ABSTRACT

PARRILLO-CHAPMAN, LISA, L. Textile Design Engineering within the Product Shape.
(Under the direction of Dr. Trevor J. Little).

This body of research seeks to improve the design and development of a class of products referred to as *engineered designs*. Specifically, the process for textile design engineering within the shape of a product. *Textile Design Engineering within the Product Shape* is an iterative and often highly collaborative design process. The purpose of this type of engineered design is to i) improve the performance of the product and/or, ii) to improve the aesthetics of the design. Products engineered for aesthetic purposes can create a seamless design by continuing a motif or fabric structure across a seam, dart or closure, and accentuate shape or movement. Products engineered for functional purposes can improve performance, comfort, fit, and movement, reduce waste, and reinforce areas of high wear.

Expert practitioners from industry, academia, and research institutes were surveyed on their use of engineered design. In addition, case study analysis was conducted on the engineered design process. Results from the survey and case study analysis assisted with building a four stage process model. The research uncovered a need for increased input from designers and the need for improved communication and collaboration between members of design and product development teams. New and emerging technologies such as digital printing, integral knitting, and 2D and 3D simulation software facilitate the engineered design process; however, these technologies are underutilized.

Textile Design Engineering within the Product Shape

by
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DEDICATION

This dissertation is lovingly dedicated to my husband Chris, in respectful admiration for his strength, patience and love, to my beautiful daughter Mia for her humor and kindness, and to my brother and sisters for their encouragement and support. Lastly, to my parents who taught me to lead, not follow.

BIOGRAPHY

Lisa Parrillo Chapman is employed by the College of Textiles and teaches computer aided design for textiles and introduction to textile technology courses. Lisa also manages the College's *Digital Design Lab*. She received a B.F.A in fibers from the University of the Arts, Philadelphia PA. While working as a buyer and a manager of a home specialty store she completed a Master of Textiles from North Carolina State University, College of Textiles. Continuing at the College of Textiles, Lisa worked toward her doctoral degree in Textile Technology and Management. Current research interests are in emerging technologies in digital design, particularly ink jet printing, and integral knitting.

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1. INTRODUCTION

The most time consuming and resource intensive part of the production of textile products is the product design and development cycle. Even after considerable time and resources are allocated to development, the product can be rejected for a number of reasons, such as i) it is not technically feasible to manufacture the item, ii) it is too expensive to produce the item, iii) it is too time consuming to manufacture the item, iv) the item is not aesthetically pleasing, and/or v) the item is not appropriate for the intended market. If the product is rejected, the product design and development process starts over.

Integration of some or all of the fabric design process with the final product development process can improve prototyping, and consequently the end product can be improved. Typically a textile designer produces the fabric that is then chosen by an apparel or home furnishings department for use in the end product. Fabric is not always designed for an intended end product and vice versa, an end product is not always developed with a fabric in mind. The typical process demands that a product developer search for and then test fabric that will be appropriate for the end use of the product (Brown & Rice, 1998). However, if the fabric and end product are designed simultaneously, i.e., if some or all of the fabric design properties are engineered for the end product, then aesthetic and functional aspects of the product are improved.

The engineering of fabric design properties within the shape of a product is an iterative and often highly collaborative design process within the textile complex. The purpose of this engineered design is to i) improve the performance of the product and/or,

ii) to improve the aesthetics of the design. Products engineered for aesthetic purposes can hide seams, accentuate shape or movement, divert attention from an area of the body, or continue a motif or pattern across a seam, dart or closure. Performance engineered design can reinforce areas of high wear, reduce waste, or improve comfort and fit. For example, to improve performance, a sweater could be engineered to have a more elastic structure knitted into areas of high stress. In contrast, a print design with a large, central motif that is strategically placed on the garment to accentuate the body would be considered an engineered design for aesthetic purposes.

Tools and processes that enable engineered designing, especially digital technologies, also facilitate the translation from the prototype process to the manufacturing process. In fact, in some instances the prototype method and manufacturing process are the same. Two emerging technologies, ink jet printing and integral knitting epitomize the ability of digital technologies to alter the design workflow and enable engineered designing. With both technologies, the end product can be simulated before production, facilitating strategic placement of fabrication features and properties. Thorough analyses of new and emerging technologies such as these, that support engineered designing, are needed to understand how this process can successfully be implemented into the product development and manufacturing process. Information gathered from this study may also assist software developers and machine manufacturers in redefining the available tools for engineered designing. Three dimensional visualization technologies exist or are being developed to assist with placement. While

these technologies are geared toward aesthetic visualization, they may also aid in the strategic placement of functional factors.

1.1. Purpose of Research

The purpose of this study is to provide a rich understanding of the various methods of engineered designing, and to build a comprehensive model of this product development process. Engineered designing, while not applicable to every product development process, has the potential to promote product innovation, and the ability to increase the quality of the product. New technologies and digital processes enable new design practices such as engineered designing, yet traditional methods of product development are still the norm. A review of existing textile and apparel product development models, coupled with the acquisition of quantitative and qualitative data will help in building a comprehensive model of engineered design. Data in the form of visual and written documentation of the engineered design process is gathered from expert members of industry and the research community. Once documented, engineered designing has been developed into a “Textile Engineered Design Model” (see section 4.4) that shows why engineered design requires a different approach than traditional textile design. The information gleaned from this data provides more advanced skills for users of this process, provides a comprehensive understanding for individuals who have no prior experience or knowledge in this area, and contributes to the wider adoption of engineered designing.

2. LITERATURE REVIEW: TECHNOLOGIES SUPPORTING ENGINEERED DESIGN

New and emerging digital technologies in the textile and apparel arena have the capability of altering product development and manufacturing processes. To gain an appreciation of the advances to date, the following literature review will explain in detail the evolution and adoption of two emerging digital technologies; digital printing and integral knitting. Although the technologies and markets for digital printing and integral knitting are significantly different, both processes improve product development by i) enabling rapid prototyping, ii) facilitating communication between design and technical production, and iii) enabling integration of fabrication design with end product design. The purpose of this literature review is to contrast the traditional product development routes of both fabric printing and knitted apparel manufacturing with the new product development paths that digital printing and integral knitting permit. Markets, technologies, and product development processes for integral knitting and digital printing will be reviewed, and factors that enable or prohibit adoption of these digital technologies will be reviewed. Once the product development paths of integral knitting and digital printing have been documented the literature review will attempt to place these new technologies in the context of existing product development models. Inadequacies and efficiencies of existing models will be used in developing a new model for engineered designing. In addition, the literature review will establish the use of engineered designing in digital printing and integral knitting and show commonalities of principles.

2.1. Digital Printing

The textile print market is robust, but it is also a swiftly changing market and one that is strongly affected by fashion trends. Ink jet printing, a developing technology for the print market, has the capacity to more quickly respond to changing trends. Ink jet printing filled a need in the market for a more cost effective and faster sampling process, a direct result of consumer demand for more variety of prints in the market. The continued support and development of ink jet printing are dependent on varied and interdependent, factors. Push factors such as improved dye chemistry and machine engineering could eliminate fabric pre-treatment and post treatment and allow for increased print speeds. Continued research and development activity and funding will help to improve and continue innovation in ink jet printing. While educational support provided by professional, and research organizations will insure that ink jet printing is optimally used in the product design process. But most likely it will be consumer demand for customized and novel prints and more variety of prints that will pull the market.

2.1.1. *Global Print Market*

The worldwide print market is a vigorous enterprise, accounting for 15% of the revenue of all textiles products (Byrne, 2004). There are three main markets for printed goods: *Apparel*, which can be divided into greige good printing or made-up garment printing; *Interior Fabrics* such as sheets, upholstery and curtains; and *Technical Textiles*. Technical textiles differ from the two previously mentioned categories in that the print is added to the fabric for added performance rather than for decoration. In addition to

these three categories printing is used for carpet and automotive design, labels for garments and for signage.

By far, the largest end use for printed goods worldwide is for the Apparel sector which accounts for, on average, 54% of all printed goods. In Asia, Africa, Western and Eastern Europe 50% of each region's printed fabric is for the garment industry. In fact, in Asia where more than half of the world's printed fabric is made, more than 70% of the printed goods are for apparel (Teunissen, Kruize, & Tillmanns, 2002). The majority of printing is done on fabric lengths but garment printing is gaining momentum largely due to demand for printed t-shirts; which has now grown to a \$20 billion business within the United States alone (Williams, 2006).

Worldwide, printed interior textiles comprise 30% of the textile print market; nine million square meters are printed annually (Byrne, 2004). Interior textiles, or home furnishings, include bedding, upholstery, carpet and decorative accents such as mats and pillows. In the U.S., 50% of printed production is for interior textiles, a larger market segment than that of apparel which makes up 30% of the market. Although print production for apparel and interior fabric has declined in North America, the percentage of printed fabric for technical textiles has increased to 20% of all printed goods. The global market reflects similar growth; on average there has been a worldwide increase in technical textiles (Teunissen et al., 2002).

The global printed textile market produces 29 million square meters or 18.63 billion linear meters annually, yielding a \$160 billion (U.S.) a year business (Byrne, 2004). This equates to about 15% of the revenue of all textiles products. Of this only

about .01% is estimated to be printed via an ink jet printer (Teunissen et al., 2002). In 2002 the annual worldwide growth was estimated at 13% (Cahill & Ujiiie, 2004). However, I.T. Strategies, a consulting firm specializing in the ink jet printing market, states that in 2005, ink jet printers printed 71 million square meters - a larger growth than anticipated. Asia has experienced the largest growth in print production, not surprising considering that the majority of the world's printed fabric, more than 50%, is produced in this region. This has proved detrimental to other regions, for example, although Africa and Latin America have experienced modest growth, all other regions such as North America, Eastern and Western Europe, and the Middle East have all seen declines in their production of printed goods. Worldwide, printing tends to be a localized market, on average 63% of printed textiles are produced for a region's own market. The exception to this is Asia, that region exported 57% of their printed goods in 2001 (Teunissen et al., 2002).

Two factors which support ink jet printing are smaller run lengths and increased number of colors per design. Small run lengths, less than 1000 meters are not cost effective for traditional screen printing (see section *4.1.1 Sampling* and *4.1.2 Small Production Runs*). Each additional color also adds a substantial cost to the printing process. However, with ink jet printing there is no cost increase for additional colors, and there are no minimum yardage requirements for printing. In fact, there is no difference in price/yard between printing one yard or 10,000 yards and likewise it costs the same to print one color or 100 colors. From 1992 to 2001 the average run length for screen printed fabric decreased by almost 50%, from 4160 meters to 2235 meters, and

the decline is continuing (Teunissen et al., 2002). Overall the average number of colors per print design has remained constant at six. However, the largest print producer, Asia, has seen an increase in number of colors per design, from 6 in 1994 to 7.3 in 2001 (Teunissen et al., 2002). This is mainly because of the demands from Asia's markets, namely North America and Europe, which call for higher quality and more fashion forward prints, which translate to an increase in colors and variety of prints. More variety in prints equals more runs, but with shorter run lengths.

2.1.2. *United States Print Market*

An industry survey from 1984 found 23 firms in the U.S. who had printing facilities. More than half of these firms were located in the southern states with an average size of 51 to 100 employees. The majority of the printing companies used rotary screen printing (34%) followed by roller printing (12%), heat transfer (11%) and flat bed (8%) (Amidon, 1991). Information from the printing survey states that the 1984 U.S. Department of Commerce's *Current Industrial Report* included detailed information on print production facilities such as geographic location, method of printing and whether the firm was a commission or non- commission printer. The time from the late 1980s until the early 1990s was a period of strong economic growth for the U.S. printing industry but from 1994 to 1997, U.S. printed fabric production dropped 20%, one of the severest downturns of print volume in U.S.'s history (Byrne, 2004) ¹. It is not a

¹ 1986 was the last year the U.S. Census bureau included data for the printing segment. For this

coincidence that during this economic downturn the textile printing industry had a marked increase in the number of ink jet printers placed in production (see Figure 1).

Figure 1. Digital textile placements by technology (Byrne, 2004)

2.1.3. Machine Technology

“Ink jet is a non-impact dot-matrix printing technology in which droplets of ink are jetted from a small aperture directly to a specified position on a media to create an image (Le, 1998).” As shown in Figure 2, there are three main types of print heads for ink jet printing: continuous or charged drop; pulsed jet; and drop-on-demand (Tyler, 2005). Charged drop type operates by ejecting a stream of ink at a high pressure ($15\text{--}35 \times 10^5$ Pa) through a very fine nozzle, causing the liquid to break up into a train of small droplets. “Charged drop formation is the fastest method of printing; with the next fastest

being piezo followed by bubble jet and with valve operated the slowest (Dawson, 2000).” While the method of ejecting the ink drop varies by type of print head, all three print heads form the same type of ink drop; the dye is forced from the print head forming a tail, the ink tail collapses onto its head forming a sphere and the spherical ink drop strikes the fabric. The size of the ink drop can vary considerably, from 50 to 1000 picolitres (T. L. Dawson, 2001).

Figure 2. Classification of ink jet printing technologies (Tyler, 2005)

In 1878 Lord Rayleigh devised a method for breaking up a stream of ink into smaller droplets (Rayleigh, 1878). It was not until 1952 though that the first patent for an ink jet mechanism was filed by Elmqvist an employee of Seimens (Elmqvist, 1951). In the 1960s Dr. Sweet, from Stanford University, broke the ink jet stream into droplets using a pressure wave valve and proved that by applying an electrical charge to the ink

drops the drop size and formation could be controlled (Sweet, 1965). IBM acquired Sweet's continuous ink jet technology in the 1970s and in 1976 launched the IBM 4640, the first low cost ink jet printer (Le, 1998). Home and office use of computers began to rise in the 1950s through the 1970s, and the need for printers increased as consumers demanded the ability to print data generated from the new computers (Webster, 2000). As computers sales increased and the cost of ink jet printers decreased sales of printers skyrocketed - from 30,000 units sold in 1960 to over 50 million units sold in 2000 (Webster, 2000).

A subset of ink jet printers is the large format ink jet printer, defined as any printer with a print width larger than an A2 size paper or 594 mm by 420 mm. (Presgrave & Provost, 1996). Large format printers are used by the graphics art industry and for sign and banners. Although a smaller market than desktop printers the large format market has shown a steady increase. By the mid 1990s, worldwide, the paper printing industry had 15,000 units of large format ink jet printers installed and in 2004 over 130,000 wide formats printers were in use (Williams, 2002).

The increased market demand for wide format printing helped the development of textile printing in two ways. First, wide format printers accommodated printing of large and multiple repeats of textile designs. Second, wide format printing, unlike a typical home or office printer, requires rolls rather than sheets of paper. The ability to print on a continuous roll, rather than a sheet of paper, is conducive to textile yardage printing. With roll to roll printing capability, wide format printers were able to

physically handle printing a roll of fabric, but the print heads were not designed for textile inks. What was missing was the ability to print with textile specific inks so that the printed fabric would have the same fastness properties as screen printed samples.

In 1991 Stork marketed an ink jet printer for textiles that used reactive dyes developed by ICI. Stork's textile printer, which used a charged drop print head, was the first textile fabric printer (T. L. Dawson, 2004). It was marketed as a sample printer and although the print speed was slow by production standards, the time and cost to produce a sample decreased. The first ink jet printers to print on a textile substrate were introduced in the mid 1970s by Milliken for use on carpets. The printer, called Millitron, had pulsed air jet print heads (Tyler, 2005). Unlike Stork's fabric printer, the Millitron had the required speed needed to print high volumes of textiles. The difference between Stork's and Milliken's printer was the type of substrate printed. The Millitron printed on carpet, while Stork's printer was developed for fabric printing. Carpet pile has a highly irregular surface and therefore a high resolution is not needed. Because the resolution was low, larger drops of ink were sufficient. Needed, was the high resolution of Stork's printer and the production speed of the Millitron. It took two decades, until 2001, for the introduction of DuPont's Artistri, the first high-resolution production printer.

Table 1. Original Machine Manufacturers

Company name	Country of origin	Original machine supplier
Dua Graphic Systems (DGS)	Italy	Mimaki
Digital Printing Systems (DPS)	USA	Mimaki, Reggiani
Dupont Ink Jet	USA	Inchinose, Vutek
Gali Internacional	Spain	Roland, Mutoh
La Meccanica	Italy	Mimaki
Macchine e Servizi (MS)	Italy	Mimaki, Roland
Spuhl	Switzerland	L&P Digital
Stork Digital Imaging	Netherlands	Mimaki, Konica

The majority of technological advances in textile ink jet machines continue to be driven by the sign and banner industry. In fact, of the 2,300 textile digital printers installed by 2005, 75% of the textile substrates printed are for the sign and banner market (I.T. Strategies, 2006a). Because much of the current technology for textile ink jet printing was developed by the paper printing industry there are inherent problems. Ink jet textile printing unlike paper printing is affected by the following attributes: “fabric structure (e.g. whether the print cloth is a plain weave, knit, etc), yarn fineness and thread count, type of yarn (e.g. combed versus carded) and the fabric pre-treatment process (e.g. bleached or mercerized)”(Tse, Briggs, Kim, & Lewis, 1998). Additionally,

inks used for textile printing require up to 15% more colorant than inks for paper printing (Geisenberger & Zeller, 2000).

Although initially innovation in ink jet machine technology was driven by the paper industry, by 2003 (as evidenced by the number of textile printers at ITMA 2007) the textile sector had invested significant resources into research and development. The textile ink jet machine market began to have three distinct categories: “1) print head manufacturers, 2) companies that manufactured original machines and 3) companies that modified and rebranded machines (Tyler, 2005).” See Tables 1 and 2. Two other factors that strengthened the textile ink jet machine market and showed market maturity were partnerships between machine developers and dye manufactures, and specialized printers. At the 2005 FESPA Trade Show specialized printers included, t-shirt, flag and banner and a three dimensional printer for buttons and seals (Early, 2005).

Table 2. Machine by Print Head Type (Tyler, 2005)

Company name	Country of origin	Print head type
ColorWings	Netherlands	Thermal DOD
Inchinose – Toshin Kogo*	Japan	Lexmark Thermal DOD
Filteco	Italy	Valve Jet
Fratelli Robustilli	Italy	Epson Piezo DOD
Konica*	Japan	Konica Piezo DOD
L&P Digital Technologies*	USA	Spectra Piezo DOD
Mimaki*	Japan	Epson Piezo DOD
Mutoh*	Belgium	Piezo DOD
Optotexform	Germany	Piezo DOD
Osiris	Netherlands	Image Continuous MD
Reggiani *	Italy	Aprion Magic Piezo DOD
Roland*	Japan	Piezo DOD
Vutek*	USA	Piezo DOD
J. Zimmer Mashinenbau	Austria	Jemtex Continuous MD

* Have their machines modified and sold-on by other companies

2.1.4. Dye Formulation and Market

In order for ink jet printed fabrics to be marketable they must have the same as or better properties than screen printed textiles already on the market. A good quality print is dependent on the interaction between ink and print head; mainly the ability for the print head to remain unblocked by the inks (T. L. Dawson, 2001). In addition the inks must

remain stable, the printed fabric must have approved fastness properties and the correct target color must be achieved (T. L. Dawson, 2001).

Achieving the correct color in ink jet printing is a complex process. There are major differences between ink jet printing and screen printing in how each achieves color. In screen printing spot colors are used, while ink jet printing uses process color. A spot color is mixed to its exact shade, using any number of required colors, every time a new pattern is printed. Process color is laid down in a dot matrix pattern from a set of fixed colors (anywhere from 6 to 12). The color effect is much like pointillism as the dots visually blur together or mix to form other colors. For instance to form green, tiny dots of yellow and blue would be laid down side by side or overlapping each other. These dots are not randomly placed rather they are dropped within a matrix pattern so as to appear random.

To achieve the millions of colors possible in ink jet printing, a printer's rip software must be capable of producing halftones by either varying the size of the individual drops or being able to fire a series of micro drops onto the same position. This increases the number of shades that can be attained. Another way to increase the number of colors produced by ink jet printing is to add an additional strength of ink. For example, if one were to add a second cartridge of magenta or cyan at a stronger or weaker strength, then the number of colors increases from 4,913 to 1.4 million, almost a 300% increase (T. L. Dawson, 2001). (This is assuming a 4x4 matrix.) The sets of cartridges that contain two strengths of ink are commonly called hi/lo sets. A hi/lo set is

comprised of the typical four cartridges, each containing full strength solutions of cyan, magenta, yellow and black but then anywhere from two to four additional cartridges are added that are made up of half strengths solutions of dye. Using a hi/lo set of inks will extend the number of shades but will not extend the limits of the gamut. As shown in Figure 3, in order to extend the limits of the gamut (number of colors) an additional dye color such as a brighter orange red or reddish blue or violet can be added to the ink set (T. L. Dawson, 2000).

Figure 3. Extending color gamut with additional colors (Sarma, 2004)

Equally as important as achieving the correct color is obtaining color fastness properties and maintaining the hand of the fabric. Paper printing generally needs one type of dye while textile printing requires a variety of dyes based on the fiber composition of the substrate. As stated previously, in order for ink jet printed fabrics to

be marketable they need, at the minimum, the same properties as conventionally printed fabrics. The various ink systems available for textile ink jet printing are shown in the Table 3.

Table 3. Ink Systems (Presgrave & Provost, 1996)

<u>Aqueous Dyes</u>	<u>Aqueous Dispersion</u>	<u>Solvent Based Dye</u>	<u>Non Aqueous Dispersion</u>
Direct	Pigment	Solvent Soluble	Pigments
Acid	Disperse		
Reactive	Vat		

A study by Canon Inc. Japan compares the print quality between ink jet printed and screen printed textiles (Kiatkamjornwong, Putthimai, & Noguchi, 2005). The printed fabrics were evaluated on several factors such as color saturation, gamut and volume. Other factors used for evaluation were ink density, tone reproduction, stiffness, air permeability and crock fastness. The tests concluded that both the screen and ink jet printed textiles had the same or nearly the same color saturation and gamut as well as ink tone reproduction. However, ink jet printed textiles were found to be superior in such factors as gamut volume, stiffness, air permeability and crock fastness. It was determined that the acceptable pigment particle size for ink jet printing is between 80 and 300 nm. See Table 4 for particle size by colorant used.

Table 4. Particle Size by Colorant (Kiatkamjornwong et al., 2005)

Colorant	Particle Size
Cyan	98nm
Magenta	200 nm
Yellow	177 nm
Black	132 nm
S-711 Binder	161 nm

Although the density was superior for ink jet printing it took three passes to obtain the density of color as for screen printing. Additionally it was found that the gamut volume of treated fabric is higher or much better than those fabrics that are not pre-treated and also of screen printed fabric. Another factor that affected the print quality was the penetration of ink. More colorant is used for ink jet printing and the colorant used is more aqueous therefore ink penetration is increased. This causes shifts in the printed hue, a reduction in saturation, and a smaller printed color gamut.

