.0919	<.0001	<.0001	<.0001
12	0.0022	0.0051	0.0587	<.0001	<.0001	<.0001
i/j	7	8	9	10	11	12
1	0.4085	0.0005	0.0008	0.1817	0.0034	0.0022
2	0.7137	0.0011	0.0017	0.3881	0.0079	0.0051
3	1.0000	0.0117	0.0186	0.9945	0.0919	0.0587
4	0.0007	<.0001	<.0001	0.0003	<.0001	<.0001
5	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001
6	0.0001	<.0001	<.0001	<.0001	<.0001	<.0001
7		0.0217	0.0344	0.9999	0.1655	0.1076
8	0.0217		1.0000	0.0567	0.9621	0.9935
9	0.0344	1.0000		0.0895	0.9937	0.9996
10	0.9999	0.0567	0.0895		0.3781	0.2607
11	0.1655	0.9621	0.9937	0.3781		1.0000
12	0.1076	0.9935	0.9996	0.2607	1.0000	

Table 4.22 illustrates the pairwise comparisons of all means of color coverage and Figures 4.11 to 4.13 graphically show the numeric results for the three different factors. Table 4.23 shows the results of ANOVA for the color coverage for the three different factors.

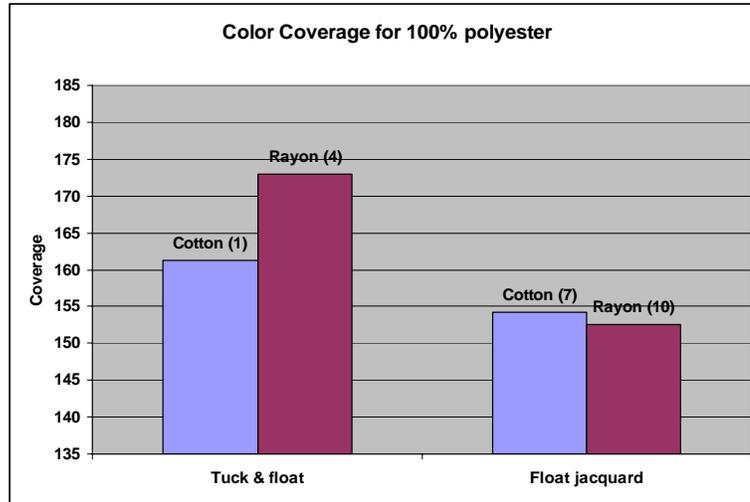


Figure 4.11 Color coverage for spun polyester.

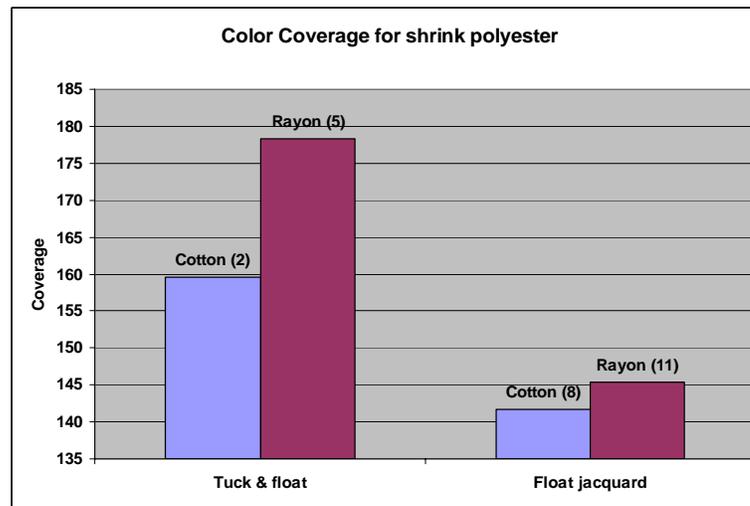


Figure 4.12 Color coverage for shrink filament polyester.

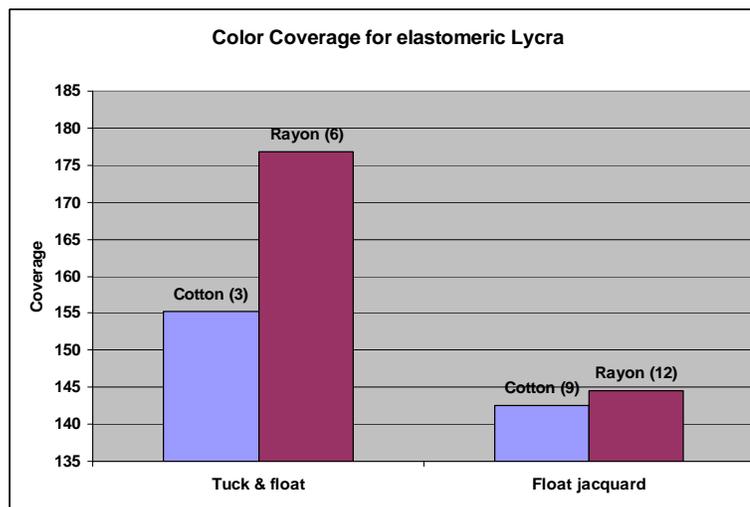


Figure 4.13 Color coverage for elastomeric Lycra® yarn.

Table 4.23 ANOVA Table for color coverage

Source	DF	Type III SS	Mean Square	F Value	Pr > F
Gathering structures (JT)	1	2547.684628	2547.684628	347.35	<.0001
Yarns for sample fabrics (Y)	1	523.600417	523.600417	71.39	<.0001
JT*Y	1	385.521504	385.521504	52.56	<.0001
Gathering yarns (G)	2	127.644743	63.822371	8.70	0.0035
JT*G	2	149.160274	74.580137	10.17	0.0019
Y*G	2	55.342939	27.671469	3.77	0.0489

Through the above data, the following results of the relationships for color coverage can be explained;

1. For color coverage, the three-way interaction is not significant (P-value .5533). However, all three two-way interactions are significant (the P-value for each two-way interaction refer to the ANOVA table, see Table 4.23).
2. In the interaction between the gathering structures and base yarns for the sample fabrics, averaged over the gathering yarns, if the gathering structure is created in the tuck & float structure, the sample fabrics created by cotton have a more black coverage<sup>14</sup> than the samples created by rayon. On the other hand, if the gathering structure is created in float & jacquard, the sample fabrics created by both cotton and rayon have the same coverage (see Figures 4.11, 4.12 and 4.13).
3. In the interaction between gathering structures and gathering yarns, averaged over the yarns for sample fabrics, no matter which gathering yarn is used, the sample fabrics with tuck & float structure have a more white coverage<sup>14</sup> than the sample fabrics with float jacquard structures. However, when cotton as a sample fabric and spun polyester as a gathering yarn were selected, the sample fabrics with both tuck & float and float jacquard structures have the same coverage (see Figures 4.11, 4.12 and 4.13).

<sup>14</sup> GLCM test in ImageJ software is measured based on a gray tone color. Thus, coverage is only read in a black or white tone.

4. In the interaction between the base yarns for sample fabrics and gathering yarns, averaged over the gathering structures, all sample fabrics created by rayon have the same coverage in each gathering structure no matter what kinds of gathering yarns are used. However, for sample fabrics created by cotton, spun polyester has a more white coverage<sup>14</sup> than shrink filament polyester and elastomeric Lycra® in float jacquard structures (see Figures 4.11, 4.12 and 4.13).

From the whole results of the experiment in Hypothesis 3, the following conclusion can be achieved;

- In tuck & float structures, patterns on cotton fabrics have a higher contrast, a higher randomness and a more black coverage than patterns on rayon fabrics.

The result is due to different yarn characteristics between cotton and rayon. Compared to cotton, rayon has a higher luster, a higher translucence and a brighter appearance (see Table 3.1). In addition, rayon has a better drape than cotton. The characteristics of rayon and cotton affected the this result. From the result, it can be inferred that use of each different type of yarn as sample fabrics can result in different resist effects in color penetration.

- In sample fabrics created by rayon, compared to the sample fabrics gathered as tuck & float structures, the sample fabrics gathered as float jacquard structures have a higher contrast, a higher randomness and a more black coverage.

The result can be affected by the following two reasons. First, in float jacquard structures of this experiment, the gathering yarns were left on the sample fabrics. Gathering yarns, which have the capability of shrinkage, affect color contrast, color randomness and color coverage of the dyed images. Second, structurally, float jacquard

structures are different from tuck & float structures. Float jacquard structures are comprised of knit, tuck and float loops, while tuck & float structures are composed of tuck and float loops. Thus, the different structures of tuck & float and float jacquard enable the resist-dyed patterns to show up differently.

- When shrink yarns or elastomeric yarns such as shrink filament polyester or Lycra® were utilized as gathering yarns, results are unpredictable compared to non-shrink yarns or non-elastomeric yarns such as spun polyester in float jacquard structures.

From the results in float jacquard structures, it is identified that compared to sample fabrics with spun polyester as gathering yarns, sample fabrics with shrink polyester and Lycra® as gathering yarns have more inconsistent results. This result is also due to yarn characteristics. Both shrink polyester and spandex Lycra®, which have a high shrinkage, created three-dimensional irregular and undulated patterns since both yarns are permanently secured on the sample fabrics in float jacquard structures. Thus, it is difficult to predict the resist dyed patterns on sample fabrics created by shrink polyester and Lycra® as gathering yarns.

From the results, it can be said that Hypothesis 3, which tested resist dye patterning according to the different yarn applications, was accepted. Therefore, use of each different type of yarn for sample fabrics or gathering yarns can result in different resist effects in color penetration.

#### 4.4. Hypothesis 4: Resist-Dyed Patterning as Complex Structures

- Resist patterns on knitted fabrics can be developed through various complex structures affecting resist dyed images by computerized flat V-bed knitting machines.

In Hypothesis 4, through varied knitting techniques including flechage, loop transference, purl structures, intarsia knitting or held loop structures, more complicated three dimensional resist-dyed patterns were explored.

##### 4.4.1. Float Patterning

1) Float Patterning (by a flechage structure)

One of methods to create a diagonal-line pattern in knitting is to use a flechage structure. Figure 4.14 illustrates a figure of diagonal loops on the sample fabric and its design structure on Shima Seiki SDS-ONE® CAD system, which includes diagonal lines in one direction and zigzag diagonal lines.



Figure 4.14 Diagonal loops for gathering yarns by use of flechage technique.

For this experiment, a gathering yarn every twentieth course, one tuck for every four floats for a gathering yarn, and a medium loop length for a sample fabric was chosen. Figure 4.15a depicts a knitted sample with flechage structures before resist dyeing and Figure 4.15b shows a resist-dyed sample after dyeing. The resist dyed pattern in Figure 4.15 is not visually very different from the resist-dyed patterns with gathering yarns in a horizontal direction. However, as can be see in Figure 4.16, interestingly, the resist-dyed diagonal line patterns are shown according to the gathering yarn positions. In addition, the image reveals that the smaller the spaces created by the flechage structures, the lighter coverage the area has. Therefore, we also can see some gradation effects in Figure 4.16.

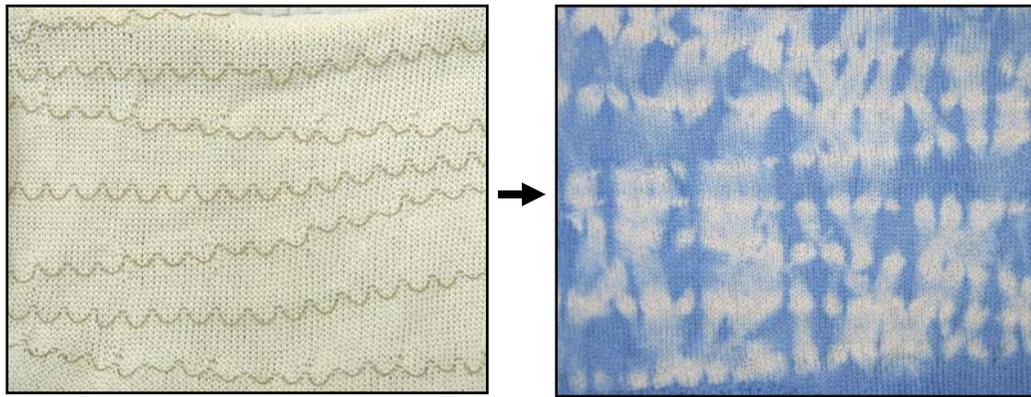


Figure 4.15a

Figure 4.15b

Figure 4.15 A knitted sample with flechage structures before dyeing and the sample after dyeing.

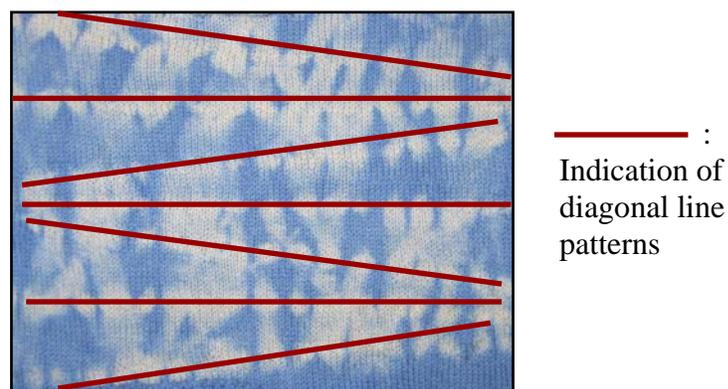


Figure 4.16 Indications of diagonal line patterns

## Knitting and Dyeing Process

The process of creating the knit structures can be explained as the followings;

1. Flechage structures by the use of knit and tuck loops are designed on the CAD system (see Figure 4.17).
2. The position of the gathering yarn can be decided between each diagonal line.
3. Each flechage direction can be selectively controlled as seen in Figure 4.14 such as diagonal lines in one direction or zigzag diagonal lines in one or the other direction.
4. After designing, the data can be transferred to the knitting machine and knitted.
5. After knitting, the gathering yarns are on the first edge of the sample are secured. The loose gathering yarns at the opposite edge of the sample are then tightly pulled up by hand and knotted.
6. This compact gathered fabric is then dyed.
7. After the fabric bundles are dry, the gathering yarns may be taken out and diagonally resist-dyed patterns are obtained as can be seen as Figure 4.15.

## Loop notation

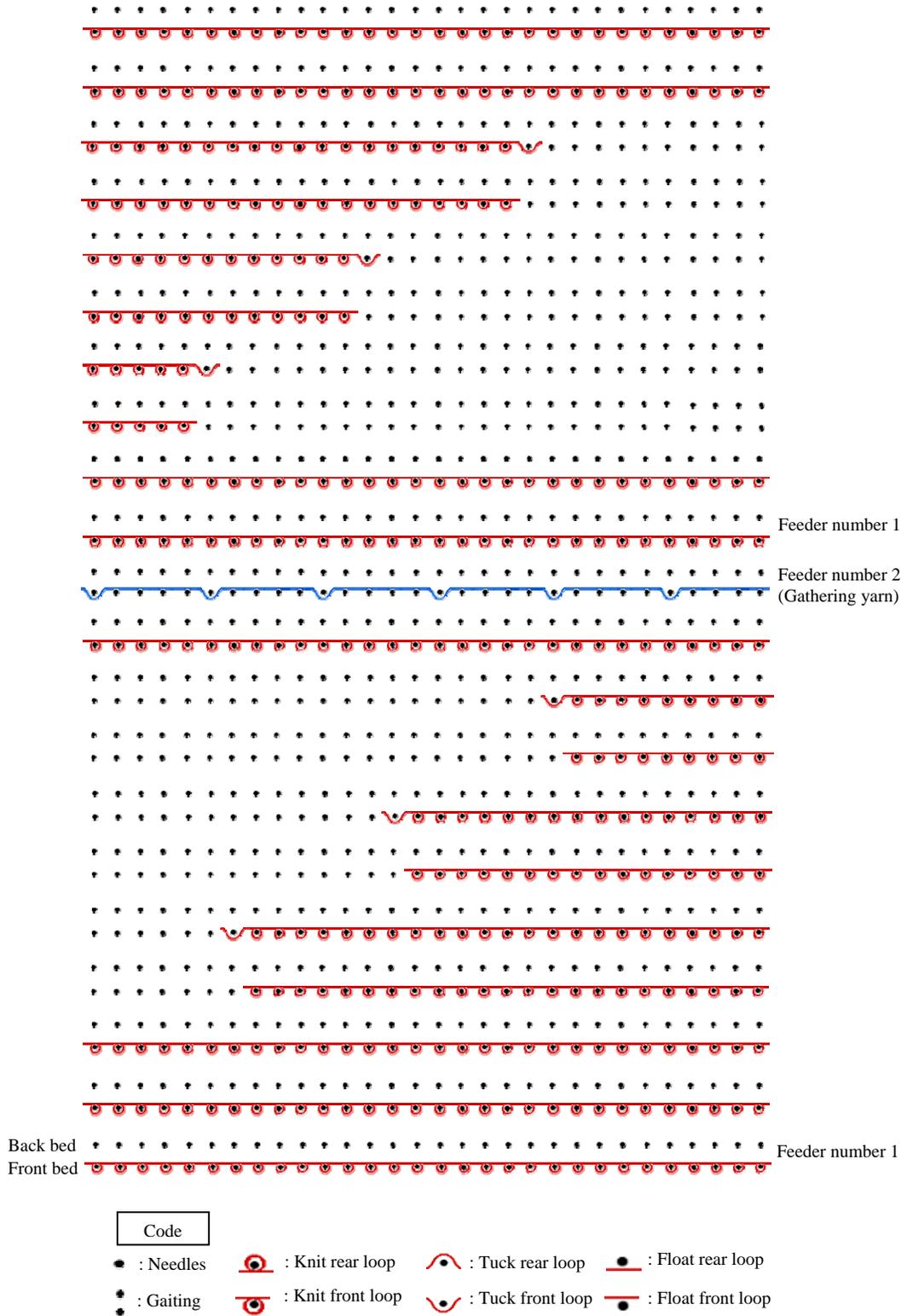


Figure 4.17 Loop notation to create diagonal loops for gathering yarns by use of flechage structures.

## 2) Float Patterning (by loop transference)

By consecutive loop transferences in different direction, more diverse undulated and distorted resist patterns can be accomplished. Figure 4.18 illustrates a figure of undulated loops on the sample fabric and its design structure on Shima Seiki SDS-ONE® CAD system.

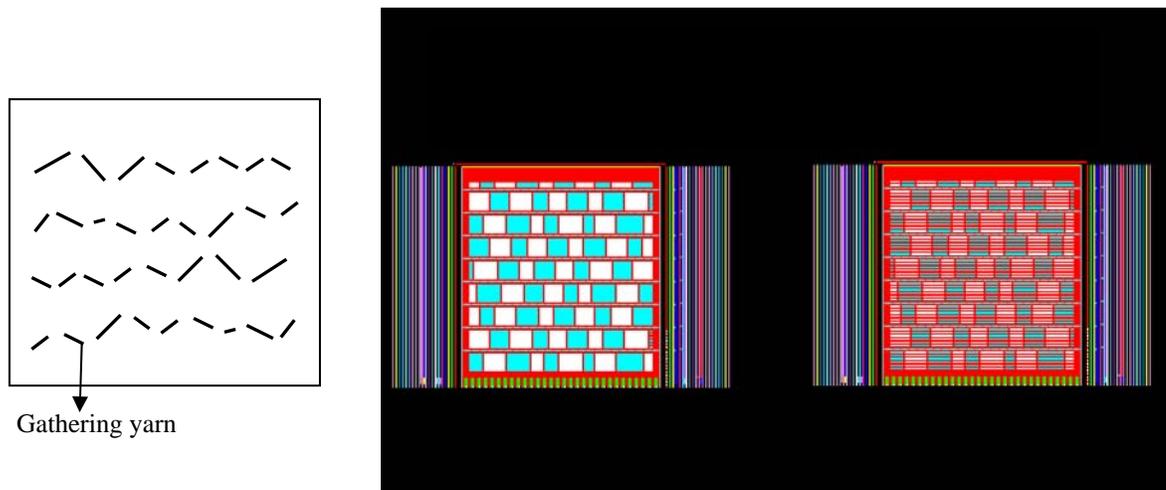


Figure 4.18 Undulating loops for gathering yarns by loop transference.