2.1.5. Sampling and Strike-Offs

Sampling onto textiles is at present the largest market use for textile ink jet printers. I.T. Strategies, a U. S. based consulting firm for digital printing, defines textile print sampling as a process for printing on paper or textiles for accurate reproduction of a screen printed fabric. A Strike-off is described as “producing a sample of single, saleable items for markets such as luxury, entertainment or special events (Ross,

2000).” Traditionally sampling has been a very time consuming and costly part of the process of bringing a new design to market. In 2001 DuPont estimated that to produce the screens needed to print one new textile pattern containing six to eight spot colors costs between \$4,000.00 and \$8,000.00 (U.S.) dollars (Ross, 2000).

Screen costs alone do not show the total capital investment. In 2003, Ann Noonan, then CEO of Sophis Systems (Sophis software is currently part of Blue Fox Enterprises), compared the costs of sampling using ink jet printing as opposed to the traditional method of screen printing. An example of a typical sampling job, assuming certain costs and quantities is represented in Table 5. Noonan made assumptions that the print collection would contain 40 designs and that for every five designs sampled only one would be accepted for production. Therefore, to select the final 40 designs 200 designs would need to be sampled. Once the prints were narrowed down to the final 40, ten color ways of each would be printed. Noonan estimated that it cost \$3000.00 for the color separation for a ten color design, \$4,000.00 for rotary screens (she used the lower estimate above by DuPont), and \$50.00 for the first five yards of each design (Noonan, 2003).

Table 5. Costs for Sampling (Noonan, 2003)

Payback for Rotary and traditional screen Sampling (in US dollars)		
<i>Assumptions:</i>		
Collection of 40 designs for sale to the buyers		
Five design ideas have to be made to have one design chosen for the collection		
Separation costs for one design with ten colors = \$3000.00		
Rotary Screen costs = \$4000.00		
Sample table prints = \$50.00 per five yards (for one design)		
Sample table prints = \$500.00 per design (\$50.00 x 10 color ways)		
Digitally printed samples = is \$7.00 per yard		
Digitally printed samples = \$1400.00 (used to narrow 200 designs to 40)		
Screen separation of the 40 successful designs = \$120,000.00		
Screen costs for the 40 successful designs = \$160,000.00 (40 x \$4000.00)		
Digital printing costs to sample the separated design samples = \$280.00		
<i>Comparison:</i>		
Description	Digital Printing	Traditional Screen
Sampling of 200 designs	\$1400.00	\$1,000.00
Separation for designs	\$120,000.00 (40 designs)	\$600,000.00
Making of screens	\$160,000.00 (40 designs)	\$800,000.00
Samples (10 color ways)	\$2,800.00	\$20,000.00
Total	\$284,200.00	\$1,430,000.00

As seen in Table 5, digital printing for sampling costs considerably less because of the early narrowing of 200 samples to 40. In the comparison section of the chart in Table 5 the separation of the screens for digital printing (narrowed to 40) was \$160,000.00 compared to \$800,000.00 for the 200 designs that were screen printed. A slightly smaller, but still substantial, savings occurs when the ten different color ways are sampled; \$2,800.00 for 40 designs as opposed to \$20,000.00 for 200 designs. One million, four hundred and thirty thousand dollars for screen printing compared to two hundred eighty four thousand for digital printing is a huge savings and is in line with a global printing market report put forth by RocSearch that estimates that by using an ink

jet printer, costs for sampling are reduced by up to 80% (RocSearch, 2005). Blumenthal print works, a weaver and printer of jacquard damask that services the home furnishings and decorative fabrics industries, purchased an ink jet printer in 1999 for sampling and within two weeks the cost of printer was recouped (I.T. Strategies, 2006b).

In 2002, Jerry Bruce from Cone Finishing (a division of ITG, the International Textile Group) described the job of a commission printer as interpreting the ideas or artwork of the fashion designer. He states that this is a difficult process because often the artwork does not lend itself to the current process of screen printing and therefore is not always interpreted by the converter correctly. Most often the sampling process is done not once but many times. Cone typically produced 1,000 to 1,200 prints each year and each design averaged 14 colors. If five color ways are requested, the sampling process would involve 70 screen lay downs per design (Isaacs, 2002). However, this does not guarantee that the consumer will like and purchase the product; it only increases the chances that the designer will approve it. Savings in cost are not the only advantages to sampling via ink jet printing, savings in time are also substantial. Sampling by rotary, flat and other screen printing methods accounts for more than 50% of the time needed to produce a printed fabric. While the approval of samples done by screen printing can take six to eight week or longer, sampling by ink jet printing can take hours. This greatly reduces the overall time to produce a print as seen in Figure 4 (Choi, Yuen, Ku, & Kwan, 2003).

Stork Screens, an engraver and machine manufacturer, developed the rotary screen printing process in 1963 and was an early entrant into textile ink jet printing

market. Stork recently developed a sampling system called Stork-U-See. Samples can be produced in their print bureau in Thailand or customers can set up ink jet printing systems in house using Stork's hardware, software and consumables. Following the procedures advised by Stork guarantee that samples will match production screen printing (Van der Meij, Jorg, 2005).

2.1.6. Small Production Runs

Similar to sampling, short runs (print runs under 500 yards) are not usually cost effective for screen printing because of the amount of time needed for set up and cleanup, which can take between two to four hours. Screen printing machines generally run 40% of the time so a 30 yard/minute printing machine would actually average only 12 yards/minute. At 12 yards/ minute, more than 720 yards would need to be printed to equal just one hour of set up time (Tippett, 2001). The lengthy set up, cleanup and screen preparation time prohibit short run productions. Robert Polk, from CSI Fabrics and Andy Graven from Zenith Engraving Company, Inc. both print more small run production than samples. For these companies, a print order between 600 to 1000 yards constitutes a small run. Because of the high cost of setting up a print job, it is more cost effective to print small runs with an ink jet printer rather than by screen printing (see Figure 5). Polk further states that some designs are not reproducible by screen printing. For example, designs that are photographic in nature or have a gradient fill can only be printed via an ink jet printer. (Private communication with Polk).

Figure 4. Screen Printing and Digital Ink Jet Printing Production Routes (Choi et al., 2003)

Figure 5. Small run advantages (provided by DuPont Industries)

Finding an economical means of printing less than 1,000 yards has always posed a challenge for those manufacturers in small or niche markets, or for startup companies. *Gild the Lily*, a partnership between Jacqueline Rice (the former Dean of Fine Arts at Rhode Island School of Design) and Uosis Juodwalkis (owner of a photography, signage and color business) takes advantage of the small run capabilities of ink jet printing. Founded in 1998, the business sells one a kind and limited edition apparel. Juodovalki says that “We need to be inventive and produce in small quantities and this is where we have an advantage using ink jet” (I.T. Strategies, 2006b).

2.1.7. Mass Customization

Consumer demand for shorter and more varied fashion cycles forced manufacturers to shorten the prototyping process. Adopting inkjet printing for sampling significantly reduced the product development cycle. Using ink jet printing for sampling led to short run production. A natural progression then occurred from short run production to mass customization. Mass customization is defined by Anderson and Pine as “the ability to design and manufacture customized products at mass production efficiency and speed” (Anderson, 2003). Dr. Anderson, a pioneer of mass customization, states that mass production thrives when the market is stable and there is a low consumer demand for a variety of items. As market variety increases and the market becomes more volatile, mass production methods are less feasible due to increasing costs (see Figure 6).

Figure 6. Mass customization advantage (Anderson, 2003)

Demand from the consumer for more variety of fashion prints would shorten the print run making ink jet printing cost effective. The ability to print on demand with no difference in cost between one or one thousand yards has led to the adoption of ink jet printing for a multitude of mass-customized products. For example, CS Fabrics Inc., founded by Robert Polk (a quality control engineer) and Gina Polk, (a textile artist) have incorporated a mass customization model into their business plan. As well as providing printing services for sampling and small runs, the owners designed a website for customized fabrics. Customers are able to browse a library of textiles design patterns created by various artists. Working directly with the artists, customers can make changes in color, scale, etc. (*Enabling textile creativity: Fabric with S.P.A.*TM.2005). The Polk's targeted the interior design business with their **S.P.A.** approach: **Select** a fabric type, **Pick** a pattern and **Assign** colors. "Current costs for custom fabric production can run into hundreds of dollars per yard and take up to six weeks to produce," said Gina Polk. CS Fabrics can produce custom fabric in one week. They use a DuPontTM ArtistriTM textile printer which prints at speeds up to 150m/hour. Even with these advantages Robert Polk says that his company has a hard time convincing interior designers to change to this method. Polk thinks that his customers may be confused with too many choices. This idea of too many choices for the consumer is echoed by Huffman and Kahn who say that for the customer "the huge number of potential options may be confusing and overwhelming rather than beneficial" (Huffman & Kahn, 1998). This may explain why the majority of the inkjet printed products that are customized are bags, t-shirts, pillows or floor mats. What these items all have in

common is simple construction and design so that customers are not flooded with choices.

One of the market sectors to use ink jet printing successfully for customization is the garment printing industry. Both t-shirt and sweater printing machines are available and are being used to allow customers to purchase customized clothing. In 1993 the first t-shirt printer was developed by Embleme as a result of a French government sponsored project. The machine looked like a t-shirt printing machine, however it used UV curing technology. Industrial print heads had UV lights attached to cure the ink as it was printed. Currently the United States' t-shirt industry is valued at over 20 billion dollars (Williams, 2006). Rich Hoffmann from M&R Sales and Service Inc. is a 25 year veteran of the t-shirt printing business. In 2004 he estimated that T-shirts sales are increasing at a rate of eight to ten percent. The demand for more complex designs is also increasing; in the late 1990's the average of number colors required for a screened t-shirt design rose from eight to eighteen, similar to what is happening in the textile sampling market.

Although the complexity of designs has risen the cost has not. Hoffmann says that the margin for profit has fallen in the past several years. Printers who once made from \$1.00 to \$1.50 per shirt are now profiting only \$0.35 to \$0.50 per shirt. Specialty products offer a market advantage because cost is not the only deciding factor for the customer's purchasing decision (Sexton, 2005).

Ink jet printing directly onto textiles fits in well with specialty markets. It offers two advantages without an increase in cost: the option to print small runs for unique or one of kind designs, and the ability to print an unlimited number of colors. Girly Chic Inc., a boutique located in Los Angeles, CA, and owned by Charlene Casabonne, capitalizes on this by allowing its customers to customize t-shirts. Clip art is provided or customers can bring in their own designs. Creative Concepts of Jonesboro Inc., another t-shirt retailer previously spent \$3.00 to \$4.00 per shirt for sublimation printing but now spends only \$0.70 per shirt using the ink jet technology. Both Girly Chic Inc. and Creative Concepts of Jonesboro Inc. use the t-shirt printer for low volume (under 400) and but have printed up to 1500 shirts when the design had special effects requiring an ink jet printer. Customized shirts typically cost one to two dollars more (Sexton, 2005).

2.1.8. Engineered Print Design

In 2005 Issey Miyake designed table linens, bedding and a bath line for Target Corporation. The ink jet printed items had a single, large flower strategically placed within the home furnishing item. These linens are an excellent example of a mass produced product that uses ink jet printing technology to engineer a print design for aesthetic purposes. Digital printing has enabled new methods of engineered designing. Surface printed engineered design is no longer restricted to matching up patterns repeats. Instead the textile design can be one large scene or motif, which does not repeat, but instead is created within the shape of the garment or home furnishing. The garment

shape, filled in with the textile design, is printed via a digital printer. Digital printing can occur for prototyping purposes, or in some instances can also serve as the production process.

In Braddock's and O'Mahony's book, *Techno Textiles*, an engineered design is defined as "a design printed directly on to fashion garment, usually for catwalk designs, by the textile designer. It can be placed with exactness, avoiding seams, etc. A successful design that goes into production is reworked and printed on a continuous length of fabric." (Braddock & O'Mahony, 1998) Braddock and O'Mahoney's definition of an engineered design is limited in that it only discusses engineered design for aesthetic purposes and is only in terms of surface printed fabric. Typically, this type of engineered print design relies on yard goods of cloth. In this traditional method, garment pieces are strategically set on the fabric for design placement rather than for fabric utilization. Cost is high because although the design is improved, fabric utilization decreases (Brown & Rice, 1998).

In 2004 Chapman and Istook proposed an updated definition of an engineered print design. As depicted in Figure 7 a-c, Chapman and Istook engineered the print design within the garment marker (L. P. Chapman & Istook, 2002). Chapman (2004) describes the process:

To engineer a print, a product developer brings the garment marker into a textile design software program and creates the textile design within the marker. This design engineering process requires the collaborative efforts of both a product and textile designer, allowing a better marriage of shape

and pattern design. For instance, a panoramic scene could continue across a product, or around a three dimensional form. The textile design once created on a two-dimensional surface, now is manipulated across the shape of the body so that it becomes a three dimensional design.

Figure 7a. The finished marker has design elements that are split across seams, darts and closure points.

Figure 7b. The finished marker, filled in with the textile design, being printed via an inkjet printer directly onto fabric.

Figure 7c. The finished garment showing motifs continuing from the front panel onto the back of the dress, and flowing seamlessly across seams and closures.

Figure 7. Engineered Print Design (L. P. Chapman & Istook, 2002)

Target Corporation was able to produce and sell their engineered items relatively inexpensively. However, most instances of using ink jet printing for engineered designing are in the high-end, specialty market. For instance, as seen in Figure 8a, Stella McCartney

used Jeff Koons' artwork for her 2006 Spring/Summer collection. Koon's paintings are printed across five chiffon dresses by McCartney (Brener, 2005). First2Print, LLC, a textile ink jet printing bureau, allows designers to quickly produce one of a kind items for fashion shows or sale. An example, seen in Figure 8b, is a creation by designer Jeremy Scott. Scott's designs inspired by cartoons and fast food use large, oversize, motifs that wrap around the body. As well as allowing for engineered designs, ink jet printing is faster for one of kind items. "What really drove me to work with First2Print, LLC is the idea of doing something custom," said Jeremy Scott, couture designer. "A lot of flatbed or even rotary printing companies just can't handle the time constraint and the fact that I wanted to print on fabrics like raw silk" (*Digital printing dresses up couture*", 2006) Peter Mui, the owner of YellowMan, LLC also takes advantage of the engineer printing process by encompassing the body with wearable tattoos (see Figure 8c.). The tattoo imagery, collected from tattoo artists all around the globe is carefully engineered within the garment shape so that the "art falls on the body where the artist intended " (Mui, 2006).

Engineered designing is not a new process; rather it is a historical technique, dating back thousands of years. Christine Knight, explores historic use of printed pattern placement in her thesis "Area Pattern Designed Specifically for the Garment Shape" (Knight, 1972). Knight researched use of design placement in cultural costume such as Japanese printed kimonos, ancient Greek dye painted garments, and African printed robes. Japanese textile designers had several distinct methods for design placement within the kimono shape and the Greeks used surface design to accentuate the pleats or folds of

their garments. Knight divides design placement on the body into two distinct categories; contrived area pattern, and accidental area pattern.

Figure 8a. Stella McCartney dress with artwork by Jeff Koons engineered for placement on the garment (Brener, 2005)

Figure 8b. *Icing* dress by Jeremy Scott. The icing design is engineered within the garment shape to encompass the body (Scott, 2006)

Figure 8c. Tattoo t-shirt from Yellowman.com. The tattoo imagery is placed with exactness to wrap around the body (Horitoyo, 2007)

Figure 8. Examples of Engineered Print Design

Likewise, Townsend (2001) researched historical integration of print design with the garment shape. Townsend's research focused on the early twentieth century. From this overview, Townsend (2001) defines four approaches to engineered print design; i) *garment led*, a process where the end product design is led by the garment

designer and the fabric design is made to suit the garment, ii) *textile led* a process where “garments are designed in accordance with the characteristics of the surface detail of the cloth”, iii) *garment as canvas*, a method favoring a simple garment shape used as a canvas for highly pictorial or graphic imagery, and iv) *simultaneous design*, an approach where the garment shape and the surface decoration are conceived at the same time. Townsend cites Mario Fortuny as an example of a designer who utilizes a *textile led* approach. Fortuny’s garments were often created in order to highlight his exquisitely printed cloths. Sonia Delauney is given as an example of a *simultaneous designer*. Townsend includes a quote by Delauney regarding her method of working. Delauney states that “the cut of the dress is conceived by its creator simultaneously with its decoration. Then the cut and the decoration are both printed on the same fabric” (Townsend, 2001).

Current apparel production methods rarely allow for the full integration of clothing shape with textile design but ink jet printing is well suited for concurrent design of the garment and pattern. This may explain why a number of studies investigating engineered designing with ink jet printing are for art-to-wear. Townsend (2001), Campbell and Parsons (2005), Gordon (1997), and Bunce (2005) have all produced one-a-kind items that used graphic, digitally printed imagery that was placed within the garment pattern to accentuate shape.

2.2. Integral Sweater Knitting

The evolution of the technologies for sweater manufacturing, toward integral knitting, is supportive of engineered designing. Integral knitting is one the four primary methods of sweater construction, the other three are cut and sew, garment knitted lengths, and fully fashioned. The term *integrally knitted garment* refers to apparel items that have typical cut and sew operations that are knitted on the machine. These operations include addition of button holes, collars, and pockets and attachment of sleeve to the garment body. Cut and sew, garment knitted blanks, and fully fashioned differ from integral knitting in that they require seaming to complete production. However, fully fashioned knitting is closer in technology to integral knitting because, unlike cut and sew and garment knitted lengths, all shaping occurs during fabric formation. Complete-garment knitting, also called knit-and-wear or WholeGarment® knitting (a registered trademark of Shima Seiki Mfg., Ltd.) is an extension of the technology of integral knitting. With complete garment knitting, no further seaming or making up processes are required upon leaving the knitting machine. Integral knitting developed from the sweater industry but now is being applied to other knitted products.

2.2.1. Market Overview

The knitted apparel market is broadly separated into four segments; knitted outerwear, knitted yard goods, hosiery, and underwear (Reichman, 1972). Sweaters, also called pullovers, vests, jumpers, jerseys, cardigans, woolies and Guernsey's are a subsection of the knitted outerwear market, which also includes golf shirts, woman's blouses, t-shirts,

etc. All of knitted apparel, regardless of market segment, has commonalities of processes and technologies with sweater manufacturing. A distinguishing factor between sweaters and other knitted products is the gauge or coarseness of the knit. OTEXA, the Office of Textiles and Apparel within the U.S. Department of Commerce's International Trade Administration, defines a sweater as a knitted outerwear garment intended to cover the upper part of the body having nine or fewer stitches per two centimeters in the horizontal direction (*OTEXA reference.2007*). Spencer states that, generally, knitwear is knitted on machines with gauges of 14 or less (Spencer, 2001b). Both of these definitions may not accurately reflect the current market which includes finer gauge sweaters.

There are several notable technological advancements and social events that shaped the current sweater manufacturing market. It is difficult to determine when the sweater industry started, but depictions in paintings, references from historical documents and fragments of knitted fabric lead us to believe that knitted garments worn on the upper body were common by the 14th century. Knitting dates back thousands of years; remnants have been found from 280 B.C in Syria (Collier & Tortora, 2001) and from 250 A.D. near present day Palestine (Kadolph & Langford, 2002). A painting from the late 1300's depicts The Madonna hand knitting a seamless sweater, (Karasaunu, 1995) and by the 15th century hand knitting was recognized as a professional trade requiring six years of apprenticeship (Rowlands, 1985).

Hand knitting continued until 1579 when William Lee invented a knitting frame to improve the speed of stocking knitting. The next major technological advancement in knitting occurred 200 years later when Decroix developed the circular knitting machine

(Goadby, 1989; Nutting, 1989; Spencer, 2001b). In 1849 Mathew Townsend patented the self-acting needle from which the modern day latch needle is derived (Goadby, 1989). The flat bed knitting machine followed the circular knitting machine by more than fifty years. Lamb filed a patent for first flat knitting machine in 1866 (Nutting, 1989). By 1879 the first power operated knitting machine was in use, and in 1887 needle pickers were added to allow shaping of the heels and toes of hosiery (Goadby, 1989).

The technological advancements in knitting achieved during the Industrial Revolution helped to push the sweater market, and mass production of sweaters was evident in 1862 (Rowlands, 1985). Sweaters, often called jerseys, gained prominence during the late 1880s and early 1900s for sporting attire. The durability, stretch and warmth that knits provided were suited to outdoor activities. Although sweater manufacturing was an established industry by the 1900s, Nutting (1989) states that “prior to 1939 much of the effort of knitting technologists focused on the Lee tradition of attempting to achieve by machine what could be done by hand”. Nutting identified five trends that occurred during or after the mid 20th century that pushed technological advancements in the knitting industry. These five trends were i) emergence of new fibers and yarns, ii) integration within the knit industry of electronics, computers and computer aided design, iii) full fashioning capability, iv) increased machine productivity, and v) better quality control.

While the above technologies (particularly integration of electronic control) undoubtedly had a profound effect on sweater production, social factors also influenced sweater manufacturing processes and helped to drive machinery development. Pringle of

Scotland's twin sweater sets from the 1930's, the 'sweater girls' of the 1940s and 1950s, the black turtleneck from the 1960s, craft revival of the 1970s, and casual work wear of the 1990s kept the sweater market strong (Black, 2002). In the United States, in a ten year period, knitted apparel fabric almost doubled; from 24% of apparel fabric in 1962 to 44% of apparel fabric in 1972. This percentage has increased to 50% of the current market. (Hatch, 1993b) The United States import market of sweaters, pullovers and vests comprise the largest category of knitted-apparel by dollar value; a \$13.4 billion annual-market (see Figure 9). This data has held true since at least 1989, the earliest year that data could be gathered from OTEXA

In response to the shortage of skilled labor, Shima Seiki Mfg., Ltd. introduced the first WholeGarment® knitting machine in 1995. Shima's FIRST Machine knits a completed garment with no sewing involved. At about this same time, Benetton Group S.p.A., one of the largest producers of wool sweaters revolutionized the sweater market by introducing the idea of postponement. In this model, Benetton Group S.p.A. garment dyed their sweaters instead of using dyed yarn. This allowed Benetton Group S.p.A. to respond to the market more quickly and eliminated the risk associated with carrying large inventories of dyed yarns (Signorelli & Heskett, 1984). Shima Seiki Mfg., Ltd. furthered the concept of quick response to the market by introducing a sweater printing machine. Shima's SIP-100f prints directly onto sweaters via an ink jet printing system (Shima Seiki Mfg., Ltd. Japan, 2007b).

Figure 9. OTEXA Import Value of Knitted Apparel by Product Category (*OTEXA reference.2007*)

2.2.2. Machine Technology

Knitting Machines can be broadly classified as either warp or weft knitting machines.