One gathering yarn every fourteenth course, one tuck for every four floats for a gathering yarn, and a medium loop length for a sample fabric were utilized for this experiment. Figure 4.19a shows a knitted sample with undulated structures by loop transference before resist dyeing and Figure 4.19b shows a resist-dyed sample after dyeing. As can be seen in Figure 4.19, irregular undulated gathering yarn lines and resist patterns can be achieved. One interesting fact is that this knitted structure can not only can have lace structures, but also create resist dyed-images. It is noted that a round area in Figure 4.19b was not resist-dyed since a gathering yarn was cut out from the sample

fabric during dyeing. Figure 4.20 depicts the resist-dyed undulated-line patterns according to the gathering yarn positions by the directions of loop transference.

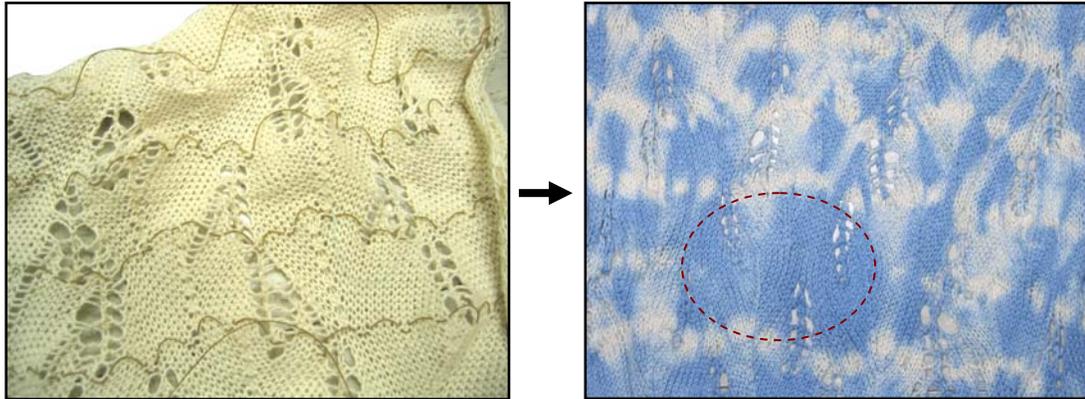


Figure 4.19a

Figure 4.19b

Figure 4.19 A knitted sample with lace structures before dyeing and the sample after dyeing.

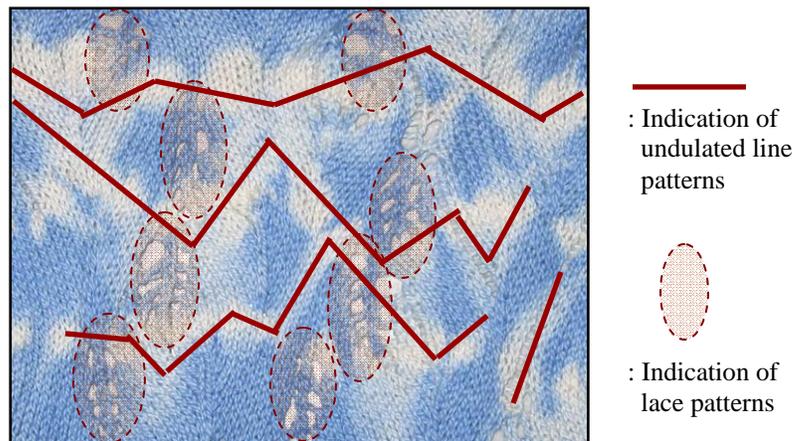


Figure 4.20 Indications of undulated line patterns and lace patterns.

### Knitting and Dyeing Process

The following shows the process of creating the knitting structures.

1. Various undulated and distorted patterns by the use of knit and loop transferences are created (see Figure 4.21).

2. Consecutive courses of knitting and loop transferences in different directions create undulating or irregular structures.
3. Each gathering yarn can be located between courses with different directions by loop transference.
4. After designing is complete, the design data can be transferred to the knitting machine and the samples run.
5. After knitting, the gathering yarns are secured, pulled up and tied.
6. After gathering, the fabric bundles are then resist-dyed.
7. Finally, the gathering yarns may be removed, and the undulated resist dyed patterns are revealed as can be seen in Figure 4.19.

## Loop notation

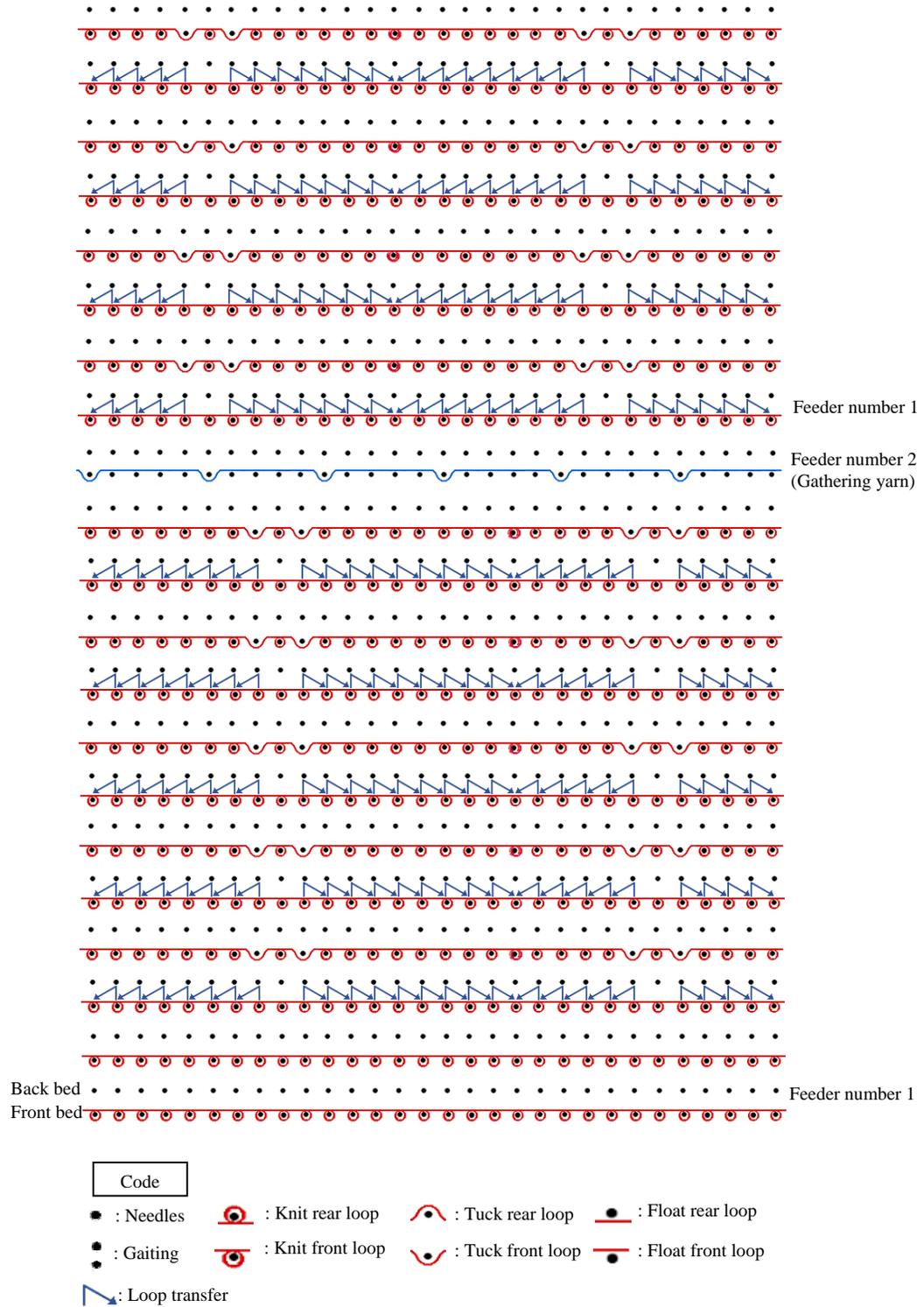


Figure 4.21 Loop notation to create undulating loops for gathering yarns by loop transference.

### 3) Float Patterning (by cutting gathering yarns)

Isolated shapes such as the diamond shape were created by diagonally cutting the gathering yarns. Figure 4.22a illustrates a knitted sample with diamond shaped gathering yarns, and 4.22b illustrates this resist-dyed sample after dyeing. As can be seen in Figure 4.22, isolated patterns can be created by selectively cutting the gathering yarns.

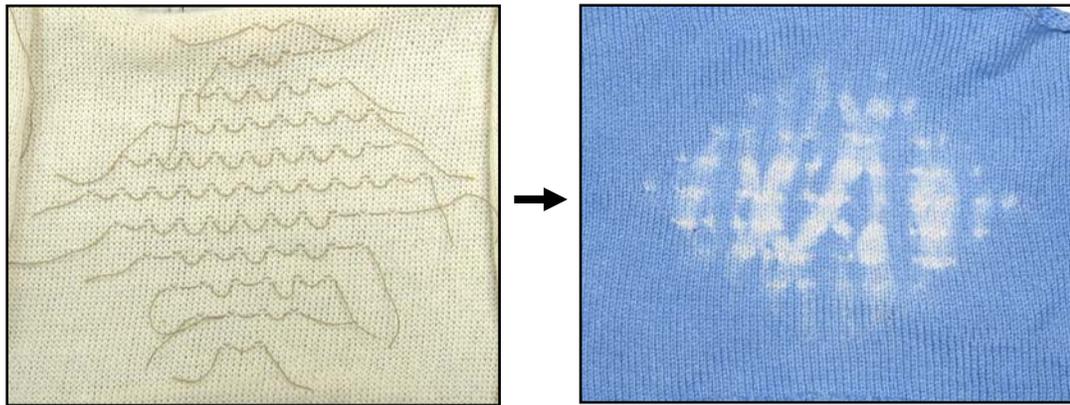


Figure 4.22a

Figure 4.22b

Figure 4.22 A knitted sample with a diamond shape before dyeing and the sample after dyeing.

## 4.4.2. 3D Knit Binding

### 1) 3D Knit Binding (by rib and purl structures)

Three-dimensional knitted structures can be created by the effective use of rib and purl structures. Figure 4.23a depicts a three-dimensional cotton fabric and a method of binding the fabric shape with a cord or a yarn. Figure 4.23b shows the design structure to create the three dimensional cone of fabric on the Shima Seiki SDS-ONE® CAD system.

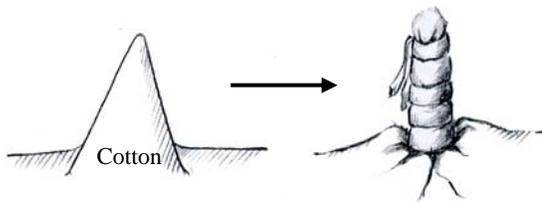


Figure 4.23a

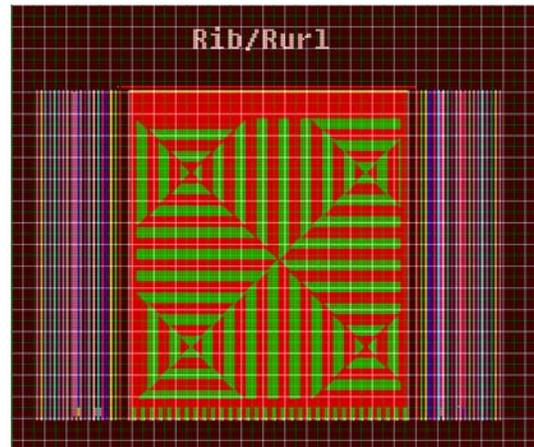


Figure 4.23b

Figure 4.23 Three dimensional knitted structures by use of rib and purl stitches

Figure 4.24 shows a three-dimensional knitted sample fabric bound by a yarn before resist dyeing and a resist-dyed sample after dyeing. After resist dyeing, a three dimensional effect remains on the fabric without any hand process or chemical treatment. It is to be noted that no gathering yarns for resist dyeing were utilized in this experiment.

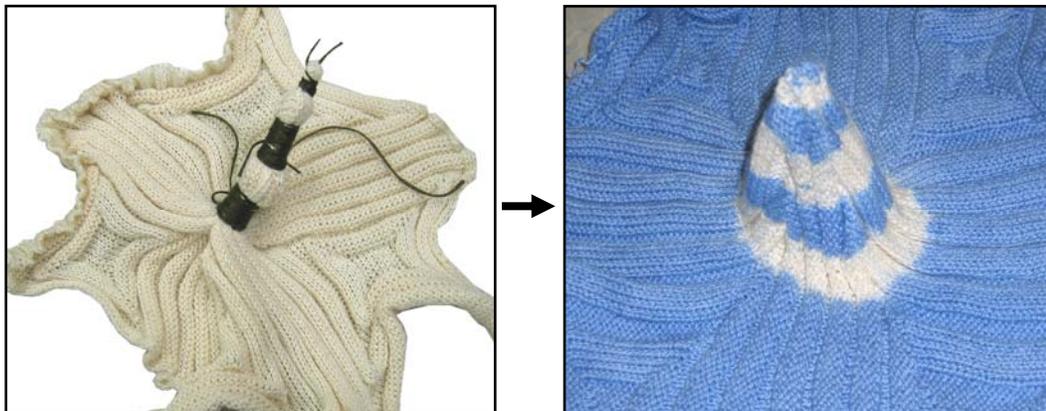


Figure 4.24 A 3D knitted sample before dyeing and the sample after dyeing.

## Knitting and Dyeing Process

The following process shows how the three-dimensional structure can be knitted and resist-dyed.

1. A three-dimensional knitted pattern can be designed by the use of rib and purl structures according to the following loop notations. (see Figure 4.25).
2. During knitting, a three dimensional fabric can be created on the machine.
3. Through diverse binding materials such as yarns, cords, wires or tapes, the fabric can be bound by hand as seen in Figure 4.24.
4. After binding the fabric, the sample can be dyed.
5. Finally, the binding materials can be removed and a three dimensional resist dyed pattern is obtained as seen in Figure 4.24.

## Loop notation



Figure 4.25 Loop notation to create three dimensional knitted structures by use of rib and purl stitches.

## 2) 3D Knit Binding (by an intarsia structure)

Three dimensional knitted structures also can be achieved by the use of yarns with different characteristics, such as shrinkage or felting. Figure 4.26a shows drawings of a three-dimensional fabric where the protruding shape is knitted with cotton surrounded by a flat knitted area of wool. The resulting fabric shape is bound by a cord or a yarn. This intarsia design structure on Shima Seiki SDS-ONE® CAD system is shown in Figure 4.26b

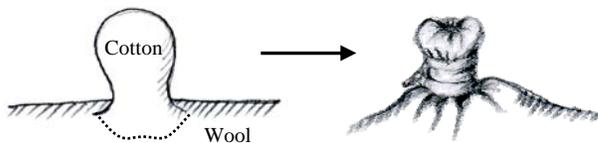


Figure 4.26a

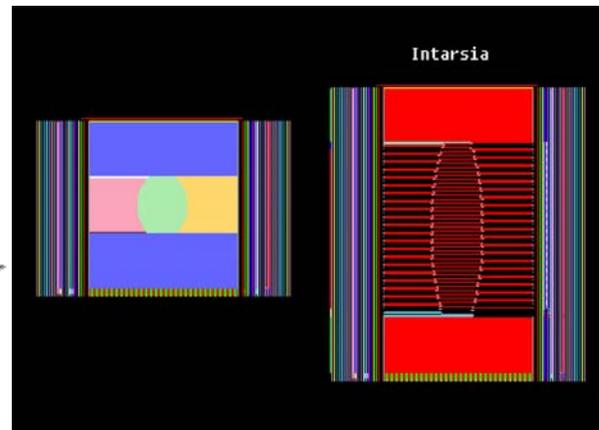


Figure 4.26b

Figure 4.26 Three dimensional knitted structures by use of intarsia knitting.

Figure 4.27a illustrates a three-dimensional knitted sample fabric and bound by a yarn before resist dyeing and the sample after dyeing. After resist-dyeing, a three dimensional effect remains in the felted fabric as can be seen in Figure 4.27b.

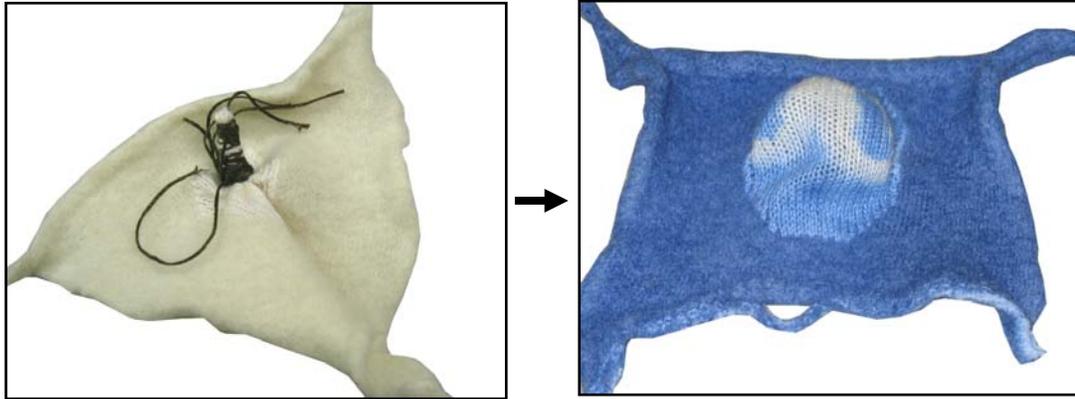


Figure 4.27a

Figure 4.27b

Figure 4.27 A knitted sample by intarsia knitting before dyeing and the sample after dyeing.

### Knitting and Dyeing Process

1. A three-dimensional knitted pattern can be designed by the use of an intarsia knitting structure with yarns of two different characteristics such as a high shrink (wool) and a low shrink (cotton) (see Figure 4.28).
2. After designing on the CAD system, the design data can be transferred to the knitting machine and samples completed.
3. An intarsia knitting structure can be created by use of several different yarn carriers. Each area knitted with different types of yarns can be connected by a tuck structure.
4. Various binding materials such as yarns, cords, wires or tapes, the fabric can be wrapped as seen in Figure 4.27.
5. After binding the fabric, the sample may be dyed.
6. Finally, the binding materials are removed and the three-dimensional resist-dyed pattern is revealed (see Figure 4.27).