Warp and weft machines differ from each other in the way the yarn is fed to the needles.

In weft knitting, one knitting yarn is fed to a series of needles while in warp knitting each knitting yarn end is supplied from a warp beam, or creel to one needle (Reichman, 1972). Warp or weft knitting mechanisms and the fabrics produced on each are markedly different. Warp knitted fabric has loops that are formed in the wale direction on a set of warp yarns, while weft knitted fabric has loops that are formed in the course direction by a continuous thread. Generally, weft fabrics have more stretch than warp knitted fabrics and therefore weft knitted fabrics are used more often in apparel. Weft knitting accounts for one fourth the world's apparel fabric, while warp knitting makes up one sixth of the market (Spencer, 2001b).

The majority of innovation for integral knitting has occurred with weft knitting machinery, with one notable exception. At ITMA Asia 2005, Karl Mayer Textil GmbH introduced the RDPJ 6/2. This double bar raschel machine is able to form seamless garments by knitting tubes. The tubes, formed on two needle bars, can be joined at any point on the garment allowing for a seamless apparel item to be knitted. Currently the RDPJ 6/2 is available in gauges of E16 thru E24. Although a thorough literature search showed no wide spread use of warp knitting for sweater manufacturing, this warp knitting seamless machine is considerably more productive than current weft machines for integral knitting. The RDPJ 6/2 produces 12.8 meters/hour (Lo, 2006).

2.2.2.1. Weft Knitting: Straight and Flat

Weft knitting machines are distinguished from each other by the machine's arrangement of needles and configuration of the frame (Spencer, 2001b). All three types of weft

knitting machines straight bar, circular and flat are widely used for knitwear production. In addition, circular and flat machines can have several variations of needle arrangement and/or type of needle. The variety of different weft knitting machines makes knitwear manufacturing (and knitting in general) a specialized industry. Designing and construction of sweaters can vary greatly depending on the type of machine used to produce the garment or garment parts. For instance, sweaters produced from circular knitting machines are most often constructed by cut and sew, while sweaters produced on flat knitting machines are usually fully fashioned. The amount of shaping that can occur during fabric formation is dependent on the type of knitting machine. Circular machines have the least shaping capability, moderate shaping is possible with straight bar machines and extensive three dimensional shaping can occur on V-bed machines. However, V-bed machines have the lowest production speeds while circular machines have the highest speeds (see Figure 10). While knitting action of the needles is the same regardless of flat or circular knitting, circular machines typically knit in one direction while flat beds knit from left to right and then right to left, a factor that contributes to slower speeds of flat bed machines (Cotton Incorporated, 2006). Another factor that makes circular machines more productive is the number of yarn feeds. An increase in yarn feeds increases production. The production capability on flat machines can be increased by increasing the number of carriages and/or by increasing the number of knitting systems. For instance, a flat knitting machine with two carriages can knit two panels side by side, doubling production. Likewise, a two system machine can knit two courses of rib per traverse (Cotton Incorporated, 2006). Even with additional carriages or CAMs, flat bed knitting

machines cannot match the speed of circular machines. However, the advantage of using a flat bed machine is the flexibility allowed when designing intricate structures or shaped garments.

Figure 10. Weft knitting machine classifications and shaping and production capabilities

Shaping capability and production speed, two primary considerations when manufacturing a sweater, often dictate the type of knitting machine. For example, straight bar frames are very productive for the manufacture of full fashioned sweater components; modern machines can knit up to sixteen garment parts across the width of the machine (Spencer, 2001b). Although capable of knitting integrate patterning, they are rarely used for this, rather, straight bar machines are exploited for their ability to knit garment panels that are “shaped at the selvages by progressively increasing or decreasing the number of loops in the width of a fabric”(Brackenbury, 1992). This fully fashioned method of

shaping referred to as, wale fashioning (see Section 2.2.3.1 Wale Fashioning) produces garment pieces that are shaped and bound around all edges. For this reason, straight bar machines are often referred to as full fashioned knitting machines.

Prior to the last decade, straight bar machines were the dominant equipment used for fully fashioned garments. Now, new technology has allowed V-bed knitting to become competitive with straight bar machines for production of shaped sweater panels. Spencer (2001) states that

Over the past thirty years, many innovations and refinements in knitting technology have gradually evolved and combined to transform the mechanically controlled V-bed machine into a computer-controlled, highly efficient and versatile knitting machine, not only for cut and sew knitwear but also for integrally-shaped panels and whole garments. In this process of evolution it has rendered the flat bed links-links superfluous, blunted the productive challenge of the circular garment-lengths machines, surpassed the straight bar frame in shaping potential both in types of shapes and knitted structures, and has extended its own gauge range capabilities.

Innovations in V-bed knitting include electronic control of machine parts, improved takedown mechanisms, and increased memory capacity on knitting machines. Prior to electronic control, the knitting machine's elements were controlled by mechanical movement. Electronic control allowed individual movements of needles and take down mechanisms. With individual needle control, each needle can be raised to a varying height to either, knit, tuck miss or transfer. In addition, individual needles can be

taken in or out of action, allowing for more complex structures and shaping possibilities. An increase in the complexity of structure and shaping (enabled by electronic control) require that knitting machines have larger memory and processing capacity.

2.2.2.2. *Weft Knitting: Circular Strip and Bodysize*

Circular machines for sweater manufacturing are generally employed because of their high production rate. These machines are classified by their type of needle bed. For instance, a circular machine can have a single cylinder, a cylinder and dial, or double cylinders. Single cylinder machines have one set of needles while both cylinder and dial and double cylinder have two opposed needle beds. Single cylinder machines are only capable of knitting continuous yard goods, while cylinder and dial and double cylinder can knit garment knitted lengths. While circular yard goods machines are still in use, garment-length circular machines are preferred for sweater manufacturing.

Garment length circular machines for sweaters are generally of two types, bodysize or sweater strips (Spencer, 2001a). Sweater strip machines (so named because of the coarser gauge) knit lengths of fabric with a welt at the start of each garment blank. The knitted fabric length can then be slit open and multiple pattern pieces can be cut, including the sweater's front and back body, and sleeves. A body size machine's diameter corresponds to the girth of the garment and so different machines are needed for each size. As with sweater strip machines, bodysize machines can produce a tube with a side seam that is later slit open for laying out and cutting. On a bodysize seamless machine, (unlike a body size machine), there are no side seams. Circular knitted garments

are often called “seamless” because of the lack of side seams. They do, however, need to be finished and shaped around openings such as necks and armholes. Sleeves and collars can be attached by sewing methods such as linking, overlocking or cup seaming. See Section 2.2.4 Construction Methods.

2.2.3. *Shaping Methods*

Shaping, an important component of sweater design, is achieved post knitting, or during fabric formation. Post-knit shaping is primarily obtained by cutting the silhouette from the fabric cloth and seaming (see Section 2.2.4.1 Cut and Sew Manufacturing). However, some shaping can occur during the finishing process by either blocking the wetted out garment or by heat setting a sweater that contains thermoplastic yarns. Shaping that occurs during fabric formation can be achieved by four methods i) varying the stitch length, ii) altering the knit structure, (see Figure 11a-b), iii) taking needles in or out of action (Spencer, 2001b), or v) stitch transfer. Sweaters that are shaped by altering the stitch or changing the structure are called *stitch-shaped garments* (Hatch, 1993a). Varying the stitch length is achieved by electronically selecting the stitch cam depth, allowing more or less yarn to be fed into the knitted loop. Methods for taking needles in or out of action are *wale fashioning*, *needle selection shaping*, and *reciprocal shaping*.

Figure 11a. Stitch Shaping with five structures (Spencer 2001b)

Figure 11b. Stitch shaping with combination of 1 x 1 rib with 2 x 2 rib (Shima Seiki Mfg., Ltd. Japan 2007b)

Figure 11. Stitch shaping examples

2.2.3.1. *Wale Fashioning*

In *wale fashioning*, also called *Needle to point to needle loop transfer*, transfer of loops happens within the same bed. Wale fashioning can be achieved on straight bar machines or a V-bed machine using stitch transfer (Hewitt & Smith, 1981; Spencer, 2001b). A fashioning point is a mechanical, knitting machine-element that extracts and holds a selvedge loop, traverses the loop across the needle bed, and then transfers the loop onto a new needle (Hewitt & Smith, 1981). This method of shaping produces a firm, well defined selvedge edge.

2.2.3.2. *Needle Selection Shaping*

Needle selection shaping can occur by i) transferring rib loops by racking the needle beds, ii) pressing off loops, or iii) holding loops (Spencer, 2001b). In this method of shaping, referred to as needle to needle loop transfer, narrowing and widening is achieved by racking (moving one needle bed in relation to another) and transferring loops from the front bed to the back bed and then back again. Needle to needle loop transfer requires that needles be free to accept loops. This requires more usage of the needle bed width and slows productivity. V-bed machine manufacturers have addressed this problem by outfitting machines with four beds or placing an extra set of offset needles. Compound needles are often used as they require less space.

Individual selection of selvedge needles is the simplest method of widening and narrowing during knitting. For widening, additional selvedge needles are introduced at the fabric's edge in stepped increments to gradually increase the knitted width. When narrowing, needles are simply pressed off. Although the widening method is very good, narrowing by pressing off tends to cause loops to ladder and run if the takedown tension is not reduced simultaneously with needle reduction (Hewitt, Smith 1981). This has led to a number of technological advances in take down mechanisms aimed at better control of takedown tension.

Take down mechanisms serve to apply tension on newly formed loops, pulling them down away from the needle bed and out the way of the next knitted course. The ability to control take down in specific areas, (rather than having the same takedown pressure across the entire knitted width) is conducive to knitting shaped garments.

Shaped garments have varying widths which require an adjustment of tension when needles are taken in or out of action or when loops are being transferred. Improved takedown mechanisms include the presser foot, takedown comb, and the sinker. Developments of these takedown devices were all aimed at improving capability of varying takedown tensions (Guy, 2001).

A patent for a presser foot was filed in 1867 by Thomas Crane, and research using the presser foot for shaping garment panels was conducted by Courtlauds and Dubied in the 1970s (Betts & Robinson, 1979; Jeanneret, 1982). Courtlauds also licensed this technology to machine builders Shima Seiki Mfg., Ltd. and Bentley-Cotton (Spencer, 2001b). Jeanneret (1982) of Dubied explains the presser foot mechanism and movement in the following statement:

The presser foot mechanism is securely fixed to the carriage of the machine, and moves across the machine with the carriage. The presser feet precede the needles which are rising. The wire of the presser foot slides just underneath the crossing or intersection of the opposing needles of both needlebeds and presses against the stitches laced against the needle beds. The consequence of this is that the takedown-roller becomes unnecessary.

Shima Seiki Mfg., Ltd. and H. Stoll GmbH & Co. led the development for takedown combs and recently Universal Knitting Machines GmbH developed a novel takedown comb (Goller & Walker, 1985; B. Hunter, 2004b; Shima & Nishida, 1984). Take down combs aid knitting set-up and initial takedown. The combs are able to rise up between the

needled beds to grab the first row of loops. Loop controlling sinkers were used by Shima Seiki Mfg., Ltd. on their glove knitting machines (B. Hunter, 2004a). Sinkers apply pressure to formed loops thus reducing the amount of tension needed by the takedown comb or roller. This pressure is applied at each individual needle and so varying tension can be obtained across the width of the shaped garment piece (Guy, 2001).

Holding loops is a technique where “the length of the courses being knitted is diminished or extended successively. No loops are lost by casting off or pressing off (dropping); all loops are stored (held) to knit at a later stage” (Brackenbury, 1992). Common names for these techniques include *flechage*, *short row knitting* or *gore technique*. This shaping technique requires that the carriage traverse be able to be varied, traveling shorter or longer distances when needed.

2.2.3.3. *Reciprocal Shaping*

Reciprocal knitting is a process of holding loops on a circular knitting machine in order to vary the number of courses. Circular knitting machines capable of reciprocal shaping must have cylinder needle beds that can oscillate (Spencer, 2001b). This process requires that a number of needles not knit during shaping. Inactive needles, coupled with the direction change of the knitting action make reciprocal knitting a slow process. Reciprocal shaping was used for a brief time during the 1970s for knitting of children’s pullovers (Offermann, Tausch-Marton, & Haupt, 1971). Improved technology on circular machines may make reciprocal shaping a viable shaping process for sweaters in the future.

2.2.4. *Construction Processes*

As depicted in Figure 12a-b, the main methods of sweater construction are; i) fully cut and sew, ii) garment knitted lengths, iii) full fashioned knitting, iv) integral knitting and v) hand knitting (Brackenbury, 1992). Construction methods are differentiated from each other by the amount of shaping that happens during or after fabric formation. For instance, in cut and sew construction all shaping occurs after the fabric leaves the knitting machine. Garment knitted lengths combine some machine shaping and some cut and sew shaping. Fabric is knitted to a length that corresponds to the size of the sweater. The knitted, rectangular, panels have one edge, typically the hem, which has a rib trim, all other sides are cut. Fully-fashioned construction and integral knitting differ from both fully cut and sew and garment knitted lengths in that the majority of the shaping is executed on the knitting machine rather than by pattern cutting.

Fully-fashioned sweaters are constructed of panels that use shaping technology, (discussed in the previous section) to knit shaped-garment-components. Integrally knit sweaters use the same shaping methods as fully-fashioned sweaters but this technology “improves upon shaping by "knitting-in" or "integrating" trimmings, pockets and other accessories such as buttonholes to avoid sewing together these items (Shima Seiki Mfg., Ltd. Japan, 2007a).

Figure 12a. Fully cut and sew

Figure 12b. Garment knitted lengths

Figure 12c. Fully-fashioned

Figure 12d. Integral knitting

Figure 12. Primary sweater construction methods (Brackenbury, 1992)

Technologies for sweater manufacturing have increased productivity and efficiency, but the knitwear industries are still heavily dependent on manual labor, particularly for the cut and sew industry. Shortages of skilled labor in the sweater industry have led to a progression from cut and sew construction to full fashion knitting (Karasaunu, 1995). The hosiery and glove market followed the same progression toward fully fashioned knitting and now both markets are dominated by integral knitting

technology. The question remains whether sweater manufacturing will follow the same path. There have been a number of technological developments by knitting machine builders that would lead one to believe that integral knitting will be a key technology for sweater production. A progression toward integral knitting eliminates many steps in sweater assembly (see Table 6).

Table 6. Comparison of Production Steps for Sweater Construction
(Brackenbury, 1992)

Cut & Sew	Fully Fashioned	Integral
1. knitting (front, back Body)	1. knitting (front Body with NeckTrim)	1. knit (front and back body with sleeves)
2. knitting (sleeves)	2. knitting (back body)	2. pressing
3. knitting (trim)	3. knitting (sleeves)	3. attaching label
4. cutting fabric to specification	4. steam setting	4. finishing
5. manual folding of fabric	5. sewing	
6. sewing edges for framing	6. linking neck trim or back-body side	
7. Framing	7. second press	
8. steam setting	8. attaching label	
9. removing frame	9. finishing	
10. cutting fabric to garment spec.		
11. overlock of side, shoulder & sleeve		
12. bar tacking		
13. sewing or linking of neck trim		
14. second press		
15. attaching label		
16. finishing		

2.2.4.1. *Cut and Sew*

Cut and sew processes tend to be faster, and less expensive than other sweater construction processes. For the cut and sew method, fabric can be knitted in continuous yardage or knitted in garment lengths on a flat bed or a circular knitting machine. Both yardage and garment lengths can be knitted in an open width or circular tube. Cutting can be done by hand by a pattern cutter or by an automatic cutting machine. In a cut and sewn sweater a pattern cutter, (sometimes referred to as the makeup person) or apparel designer, can generate the shape of the sweater (Eckert, 2001). Cut and sewn garments usually use the horizontal direction of the fabric for the circumference of the body. While knitted fabric is extensible in the horizontal and vertical direction, vertical extensibility is generally only half as great as horizontal extensibility. Vertical elongation is equal to one half the loop lengths while horizontal extension is equal to almost the entire loop length. This allows the greatest stretch to be used around the garment's girth while ensuring that the garment length has the least potential for sagging and distorting (Brackenbury, 1992).

For a fully cut and sewn sweater the sizing and shape are solely determined by the designer or pattern cutter. An advantage to this is that the silhouette can be changed up until the moment of cutting. A disadvantage is that, depending on the garment shape, a tremendous amount of knitted fabric can be wasted – up to 17% to 50% of the total (Brackenbury, 1992). Fully cut and sewn sweater construction is most similar to cut and sew for woven fabrics. A major difference is the extensibility of knit fabrics. The

marking, cutting, sewing, and finishing processes can be challenging for knits because at each of these stages the fabric has the potential to distort (Brackenbury, 1992).

Knitted garment lengths are knitted in a predetermined length of fabric that corresponds to the finished garment length. Sweaters that are knitted as garment lengths may also be called *stitch-shaped cut*, because the change in structure from the waist band to the body imparts some shape to the garment (Brackenbury, 1992). Typically, garment knitted lengths have a ribbed cuff knitted in to the bottom of the fabric so that no finishing is required at the sweater's bottom edge. These pre-determined body lengths can be knitted as separate articles or knitted as a series of garment blanks strung together (Spencer, 2001). If knitted as a string, then a removable separator-thread is knit between the last course of the previous panel and the first course of the new panel's welt. See Figure 13.

1. Last course of previous panel.

2. The draw thread.

3. Threading of new panel and welt.

4. The rib border.

5. The transition from 2x2 rib to next panel.

6. The next panel body

Figure 13. Diagram of separator thread insertion for garment knitted length (Raz, 1993)

2.2.4.2. *Fully Fashioned*

Shaping on the knitting machine by narrowing or widening is called fashioning, and garments shaped by this manner are referred to as fully fashioned. Fully fashioned sweaters are defined as “garments constructed from pieces of weft knitted fabric with perfect selvages. The shapes of the pieces are generated by movement of loops at the edges to diminish or enlarge the width of the fabric (Brackenbury, 1992).” Fully fashioned or shaped sweaters are typically produced on either straight bar or V-beds. The shaping is achieved by wale fashioning or needle selection shaping.

To obtain the desired shape, the frequency of narrowing or widening must be calculated. An example by Raz (1991) of a frequency calculation is given in Figure 14, a depiction of a fully fashioned sleeve. Figure 14 shows the fully-fashioned sleeve's dimensions in centimeters on the left hand side figure. In this example we assume that the sleeve's density will be four wales per centimeter and six courses per centimeter. The sleeve on the right hand side of Figure 14 shows the sleeve's dimension converted from centimeters to wales and courses. In the first fashioning sequence, the sleeve is widened from 72 wales to 128 wales over a distance of 192 courses. We calculate that $128 - 72 = 56$. Because the widening sequence must take place over two courses (one on either side of the panel), it is necessary to divide 56 by 2, leaving 28 widening routines needed. Four courses are required for each widening sequence. Therefore we divide 192 (the total distance of courses) by four (number of courses required for each widening routine). The result is 48 widening cycles. Because only 28 widening cycles are needed the additional

twenty are distributed among the needed 28. Therefore there are 20 fashionings at eight course intervals and eight fashioning at four course intervals.

Figure 14. Calculation of a fashioning frequency. (Raz 1991)

R.W. Mill (1965) researched fashioning angle and devised calculations to determine fashioning frequencies. However, these calculations were based on fashioning with a straight bar frame and according to Guy (2001) Mill's calculations do not reflect current shaping possibilities using fully electronic V-beds. Guy states that current designers use a combination of fashioning calculations and trial and error.

Assembly of fully-fashioned garments may require multiple sewing machine types, depending on the complexity of the garments. The majority of fully-fashioned garment pieces are linked or cupped seamed together. As with fully cut and sewn sweaters, a primary concern for seaming is maintaining the extensibility of the knitted garment. Another concern is providing a seam that is continuous, smooth, and lies flat against the body.

2.2.4.3. *Assembly*

The majority of sweater construction methods, with the exception of integral knitted garments require some type of seaming or joining method. “Seams are used to assemble fabric panels, to create the structure and detail of a garment (Brown & Rice, 1998b).” Seam strength is a major consideration for good quality seams for woven garments. Seams need to be as strong as the fabrics they are joining (Brown & Rice, 1998). However, for knitted garments, along with strength, a primary concern for seams is extensibility (Brackenbury, 1992).

Run-in ratio is the primary parameter influencing extensibility and strength in seams for knitted apparel. Run-in ratio is defined as the “ratio of the length of thread absorbed by the seam to the length of the seam” (Brackenbury, 1992). This ratio expresses three variables; i) number of stitches per unit measurement, or stitch density, ii) thickness of knitted cloth to be seamed, and iii) thread tension (Brackenbury, 1992). Seam type also influences stretch and strength of seam. Typically, seams used for joining sweaters are either an overlock stitch or a single or double chainstitch. The primary seaming or joining equipment for sweater components include an overlock, a cup seamer, and a linking machine. Both cup seaming and linking use a chain stitch, while the overlock machine uses an overlock stitch

2.2.4.3.1. *Overlock*

The overlock stitch is a highly extensible stitch that joins, binds (Brackenburg, 1992) and trims knitted sweater components. The overlock also called overedge, serge, overcast or Merrow falls under class 500 in the ASTM 6193, Standards Relating to Stitches and Seams (Glock & Kunz, 2005). Overlocking is the predominate method of seaming for sweaters that are fully cut and sewn because it can cover the raw edge of the sweater. The most widely used overlock seam, type 504, has three threads comprising one needle thread and two looper threads. Quality factors of the overlock stitch include; i) stitches per unit length, ii) the bite (the distance from the edge of a fabric that the needle thread penetrates), iii) run in ratio of the three seams and, iv) the balance in run between the looper threads (Brackenburg, 1992).

Use of an overlock machine has some disadvantages. The seam tends to form a 90° angle with the fabric, creating a bulky seam. See Figure 15a (Brackenburg, 1992) A bulky seam may cause discomfort to the wearer and is aesthetically displeasing. Also, it is difficult to achieve a good balance between too high or too low of a stitch density. A high stitch density causes the seam to meander (see Figure 15a), while a low stitch density does not provide enough cover, resulting in yarns escaping from the bound edge seam. See Figure 15b. In addition, it is difficult to match knitted loops across the seam (see Figure 15c).

Figure 15a. The seam forms a 90° angle to the sweater

Figure 15c. Yarn that has broken loose from the bound seam edge.

Figure 15b. Sweater parts are not lined up loop to loop.