## Loop notation

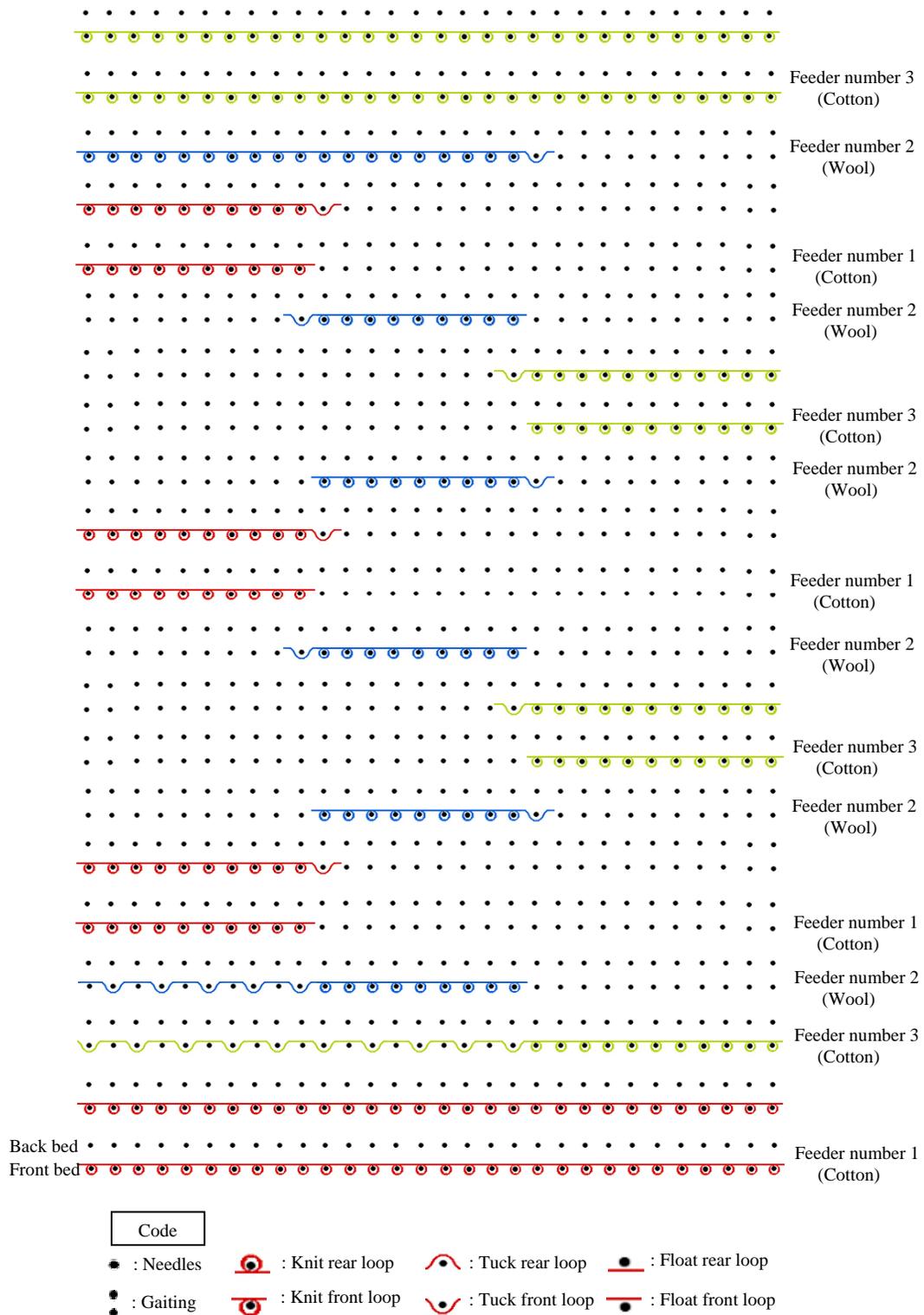


Figure 4.28 Loop notation to create three dimensional knitted structures by use of intarsia knitting.

### 4.4.3. Folding

#### 1) Folding (by pleats)

Fold dyed images can be achieved on knitted fabrics through rib structures. Figure 4.29a depicts figures of a folded or pleated knitted fabric by rib structures and its design structure on Shima Seiki SDS-ONE® CAD system in Figure 4.29b.

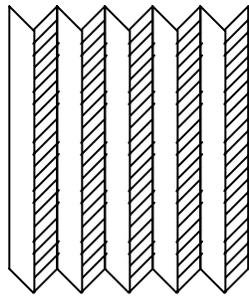


Figure 4.29a

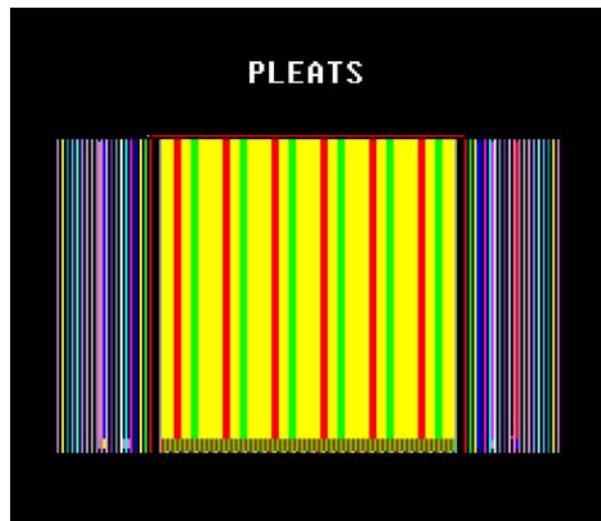


Figure 4.29b

Figure 4.29 Folded (pleated) knit structures by the use of rib knitting.

Figure 4.30a depicts a pleated knit sample which was clamped with wooden strips secured with yarn bindings, which more tightly compress the fabric into folds before dyeing and resists the dyestuff. The resist-dyed sample is shown in Figure 4.30b after dyeing.

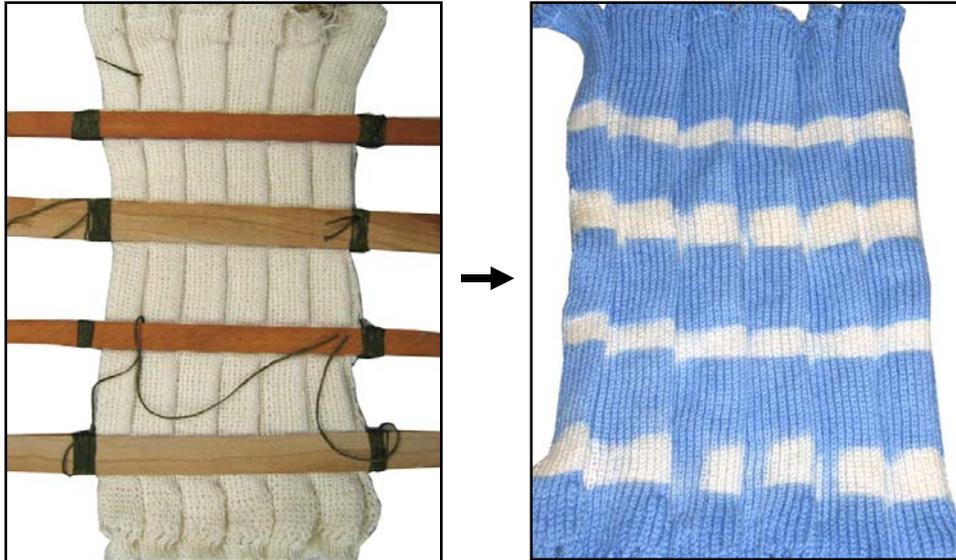


Figure 4.30a

Figure 4.30b

Figure 4.30 A pleated knit sample before dyeing and the sample after dyeing.

#### Knitting and Dyeing Process

The creation of pleated knit and dyed fabrics can be created by the following process.

1. A permanently pleated pattern on knitting machines can be created by the use of a rib structure as seen in the loop notation (see Figure 4.31).
2. After knitting, various compressible materials such as poles, tapes, clips, wooden shapes, metal or plastic objects etc. can be utilized to create a resist-dyed pattern as seen in Figure 4.30.
3. After compressing the fabric folds, the fabric can be dyed.
4. Finally, the materials used for resist dyeing are removed and a pleated resist dyed pattern is achieved as can be seen in Figure 4.30.