Figure 15. Examples of overlock seaming problems

2.2.4.3.1. *Linking*

Linking, sometimes referred to as point seaming or looping, is the method of joining two fully fashioned panels, selvedge loop to selvedge loop to give the appearance of uninterrupted knitting (Cotton Incorporated, 2006; Reichman, 1963). Two common types of industrial linking machines for sweater manufacturing are a collar linking machine for attachment of collar to body, and a body linking machine for selvedge seaming. Linking joins two garment pieces, course to course, course to selvedge, or selvedge to selvedge (Reichman, 1963). A linking machine shown in Figures 16a-c, has a circular dial with points on which one loop from each of the two pieces to be joined is placed. The distance between the points corresponds with different gauges (Brackenbury, 1992).

Figure 16a. Linking Machine

Figure 16b. Sweater parts set on the points of the dial.

Figure 16c. Chain stitch formation

Figure 16. Hague 420 linking machine

Sweater making-up companies typically have several gauges of linking machines. Once the loops are placed on the dial points a chain stitch, using a similar or same yarn as the knitted fabric joins the sweater pieces. Linking is a time consuming process requiring a skilled operator, therefore it is used only where flat, elastic seams are required, or in highly visible areas. The most common linked sweater parts are; rib collar to garment body, shoulder of body back to shoulder of body front, and top of sleeve to shoulder (Reichman, 1963).

2.2.4.3.2. *Cup Seaming*

While linking is closer to a knit technology, cup seaming is closest to a sewing technology (Reichman 1963). A cup seamer is used to close sleeves and sides seams of fully fashioned components. A cup seamer is so named because of the two rotating cups that help to feed the knitted fabric through the seaming area in a line. Cup seaming and linking both employ a chain stitch, but they are differentiated from each other by the fact

that linking lines up the fabric to be joined loop to loop while cup seaming does not (Reichman, 1963). Cup seaming is often preferred when the knitted panels show pronounced curling at the edges as uncurling devices can be used during seaming. However, a skilled cup seam operator can often match up fabric components loop to loop, or match up stripes and patterns. Cup seaming is much more productive than linking and does not require the high skill level needed for linking.

2.2.4.4. Integral Knitting

In 1995 Shima Seiki Mfg., Ltd. introduced two new V-bed knitting machines the SWG-V and the SWG-X, both capable of knitting complete garments. According to Shima Seiki Mfg., Ltd., they were the first commercially viable knitting machine capable of producing an integrally-knit sweater that required no further seaming (Nakashima & Karasuno, 1995). The WholeGarment® sweater was knitted in tubular form, one tube for the body and two tubes for each sleeve (see Figure 17). Hunter (2004) explains the process for complete garment knitting in tubular form:

In this method the machine's carriage firstly travels from left to right knitting alternate needles on the rear bed, then reverses from right to left and knitting alternate needles on the front bed. The sequence is then repeated over a number of courses to produce a knitted tube. The tubular complete garment machine uses this principle but knits side by side (sleeve – body – sleeve) with three different yarn carriers. Knitting commences using the three carriers and continues to the underarm point at

which time, the yarn carriers knitting the sleeves are taken out of the knitting zone. Knitting of the garment is completed by the remaining carrier which knitted the body tube. Fashioning the tube from the underarm point allows narrowing towards the neck where a number of techniques can be used to complete the garment.

In needle selection shaping, needles must be free to accept transferred loops. Ribs and other complex structures such as cables also require extra needles for loop transference. This problem has been addressed by having four beds, as is the case with Shima Seiki Mfg., Ltd.'s SWG-X, or by knitting half gauge. In half gauge knitting every other needle is used for knitting. For instance, a 7 gauge sweater would be knitted on a 14 gauge machine.

Figure 17. Tubular method for complete garment knitting

Hunter states that by 2004 complete garment knitting had shown maturation (Hunter, 2004a). Several machine builders, Shima Seiki Mfg., Ltd., H. Stoll GmbH & Co., Universal Knitting Machines GmbH, Steiger SA and Protti Fashiontronix S.r.L now offer multiple machines for complete garment knitting. There have been a number of technological advances such as improved takedown devices, improved computer aided design systems, patents for improved needles, and even yarn engineered solely for complete garments. Spiro, developed by Spectrum Yarns, Inc., is a merino lambs-wool yarn, with high elastic properties, used for complete garment golf sweaters (Mowbray, 2004). Knitting with the half gauge technique can produce rib cuffs and waistbands that are too loose. Yarns with high elasticity, such as Spiro, help to pull in loose loops. An added bonus, because of the high tensile strength of the yarn, machines can run unattended without fear of yarn breakage.

H. Stoll & Co GmbH developed a complete garment knitting machine (the CMS TC Knit and Wear) that produces an integrally knitted sweater using greatly reduced needle bed space. The CNS 330 can knit a coarse gauge sweater using only the amount of needles required for the garment body. Reduction of needle space usage is accomplished by knitting the arms in a vertical line with the body and using gore shaping. See Figure 18, H. Stoll GmbH & Co.'s *gore technique* and compare with Figure 17, a complete garment knitted in tubular form. H. Stoll GmbH & Co.'s *gore technique* uses considerably less needle bed space. Utilizing less needle bed space saves time on each knitting traverse. In addition, shaping by the gore method does not require the needle bed to rack, further increasing knitting production (B. Hunter, 2005).

Figure 18. Stoll's *Gore Technique* for complete garment knitting . (Hunter, 2005)

A complete garment offers many advantages over cut and sewn garments such as more comfortable feel and fit, smoother drape on the body, softer handle, no side seam failure, and less waste. One of the most profound advantages may be the savings in time and cost for sampling and production. Pitimaneeyakul's survey of a large US sweater manufacturer found that the time to market for a typical sweater was three to seven months (Pitimaneeyakul, LaBat, & DeLong, 2004). Once in the market, the cost of markdowns and stock out were considerable if sweater suppliers had not adequately

tested consumer preferences. The company's owner states that "Apparel products are not like diamonds or antiques, the longer you have them, the less value they have " (Fellingham, 2007). Complete garment knitting can drastically reduce sampling time and allow more samples to be produced ensuring better success in the marketplace.

An advantage to full fashioned and integral knitting is that a better product can be developed more rapidly. The product development process for knitwear involves a team of specialist, therefore several technologies are involved. A typical product development process, see Figure 19, involves the following steps; research of previous sweater designs, design of the sweater, selection of best design, technical specifications, sampling, selection of best sample, and finally production. The bottlenecks in this process occur at the selection stages. In the first selection (which occurs prior to sampling) the main concern is whether the designer's idea is technically feasible. Can it be knit? Is the yarn the correct size and of sufficient strength and/or elasticity for the desired knit structure and finishing processes? Does the design of the knit structure fit within the garments intended shape? The next selection stage (occurring after sampling and prior to production) is most concerned with style of the sweater. After the necessary modifications were made for the garment to be technically feasible is the sweater still aesthetically pleasing?

Figure 19. Knitwear design process (Eckert, 2001)

2.2.5. Coloration

The coloration of sweaters is a primary product design consideration. Because of the high level of skill required to design a sweater, knit product developers tend to use the same or similar styles of yarns and silhouettes (Eckert, 2001; Guy, 2001). For this reason, color is often the primary distinguishing factor of one sweater to another from season to season. Coloration can be achieved prior to knitting by using dyed yarns, or the coloration can be

added after the sweater is knitted, for instance by garment dyeing or printing (see Figure 20).

Figure 20. Sweater Coloration and Finishing Processes

2.2.5.1. Yarn Coloration

Perhaps one of the most widely used methods of coloration is to knit with dyed yarns and fibers. This ensures consistent coloration throughout a knitted component and also between garment pieces. When knitting with dyed yarns or fibers the sweater's coloration

can be simple such as one overall color. The garment can also be knitted with specialty yarns that are fiber dyed, space dyed, or that have a bouclé or mélange effect (see Figures 21a-c). More complex coloration, using dyed yarn, can occur during fabric formation by striping, plating, intarsia, or jacquard knitting.

Figure 21a. Yarn Dyed

Figure 21b. Fiber Dyed Yarn

Figure 21c. Dana Buchman (2005) Sweater knitted with space dyed yarn.

Figure 21. Examples of sweaters knitted with dyed yarn

2.2.5.2. *Striping*

One of the simplest methods of coloration is striping. “Technically, horizontal or engineered stripes are the easiest ways to achieve a colored pattern effect in weft knitted fabrics, as there are no changes of color within the actual row (Bremmer, 2005).” Striped sweater material or striped garment knitted lengths can be produced by strategically alternating different colors of yarn packages around a multi-feed circular machine. The stripe repeat corresponds to one machine rotation. With the advent of electronic control it

is now possible to employ striping mechanisms. Automatic striping mechanisms, or striper boxes, are installed at the yarn feed of circular machines and each “finger” is threaded with a different colored yarn. The yarn fingers can be activated to bring a new colored thread to a knitting needle at the beginning of new machine rotation. Modern striping mechanism can have up to six yarn fingers at each yarn feed allowing complex striping sequences to be achieved in sweater design (Bremmer, 2005). Flat and straight bar machines utilize yarn carrier changes to bring various colored yarns in or out of action at the beginning or end of the carriage traverse

2.2.5.3. *Jacquard*

Jacquard structures include weft knit, single jersey, and rib jacquard. Rib jacquards are comprised of flat jacquards and relief designs. Flat designs are described by i) the design area, whether it is a full, large or small design area, ii) number of colors, and iii) type of backing, ex. birdseye, ladder, twill or pique (Spencer, 2001b). Jacquard knitting offers distinct design advantages. Design motifs can be large and very complex. Multiple colors and types of yarns can be used, and if striping mechanisms are used simultaneously with jacquard patterning, the number of colors can be further increased.

Choice of jacquard structure yields different effects. For instance, in single jersey jacquard, when a colored yarn is not in use on the technical face of the knit it floats across the back of the fabric. When knitting the same pattern with rib jacquard, the colored yarn not in use on the face of the fabric is knitted into the back of the fabric. Figure 22 shows how the technical face of a float and rib jacquard look nearly identical

but the technical backs are different. Float jacquard uses less yarn, but the floats may cause snagging when knitting with filament yarns. Another consideration is that float yarns tend to make fabric less extensible (Hatch, 1993; Spencer, 2001b). Both jacquard structures cause the fabric weight and thickness to be higher than a non jacquard knit of the same structure (Raz, 1993). The additional yarn needed for jacquard patterning adds to the cost of the garment. For expensive yarns, such as cashmere, the cost can be prohibitive. Jacquard jersey knits have better color definition than double jersey jacquards because they have only one layer of loops (Spencer, 2001b). The color blocks of a jacquard design have one color on the face of the fabric while the back of the fabric contains the colored yarn not used for the surface design. This causes the front color blocks to have a grin through of the colored yarn used on the fabric's back (Spencer, 2001b).

Figure 22a. Technical Face

Figure 22b. Technical Back

Figure 22. Jacquard Float compared to Jacquard Pique

2.2.5.4. *Intarsia*

Intarsia knitting is a coloration method where two or more colored yarns overlap along the course of the fabric to form separate fields of color within a design motif. Each colored yarn is fed through a different carrier that knits across to the adjoining color (Hatch, 1993). The different colored yarns are used to build up a figure or block of color, course by course. Unless manufacturing a cardigan, the technical back of an intarsia knit sweater will be hidden and so join lines between colors are not seen (see Figure 23a). The face of an intarsia knit sweater, as depicted in Figure 23b, provides a seamless transition between color fields and clear color definition. In jacquard knitting the aesthetics of the design coloration may be compromised because of grin through of color. Intarsia, provides the best color definition for figured motifs because each colored yarn knits only in its own color field rather than floating across the back of the fabric. In addition, less yarn is used and knitted fabrics extensibility is not altered (Hatch, 1993). This makes Intarsia ideal for pricey yarns such as fine wools and cashmere.

Intarsia knitting for sweater design has become more prevalent and more complex, a result of advances in computer software and developments in intarsia attachments on v-bed machines. At ITMA Asia 2005, both Shima Seiki Mfg., Ltd. and Steiger SA showed new machines for intarsia knitting. Shima Seiki Mfg., Ltd.'s SES123Si has increased memory for processing larger files. In addition, the SES123Si has more compact carriers that reduce noise, and up to 30 yarn carriers that can be used to create more complex intarsia designs (Lo, 2006). Steiger SA's Aries.3 can accommodate 32 intarsia motorized yarn carriers. Motorized yarn carriers can move independently of

the direction allowing intarsia carriers to swing out of the way when not in use (Schenk, 2005).

Figure 23a. Technical Back Intarsia

Figure 23b. Technical Front Intarsia

Figure 23. Example of Intarsia Knitting

2.2.5.5. *Garment Coloration*

Post-knitting sweater coloration processes include garment dyeing, piece goods dyeing, printing, or a combination of dyeing and printing. An advantage of post-knit coloration is that the choice of color can be postponed almost up until the point of sale. In 1972 Benetton Group S.p.A. an Italian knitwear manufacturer revolutionized the sweater coloration process by garment dyeing, rather than yarn dyeing their products. Although garment dyeing cost 10% more, this process allowed Benetton Group S.p.A., a fashion-driven company, to rapidly replenish their best selling items (Signorelli & Heskett, 1984). In 2007, Quantum Clothing Group Ltd claimed to have the “fastest knitwear route

anywhere”. The knitwear company manufactures complete garments in grieg which are then garment dyed (Mowbray, 2007).

Like garment dyeing, sweater printing allows manufacturers to postpone coloration. Charles Reichman, (1972) stated that printed tricot fabric had grown to 75% of outerwear knits, and that printed single and double knit jersey had increased threefold in the past ten years. Reichman attributed this increase to improved print technology but also to the cost savings that printing provided when compared to jacquard coloration. When color is introduced via jacquard patterning the yarn is colored. Stocking an assortment of colored yarns is a huge and sometimes risky venture. Printing on the other hand allows yarns to remain in the grieg state longer (Reichman, 1963).

A disadvantage of post-knitting coloration is that there is a higher risk that the entire garment will be ruined. Postponing the coloration process complicates prediction of knitted fabric properties such as hand, elasticity, and sizing calculations. A knitted fabric starts changing shape the moment it leaves the knitting machine. Bailey (2004) states two types of dimensional changes that can occur in a knitted fabric. They are; i) construction shrinkage “defined as the amount of dimensional change in a fabric based solely on the construction variables used to create the fabric.”, and ii) processing shrinkage, “defined as the dimensional change that a process adds to or removes from the construction shrinkage of a fabric.” All knitted fabric (regardless of coloration method) will experience construction shrinkage and any additional processes (such as dyeing) will further change the properties of the fabric. In fully-fashioned and complete garment knitting dimensional changes due to wet and dry processing have to be accurately

calculated before knitting. If the knitted goods shape and size change too drastically after finishing then the entire sweater or garment panels are worthless.

An answer to this problem may come from ink jet printing technology. Ink jet printing (often referred to as digital printing) is a non-contact method of printing. If pigments are used, wet processing is minimal. Shima Seiki Mfg., Ltd. has developed two ink-jet printers, the SIP100 and SIP-160F for printing onto complete sweaters and fully-fashioned garment pieces. Ink jet printing, allows for photo realistic, multi-tonal, and multi-color images to be applied to knits. Synchronization with CAD stations allows complex designs to be engineered onto sweaters; design motifs are strategically placed within a garment's shape so that imagery wraps around the body. Grace International Ltd., a Japanese sweater manufacturer, has incorporated ink jet printing technology into their sweater coloration process. Areas of intarsia are digitally printed providing for more intricate designs ("Graceful Design", 2005).

2.2.6. Computer Aided Design

Computer aided design (CAD) for sweater manufacturing is mainly used for file preparation and product visualization. File preparation can include generating the garment shape, creating the knitted fabric structure and programming the technical information needed to run the machine. Kathlyn Swantko states that: "CAD packages reduce the time-consuming and expensive artistic design steps of doing color reductions, color separations, creating colorways, pattern repeats, engineering stripes and jacquards,

3D model renderings, fabric draping, and driving actual production equipment” (Swantko, 2005).

The integration of CAD/CAM is achieved by Shima Seiki Mfg., Ltd. and H. Stoll Gmbh & Co. who both distribute proprietary software specifically designed for use with their knitting machines. Shima’s software, the SDS-one and H. Stoll Gmbh & Co.’s software the M1 pattern preparation system can prepare files for knitting as well as provide the necessary information to drive the machines. Both offer a dual design and technical interface. The design view shows pictorial imagery of stitches while the technical view gives accurate representation of needle selection, racking, and stitch length (Hunter, 2004b). Shima Seiki Mfg., Ltd.’s loop simulator allows complete garments to be virtually knitted to check for production errors. In the SDS-one software, Shima Seiki Mfg., Ltd. stores modules for complete garments and fully-fashioned panels. These libraries of garment shapes and styles can be altered for size and then knit structures can be applied.

CAD visualization tools allow for realistic representation of the fabric structure and texture, aiding the product evaluation process prior to actual knitting (Cotton Incorporated, 2006). Corey Schwartz, from textile software company Pointcarre USA, emphasizes the importance of virtual knitting:

In order to compete in the market today, with the market being so much more global, the need for instantaneous information sharing has become a necessity. The software reduces the cost of sampling. So you don’t have to make up actual knit-downs. You

have virtual samples. The use of virtual sampling cuts down on sampling time and also cuts costs (Swantko, 2005).

Companies such as Pointcarre USA, Lectra SA, Tukatech Inc., and Yxendis also offer software for knit design. Pointcarre USA's software is capable of creating and simulating fabric structure and can also interface and drive a multitude of machines by various builders (Swantko, 2005). Lectra SA, an apparel and textile design software company teamed with machine builder Steiger SA, and combined the design tools of Lectra SA's PrimaVision with the knit production capability of Steiger's KnitExpert. The integration of these programs allows complex knit structures, and coloration structures such as jacquard and intarsia to be added to fully-fashioned garment panels (Hunter 2004). Tukatech Inc. and Yxendis are apparel software companies that have recently added knit design capabilities. Tukatech Inc. offers "apparel and textile development, grading, marker making, 3D PDM, PLM, MRP and ERP, sourcing, accounting, and manufacturing controls (Swantko, 2005)." Yxendis has developed a 3D simulator for knit structures for both circular and flat knitting machines (Hunter 2004).

2.3. State of the Art in Engineered Designing

Digital printing and integral knitting clearly support engineered designing by allowing the product developer to design fabrication simultaneously or purposely for the end product. In addition, there are other emerging textile and apparel processes that are also conducive to engineered design. For example, Jiri Evenhis and Janne Kyttenen, founders of Freedom of Creation BV, developed a process for three dimensional fabric formations

in 1999. Their patented process uses laser sintering technology to build links that form an intermeshed fabric (Kytanen & Evenhuis, 2003). Fabric geometry is based on the link structure rather than on a woven, knitted, or non-woven structure. The characteristics and appearance of the three dimensionally printed fabrics can be altered based on the shape of the individual links and the configuration of how the links are joined together. See Figure 24 for examples of three dimensionally printed fabrics.

Figure 24. Three dimensionally printed fabric structures (Kytanen, 2007)

The laser sintered fabrics can be produced as a product, (see Figure 25a). Other projects that involve this technology are geared toward shoe design. Prior2Lever, a collaborative effort between a podiatrist and industrial designer, uses laser sintering to make bespoke soles for football shoes. The podiatrist scans each client's foot in order to make a custom fitted sole. Head Over Heels, another customized footwear designer takes the concept of engineered product design further with their shoes that are manufactured in one process. The shoes are designed in a three dimensional CAD program and this information is sent

to the laser sintering machine to produce the entire shoe (see Figure 25b) in one step (*Prior2Lever football boots: The interview part 1.*).

Engineered designing is also being used in jacquard weaving. Mei International S.r.l, an Italian label making company, has experimented with weaving jeans that have photographic imagery that is woven to follow the shape of the garment. The end result is similar to engineered digital print design, where the graphics can be placed to wrap around the body. The photographic imagery is accomplished by using six colors for the warp; black, white, red, green, yellow, and blue. The woven pattern need not repeat, but instead can be one large graphic motif.

Figure 25a. Laser Sintered Garment from Freedom of Creation BV (Kytanen, 2007)

Figure 25b. Laser sintered outsole by Prior2Level (Prior2Lever football boots - the interview part 1.)

Figure 25c. Complete laser sintered show by Head Over Heels (Hague, 2005)

Figure 25. Examples Laser Sintered Items

2.4. Review of Models

A series of product development models were reviewed in order to gather information about the textile and apparel product development process. Information gathered from these models was used as a base point for developing a conceptual model for engineered designing. Models selected for review provided a macro view of the textile and apparel product development process and a micro view of the textile and apparel product development process. In addition, select well known product development models outside of the textile and apparel complex were reviewed in order to gain a more comprehensive perspective of the design process. Models depicting a micro view of the textile and apparel product development process were selected for one of the following reasons; i) the level of detail for design of fabrication and product; ii) a description of the relationship between fabrication properties and end product; and iii) depictions of digital processes that aid integration of fabric and end product design.

2.4.1. *Macro View*

Belliveau, Griffin, & Somermeyer, define the product development process as a disciplined and defined set of tasks, steps and phases that describe the normal means by which a company repetitively converts embryonic ideas into saleable products and services.” p. 504 (Belliveau, Griffin, & Somermeyer, 2004). The number of product development models has proliferated in the past twenty years and an exhaustive review of significant models would be beyond the scope of this paper. Krishnan and Ulrich provide a comprehensive review of the literature on product development models, by reviewing

200 papers. In this review, Krishnan and Ulrich surveyed 50 researchers working in design and development and asked them to provide recommendation for influential papers. Based on this review, Krishnan and Ulrich identified four decision categories needed in the design of a product; concept development, supply-chain design, product design, and production ramp-up and launch (Krishnan & Ulrich, 2001).

One notable model, the Spiral Model developed by Boehm in 1988, and still widely cited today (2,781 citation within Google scholar as of this writing) provided a breakthrough in software product development in that the model emphasized the importance of prototyping to reduce risk (see Figure 26) Boehm's representation of software processes built upon previous models such as the Stages model, where a process flow was broken down into successive stages, and the Waterfall model that portrayed the feedback that was necessary between the stages (Boehm, 1988). This model was reviewed because the spiral shaped model depicted the back and forth movement, or iterative process, needed between the stages of design. In addition the Spiral Model addresses the need to set objectives and to fit criteria in each stage of the process, and also the need to consider alternative solutions or processes throughout in order to meet the objectives.

Figure 26. The spiral model (Boehm, 1988)

Glock and Kunz describe the textile and apparel product development process as “the design and engineering required to make products serviceable, salable, producible, and profitable” (Glock & Kunz, 2005) p. 85. The textile and apparel product development process can be broken into two main categories, creative design and technical design. Creative design focuses on the research analysis of trends and past sales data, while technical design involves perfecting style and fit, and the development of the products’ manufacturing specifications.

The set of models summarized in Table 7, consist of traditional product development processes for textile and apparel products. As can be seen by the diagram, each model lists similar steps and activities for the textile and apparel product development cycle. The product development cycle consists of a number of steps that include: initial planning, trend analysis, and research; a preproduction stage that involves design and development; a prototype, testing and/or evaluation phase; material sourcing for final product; marketing the line; and finally distribution of the product or product line (Brown & Rice, 1998; Burns & Bryant, 1997; Kunz, 2005; Lamb & Kallal, 1992; May-Plumlee & Little, 2006; Wickett, Gaskill, & Damhorst, 1999). Textile and apparel products can be developed in house by a product development team or individual, or items can be purchased or sourced. (Kunz, 2005)

In the Apparel Production Cycle, an attempt is made to quantify the amount of time that each step requires (Brown & Rice, 1998). It's interesting to note that in Brown's model the pre-production processes such as trend evaluation, design, sourcing and preproduction account for 65% of the time needed for the entire apparel production cycle. Therefore, any steps that would reduce preproduction processes would have a significant effect on the entire production cycle. In fact Kunz (2005) states that the aim of most firms is to decrease the number of steps in the product development process. Another time consuming step is prototyping which Brown states as being a three to six week process.

Burns' and Bryant's model (1997) consists of a series of steps presented in a flow chart diagram. The purpose of this flowchart is to present a macro view of the steps

needed to create an apparel item. The authors explain that although the steps are presented as sequential, some processes may occur simultaneously. In fact, all of the models shown in Table 7 represent steps and processes that at times may be concurrent. Kunz envisions *The Taxonomy of Apparel Merchandising Systems*, (listed third) (Kunz, 2005) as a cylindrical model where processes and decisions flow backward and forward. Likewise, in the *No-Interval Coherently Phased Product Development Model for Apparel* (fifth model) the authors state that textile and apparel design requires a backward and forward movement through processes. (May-Plumlee & Little, 1998) Wickett, Gaskill, and Damhorst (1999) surveyed 21 retail stores involved in product development and validated that the steps involved in product design are not linear. Working concurrently on processes as well as reducing steps can decrease the overall time needed to develop and bring a product to market.

Another commonality of the models represented in Table 7 is that the voice of the consumer is paramount to successful product design. For example, in Lamb and Kallal's model titled the *Apparel Design Framework*, the consumers' needs are divided into three categories; functional, expressive, and aesthetic. Functional needs could include protection from the environment, comfort or ease of movement. Preliminary ideas for the product are driven by specific needs of the consumer. The prototype is then evaluated based on how well the criteria of the consumer are met.

Table 7. Textile and Apparel Product Development Models

Apparel Production Cycle	Design & Manufacture Process	Taxonomy of Apparel Merchandising Systems (TAMS)	Apparel Design Framework	No-Interval Coherently Phased Product Development Model for Apparel	Revised Retail Product Development Model
			Problem Identification		
Evaluation 2-4 weeks	Research	Line Planning	Preliminary Ideas	Line Planning and Research	Research
Design 2-3 weeks	Design	Line Development	Design Refinement	Design & Concept Development	Line Concept
Sourcing 2-3 weeks	Design Development	Line Presentation		Design Development & Style Selection	
Preproduction 2-6 weeks	Marketing the Plan		Prototype Development		Product Visualization & Evaluation
	Preproduction		Evaluation		Technical Development
	Sourcing	Garment Production			
Production 1-2 weeks	Apparel Production			Marketing the Line	
Distribution 1-3 weeks domestic 3-5 weeks imports	Distribution		Implementation		
Sales 3-6 weeks					
(Brown & Rice, 1998a)	(L. D. Burns & Bryant, 1997)	(Kunz, 2005)	(Lamb & Kallal, 1992)	(May-Plumlee & Little, 1998)	(Wickett et al., 1999)

2.4.2. *Micro view*

Kunz's Taxonomy of Apparel Merchandising Systems (TAMS), May-Plumlee's No-Interval Coherently Phased Product Development Model for Apparel, and Wickett, Gaskill's and Damhorst's Revised Retail Product Development Model all included fabric design or selection as an important component in product development. May-Plumlee's model provided two avenues for fabrication; fabrication is developed in-house by company or fabric is co-developed with outside companies (May-Plumlee & Little, 1998). Kunz's implies that apparel companies must decide to "make-or buy" fabric for end products (Kunz, 2005)p. 264. Over 45% of the retail companies that Wickett, Gaskill and Damhorst surveyed developed their own coloration and fabric design for prints and plaids.

In contrast, Brown's model specifies that companies must "seek and find" correct fabric for a garment rather than developing co-developing fabric along with the product. (Brown & Rice, 1998) Wickett, Gaskill and Damhorst found fabric sourcing to be a time consuming and difficult process, stating that lead time for fabric development is long. Burns and Bryant recognized fabrication as the greatest material cost for a garment (Burns & Bryant, 2001). However, Burns and Bryant saw fabric development as separate from product design in most instances, and cite Pendleton Woolen Mills as an exception. Pendleton Woolen Mills uses engineered designing principles for development of apparel. For example, when producing a skirt Pendleton designs the woven plaid so that the repeat of the plaid motif coincides with the repeat of the skirt's plaid.

While the models represented in Table 7 provided a solid overview of the traditional textile and apparel product development process, another model was needed to grasp how a model can change once new technology is introduced. For example, with both digital printing and integral knitting, the prototype process and the manufacturing process can be the same, therefore prototyping is simplified and fewer steps are involved. One model, by Chenemilla, incorporated engineered designing into a mass customization flow chart. Chenemilla's functional, consumer-centric model, is based on the theoretical decision making process that the customer undergoes when purchasing a customized printed garment (Chenemilla, 2001). In this model, much of the decision making process about the end product is derived directly from the consumer. The various design choices, such as type of fabric, textile design style, and apparel fit are revealed. Chenemilla also acknowledges a need for approval from the customer via digital simulation prior to the item being produced. In addition this model supports use of digital archives of previous designs. However, the relationship between a product developers design choices and the desired characteristics of the end product are not discussed. Furthermore, this model looks only at digital printing, a surface design application, and is not applicable to processes such as integral knitting where fabrication and product shape occur simultaneously.

2.5. Summary of Literature Review

In both printing and sweater manufacturing, technological advancements in machinery has shifted from the primary goal of increasing speed and efficiency to the secondary goal of increasing flexibility, quick response to market, and design innovation. While speed and efficiency are still important, major progressions in machinery development, particularly digital control, has allowed the designer to have more access to machinery and, more flexibility in design choices, variables that are favorable for engineered designing. However, existing models for textile and apparel product development have not evolved to fully exploit the advantages of new technology such as integral knitting and digital printing. A consequence of increased access to machinery for product development is that designers now have greater involvement in the prototyping and production process. While these advances have been detrimental to speed of machinery (both integral knitting and digital printing are slow by production standards), product developers may opt to bear the disadvantage of decreased speed in order to gain the increased design potential, flexibility and control over prototyping and production. Hague (Hague, 2005) p. 5 states that:

One of the principal advantages to taking an additive (Rapid Manufacturing) approach to manufacturing over more conventional subtractive or formative methods comes not from manufacturing approach per se but from the dramatic advantages that are possible in the area of *design*. This potential for radically different design methodologies is one of the major drivers for the development of Rapid Manufacturing systems and materials and is a powerful reason why some

organizations are able to put up with the sometimes severe limitations associated with current Rapid Prototyping (RP) systems to gain an advantage today.

As the textile and apparel market shifted from a manufacturing centric market, where demand was dictated by the amount of goods that could be profitably made to a consumer centric market, where consumers pulled the market. Research naturally shifted from increasing production speed and efficiency to a consumer centric market. Therefore theoretical models were developed to gauge consumer perception and influence of the consumer in product design. This led to the idea of mass customization, allowing the customer to have direct input into the product design process. Models that have deviated from the standard textile and apparel product development process have tended to focus on mass customization. Models developed gauged how much or little customer input was feasible based on product type. That is, which characteristics of a product are most attractive to the consumer and will ultimately lead to the purchase of a product? However, little research exists on how to improve the input of the designer; i.e., how to develop a designer centric model where the designer has more input and control in the decision making processes involving the manufacture of a product. Good design is critical to the success of a product. Fortunately, new and emerging digital technologies allow the designer to have more control in the entire product development and manufacturing processes. Mass customization models offer a radically new process for product development and production, and often include both integral knitting and digital printing. However, mass customization models have focused solely on the input of the customer and ignore the input of the product developer. While the voice of the consumer

is paramount, so too is the “voice of the designer”. Engineered designing enables the voice of the designer.

An informal polling by the author of machine manufacturers at ITMA 2007 revealed that machine manufacturers of integral knitting and digital printing still find resistance to these technologies because of the decreased production speed of these machines when compared to traditional knitting and printing. Production will need to improve significantly, or these technologies will need to be used in a different model; one that doesn’t rely on high production speeds. In the *PDMA Toolbook 2* Markum and Kingon define three types of “technical advantages; 1) higher performance, 2) lower cost, and 3) new needed capability”(Belliveau et al., 2004). Higher performance is certainly achieved with textile inkjet printing and integral knitting when used for sampling and short runs; both shorten lead time by speeding up production of samples. A decrease in the time to market ultimately leads to a decrease in cost. For digital printing, the time, skill, and cost to prepare a screen, and the added investment to store a screen are too high for sampling by screen printing. There is also a “sweet spot” for production printing, usually print runs under 500 yards, where cost to print is lower with ink jet printing. A current trend is for smaller run lengths and increased number of prints Shorter runs could ultimately reduce inventory, thus lowering cost. Integral knitting is not as productive as knitting for cut and sew when comparing machine productivity, however when reviewing the number of steps needed to complete a garment (revisit Table 6.) integral knitting is considerably faster.

Integral knitting and digital printing have the potential to change the textile and apparel product development process manufacturing process and the product itself. Products produced with integral knitting and digital printing can have aesthetic and functional properties engineered into the fabrication, providing new needed capabilities. Unfortunately this design potential is not being met due to lack of training of product developers (Guy, 2001; Power, 2007). The role of the product developer is changing and Universities and industry need to better prepare individuals to face these challenges. Mr. Terada, of Terada Knit Co. in Japan, expresses this change in knitting:

I wouldn't say that I am a knitwear designer per se. I am more of a knitwear architect. I can see the design possibilities, but also have the knowledge about raw materials, machinery technology, and stitch construction techniques to translate ideas into successful garments (Mowbray, 2006).

Brackenbury (1993) recognized the added skill needed on the part of the designer and machine programmers to cope with the complexities of integral knitting and saw the increase of skill requirement as an inhibitory factor for adoption. Machine manufacturers such as H. Stoll GmbH & Co. and Shima Seiki Mfg., Ltd., and as well as software developers such as Lectra SA, are working to make design software interface more easily with digital printing and integral knitting. For instance Shima Seiki Mfg., Ltd. software provides a designer friendly interface that includes high definition pictures of knit structure where users can toggle between a technical and graphic interface. In addition, Shima Seiki Mfg., Ltd. continually adds to their library of garment styles so that a product designer can start from a technically executed sweater and alter the garment if

needed. Pulling a sweater design from a library saves a tremendous amount of time and less skill is required from the product developer when compared to building a sweater from the start. Lectra SA software allows three dimensional placements of print motifs onto a garment, facilitating aesthetic engineered designing.

Problems such as bottlenecks, time delays and technical difficulties in manufacturing the product are often a result of the tug between the designer and the technician. Engineered designing often synthesizes the position of designer and technician, that is, the designer becomes has working knowledge of technical aspects of the design and the technician has knowledge of design. Therefore, an engineered designer has a blend of design and technical abilities. While engineered designing will most likely require more expertise from product development individuals or team members, an investment in expertise may save time and money. Kunz (2005 p. 184) states that:

The role of technical design has become more important as firms have sourced production from multiple contractors around the world. Consumer expectations for quality and consistency in product offerings pressure firms to improve product management. Many problems that emerge and must be resolved on the production floor could have been avoided with effective technical design.

A thorough review of the literature has established that new technologies such as digital printing and integral knitting allow some or all fabric design properties to be engineered for the end product. Exploration has occurred on integration of the print design process with the apparel marker to move away from repeat pattern (Bunce, 2005; Campbell & Parsons, 2005; Chapman, 2004; Gordon, 1997). Research conducted as part of a Master's

thesis sought to prove that aesthetic design is improved when the print design is engineered within the garment shape. Chenemilla, (2001) Fralix (2000), and Chapman and Istook (2002) incorporated engineered ink jet print design into a mass customization model. Research on integral knitting, has focused on engineering shape and fit (Fellingham, 2007; Guy, 2001; Power, 2007). In addition a historical study attempted to define how fabric was engineered for garment shapes prior to the industrial revolution (Knight, 1972). However, no research exists that documents textile design engineering within the product shape. For this reason, the dissertational research develops a process model for textile design engineering within the product shape.

3. RESEARCH METHODOLOGY

A 1998 model of research practice by discipline (see Figure 27) shows that product development research falls more into the synthetic, rather than the analytical sphere and favors real application rather than symbolic (Hancock & Algozzine, 2006; Owen, 1998). Owen argued that in order for research in product development to be more balanced, i.e. product development is positioned further toward analytic research, then design researchers would need to be sufficiently trained in theoretical methodology. Similar conclusions were reached by Pederson in her analysis of theory and how it is used and viewed. Pederson points out resistance to theoretical approaches in textile and clothing research as evidenced from survey results conducted by the International Textile and Apparel Association (ITAA) in 2000. Comments from ITAA respondents demonstrated a resistance to practicing theoretical research; instead favoring a practical approach. However, in order for research to be comprehensive a balance must be struck between theoretical and practical methodology. The following research project will comprise theoretical and practical methodology. Qualitative and quantitative data will be collected from engineered design practitioners and synthesized into a theoretical model.

The engineered designing process is relevant to both the product development and manufacturing process because it will help to produce a better product more efficiently and rapidly. However, no substantial research has been conducted that i) defines and categorizes this integration process, ii) attempts to understand engineered designing in relation to current industry methods, or iii) explores how new and emerging technologies can aid in the industrial utilization of this process. To fully understand the capabilities of

engineered designing, the various methods of this process need to be documented and categorized. Once engineered designing is categorized, commonalities of technologies and processes can be established, and new methods of engineered designing can be developed. The merits and disadvantages of the different systems can be evaluated and quantified. Therefore a multi-method research approach will be undertaken to gather and analyze both qualitative and quantitative data. The research will be carried out in three stages. *Stage One* will consist of producing a rudimentary model of engineered designing, based on the literature review and the author's own experience in engineered designing. Research procedures in *Stage Two* will assist in refining the model for engineered designing by seeking the assistance of expert users. Methodology for *Stage Three* will test the universal applicability of the model using industry practitioners. Based on the collected data, the final version of the model will be fashioned and validated.

Figure 27. Conceptual model of the relationship between design of experiment for product design versus other disciplines (Owen, 1998)

3.1. Research Objectives:

The object of study for this research project is the engineered product development and design process within the textile complex; specifically, the engineered product development and design process for strategic placement of aesthetic and functional fabric design properties in relation to the end product. The objectives of this research are to i) build a comprehensive process model of this engineered design process,

ii) validate a definition for this engineered design process within the textile process, iii) benchmark successful use of this engineered design process, and iii) contribute to the advancement of theory of this engineered design process by testing propositions (theory). The research project is carried out in three stages.

3.1.1. Stage One Objective: Develop a Base Model for Engineered Designing

The main objective of *Stage One* is to build a base model for engineered designing. This initial process model acts as a blueprint for the survey development in Stage Two, guides case study selection, and aids in the development of a case study protocol for Stage Three of the research project. Another objective of Stage One is to refine a set of propositions concerning engineered designing that will be tested in Stage Two and Stage Three.

3.1.2. Stage Two Objectives: Refine Model, Validate Definition, Test Theory

The objectives of Stage Two are to: i) add to the initial model developed in Stage One by establishing common terminology, processes, and practices, ii) validate a definition of engineered design, and iii) test hypothesis about the object of study in order to aid in theory development for engineered design.

The preliminary model will assist in determining engineered design approaches according to evaluation criteria. This research will quantify the levels of complexity of engineered designs, determine the extent that designers impact characteristics of the end

product, determine optimum interfaces between design and technology, and establish common terminology, processes and tools.

3.1.3. Stage Three Objective: Validate Model

The objectives of Stage Three are to i) validate and further refine the model in Stage Two, ii) improve the validity of results obtained in Stage One and Two with methodological triangulation iii) benchmark innovative use of this engineered design process and, iii) contribute to the knowledge base of the engineered design process for fabric design placement by building theory. A collective case study approach will be used in order to draw conclusions about a larger population of users and uses, and to provide case study documentation of the engineered design process successfully used in industry.

3.2. Stage One Procedure

Input for this model is gathered from the product development processes for digital printing and integral knitting, and the principal investigators' experience with the product development process. In addition, a survey of hardware and software was conducted at ITMA 2007. Data was collected from observing demonstrations of machines and software for integral knitting, digital printing and weaving. Interviews with company representatives were also conducted. Data gathered from these practitioners, software developers and machine developers assisted in identifying the types of tools available and those tools still needed for engineered designing.

Business process modeling software was used to build a multilayer model for engineered designing. In addition, the product development processes for integral knitting and digital printing were compared to each other to facilitate identification of Universal Knitting Machines GmbH processes and technologies for engineered designing. Comparing and contrasting the product development processes of these two emerging technologies with that of the traditional product development process for textile and apparel helped to establish a new model for engineered product design. For instance, it is presumed that digital libraries and three-dimensional visualization software would be common tools for engineered designing regardless of whether a product is digitally printed or integrally knitted (or woven or laser sintered, etc.). Likewise, the ability to hold a product in digital format longer, (in some instances up to the point of production) may be a common process for engineered designing. However, although commonalities may exist, it is proposed that varying levels of engineered designing also exist. The research will investigate whether or not an engineered print may be more or less complex to design than an integrally knit garment, and if an integrally knitted garment may be easier to manufacture. Comparing and contrasting the two technologies will help to illustrate common problems (such as distortion of motifs and patterns when resizing for production) and also begin to establish if hierarchal levels of engineered design exist. Data collected from Stage One will assist in building the survey instrument in Stage Two.

Based on the initial model rendered in Stage One, a survey instrument was developed, distributed and the data was analyzed for Stage Two of the research project.

Data analysis of the survey results established a working definition of the engineered design method, refined the process model, and tested the theoretical constraints.

3.3. Stage Two Procedures: Survey of Engineered Design Experts

The Delphi method was employed for Stage Two of this study. The Delphi method uses facilitators, in this case the principal investigator, to identify experts in a given field and question or survey these experts on a specific problem, topic or procedure. For this research, the principal investigators identified experts in the field of engineered design and solicited their help in completing a self-administered online survey. Electronic distribution allowed participants to complete the survey at their leisure. Most importantly online survey analysis expedites data analysis because data was entered electronically by the participants.

3.3.1. *Survey Development*

The survey consisted of ten pages. Each of the ten pages dealt with distinct aspects of engineered design and the questions on each page were specific to the page heading. The first five pages of the survey were common to all participants.

Page one consisted of a consent form that followed the requirements of the principal investigator's Institutional Review Board (IRB). The following page, (Page two) gathered demographic information from each participant, and also identified the context of the participants' engineered design experience. Specifically, participants were asked to state their job title, responsibilities of their current position, length of employment and types of engineered products produced in their current position. The

questions on page three, titled *Defintion of Term*, were developed to in order to validate the author's definition of the engineered design process. For question one, participants were asked to read the definition and check whether they: i) agreed with the definition, ii) did not agree entirely, but agreed in part with the definition, or iii) disagreed entirely with the definition. If participants disagreed in part or in whole with the definition, they were asked to write their own interpretation of engineered design. Questions two, three and four related to the aesthetic and functional purposes of an engineered design. For question two, participants were asked if the purpose of their engineered design was for the improvement of aesthetic or functional aspects of the end product. Choices for this question were improvement for aesthetic purposes only, improvement for functional purposes only, or improvement of both aesthetic and functional purposes. Data analysis of this question sought to establish if engineered design was used primarily for aesthetic or functional purposes. Analysis of responses gathered from next two questions sought to establish a rating scale for attributes of both functional and aesthetic engineered design. A Likert-type response format was used for these questions. A Likert-type format allows participants to "respond in varying degrees to each item" (Trochim & Donnelly, 2001). This method of data collection was used to determine if the engineered design experts polled considered some attributes of engineered design more important than others. Attributes for aesthetic engineered design were listed as accentuation of product shape or movement; strategic placement of motifs, seamless design of motifs or patterns, camouflage of seams, or diversion from an area of the body. Choices for functional attributes included the need to reinforce areas of high wear, reduce waste, or to improve

fit, comfort or performance. Participants were asked if they considered each engineered design attribute to be extremely important, important, a minor consideration, not important, or not applicable (N/A). An *Extremely Important* answer would represent the high end of a positive response, while a *Not Important* answer would indicate a negative response. The final question for page three, titled *Definition of Term*, polled participants to see if they felt that an engineered product has a superior appearance to a product that is non-engineered.

Page four of the survey was titled, *Experience*. The intent of question one was to establish the capacity in which the experts were using engineered designing. Participants could choose multiple answers from a list that included art-to-wear, couture, customization, ready-to-wear, sampling, scholarly research, or other. The purpose of questions two and three was to collect data on the experience level of each participant. Analysis of this data would provide a triangulation of expert identification initially determined by the principal investigators. Question number four on the *Experience* page asked if participants felt that adequate literature and training materials exist for engineered designing. A number of choices were posted for participants to choose from. Possible negative answers included i) No, I learned by trial and error, ii) No, I still need training, and iii) No, I can't find published material on engineered designing. Possible positive answers included iv) Yes, my educational experience prepared me, v) Yes, my past or current company trained me, vi) Yes, there are well documented strategies on the web, vii) Yes, there are books and papers that explain how to engineer a design. The last question asked participants' opinion as to which technologies, market influences, or

design processes they felt contributed to the greatest changes in engineered designing over the past ten years. This question was open ended in order to discourage any influence from the principal investigator, and to solicit frank answers from the engineered design experts.

Page five contained a skip logic question. A skip logic is used in surveys “to collect data on specific survey participants, and is accomplished by directing respondents through the survey based on responses to previous questions. The skip logic question on page five asked participants to state which type of engineered design (knitted, printed or woven) they were engaged in. Based on the response to this question participants were routed to one of three segments of the survey. From pages six onward, the survey was segmented into three parts; i) engineered knitting, ii) engineered printing, and iii) engineered weaving. The structure for each of these segments was identical, however wording and phrases were adapted to each technology. The overall structure for the survey and a summary of content and objectives is shown in Table 8. (see Appendix B for a copy of the entire survey instrument).

The questions on the remainder of the survey: Archiving and Storage (page 6); Process (page 7); Communication (page 8); Calibration (page 9); and Prototype/Simulation (page 10) sought to collect data for two main purposes. The first objective was to gather detailed information about the process of engineered design. The second purpose was to test theory about engineered design.