## Loop notation

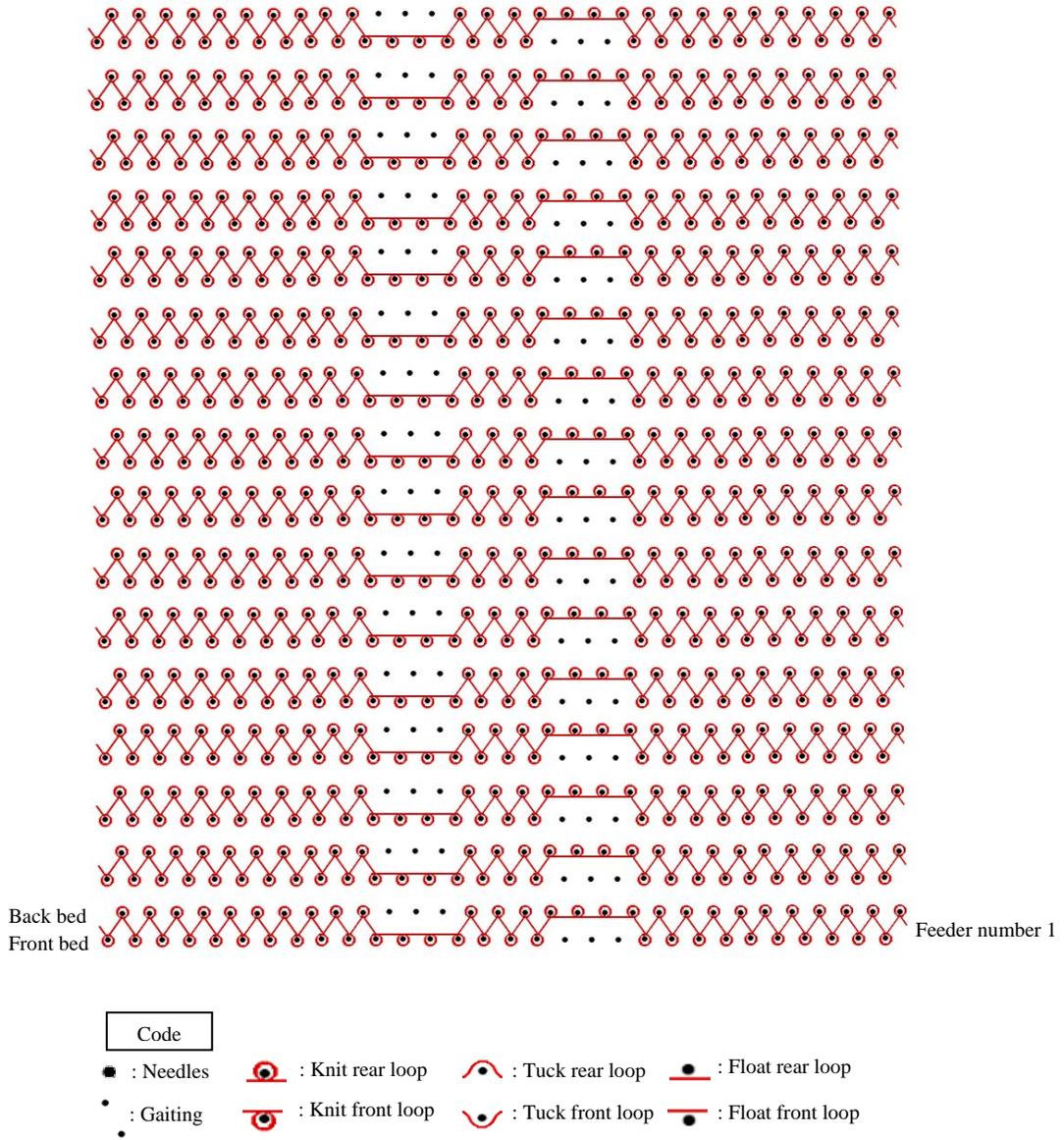


Figure 4.31 Loop notation to create pleated knit structures by the use of rib knitting.

## 2) Folding (by held loop structures)

Another pleated knit fabric was created by use of the held stitch structure. Figure 4.32 depicts figures of a pleated knit fabric by held stitch structures and its design structure on Shima Seiki SDS-ONE® CAD system.

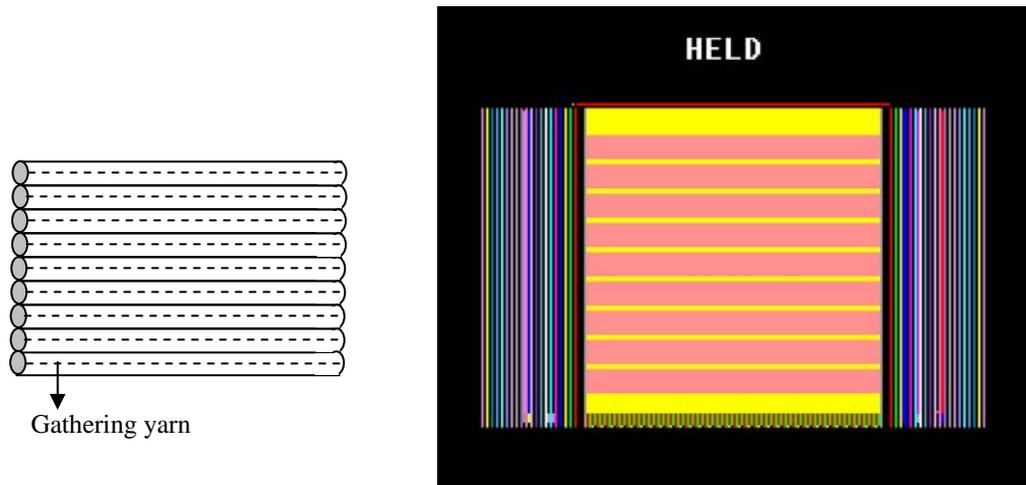


Figure 4.32 Pleated knit structures by use of held loop structures.

Figure 4.33 depicts a pleated knit sample fabric before resist dyeing and after dyeing. The knitted fabric holds gathering yarns only on the front needle bed knitting area for resist dyeing. After resist dyeing, a three-dimensional pleated effect remains in the felted fabric as seen in Figure 4.33. The gathering yarns can also be removed or permanently secured in the fabric.

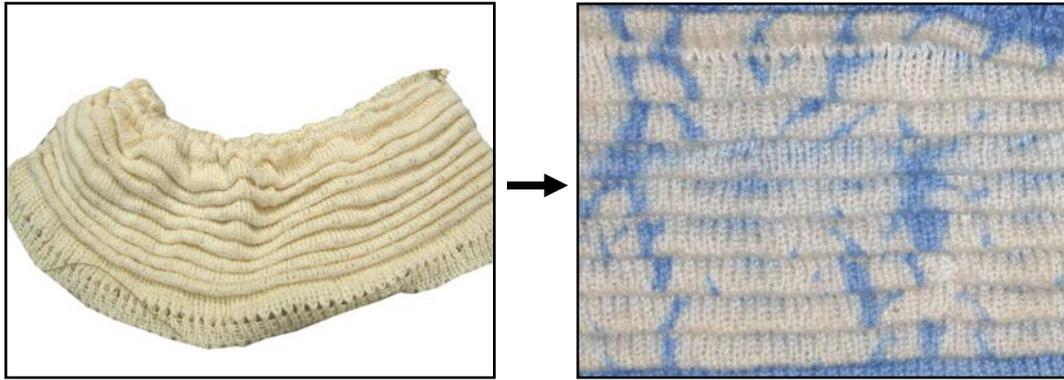


Figure 4.33 A pleated knit sample by held structures before dyeing and the sample after dyeing.

### Knitting and Dyeing Process

The following steps show the process of creating the held stitch knitting structures.

1. As can be seen in Figure 4.32, another tubular structure can be made by a held structure (see Figure 4.34).
2. After designing, the data can be transferred to the knitting machine and the sample knitted.
3. After knitting, the gathering yarns are secured, pulled up and tied by hand.
4. After gathering up the fabric, the sample can be dyed.
5. Finally, the gathering yarns are taken out and resist-dyed patterns are achieved as can be seen in Figure 4.33.

## Loop notation

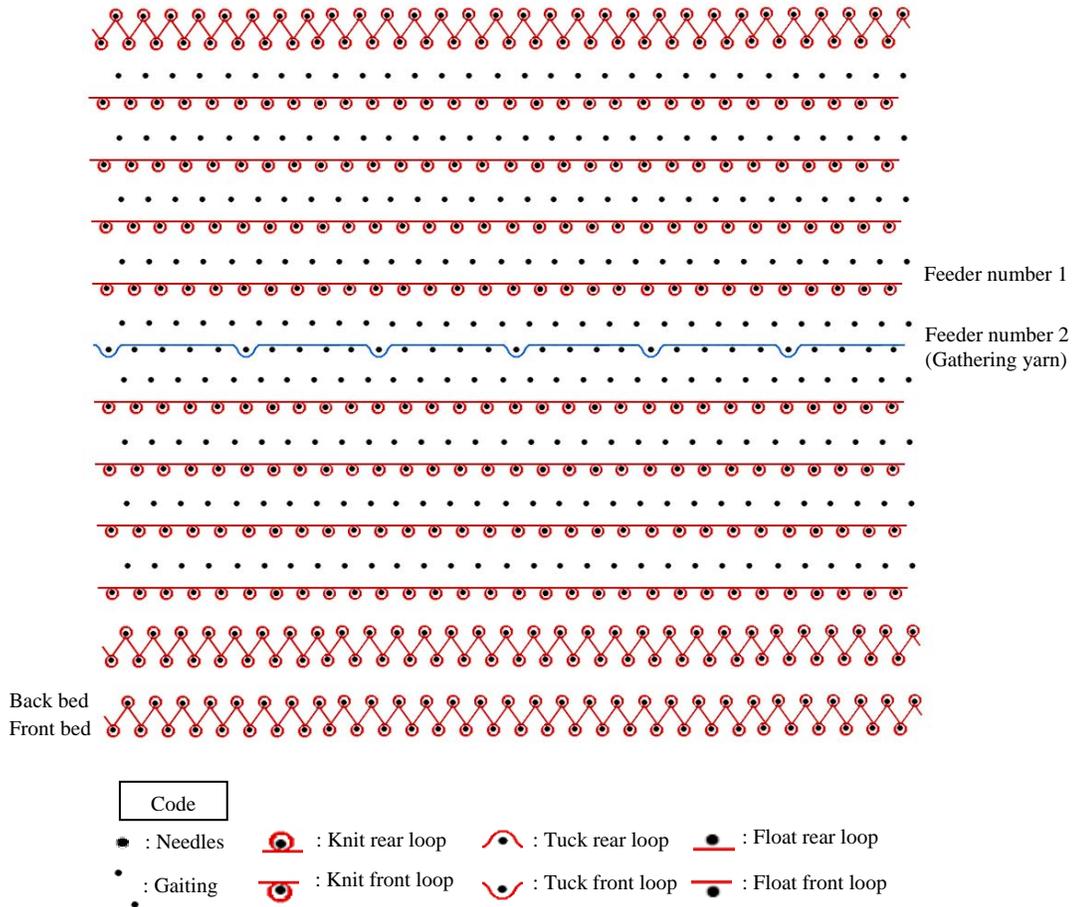


Figure 4.34 Loop notation to create pleated knit structures by the use of held loop structures.