Table 8. Summary of Survey Instrument			
Page # and Title	Questions	Description of Content	Objective
1. Consent Form	1	Consent to participate in survey	Comply with IRB
2. Contact Information	5	Current position, types of products produced, job responsibilities, business address	Provide background information for responses
3. Definition of Term	5	Agree/Disagree with definition, purpose for engineered design, rating of objectives for engineered design	Validate definition for Engineered Design
4. Experience	5	Training, experience expressed in years and capacity	Self assessment of level of expertise, triangulation of expert identification
5. Engineered Design Method	1	Type of engineered design process used; knitted, printed or woven design.	Confirm participant's expertise in knitted, printed or woven design. Direct participant to correct survey segment
*6. Archiving and Data Storage	5	Data storage, libraries	Contribute to process model, test theory
*7. Process	20	Hardware, software used, time, cost, design considerations, placement, level of difficulty.	Contribute to process model, test theory
*8. Communication	5	Verbal/graphic communication, data transmittal	Contribute to process model, test theory
*9. Calibration	4	Color communication, color processes, achieving correct color	Contribute to process model, test theory
*10. Prototype and Simulation	6	Virtual/Actual prototypes, time, number of prototypes, 3D simulation	Contribute to process model, test theory
* Designates sections that have questions that are modified for either, knit, print, or woven design.			

3.3.2. *Stage Two: Data Collection*

A list of possible survey participants was compiled by the principal investigator based on the expertise of the individuals in the area of engineered design for textile product development. The Delphi method of data collection was chosen for a number of reasons. Engineered design is a complex product development process and it was thought by the principal investigator that experts would best be able to describe the process. In addition, it was anticipated that experts would be aware of or using the latest technology and processes for engineered design and one objective of the research was to benchmark successful use of engineered practices. Kahn states that the “The objective of the Delphi method is to capture the advantages of multiple experts in a committee, while minimizing the effects of social pressure to agree with the majority, ego pressure to stick with your original forecast despite new information, the influence of a repetitive argument, and the influence of a dominant individual” (Kahn, 2006).

The principal investigators limited the choice of research participants to experts working in one of three areas; knitted, printed, or woven engineered product development and design. These three areas of engineered design were deemed to be closely related to each other as all three of these areas engineered aspects of fabric design placement in relation to the end product shape. In addition, software for design of knitted, woven and printed fabric has similar capabilities and interfaces.

Survey participants’ expertise was determined through a comprehensive literature review and from contacts of the principal investigators. An initial list of 40 experts was identified; 14 from knitting, 15 from printing, and 11 from weaving. This list

of 40 was further narrowed down to 31; nine identified experts were excluded from the survey list because correct or current contact information could not be obtained.

Two individuals from the list of 31 identified experts were chosen by the principal investigators to take part in a pilot survey. The pilot survey instrument was developed and distributed to the two engineered design experts; one identified expert in engineered knit design, and another identified expert in the field of engineered print design. The pilot participant's responses were analyzed to determine if additional questions were needed, if some questions were redundant, and if questions needed to be rephrased. In addition, the pilot survey results were reviewed by a survey design expert, Dr. Lori Rothenberg, to insure that the data collected could assist with the research.

The two individuals who completed the pilot survey were chosen by the principal investigator based on their breadth and depth of engineered design. The print designer, whom we shall designate as Pilot Expert P1, had greater than 10 years experience in the engineered printing process and worked for a non-profit research organization that maintained a printing and product development center had a focus on engineered design. The knit designer, whom we shall identify as Pilot Expert K1, also had greater than 10 years experience in engineered knit design and worked for a company that built and distributed knitting machines and software. This knitting machine manufacturer also owned a knitwear mill for knit product prototyping and manufacturing.

Based on the responses from the Pilot survey several changes were made to the survey instrument. For example, it was determined that comment sections would be useful after several of the questions. A comment field allowed participants to elaborate on

responses and write about specific concerns in the engineered design process. Several “Other” fields were added followed by a “Please specify if Other” field. The “Other” field proved very helpful as it allowed participants to fill in options not previously accounted for by the principal investigators. After the survey instrument was amended, the survey was sent to the remaining individuals on the list. The two individuals from the pilot were asked to complete any additional questions not included in the pilot survey, or questions that were changed in wording or scope from the pilot survey. The subject populations are identified experts, over the age of 18, working in the area of textile product development, and currently using engineered design methods or tools.

Study participants were contacted via e-mail (see Appendix A for a copy of the cover letter) and asked to participate in the study by completing the survey. All correspondents, as well as the survey instrument, were prepared in compliance with North Carolina State University’s Institutional Review Board (IRB). The IRB determined that this study was exempt from full review. Participants were asked to complete a self-administered online survey (see Appendix B for Survey Instrument). Collected data was transmitted using SSL encryption and data was stored on a secure, password protected server accessible only by the principal investigators. Each participant was assigned an alpha numeric code name that was used to identify him or her in the dissertation. Participant’s identifying information was used solely to cross check answers’ with participant’s occupation, and to notify participants once the research was published. Survey results are presented in aggregate terms, though individual comments are also cited. All comments and responses are kept confidential and no audio or videotaping was

conducted. The study participants were not compensated. An indirect benefit to the participants of the study is the knowledge that they are contributing to a greater body of knowledge about engineered design. A snowball approach was used, i.e., experts were asked to identify others in the area who they felt would be qualified to answer the questionnaire.

The final survey instrument was initially sent to the 29 experts identified by the principal investigators. Of these 29, eight experts worked in knit design, twelve experts were print designers, and nine worked in woven design. Experts were chosen from both academia and industry. Eight additional experts were identified by individuals from the first set of survey participants. A second mailing was sent to these eight participants one week after the initial mailing. Of these eight, five were identified by survey participants as working in knit design, and three had no particular field identified.

After analysis of response rate, the principal investigators identified five more experts; four knit designers and one print designer. A third invitation was sent asking these experts to fill out the survey. In addition, a member from the third mailing identified nine more engineered knit designers. A fourth and final e-mail invitation was sent 31 days after the first e-mail invitation.

3.4. Stage Three Procedures: Multiple Case Studies

A collective case study approach was designed to better illustrate the complexity levels of engineered designs. Collecting data from multiple users provided richer knowledge of approaches to problem solving incurred with engineered designing. A

collective case study allowed comparison and contrast of different methods of engineered designing.

3.4.1. Case Study Protocol

The principal investigator established a protocol for collecting data from the case study research. A lack of protocol in case study design can contribute to the inability to measure validity of results (Dul & Hak, 2008; Yin, 2003). Yin reinforces a commonly held belief that in all social science research, four criteria are commonly used to judge the validity of results; construct validity, internal validity, external validity, and reliability. Yin further suggests tactics for addressing these validity tests within case studies (see Table 9.). For example, Yin believes that construct validity can be achieved by citing multiple sources of information, having a chain of evidence, and allowing participants to review a draft of result. In this research, survey as well as case study data was collected from a multitude of individuals. In addition, multiple case study research was conducted. Multiple case studies allow for input from multiple sources and also helps to establish replication of results, a tactic that both Yin (2003) and Dul and Hak (2008) believe is essential for testing the external validity of results.

Table 9. Case Study Tactics to Test Validity of Results (Yin 2003)

Tests	Case Study Tactics	Phase of Research in which Tactic Occurs
Construct Validity	<ul style="list-style-type: none"> • Use multiple sources of evidence • Establish chain of evidence • Have key informants review draft case study report 	Data collection Data collection Composition
Internal Validity	<ul style="list-style-type: none"> • Do pattern-matching • Do explanation-building • Address rival explanations • Use logic models 	Data analysis Data analysis Data analysis Data analysis
External Validity	<ul style="list-style-type: none"> • Use theory in single-case studies • Use replication logic in multiple-case studies 	Research design Research design
Reliability	<ul style="list-style-type: none"> • Use case study protocol • Develop case study database 	Data collection Data collection

The principal investigator set up a case study protocol that was consistently used for each case study. As part of this protocol a series of questions were developed to guide the interview process. Notes and documentation were entered into a case study data base to establish a chain of evidence. The name of the interviewees, and date and time of each interview was recorded. Construct validity was further strengthened by allowing key informants to review a draft of case study results. Based on feedback from participants, the results were modified when necessary. The protocol steps are as follows.

1. Development of propositions
2. Selection of case studies, using propositions and process model as guidance
3. Creation of research questions using propositions, survey results, process model, and principal investigators experience of engineered design process as guidance.

4. Initial contact of case study participants via telephone call by the investigator to screen for experience with engineered designing, and to set up an interview time.
5. Telephone interviews with key personnel.
6. Conversion of interview notes into paragraph form.
7. Tabulation of data based on propositions and process model
8. Key informants review the draft of results
9. Key informants review the process model
10. Revision of results based on participants' feedback of draft.

3.4.2. Case Study Selection

For the case study research, the object of study was an instance of the engineered design process within an organization or business. A multiple case study approach was used in order to study a variety of scenarios and processes for engineered design. The principal investigator identified each case from personal experience within the textile field and with the literature review. Cases were selected based on the level at which they incorporated new technology into their engineered design process, and the level of innovation of the engineered design process or product. An attempt was made to choose instances of engineered design that were distinctly different. New technology was defined as CAD, electronic needle selection in knitting, integral knitting, digital printing, etc. An attempt was also made to compare low level integration and high level integration of technology and the effect this integration had on the engineered design process. For example, prior to this research, one case study had not previously used technology in

their engineered design process, and so a comparison was drawn between the engineered design process without technology and the engineered design process with the incorporation of technology. An instance of innovative engineered design was sought in order to benchmark successful use of engineered design. For the third criteria, cases were based on the ability to represent different processes of engineered design. For example, a knitted engineered process was chosen for one case study and a printed engineered design process was chosen for a comparison case study. The case study representative was contacted by e-mail or phone and, when possible, a person to person interview was set up. Correspondence took place predominately through phone conversation and e-mail was used to transmit written or graphic information.

3.4.2.1. Case Study One: Engineered Print Design

The first case study Case AP1, was the engineered design process for a ballet company's costume design department. This case study was chosen based on both proximity to the researcher and research facilities, and also because they had not previously worked with technologies associated with engineered designing. This ballet company had an extremely short production cycle, yet still produced all of their engineered designs by manual techniques. This case study was their first attempt at incorporating technology into their engineered design process.

3.4.2.2. Case Study Two: Engineered Knit and Print Design

The second case study, Case AKP2, involved the engineered design process for an innovative knitting and printing machine manufacturer. This company had successfully

developed the first integral knitting machine and also owned a garment knitting and product development mill. Recently, the company had developed a flat bed digital printer for engineering a print design within the shape of a sweater or other knit product.

3.4.2.3. Case Study Three: Engineered Knit Design

Case Study FK3 documented the engineered design process for a knitwear company that used body mapping to strategically place thermal properties within garments. The knitted garments incorporated silver plated threads of polyamide that are connected to a mini-power-controller. The development team for this company involved a physician, knit technician, and apparel technician.

3.4.2.4. Case Study Four: Engineered Woven Design

Case Study WK4 documented the engineered design process for a woven design expert that integrated electronics components the garments. The woven design experts worked with a cut and sew operation and an electronics manufacturer to produce the functional garment for the military.

3.4.3. Stage Three: Data Collection

Data was collected by interviewing, observing, and collecting visuals from key personal involved with commercial use of engineered designing. Hancock and Algozzine (Hancock & Algozzine, 2006 p. 16) describe case study research as a richly descriptive method since data collection involves multiple and varied sources of information. The

authors further state that “(Case study research) employs quotes of key participants, anecdotes, prose composed from interviews, and other literary techniques to create mental images that bring to life the complexity of the many variables inherent in the phenomenon being studied.” Information gathered will assist in validating the model and benchmarking successful use of engineered designing according to evaluative criteria.

4. RESULTS

The research, much like the engineered design practice, was an iterative and cumulative process. While each stage of the research built upon the previous stage, there was also considerable back and forth movement between the stages. For clarity of presentation, results are presented by the phase of the research; Stage One, Stage Two, and Stage Three. A final summation of all three of the research stages is given at the conclusion of Chapter 4.

4.1. Stage One Results

The first stage of the research, which consisted of gathering and processing data from the literature review, the principal investigator's experience, and from information gathered from software and hardware vendors at ITMA 2007 provided enough information to build a base model for an engineered design process that described the strategic placement of color within a product. Stage One data collection did not yield adequate information to address placement of functional fabrication properties, for example, increased comfort or reduction of stress points. There are several reasons the first stage of the research produced more information on aesthetic rather than functional engineered design. One primary reason was that the literature review focused on aesthetic engineered design. The term engineered design, when used within the design phase of apparel textile product development, is associated with the placement of stripes, plaids or other motifs to improve the aesthetic design of a garment. Definitions by both Brown (1995) and Braddock and O'Mahony describe this type of engineered design. Most importantly, the

majority of software for textile and apparel product development, as evidence by the ITMA review (see Figure 28) lends itself to aesthetic placement and does fully address functional placement properties e.g., reduction of stress points. In addition, the investigator's previous research efforts were slanted toward aesthetic engineered design and formed the researcher's knowledge base.

Figure 28. Summary of textile and apparel design software capabilities

Table 10 provides a full listing of the capabilities of 28 software programs for textile and apparel design. The majority of this software review was conducted at ITMA 2007; however additional software was added to the list in order to yield a more comprehensive review. The website fibre2fashion (www.fibre2fashion.com) was used to gather names and general descriptions of software capabilities. Each software was researched via the company's website and if necessary by e-mail correspondence. As evidenced by the summary of software capabilities shown in Figure 28, the majority of design software has capabilities for 2D renderings. Two dimensional renderings are very useful for aesthetic design placement. However, only a small percentage of software has the capability for more complex design processes, such as 3D rendering, and fabric drape, density and stretch simulation. These more complex processes are needed for functional engineered design.

Table 10. Summary of Textile and Apparel Software Review

	Company	Software	Woven	Knit	Print	PGM apparel	PGM Interiors	2D Simulation Fabric	2D Simulation Product	3D Visualization fabric	3D Visualization Product	Motif Placement	Motif scaling w/ Size	Yarn Simulation	Density	Drape	Stretch
1	ALEPH SL	Atrezzo 3D , Easy Step and Repeat			ps, pd			x			x		x				
2	ARAHNE CAD/CAM	ArahWeave	wd, wj					x			x		x	x			
3	ARSHAM KOOSHA	Jacquard Designer	wd, wj	kwa		x	x	x	x					x	x		
4	AVA CAD/CAM	Create and Repeat, Quick Separations, Technical Separations, Vectorize, Materialize, Digital Print	wd, wj		pd, ps				x		x						
5	BLUE FOX NEDGRAPHICS	Fashion Studio, Printing Studio, Easy Weave, Easy Knit, Evolution Print, Dobby Pro, Jacquard Pro, Vision Raschel	wd, wj	kwe, kwa	pd, ps	x	x	x	x			x		x	x		
6	Bontex Srl	StyleWay, StylePattern, Poly Pattern, ModArtis, Ajaris	wd, wj	kwe	pd, ps	x		x	x			x		x			
7	BOORIA CAD/CAM SYST.	Carpet Designer, Carpet Weaver, Carpet Print, Dobby Design	wd		pd, ps			x	x	x				x	x		
8	BROWZWEAR INT. LTD	V-Stitcher, V-Style, FTK, cMe				x				x	x	x				x	x
9	CAPITAL AUTOMATION	VEGA - Jacquard Weaving Design System	wj					x	x								
10	DUA GRAPHICS SYST.	Ramsette III, Portrait 2, MatchPrint II			pd, ps			x	x								
11	EAT	ProCAD, Design Scope	wd, wj	kwa				x	x	x		x			x		
12	ENEAS	3D Stitcher, SimulaStitch, YarnMaker, Colourways	wd, wj	kwe	pd, ps	x		x	x	x	x	x	x	x			
13	GERBER	Vision Fashion Studio, Accumark V-Stitcher, Accumark PDS, Accumark MTM	wd, wj	kwe	pd, ps	x	x	x		x	x	x	x	x	x	x	x
14	GRAFIX LTD	Design Plus, Design Plus Jacquard	wj					x						x			
15	INFORMATICA TEXTIL	Penelope Dobby, Penelope Jacquard, Penelope Terry, Atrezzo 3D	wd, wj					x	x					x			
16	JACQCAD Master	JacqCAD MASTER	wj					x					x				
17	JD&N SRL	Jacq-Design, Jacq Virtual Loom, Vectorize, Virtual Color	wj					x					x		x		
18	KOPPERMANN TEXTILES	Tex Design, Tex Store, Tex Define, Tex Web	wd	kwe	pd, ps			x	x			x					
19	LECTRA	Kaledo, Easy Grading, Modaris 3D Fit, Vector	wd	kwe	pd, ps	x	x	x	x	x	x	x	x				
20	MY VIRTUAL MODEL	MVM Dressing Room, MVM Showroom, Brand Me, AGE Clidesign: MotifStudio, Visual Search			ps, pd		x				x						
21	OPTITEX	PDS, Optitex Match, Marker Making, Optitex Nesting, Modulate, 3D Runway Designer, 3D Runway for Modulate				x	x	x			x						
22	PIXELART SL	Pixel Art, Pixel Jacquard, Pixel Form, Pixel Dobby, Pixel Weaver, Pixel Photo Jacquard	wd, wj		pd, ps		x	x						x			
23	POINTCARRE	Knit, Shape Software, Print, Weave Design, Jacquard Design, Dobby Design	wd, wj	kwe	pd, ps			x	x					x			
24	SCOTWEAVE	Yarn, Dobby, Jacquard, and Artwork Designer, Velvet Jacquard and Dobby, Drape, Print Presentation, Technical Weaver	wd, wj					x	x	x				x	x		
25	SHIMA SEIKI	SDS-ONE(P)		kwe		x		x	x			x	x	x			
26	STOLL	M1plus®		kwe		x		x	x			x	x	x			
27	TUKATECH INC	TUKAcad 2007, TUKAstudio, e-fit Simulator	wd, wj	kwe	pd, ps	x	x	x	x	x			x		x		
28	YOUNGWOOL CNL INC	TexPro, TexWork, Tex3D, TexWeave, and TexTricot, TexStylist	wd, wj		pd, ps									x			

4.1.1. Narrowing of the Object of Study

A result of Stage One data analysis was further refinement of the object of study. The engineered design process encompasses a broad definition that conjures up different meanings based on, for example, field of study. The Accreditation Board for Engineering and Technology (ABET) provides a widely used definition for engineered design (Ertas & Jones, 1993).

Engineered design is the process of devising a system, component, or process to meet desired needs. It is a decision making process (often iterative), in which the basic services, mathematics, and engineering sciences are applied to convert resources optimally to meet stated objective. Among the fundamental elements of the design process are the establishment of objectives and criteria, synthesis, analysis, construction, testing, and evaluation.

The object of study for this research was refined to fall within the umbrella of the ABET's term, but narrowed to be an engineered design process that specifically dealt with developing textile fabric properties for specific placement within a product's shape. After analyzing the literature review, and prior to building the initial model, the principal investigator determined that the term engineered textile design could encompass an enormous area of product development and any research into this would be too large to successfully collate. Therefore, although the design of fiber and yarn properties could be manipulated or engineered for a specific end product, this investigation only looked at fabric

design properties that are typically engineered *within the shape of the end product*. Engineering of fiber and yarn properties typically are located across the entire width of the fabric, rather than at a specified place on the product.

4.1.2. *Model building*

As a beginning point, a model was built that mapped the various points within the textile and apparel complex where an aesthetic fabrication design could be specifically engineered within a product. For clarity and simplicity of the model's design only engineering of coloration was considered at this point of model development. The principal investigator held the belief that the product development for engineered functional design could follow the same product development procedures for aesthetic design. That is, if a print or coloration design could be placed on a product then a functional aspect of design could also be strategically placed in the same manner. Figure 29 shows the initial model. Areas encircled with green depict a place in the process where with engineered design placement of coloration within a product can occur. An initial look at this model shows that engineered design for placement largely falls toward the end of the manufacturing process. For example, engineering of fibers or yarns typically occurs along the entire width and length of the fabric rather than being engineered for strategic placement within a product shape. This is not saying that yarns and fibers cannot be engineered for product placement.

Figure 29. Initial model developed to show areas where engineered design placement of coloration within a product can occur.

A project at the master's level by Meadwell explored engineering of fancy yarns to produce design effects (Meadwell, 2004). Meadwell demonstrated that coloration, diameter and texture of fancy yarns could be successfully engineered to produce design effects across the width of a fabric. Although this research did not attempt to alter design effects to follow the shape of a product, the methodology that Meadwell used would lend itself to engineering of yarns for strategic placement. Engineered placement via yarn printing is included in this model although the process is rare and difficult to implement. At ITMA 2007, Process Machines showed the Propoli yarn printing machine. Winner of the 7th Technology Awards 2007, the Propoli has a computer attached to the printing system that allows precise control of color placement on the yarn; up to six hues. During ITMA 2007 the principal investigator documented a process by which the Propoli machine was programmed to print a space dyed yarn that was used for hand knitted apparel products. The garments, knitted with the special space-colored yarns had distinct design motifs that were formed by strategic printing of the yarn (see Figure 30).

During the fabric formation process for both knitting and weaving, colored yarns can be strategically placed in order to produce design coloration effects within a product. For example, during knitting, stripes can be spaced to correspond with the size of a garment. That is, a children's knitted garment would have smaller closer stripes than an adults' apparel item. Similarly, woven fabric can have stripes or plaids that are engineered for placement within a product. An example of engineered product is a plaid, pleated skirt. In the engineered design the woven plaid (or stripe) can be sized and spaced

to correspond to the pleats on the skirt. During fully fashioned or integral knitting, an intarsia design could fit the shape of a garment and wrap around the body.

Figure 30a. Garment with engineered printed yarns.

Figure 30b. Detail of garment with engineered printed yarns.

Figure 30c. Propoli yarn printer.

Figure 30. Engineering of yarn coloration for knits using the Propoli printer

Engineered design placement of coloration within a product is also possible after the fabric is formed. Placement can occur on the uncut or cut fabric, and on the assembled product. Engineered coloration following fabric formation can be accomplished by such processes as printing, dyeing or embellishing. Examples of embellishment processes include, but are not limited to embroidery, embossing, and appliqué.

4.1.3. Theory building

A result of Stage One research was the development of propositions to test theory. At ITMA 2007 the principal investigator canvassed machine and software vendors that were involved with product development and manufacture of woven, knitted and printed design for apparel and interior products. The principal investigator observed demonstrations of software and machinery to determine applicability to engineered design. When possible, vendors were informally questioned as to capabilities of their equipment to engineer textile design properties within a product's shape. The principal investigator asked for descriptions of products that were engineered using the vendor's equipment and asked the vendor's opinion of which changes in technology had most facilitated engineered designing. As a result of this observation and informal discussion, a set of theories were developed. Theory One states that *Technological advancements in computer control for textile and apparel product development have aided the process of engineering fabric design properties within the shape of the end product.* Table 11 provides a summation of the results of theory building. The summation results include the theory, the relative propositions to the theory, and the testing method for each proposition. A primary result of Stage One research was the hypotheses that technological improvements such as ii) improvements in computer aided design software, ii) 2d and 3D simulation, iii) color calibration, iv) increased computer processing capability, and v) computer control of electronic machine components have all aided the engineered design process. It was further hypothesized that although technological advancements have aided engineered design, the process is still more difficult than a non-

engineered design. In addition, it was proposed that various levels of difficulty exist for engineered design, i.e. some processes are more or less difficult based on the end product requirements. This information is important for building the model of the engineered design process, as some types of engineered design may not require as many steps in the process.

4.2. Stage Two Results

Analysis of responses from survey participants aided in refining the preliminary model developed in Stage One, by i) refining of the definition of term, ii), testing theory about the object of study and iii) establishing common terminology, processes, and tools of the object of study. The survey response rate was 36%. Fifty three e-mails were sent to engineering design experts in the field textile and apparel product development. Of these 53 experts, 25 started the survey and 19 completed the survey.

4.2.1. Definition of Term

A preliminary definition of engineered design was developed by the principal investigators and included in the survey. An engineered design, as defined by the author, is a process or product where the fabric formation and/or design are produced simultaneously and/or purposely for the end product. The purpose of an engineered design is to i) improve the performance of the product and/or, ii) to improve the aesthetics of the design.

Table 11. Development of Propositions

Theory	Propositions	Testing Method
Distinguishable differences exist between the design phases of of an engineered design versus a non-engineered design.	Engineered design costs more to manufacture.	Survey response, case study
	Engineered design product development is more time consuming than non-engineered product development.	Survey response, observation, case study
	Engineered designing requires greater collaboration.	Survey response, case study
	Engineered design process is more centralized.	Survey response, case study
	More training and expertise is needed	Survey response, case study, observation
Various levels of difficulty of engineered designing exist.	Placement across seams, closures, and darts is more difficult than placement on a flat area.	Survey response, case study
	Designing a completely new product is more difficult than starting with an existing product and modifying.	Survey response, case study
	Certain placement processes are more difficult than others.	Survey response, case study
Technology advancements have aided the engineered design process.	Improvement in CAD software, over the last ten years has aided the engineered design process	Survey response, observation, case study
	3D Simulation aids the prototyping process for engineered design.	Survey response, case study
	2D Simulation aids the prototyping process for engineered design.	Survey response, observation, case study
	Improvements in color calibration have aided the engineered design process.	Survey response, observation, case study
	Improvements in computer processing technology had aided the engineered design process.	Survey response, observation, case study
	Improvements in machine technology have aided the engineered design process.	Survey response, observation, case study

Products engineered for aesthetic purposes can hide seams, accentuate shape or movement, divert attention from an area of the body, or continue a motif or pattern across a seam, dart or closure. Performance engineered design can reinforce areas of high wear, reduce waste, or improve comfort and fit.

For example, to improve performance, a sweater could be engineered to have a more elastic structure knitted into areas of high stress. In contrast, a print design with a large, central motif that is strategically placed on the garment to accentuate the body would be considered an engineered design for aesthetic purposes. Examples include, but are not limited to; design placement, logo placement, stripe/plaid engineering, intarsia design placement, print/knit/woven motif, structure, or pattern placement.

Participants were asked if they agreed in part, in whole, or if they totally disagreed with the definition of engineered design. One hundred percent of participants agreed in part or in whole with the stated definition. Of these participants, 73.3 % agreed in whole with the definition of term, while 26.7% agreed in part with the definition (see Figure 31). Research participants who agreed in part with the definition were given the opportunity to comment on, or add to the definition.

Figure 31. Proportion of identified experts who agree with the author's proposed definition.

Based on participant's comments, and on consultation between the principal investigators, the definition was modified. The key modification was in the term itself. *Engineered Design* was changed to *Engineered Fabric Design within the Product Shape*. The term engineered design proved to be too broad, and the definition put forth was excluding segments of the textile industry. For example, three survey participants used cut and sew processes for engineered design, and one participant engineered the fiber properties for cloth development.

4.2.2. Theory Testing

The survey instrument had a number of questions embedded in the questionnaire that sought to test theories established by the principal investigator. Expert's or leader's opinion can be used to predict acceptance or adoption of new technologies or processes.

4.2.2.1. Theory I Results

Analysis of data collected from the survey assisted in testing the theory that distinguishable differences exist between the design phases of product development processes for an engineered design versus a non-engineered design. Theory I is relevant to the core of this research because proof of this hypothesis assists in establishing a need for an engineered design process model. Additionally, data gathered from the these survey questions are vital for building the model, as expert responses provide information on the special product development processes needed for an engineered design. As seen in the Chapter 2, various process models for textile and apparel product development exist, however the scope of this research focuses on uncovering the special requirements needed for this engineered design phase within the product development process.

The investigator hypothesized that the process for engineering textile design properties within the shape of a product is more costly and time consuming than the process for a non-engineered design. In addition, it is hypothesized that this engineered process requires greater collaboration, and centralization of product development. Survey respondents were asked to rate the level of time, cost, collaboration, and centralization needed for this engineered process versus a non-engineered process. Throughout the survey, participants had the opportunity to provide comments on any further requirements needed for this engineered design process. For example, after each rated question, participants were provided space for comments. Further, the final question on the Process survey asked if respondents could explain any problems or special concerns associated with producing an engineered design.

Figure 32 shows results of the survey question asking respondents to rate the additional time needed to develop an engineered design versus a non-engineered design. Figure 32a shows the response categorized by method of fabric formation; knitted, printed, and woven. Figure 32b depicts results from all of the respondents. The majority of participants, 16 out of 19 (~84%) responded that an engineered design required additional time; at least one hour longer. More than half of the respondents (58%) stated that the process required upwards of four additional hours. Comments provided by the participants conveyed that various levels of engineered design existed and therefore time (and cost) varied depending on the complexity. See section 4.2.2.2 of Theory II Results for elaboration on the concept of various levels of engineered designing. As seen in Figure 32, based on responses from the experts, an engineered woven design requires more time on average than a knitted design.

Figure 32a. Additional time needed for an engineered design: fabric design type

Figure 32b. Additional time needed for an engineered design: all respondents

Figure 32. Additional time needed for an engineered design

Data was also collected on the additional cost needed to produce an engineered design. Participants were asked to estimate the additional cost as a percentage of the entire product cost. Participants were given six cost levels to choose from; i) no additional cost incurred, ii) cost increase of one to five percent, iii) cost increase of six to fifteen percent, iv) cost increase of 16 to 25 percent, v) cost increase of 26-40 percent, and v) cost increase greater than 40 percent. Thirteen out of the 19 survey participants answered this question; a lower response rate than the question concerning an increase in time. The lower response may be due to the fact that estimating cost is a difficult process as the

materials may affect the cost of the product more than the time and manufacturing process. One participant brought up an excellent point when stating “This is a difficult question to answer since it incorporates the entire design. Cost to produce includes the material, which may in fact be much greater than a non-engineered design. The time to knit would also increase, subject to the silhouette. Saying, 26-40% is a guesstimate.” Because an engineered design can be a highly specialized process the materials used for the product may be higher end. Another possibility for the difficulty in costing would be that not all product developers are involved with costing and there is a disconnect between the supply chain managers and designers.

Nine out of the thirteen respondents, or 69% stated that on average, the last five engineered designs they produced cost more than a non-engineered design. However, when comparing the results of cost (see Figure 33) with time (revisit Figure 32) it is interesting to note that a larger percentage of the experts polled felt that an engineered design took more time, but did not necessarily cost more.

Figure 33a. Additional cost needed to produce an engineered design; categorized by fabric design method.

Figure 33b. Additional cost needed to produce an engineered design; all respondents.

Figure 33. Additional cost needed to produce an engineered design

Experts in engineered design were also polled on whether or not they felt that creating an engineered design requires i) less or more team collaboration than a non-engineered design, and ii) that the product development process to be more centralized or less centralized than a non-engineered design. The majority of participants, 94% stated that the engineered design process required more collaboration. Likewise, most of

participants, 73% responded that the product development process was more centralized (see Figure 34).

Figure 34a. Participants who responded that an engineered design requires more collaboration than a non-engineered design.

Figure 34b. Participants who responded that an engineered design requires a more centralized process than a non-engineered design.

Figure 34. Participants who responded that an engineered design requires more collaboration and centralization than a non-engineered design

Respondents were also given the opportunity to provide feedback on special concerns for the engineered design process. One concern was that although the product development of engineered designing is more centralized, production may not be. Several respondents stated that a challenge for the engineered design process is the miscommunication with manufacturing; specifically that product specifications are not understood. One participant stated that “With the majority of production being done in

China it is not uncommon for concepts and details to be misunderstood”. Another stated that “Digital formats (are) reduced in quality once emailed to vendor. Concept for overseas vendors is not clear, if the imagery is full of extra lines, e.g. small details”.

Expert responses were collated in order to compare response rate of time, cost, collaboration, and centralization. Figure 35 clearly shows that a larger percentage of expert respondents (94%) were in agreement that an engineered design required greater collaboration than a non-engineered design.

Figure 35. Comparison of expert response rates of time, cost, collaboration, and centralization

Another distinct issue that product developers of engineered products face is the specification requirements needed for manufacturing. For instance, a print product developer states that “understanding how to align imagery across curved seam lines,

incorporating seam allowances can often confuse designers and sewing operators as the imagery must align exactly on the stitch-line and might not allow for much tolerance in straying from the line”.

Lastly, experts were asked if they felt that an engineered product has a superior appearance to a product that is non-engineered. Ninety four percent of respondents agreed that an engineered product has a superior appearance than a non-engineered product. Six percent were unsure if a noticeable difference existed between the appearances of an engineered design versus a non-engineered design.

4.2.2.2. *Theory II Results*

Analysis of the survey data attempted to prove or disprove Theory II; *Various levels of difficulty of engineered designing exist, and a hierarchal system can be established.* The survey instrument had two questions that allowed respondents to provide ratings on the difficulty level of certain engineered design processes. Both questions were based on a four point rating scale. The first rating scale, *No Difficulty* was valued at one; the second, *Minimal Difficulty* was valued at 2; the third, *Moderately Difficult* was valued at 3, and the fourth, *Highly Difficult* was valued at 4.

The first of these two questions asked: *For the Following types of engineered designs, please rank the level of difficulty.* Five engineered placement techniques were provided; i) placement only, not on a seam or closure, ii) placement across a straight seam, iii) placement across a curved seam, iv) placement across a dart, and v) placement across a closure. Four of the five choices; placement across a straight seam, placement

across a curved seam, placement across a dart, and placement across a closure were ranked between a two and three point ranking, or between minimal and moderate difficulty. Placement across a dart and closure both were ranked as slightly more difficult than placement across a curved seam. Experts also were able to check *Other*, and could then describe additional process challenges for engineering textile design properties within the shape of product. Only one respondent wrote in another choice. This other process was described as starting with an archived seamless product and then changing the structure or coloration through engineering. The respondent noted this process as requiring minimal difficulty. See Figure 36 for summation of results.

Figure 36. Rating Average for Level of Difficult with Engineered Placement

The next question sought to establish a ranking of the complexity, or difficulty level between several different design coloration processes, some specific to each fabric formation. For example, placement of a photo-realistic image was only asked of print

designers. The results are tabulated in Figure 37. The last column contains a rating average based on number of respondents per question. The rating average for all processes, with the exception of an engineered stripe design, fell between a two and three, or minimal and moderate difficulty.

Figure 37. Rating Average for Level of Difficulty for Engineering a Textile Design

Open ended responses from participants were also analyzed to determine if various levels of complexity of engineered design processes existed and if these processes could be categorized into a hierarchal system. For example, one participant when commenting on the additional number of hours needed for the engineered design process stated that “The level of challenge can vary widely depending on the complexity of the product and the amount of engineering desired. I think there are a variety of levels

that you can engineer for, and my instinct is that for many products a modest level of print engineering can provide additional benefit to the end consumer.” Another participant, again commenting on the number of additional hours needed for an engineered design stated that “This is highly depending on the individual and the design brief... too hard to estimate. For wearable art pieces, I almost always work for more than 12 hours on the engineered design.” Survey results supported part of the hypothesis that various levels of engineered designing exist. However, results were not as conclusive as to whether or not a hierarchal system could be established. Overall, respondents did not rate engineered designing as “highly difficult”.

4.2.2.3. *Theory III Results*

The theory, *New and Emerging Technologies Aid the Engineered Design Process* was tested with a number of propositions that dealt with integration of software and hardware tools into the engineered design process. Survey participants were given a series of both open ended and rated questions that asked for expert opinion on how new and emerging technologies have aided the engineered design process. The first question stated “*In your opinion, over the past ten years, have any technologies, market influences, or design processes contributed to a change in engineered designing processes? Please explain.*” Response to this open ended question varied. However, repetition of key terms was noted. For instance, forty three percent of participants stated in some form, that improvements in computer aided design software have facilitated the engineered design process.

For example, one participant stated that “CAD systems have made this process more feasible, and there are many more examples of engineered design being manufactured.....latest prominent examples are the Chinese Olympic designs done by Li Ning.”. Another participant further enforced the importance of CAD improvement by saying “I feel like the ability to automate the technical weaving processes (box motion, assignment of weaves, loom configuration) with textile specific CAD software has enabled designers to spend more time on aesthetic functionality and design.”

Other technologies that participants deemed important were improvements in machinery. For example, survey participants commented that “Advancements in technology (computer aided knitting) have enabled designers to push the boundaries of traditional knitwear. Shima’s WholeGarment® garment, seamless technology to be specific.” Another participant stated that many new technologies (and fibers) enabled engineered design such as “Digital printing, body scanning, seamless and semi-seamless knitting, and introduction of numerous new fibers with specific attributes.”

Another question also attempted to establish if technology advancements over the past ten years have aided the engineered design process. Question #14, under the Process sections (Knitted, Printed and Woven) of the survey requested that participants rate the impact that certain technology advancements have on the engineered design process. The rating was based on a three point scale with three representing a greatly improved process or technology advancement (over the past ten years), and one representing a process or technology advancement that has had no impact on the engineered design process. See Figure 38 for results.

Figure 38. Rating of Advancements that Facilitate Engineered Design

Overall, the participants in the area of knit design rated *increased computing ability* as the technology improvement that has most aided engineered design. *Improved design software* was listed by half the participants, and ranked second. *Digital stitch control* and *file storage* were ranked of equal importance.

The engineered printing experts that were surveyed agreed that improvements in design software design, digital printers, increased computing ability, and file storage all either greatly improved or moderately improved the engineered design process.

The next set of questions attempted to determine if 3-D visualization software was incorporated into the engineered design process of our experts. Incorporation of 3-D software was used by the principal investigators as a benchmark for high technology integration. The first question from this set asked participants if they felt that virtual prototyping would aid their process. See Table 12.

Table 12. Participants' Agreement that Virtual Prototyping Would Aid Engineered Design			
In your opinion, would the ability to create a virtual prototype with correct design placement of woven (knitted) structure(s), or (print) logos, repeat patterns, or other graphics mapped onto a fit model or a to-scale 3D simulation of a product (ex. a table with a tablecloth draped on it) help to facilitate the sampling or manufacturing process?			
Method	Yes	No	Comments
Knit	4	0	"that would be interesting, not sure if it would please the customer, they like something that they can touch, hold, take to buyers-- to show impressive intarsia or jacquard designs"
Print	6	1	"We already have this capability however cultural differences often force us to go for physical prototypes."
Woven	4	0	"This process is available within many leading FABRIC CAD systems -- and has been for many years (ScotWeave is only one example)."

Nearly all of the experts consented that virtual 3D prototyping would aid the engineered design process. One participant stated that this technology was common and had been available for a long period of time. Therefore the response to the next question was surprising. Question # 4 under the survey heading Prototype/Simulation sought to establish if the experts were actually integrating 3D visualization tools into their engineered design process. The results are listed in Figure 39.

Figure 39. Percentage of participants who use virtual, non-virtual, or both virtual and non-virtual prototyping.

Further analysis from the data collected from question # 4, attempted to determine if a difference in answers could be detected based on the experts' method of engineered design. Figure 40 depicts a mosaic plot of the virtual (V), non- virtual (V) and a mix of both virtual and non-virtual (M) prototyping, categorized by woven, knitted or printed.

Analyses of the results show that knit designers were the only group that used no virtual modeling, instead relying solely on physical prototypes

Figure 40. Mosaic plot of the use of virtual (V), non- virtual (V), or a mix of both virtual and non-virtual (M) prototyping processes, categorized by woven, knitted or printed design

A follow up question sought to establish why experts in engineered designing had not integrated 3D simulation into their prototyping process. Question #5 in the Prototype/Simulation section asked “Why don't you use 3D visualization software to simulate your design?” The results are summarized in Figure 41.

Figure 41. Reason Cited for Not Using 3D Visualization Software

The majority of participants, 47%, listed lack of access to 3d visualization software as a reason for not incorporating this technology into the engineered product development process. The next most common reason was that “3D visualization doesn’t work well”.

Participants were polled to assess, on average, how many prototypes were typically needed for each engineered design. Ninety three percent of respondents stated that they need at least one prototype before they were satisfied with their design, 73% of respondents needed two or more prototypes and 33% of respondents needed three or more prototypes. Clearly, the ability to accurately and easily virtually simulate a prototype would aid the engineered design process.

4.2.3. *Model Refinement*

Data collected from survey participants assisted in refining the process model by establishing common processes and tools. Specifically, data collected from the experts established: i) purpose of engineered design, ii) use of archives, iii) communication procedures, iv) placement techniques, v) automation of processes, and vi) color calibration.

When asked the primary purpose for engineering a design, 79% of participants stated that they hoped to achieve improvement of both the aesthetic or functional aspects of the end product. One tenth (10.5%) of the experts used engineered designing only for aesthetic improvement and one tenth (10.5%) for improvement of functional properties.

Experts were also asked the primary considerations for an engineered product. Tabulation of the results can be seen in Figure 42. A rating average was assigned to each of the purposes for engineering a design. Participants could rate each purpose on a four point scale with *Extremely Important* designated as the highest priority of purpose and rated as four; *Important* rated as three; *Minor Consideration* rated as two; and *Not Important* rated as 1. The first column, labeled *Type*, designates whether the purpose of using an engineering process was primarily for improvement of aesthetic (A) design or functional (F) design of the product. The three top rating averages: create a seamless design; accentuate shape; and accentuate movement, were all for aesthetic considerations. Reduction of waste and improvement of fit, both functional properties had the next highest rating average.

Figure 42. Primary Purpose for Creating an Engineered Design

Based on participants' responses to questions concerning use of archives, communication procedures, placement techniques, automation of processes, and color calibration the process model was refined. The refined model shown in Figure 43, depicts four main product development phases for textile design engineering within the product shape; i) idea generation, ii) idea communication, iii) idea implementation, and iv) idea assessment. At the center of the model is the engineered product, as the requirements of the end product drive the product development process. The process begins with idea generation. An important part of the generation process is to review existing products and samples. Ninety five percent of survey participants had access to either analog, digital, or both analog and digital libraries of samples. Twenty one percent of respondents used

digital samples only, 32% of experts surveyed used analog samples only, 42% of respondents used both analog and digital samples and 5% of respondents had neither physical nor digital samples. It is interesting to note that although the majority of respondents (95%) used digital and physical archives, most respondents, 79%, did not use any type of sample or product archiving software.

Once the idea is formed, the objective of the next product development phase is to create a physical or digital description of the product. Criteria from the idea generation phase are fed into the graphic or written specification of the design communication. This description becomes a vital method of communication for the implementation part of the development process and in some instances act as the blueprint for the implementation of the product. The final phase involves assessment of the engineered product. Each of the phases acts as a gatekeeper for the next phase, with the assessment phase being the last gate. An engineered design process is highly iterative. See Figure 43.

Figure 43. Process model for an engineered design.

4.3. Stage Three Results

The following case studies profile the engineered design process of a group of experts within the textile complex. Case study research provides an opportunity to observe the object of study in a “real life context” with no manipulation of processes or variables (Dull and Huk p.4). Cases were chosen based on the incorporation of innovative engineered design into their product development process. Case study methodology allowed examination of an event in the engineering process. This case examination by the principal investigator provided insight into the engineered design process, and the relations of its elements to the entire process. Data collected from the case study was used to refine and validate the process model (see Figure 44). Results from the case study research are organized to correspond with the process model.

Figure 44. High level process model for design of an engineered textile product

4.3.1. Case Study One (AP1) Input to Model

A ballet company was chosen for a case study for engineered print design. Typically, the ballet will use hand painting or screening techniques to engineer a print design onto a dancer's leotard. The ballet puts on about 12 productions per year, and introduces one or two new routines into their repertoire each year. Of these twelve, only two productions require that all of the costumes be created from scratch, the other ten productions require only adapting, refitting or adding to existing costumes. Depending on the complexity of the ballet anywhere from 30 to 50 new leotard designs are needed for each production. Further, because performances are scheduled in several consecutive nights, duplicates of each outfit are needed.

The engineered design team comprised the ballet's choreographer, the ballet's costume designer, and a team from a Textile College that involved fabric testing technicians, an engineered design expert, and a technical designer. The costume designer has a MFA in theatre design and prior to working at the ballet had designed wigs. The sculptural nature of wig design prepared her for the 3D design of costumes. The costume designer also was a dancer so was familiar with movement and choreography. The costume designer worked for five years with the ballet company, and her work provided a full immersion and very time intensive experience. This immersion in the dance world led the costume designer to be able to visualize the costumes and dancers prior to creation of the costumes. See Table 13 for a summary of the input to model of case study AP1.

Table 13. Summary of Case Study AP1 Results

Phase	Case Study AP1 Results: Input to Model
Generation	<ul style="list-style-type: none"> Idea generation is a collaborative process, but the director of the ballet, and the theme of the ballet, led the design. Existing costumes, images related to the “story” of the ballet are reviewed. Costumes have set criteria prior to generation. For example, fabric needs to have high stretch, and fastness properties.
Communication	<ul style="list-style-type: none"> Based on ideas generated from Phase I, a highly descriptive illustration is created. Communication is vital between, costume designer, director, choreographer, lighting technicians, and dancers. Approval of drawing of engineered design allows acts a stage gate to implementation Physical samples, prototypes, and drawings are primary means of communication between parties. Introduction of CAD and digital simulation facilitated the communication process.
Implementation	<ul style="list-style-type: none"> Production equipment and personnel may change due to ability to meet set criteria of the engineered design. Introduction of digital printing facilitated the implementation process. Introduction of digital silhouette design facilitated the generation process.
Assessment	<ul style="list-style-type: none"> Assessment is extremely critical. If dancers, director, choreographer, or lighting technician disapprove of the design, the product is reworked. Assessment occurred throughout the process
Iterations:	<ul style="list-style-type: none"> Unlike new product development, where a product can be rejected if not successful, an engineered costume design <i>has</i> to work. Iterations are performed until the design works – often many, many times.