From the all experiments in Hypothesis 4, it can be concluded that Hypothesis 4, which tested resist dyed patterning for complex knitted structures, was accepted.

## 4.5. Seamless-Knitted and Resist-Dyed Garments

Based on the experiments, a seamless knitted and resist-dyed garment was created. The garment was knitted on the Shima Seiki SWG-V WholeGarment® 7-gauge knitting machine considering the knitwear patterns as well as shibori design structures.

The garment was created by four different yarns including one end of 118 Tex 95% cotton and 5% nylon blended yarn for a dress, two ends of 100 Tex 100% wool to create felt the effects for the bodice of the garment, one end of 94 Tex Invista's Lycra® with 280 percent elongation to create folded effects for the garment, and one end of 90 tex 100% polyester as gathering yarns.

This garment was accomplished by the following processes. Initially, numerous product ideas were generated through various related investigating research in magazines, articles, newspapers or internet. Based on the research, several design concepts were sketched and color palettes were created. After idea generation, the shibori-patterns and knitwear patterns were designed through the Computer-aided design (CAD) system (see Figure 4.35). In the design process on the CAD system, technical aspects, including loop notations and other technical data, and design aspects, including knitwear design and knit surface design, were simultaneously considered. When the design process was completed, the data was simulated on the CAD system to review whether or not there is any error before actual knitting. After verifying the no error message for the data, the design data was transferred to the machine. The prototype garment was knitted on the machine with consideration for loop length, takedown tension, knitting speed, and other settings (see Figure 4.36). In the evaluation of the prototype garment, several technical and design issues were recognized. The problems can be resolved through a design refinement process. The knitwear design and knit structural design considering sizes, functions, and aesthetics of the garment, were adjusted on the CAD system. The final knitted garment was completed through repetition of this refinement process.

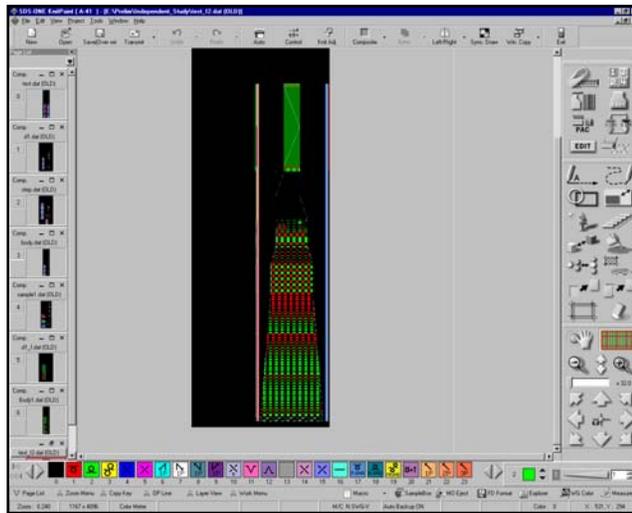


Figure 4.35 Shima Seiki SDS-One® CAD system.



Figure 4.36 A prototype garment created on the WholeGarment® machine.

Before dyeing, the knitted areas which employ gathering yarns were selectively gathered up and then dyed with several different colored reactive dyes (see Figure 4.38). Finally, by finishing process including washing, rinsing and drying, the seamless knitted and resist-dyed garment was completed (see Figure 4.37).



Figure 4.37 A seamless knitted and resist-dyed garment created with cotton and wool.



Figure 4.38a Shibori patterns on a neck area.

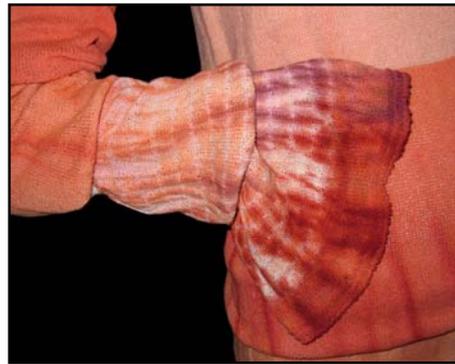


Figure 4.38b Shibori patterns on a cuff area.

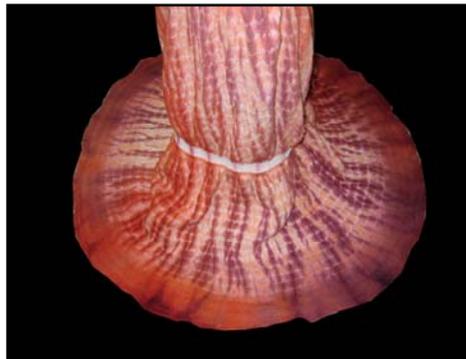


Figure 4.38c Shibori patterns on a skirt area.

Figure 4.38 Seamless-knitted and resist-dyed patterns.

Figure 4.39 illustrates another seamless-knitted and resist-dyed garment using a hand dyeing method with the gathering structures created on Shima Seiki SWG-V WholeGarment® machine. Figure 4.40 shows detail images for each main resist-dyed part of the garment.

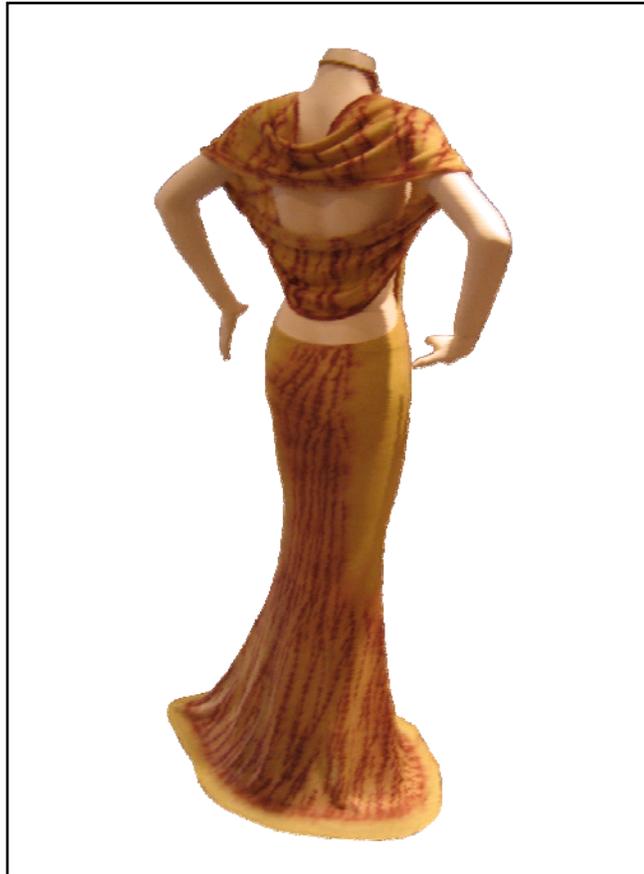


Figure 4.39 A seamless knitted and resist-dyed garment created with Tencel®.

Source: Razulis, D. & Choi, W. (2005). *Unfolding Evolution*. Mounted Design Exhibit. International Textile and Apparel Association, Washington D.C.



Figure 4.40a Shibori patterns on a bodice of garment.



Figure 4.40b Shibori patterns on a neck area.



Figure 4.40c Shibori patterns on a skirt area.



Figure 4.40d Shibori patterns on a hip area.

Figure 4.40 Seamless-knitted and resist-dyed patterns.

Table 4.24 shows a flow chart required to create (seamless) knitted and resist-dyed fabrics or garments. According to new product development process from idea generation to launch, two different fields including knitting and resist dyeing are separately explained. However, both fields must work together to create successful products.

Table 4.24 Flow chart for (seamless) knitted and resist-dyed fabrics or garments

		(Seamless) Knitting	Resist Dyeing
New Product Development (NPD) Process	<b>Idea generation</b>	<u>Inspiration</u> - Knitwear structures, surface designs and yarn selections  <u>Research</u> - Technical research, market research and design research  <u>Illustration and sketches</u> - Identification of product  <u>Scoping Process</u> Ranking and selection of best opportunities	<u>Inspiration</u> - Color inspiration and design patterns  <u>Research</u> - Technical research, market research and design research  <u>Color palette</u>  <u>Scoping Process</u> Ranking and selection of best opportunities
	<b>Design and development</b>	<u>Technical design</u> - Knitwear performance in knitability/production, garment design on CAD systems and technical notations  <u>Industrial design</u> - Development of styles, decorative patterns and knit/fashion design  <u>Creation of prototype</u> - Development and refinement of prototype  <u>Completion of design</u>	<u>Technical design</u> - Performance of gathering structures according to yarn properties, choice of dye stuffs and study of resist-dyeing techniques  <u>Industrial design</u> - Development of colors and resist patterns  <u>Creation of prototype</u> - Development and refinement of prototype  <u>Completion of design</u>
	<b>Testing</b>	<u>Technical analysis</u> - Validation of resist dyed patterns on knitted fabrics/garments - Test and modifications of final fabrics/garments - Validation of product process  <u>Market testing</u> - Research for the textile and apparel market - Preparation for the launch strategy including service, branding etc.	
	<b>Launch</b>	<u>Commercialization</u> - Performance of the marketing launch plan and production plan  <u>Manage launch program</u>	

## 4.6 Fishbone Diagram for Knit Shibori Fabrics or Garments

Figure 4.41 depicts a fishbone diagram of major factors required for successful knitted and resist-dyed fabrics or garments. This diagram is composed of three main fields including knitting, resist dyeing and design development. In knitting, three characteristics including knit structures, yarn properties and machine variables are listed. Resist dyeing is classified into dyeing characteristics, fabric properties and machine variables. Finally, design development is divided into idea generation, industrial design and engineering design. Successful knit shibori fabrics or garments are accomplished through effective operations of the following factors for three different areas influence as can be seen in Figure 4.41.

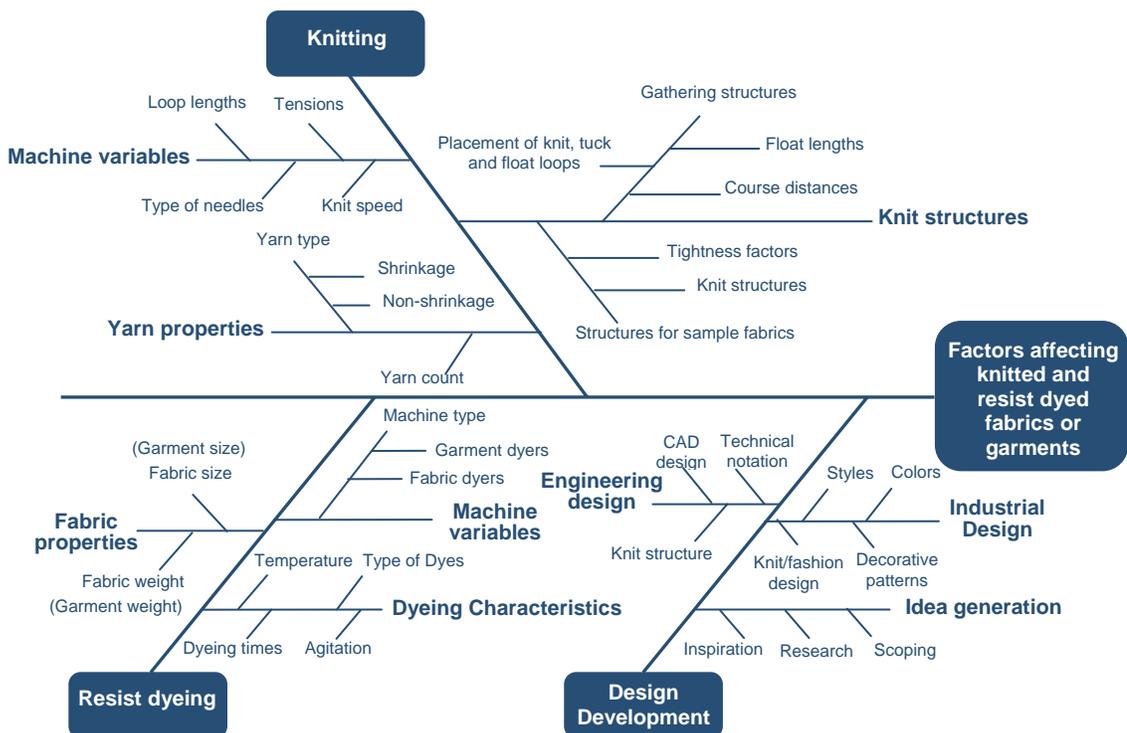


Figure 4.41 A fishbone diagram for knit shibori fabrics or garments.

## **Chapter 5. SUMMARY, CONCLUSIONS, IMPLICATIONS AND RECOMENDATIONS**

The purpose of this research was to evaluate the possibilities of resist-dyed patterns on knitted fabrics created on advanced knitting equipment. This research into the new combination of resist-dyed techniques and seamless knitting was initiated by examining the traditional methods and looking at the possibilities of appropriate knit structures and yarn applications required for resist dyeing.

Four hypotheses were evaluated to verify this research. Three different knitting machines, including circular and flat V-bed knitting machines, and one skein dyer were utilized to create resist-dyed patterns. Two different yarns for sample fabrics and three different types of gathering yarns were used to prove yarn applications for resist dyeing on knitted fabrics. In addition, varied knitted structures were analyzed in four different factors including tightness factor, float length, course distance, and placement of tuck and float of gathering yarns.

### **5.1. Conclusions**

Results from testing Hypothesis 1 indicated that

1. Resist-dyed patterning can be successfully accomplished on either circular or flat knitting machines through the creation of gathering yarns composed of knit, tuck and float loops, which are utilized to make three-dimensional forms required for resist dyeing.
  - Resist-dyed patterning can be created either on circular or flat knitting machines. The resist dyed patterning can be also achieved on a tubular knitted garment on complete garment knitting machines.
  - Resist-dyed patterning through the creation of gathering yarns can be achieved either by tuck & float structures and float jacquard structures. In tuck & float structures composed of tuck and float loops, gathering yarns can be taken out from sample fabrics after resist dyeing, while float jacquard structures composed of knit, tuck and float loops are permanently secured in the sample fabrics after dyeing.
  - It is noted that small openings which do not affect integrity of fabric may be left in a sample fabric after removal of gathering yarns for tuck & float structures of the sample fabric.

Results from testing Hypothesis 2 indicated that

2. Different factors of float length, course distance, and the placement of tuck and float of gathering yarns have a significant relationship to the resist-dyed image.
  - Resist-dyed patterns are changed according to different knitted structures for sample fabrics or gathering yarns.
  - In order to consistently resist-dye sample fabrics, skein dyers provide limited results and are not recommended. Especially, if the high number of sample fabrics

(about 160 samples) are dyed in the skein dyer, sample fabrics are not evenly dyed. It means that sample fabrics have different dye penetrations according to the position of the knitted sample fabrics in the skein dyer even though the sample fabrics have the same knitted structures and are dyed in the same dyeing situation. It is inferred that the results are influenced by the sample weight, water agitation, and dyeing time.

Results from testing Hypothesis 3 indicated that

3. The use of each different type of yarn for sample fabrics or gathering yarns can result in different resist effects in color penetration.
  - In tuck & float structures, patterns on cotton fabrics have a higher contrast, a higher randomness and a more black coverage than patterns on rayon fabrics. It shows that the use of different types of yarn for sample fabrics can affect resist effects in color penetration.
  - In sample fabrics created by rayon, compared to tuck & float structures, float jacquard structures have a higher contrast, a higher randomness and a more black coverage. It demonstrates that according to use of different types of gathering structures, resist dyed images can be changed.
  - When shrink yarns or elastomeric yarns such as shrink polyester or Lycra® were utilized as gathering yarns, results were unpredictable compared to non-shrink yarns or non-elastomeric yarns such as spun polyester in float jacquard structures. It proves that resist dyed images also can be changed by use of different types of gathering yarns.

Results from testing Hypothesis 4 indicated that

4. Resist patterns on knitted fabrics can be developed through various complex structures affecting resist-dyed images by computerized flat V-bed knitting machines.
  - Through varied knitting techniques including flechage, loop transference, rib or purl structures, intarsia knitting or held loop structures, more complicated three dimensional resist-dyed patterns are explored.
5. Based on the research, a seamless-knitted and resist-dyed garment is created through the complete garment knitting machine.
  - Various types of tubular complete garments with shibori structures, including sweaters, skirts, trousers, socks and gloves, can be effectively created on seamless knitting machines and can be resist-dyed.

## **5.2. Implications**

1. This research has implications for textile and apparel companies, who require information on knitted fabrics or garments (including seamless garments) with single- or multi-colored resist patterns.
2. This research can be used by textile and fashion designers, who are studying or working on traditional resist dyeing techniques.
3. Knitting manufacturers also would develop innovative machinery and methods incorporating seamless knitting technology with resist dyed techniques based on this research.
4. This research presents new possibilities of seamless-knitted and resist-dyed garment technology as new product development to researchers and industrial personnel.

5. This research confirms that level dyeing of the fabric bundles can be achieved with designated process which would be important as a base shade in multi-colored patterning.

### **5.3. Recommendations**

#### *Future Research Studies*

1. This research examined the possibilities of knitted and resist patterning created on weft knitting machinery. Future research could observe the knitted and resist patterning created on warp knitting machinery.
2. In this research, gathering yarns were created on only single jersey fabrics. Future study could test possibilities of creation of gathering yarns on sample fabrics with diverse knit structures, including rib, cardigan and jacquard.
3. Future research also could consider more various gathering structures composed of multiple tucks including double tucks or triple tucks.
4. Additional research is required to explore resist dye possibilities in the different types of dye equipment, including paddle dyers, pad dyers and others, required for mass customization of the seamless-knitted and resist-dyed garments.
5. This research examined two different yarns for sample fabrics and three different yarns for gathering yarns to create resist dyed patterns, and reactive dyes were utilized to test resist dyed patterns. In further research, more varied yarns used in the sample fabrics as well as gathering yarns could be explored with diverse dye stuffs.
6. Further research could focus on the effective integrated process of knit design and knitwear design incorporated in seamless knitting technology.

7. Future research could examine knitted and shibori patterns created on advanced printing equipment such as digital printing systems.
8. Future research could studies seamless-knitted and resist-dyed garments incorporating computerized body scanners.
9. As the most variable and time consuming process of binding is a hand method, additional research could be pursued to develop more advanced methods of drawing up the fabric, securing the fabric bundle, and binding the sample for resist.
10. Future study is needed to look for methods to perform a more quick-response production or just-in-time production for seamless-knitted and resist-dyed garments in the textile and apparel industry.
11. Future research would be required to discover methods to more effectively achieve multi-colored resist patterns through multiple dyeings and a sequential pulling-up process.
12. The seamless knitted and resist-dyed structures could be applied to more varied textile areas, including home furnishing, medical textiles and automotive textiles.
13. Three dimensional characteristics of traditional hand dyed shibori could be explored through the use of elastomeric yarns as seen as in Table 4.6 (Float jacquard construction) or through other processes such as felting, heat setting and chemical treatment.
14. The application of a resist dyed seamless knit technology to a production situation could only occur successfully if this process could be controlled for repeatability. Large scale research would be required to prove the sustainability of the process.

## Chapter 6. REFERENCES

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