4.3.1.1.1. *Generation*

When a ballet is created the directors' vision drives the style of the performance, however, the choreographer, costume designer and artistic director all have input into the dancers' attire. The artistic director envisioned Time Gallery as a more modern performance and for this reason the print design needed to be abstract. A technical designer from the College of Textiles worked closely with the costume designer to interpret her vision into an engineered design.

It was determined by the ballet that all leotards would be constructed by fully cut and sew methods. The leotard silhouette and fabric were chosen based on the ballets' past experience with both. The fabric has to have excellent elastic recovery and wash fastness properties; a dancer's uniform can last up to ten years and endure 50 or more wash cycles. The costume designer stressed the importance of not having the fabric sag or fade as the fabric needed to be bright and vibrant for each performance and also needed to fit extremely close to the dancer's body.

The leotard material was a blend of 78% nylon and 22% spandex. Analysis of the fabric by the textiles college determined that the fabric was warp knitted using a micro denier core wrapped yarn. Nylon fibers have high elongation, high elastic recovery, and high abrasion resistance. Nylon fibers also dry quickly and are light weight. All of these properties are desirable for dance garments. Dancer's leotards fit very closely to the body and must not restrict movement. Performances times are scheduled closely together, for instance a matinee and evening performance. Leotards are washed after each performance and left to air dry, therefore fabric must dry quickly. The addition of spandex further

added to the fabric's elasticity allowing the leotard to fit closely to the body. In addition, female dancers' leotards had attached skirts made from 100% silk charmeuse (19 momie).

4.3.1.1.2. *Communication*

The costumed designer had initial sketches of the costume and print pattern. Both drawings were watercolor renderings. These renderings were used to convey the visual concepts of the costume to the choreographer and technical designers. Colors for the print design were determined by these sketches. The costume designer drew inspiration for the print design from looking at the inside of watches and clocks, and noting the relationship between the mechanical pieces. Backdrops (also digitally printed) were photorealistic images enlarged to a grand scale, and so the costume designer and choreographer agreed that the print design of the costumes needed to be a softer more abstract look. The abstract imagery also supported the genre of Time Gallery, a modern ballet that incorporates modern music. The costume designer describes her typical process for engineering a design.

I start with drawings that are very specific and detailed. Usually I render a dancer in a costume. I'll research inspiration from images, and then create a rendering with a dancer wearing the costume design. For instance when I created the duck costume for Peter and the Wolf I looked at many images of ducks as inspiration before creating the illustration of the dancer in the duck costume. This initial drawing acts as my guide when I

create the engineered costume design. The rendering also allows me to share my ideas with the choreographer. The drawing is almost always a frontal and a 3/4 view. Because theater costumes are more static than dance costumes, they tend to change less from the original drawing. Dance costumes go through more iterations because each dancer's body is different and how they move is different. As a costume designer I have to take into account how the costume looks on the dancer as they move, and how they move in relation to other dancers and to the set design. Creating a dance costume is a much more collaborative process than creating a theater costume.

Concurrent to fabric and color testing, steps were taken to digitize the watercolor of the print design, the cut patterns for the male and female leotards, and the cut pattern for the female dancer's skirt. The digitized print pattern was placed in repeat and the technical designer textured mapped the digitized print onto a photograph of the dancer to help determine the scale of the print.

Based on the texture map several changes were made to the print design. A determination was made to add a few more defined motifs that were more representative of the gears of a clock. The scale of the print was enlarged so that it could be more easily seen by audience members sitting at a farther distance from the stage. The choreographer and costume designer also wanted to see the print pattern more randomly placed, rather than the set repeat of the texture mapped pattern. The digitized print pattern was

separated into multiple layers in Adobe Photoshop. Primary motifs were placed on transparent layers that “floated” on the background color. Next the costume designer sat at the computer with the technical designer to oversee placement of the new motifs, and once the scale, definition and overall placement of the motifs were finalized the technical designer began engineering the print design within the garment marker (see Figure 45).

Figure 45. Process for placement of motifs within a garment shape

While the texture mapping aided certain aspects of the engineered designing process, the technical designer stated that a 360 degree view would have been preferable in order to better visualize how the motifs looked on the side and back of the garments. The costume designer concurred with this, but stated the texture maps were still very useful and seeing the texture maps gave her confidence in the technical designer’s ability

to understand and translate the designer's ideas into a product. The texture maps were "good representations of the final product, they were clean and made the process easy to follow." Particularly useful would have been software tools that enabled three dimensional visualization of a dancer wearing a leotard with the correct scale and placement of the design motifs. Three-dimensional visualization would have aided communication between the technical designer and costume designer and also helped the technical designer in motif placement.

Dance production is very much a collaborative effort. Dancers, lighting technicians can all contribute input to the overall look of the production. The costume designer felt it would have been very helpful if all people involved with the engineered design process could have been present at the initial fitting of the prototype. This would have allowed the technical designers to hear and see what the dancer's, costume designer, and choreographer had to say about the engineered design. This meeting would have aided communication. Meetings such as these are vital forms of communication for creative parties involved with the production. Much of the communication is visual, with all parties seeing the prototype in context. For instance, the dancer might point to the length of her skirt and say "shorten the skirt to here" or the choreographer might say "move this motif up farther on the shoulder", etc. During this meeting the lighting technician can also test out the color and contrast of the engineered design to ensure that these aesthetics are not lost or altered under different lighting effects.

4.3.1.1.3. *Implementation*

The apparel technical designer digitized a paper pattern of the leotards and skirt that had been obtained from the costume designer. In addition, sketches of the desired textile print were scanned into the computer and pulled into Adobe Photoshop. Each design motif or set of motifs were traced and placed on separated layers for ease in engineering the print design in later steps. Communication between the costume designer and the technical designer proved to be difficult at times. The costume designer was most comfortable when creating her designs directly onto the leotard and had difficulty expressing her ideas to the technical designer. For this reason, texture mapping was used for virtual scaling and placement of design elements and motifs. Using the texture maps a template the technical designer strategically placed the motifs within the shape of the leotards' silhouette. The technical designer was careful to avoid placing motifs across complex curved seams. When a design placement across a complex curved seam could not be avoided, the motif was simplified. The most difficult placement proved to be the placement of a circle motif across a side seam and into the skirt seam.

This was the ballet's first experience using digital printing for their costume designs, but they had previously printed backdrops by this method. The leotard and skirt were made from very different substrates and so initially it was thought that nano-pigments would be the easiest colorant to use for color matching. Acid and reactive dyes have a distinct color shift that occurs during the fixation process, and fabric needs to be pre-treated prior to printing. This color shifts can complicate color matching. Nano-pigments do not react with the fiber and therefore no color shifting takes place during the fixation

process. The color can be proofed as the fabric is printing, without the need to wait until after fixation; a time savings of up to two hours. In addition, knit fabrics have a tendency to distort and so elimination of a pretreatment process would greatly aid the handling of the knits. Unfortunately, after fastness testing it was determined that the nano pigments were not a suitable colorant for the nylon/spandex blend. Optimum heat fixation for nano-pigments is between 1-3 minutes at 180° C. Both nylon and spandex are only heat resistant to 150 C, and nylon softens at 171 C while spandex softens at 175 C. (Hatch 1993b) Loss of elasticity and fiber degradation occur at any temperatures above a fibers heat resistant temperature. Attempts were made to heat set the nano-pigments at lower temperatures for greater periods of time, but fastness tests proved disappointing.

After ruling out the possibility of using nano-pigments, it was determined that acid dyes would be used for direct digital printing of fabric. Color testing proved challenging; several color swatches were printed, heat set with a steamer and washed before the desired color could be reached. Additionally the nylon and silk fabric had the same print design and so colors needed to match between these two substrates. A further challenge was that the nylon fabric was a knit and the silk was woven, so the color matching process had to take into account color diffusion when the nylon fabric stretched.

Fabric shrinkage was calculated prior to printing. The fabric did not shrink in the width (selvedge to selvedge) direction, but had 3% shrinkage through the length of the fabric. The principal dancer's engineered print designs were scaled up accordingly and placed in the print queue. Ten non-engineered print designs were printed for leotards for

the core dancers prior to printing the engineered design panels. The technical designer and costume designer noted that a few of the panels were shorter in length than expected, but assumed that an incorrect file may have been printed. It was then determined after printing the engineered design panels that the fabric was increasingly shrinking closer into the core of the fabric roll. The end of the roll had shrinkage of 15%, compared to 3% shrinkage at the beginning of the roll.

4.3.1.1.4. *Iteration*

After a drawing is rendered a prototype is made in order to test fit. This prototype also contains markings that indicate the color and motif placement. Another, more final, prototype is also needed so that the costume designer and choreographer can see the dancer in movement. Dancers will also provide input as to where the costume elements should fall on the body. A good dancer is very astute as to what elements of a costume will compliment their movement. The prototype has to be very well executed and in a nearly complete state so that the choreographer can visualize what the final product will look like. After this prototype is made small changes, not major ones, are made to the costume, but the costume designer has already seen the movement.

4.3.1.1.5. *Assessment*

There were multiple criteria from a variety of sources that needed to be met for the engineered costume design. It was a necessity that the costume fit very closely to the body. Leotards and tights are a fairly simple silhouette, but they must fit exactly to the dancers' body. When the leotard was engineered, the images that were placed within the

garment shape had to be accurately sized to within 1/8 of an inch. For this reason shrinkage had to be precisely calculated. One of the biggest problems with the engineered print design process came from unpredictable shrinkage from the knit fabric. Another challenge for the technical designer was engineering the rounded motifs across curved seams of the leotards. Round motifs had to line up exactly or they became ovals or ogees. Some motifs were simplified or strategically placed to avoid complex curved seams.

The engineered leotard design had to be evaluated for aesthetic appeal on the dancer's body, and also for aesthetic appeal within context of the scenery and with the other dancers. Engineered design for costumes is very much a collaborative process. New work is dependent on several people and their vision of what the engineered costume design should look like. Visual communication was difficult because the dancers were in Wilmington, NC and designers and technical designers were in Raleigh NC, about a 3 hour drive. The costume designer, choreographer, director, and lighting technician all assessed i) movement of each dancer in the engineered garment ii) the aesthetic appeal of the dancers against the backdrops, and iii) how the dancers looked collectively in the engineered designs.

4.3.1.1.6. *Special Concerns*

A challenge in general when working as a costume designer is the short amount of time given to produce the costumes, with a very limited team of people to do so. For Time Gallery, the costume designer went from concept to finished costumes in less than four weeks. In addition, creative concepts for the costume were not fully developed at the

start of the four week period and continued to evolve and change during the four week time. Costume design is very fast moving and time intensive. The dance choreography continues to change almost up to the point of the opening performance. When the choreography changes, costume design is affected. New dancers may be added necessitating a need for additional costumes or for changes in the existing costumes. Because the choreography happens late in the process, preparation for engineered designing is difficult. Ballets typically purchase supplies on a show to show basis, and patterns are created to the specification of each dancer. These factors result in supplies being ordered (or reordered when more supplies are found to be needed) and received on a very short time frame and prohibits any mock-ups of garments.

4.3.2. Case Study Two (AKP2) Results: Input to Model

Case Study AKP2 collected data on the engineered design process of a knitted garment manufacturer and product development firm. Company AKP2 is unique in that they manufacture knitting machines and software, own a knitting mill, and they recently built and marketed a printer for sweaters. This company produces a variety of engineered design knits using intarsia, striping, jacquard, and structure placement, splicing, placement of elastomeric yarns, and printing. In addition to producing couture examples of sweaters (printed and non-printed) for ideas, and display for their customers (to promote their machine and software capabilities) Case AKP2 also contracts out knitting and printing services to assist companies with their product development and prototyping processes. Case AKP2 started out a glove manufacturing machine maker and evolved this

business into a state of the art V-bed machine producer. At the 1995 ITMA machine show, Case AKP2 premiered a WholeGarment® knitting machine; a V-bed machine capable of integrally knitting a complete garment with no sewing upon leaving the knitting machine – the ultimate technology for facilitating engineered textile design placement.

Since 1995 Case AKP2 has unveiled many more technological advances in the area of garment knitting machines. Notable technological advancements that enable engineered designing are Case AKP2's flat bed ink jet printer for sweater printing; Case AKP2's software program capable of virtually simulating a knitted garment stitch per stitch, and of being able to virtually dress a model in a knitted garment; and intarsia carriers that allow up to 32 carriers. See Table 14 for a summary of the input to model of case study AKP2.

Table 14. Summary of Case Study AKP2 Results	
Phase	Case Study AKP2 Results: Input to Model
Generation	<ul style="list-style-type: none"> • Ideas for the product come from outside of the company. The company is responsible for interpreting ideas. • The company extends considerable effort in producing and maintaining a physical and digital archive of engineered designs. • The archive of fabric and product samples contains information on style, material properties, and technical data for production. • Archive supports both functional and aesthetic engineered design.
Communication	<ul style="list-style-type: none"> • Although the company has sophisticated digital simulation software, most customers provide hand sketches.
Implementation	<ul style="list-style-type: none"> • The prototype methods are the same as the production methods, therefore once the prototype is approved, no further adjustments are necessary. • Archive of existing products greatly facilitates implementation.
Assessment	<ul style="list-style-type: none"> • Some assessment can occur digitally, as the company has software capable of virtually knitting.
Iterations:	<ul style="list-style-type: none"> • Iteration can occur digitally but the vast majority of customers want physical samples.

4.3.2.1. *Generation*

This knitwear company does not typically generate their own designs for production, rather they assist companies in developing their ideas into knitted products. For example, a company will bring an idea for a knitted garment to Case AKP2 and either ask for a prototype, or a production run. However, the knitwear company extends considerable effort into research and development of a physical and digital archive of engineered knit

designs. This archive is available to view in the company's showrooms. In addition, an extensive amount of the collection is available online, and the company will send physical samples when requested.

4.3.2.2. Communication

Although Case AKP2 created software capable of 3D simulation, their designer's do not use this technology. The company's VP offered the following explanation.

We've not been as successful as we'd hoped promoting our 3D system.

The technicians are reluctant to use it as they feel it may put them out of business, and most designers don't want to sit at a computer. Technicians also felt that (by using 3D software) you are taking away the hands on experience. There has always been a break between designer and technicians. Our 3D program would help, but companies don't see how it would help them. The thing is, most companies ask for sample garments prior to production. They usually need at least three prototypes. Our software could cut down on the number of prototypes needed.

4.3.2.3. Implementation

Case AKP2 has a staff of knit technicians and also makes use of a consultant who has both technical and design skills. The consultant is very technically adept and has greater than 20 years experience in knitwear design. The consultant's practical experience from garment knitting enables him to rapidly produce items. A knitwear technician from Case AKP2 was interviewed about the sweater printing process. The technician had not heard

of the term engineered design but rather used seamless design to describe a garment that had a print pattern or motif strategically placed on the garment. The technician explained the process as follows.

We have a flat bed ink jet printer with a 100" or 160" table. The sweater is printed as an assembled garment; the sweater, or garment is either knitted as a WholeGarment® or the sweater or garment is knitted as fully fashioned panels and then linked together. A cardboard template of the sweater (with a ¼" allowance all around) is cut out and placed inside of the sweater. The cardboard template stretches the sweater by ¼" all the way around. First one side of the sweater is printed then the cardboard is taken out repositioned and the other side is printed. The design is mirrored across seams for a seamless flow.

For setting up the ink jet print within the garment's shape, the designers use Case AKP2's proprietary software, or more typically Adobe Photoshop or Coral Draw. The process of engineering a print design within the sweater shape and then printing a panoramic print design across the sweater results in unique and beautiful design creations. However, Case AKP2 admits that this process is time intensive. First, the sweater has to be pre-treated with a solution of urea, a bi-carbonate, and thickener. Sweaters are generally printed with reactive dyes. Great care is taken not to distort the garment during the pre-treatment process. The garment is carefully positioned on the flat bed printing table which has a camera that feeds back to the print software for ease of positioning the print with the

garment. The garment is printed on one side, taken to a side table to dry and then flipped over and the other side of the sweater is printed. A representative from Case AKP2 describes the market for their engineered printed garments.

Currently the largest market is in Italy. Our printed sweaters are high end, small quantity – one sweater to no more than 500 hundred sweaters, and/or couture lines. The engineered printed garments consist of materials such as leather, cashmere and silk. The process is expensive and slow, but the uniqueness of the garment justifies the cost. One of our customer's also uses this process, but for sampling only. Our customer at times has difficulty translating their printed prototype garments into production garments. This method of printing is slow by production standards, but it speeds up sampling considerably. Previously, when this customer wished to have a prototype made, their manufacturer was requiring a ten meter minimum. In addition, 50% of samples produced had to be returned for a *third* time. By owning a printer, our customer was able to keep design in house, and produce any minimum meters needed. After trial and error, they decided to limit the number of colors of each ink jet printed garment to ten colors in order to facilitate color matching of sample colors to production colors. This customer's engineered designs are for couture line only and cannot be mass produced.

Case AKP2 knit designer felt that the designing was not difficult, but that the process for printing was extremely difficult, especially pre and post treatment and the shift in color.

4.3.2.4. Iterations

While virtual simulation is possible, and could possibly decrease the number of iterations, the majority of the company's customer's demand physical prototypes. The company's design center manager explained that the idea of a virtual prototype is difficult to sell as people are used to a physical prototype and resistant to change. The manager believes that a physical prototype will always be necessary; however, some of the iterations could be digitally produced. The manager stated that because digital simulations could speed up and improve the process, more innovative designs would make it to market. The manager further stated that the industry is slow to change "knit designs improve gradually each year as designers make small changes to past designs. So, real change in designs is not seen for several years. This is because drastic changes require more prototypes and a longer development period." The manager reinforced that virtual prototyping could decrease the cost of prototyping and increase innovation. Hamel (2007) echoed the tug between the demand to produce a product cost effectively and the demand for innovative products.

Despite all the pro-innovation rhetoric that one encounters in annual reports and CEO speeches, most still hold the view that innovation is a rather dangerous diversion from the real work of wringing the last ounce

of efficiency out of core business processes. Innovation is fine so long as it does not disrupt a company's finely-honed operating model... As change becomes ever less predictable, companies will pay an ever-escalating price for their lopsided love of incrementalism." (Hamel, 2007)

4.3.3. Case Study Three (FK3): Input to Model

Case study FK3 researches the engineered product development and design process of a knitwear company that produces a functional knit. Established in 1896, this family owned company produced knitted fashion items for domestic sales within Germany and they also export goods to European companies. All of the knitwear is manufactured in house on V-bed knitting machines. The company has 24 employees and also employs external designers.

In 2001, when import taxes were dropped, knitwear companies within this region faced unprecedented competition from imported knitwear from China; many knitwear companies in this German state closed. Case study FK3 began looking at innovative product design that would differentiate their company from the flood of imported sweaters. The product developers were already using engineered designing processes for sweater design, such as intarsia, and structure placement. Using similar design techniques FK3 began development of functional knitwear products capable of conducting heat. This patented product line consists of underwear such as sleeveless tanks, long and short sleeve undershirts, tights, and full body suits. All underwear fits closely to the body and has silver wrapped polyamide yarns that are knitted into areas of the garment. The

silvered yarns are supplied with electricity by a rechargeable battery that is smaller than a cell phone. When the electricity is turned on, the areas of the garment with silvered threads conduct heat. The areas of the garment that contain the silver conductive threads are strategically placed on the product to best warm the entire body of the wearer. This body mapping is a collaborative process involving a knit designer and physician. See Table 15 for the input to model of Case Study FK3.

Table 15. Summary of Case Study FK3 Results

Phase	Case Study FK3 Results: Input to Model
Generation	<ul style="list-style-type: none"> • Ideas for new product development came from adding a new function to existing product line. • The new function had never been attempted. • The idea for the new product was inspired by a new type of yarn with conductive properties.
Communication	<ul style="list-style-type: none"> • The company hired a design consultant who had extensive experience in computer aided design, knit wear and had personal experience as an outdoorsman. • Design consultant produced highly detailed, virtual renderings of the product. • Renderings and digital specifications were detailed enough that group members could communicate mainly through e-mail. • Renderings became part of market material for the product, and were used to explain the product to the consumer.
Implementation	<ul style="list-style-type: none"> • The team manager stated that production of the garment was fairly simple, as they produced engineered design for coloration for a number of years and were able to use the same processes.
Assessment	<ul style="list-style-type: none"> • Extensive amount of wear-testing occurred.
Iterations:	<ul style="list-style-type: none"> • Iteration can occur digitally but the vast majority of customers want physical samples.
Special Concerns:	<ul style="list-style-type: none"> • Marketing of the product was the main obstacle.

4.3.3.1. *Generation*

The idea for the heated knitted apparel happened by a chance conversation with an acquaintance outside the field of textiles. This acquaintance showed the business manager samples of silver coated nylon yarns. James Russell Lowell (1819-1891) said that “Creativity is not the finding of a thing, but the making something out of it after it is found.” The business manager of case study FK3 knew the silver coated yarns could potentially be used to produce conductive properties and so he began testing procedures with samples knit with the special yarn. In order to help generate product ideas, the business manager hired an outside consultant who specialized in outdoor apparel. The business manager specifically looked for a designer with knowledge of outdoor apparel. He states that “Our design consultant was also a rock climber and mountain biker. This allowed him to draw on his personal experience and design for the distinctive needs of an outdoor sportsman. He understood the physiological needs our product needed to meet.”

4.3.3.2. *Communication*

The consultant designed garments on the computer and created very detailed storyboards in order to communicate his ideas (see Figure 46) Communication between the design consultant and the knitwear company occur almost entirely by e-mail. The business manager stated that the designer has only visited the company twice and while they communicate by phone occasionally most correspondence happens via e-mail. The design consultant is very proficient at graphic communication and so his storyboards are well understood by the knit technician, marketer and physician. In addition the design

consultant has experience with knitted garment production and so he has tactical knowledge of what information needs to be communicated.

Figure 46. Design consultant's storyboard rendering of the product idea.

4.3.3.3. Implementation

Case study FK3 engineered design team is comprised of a group that has diverse and highly experienced skill set. Leading the team, and part owner of the company, is a business manager. Another part owner is in charge of marketing and has an MBA and over 20 years experience in the knitwear market sector. Also, there is a knit technologist, who is proficient in H. Stoll GmbH & Co. knitting machine programming. This knit

technologist has both a textile technology and information technology degree. The company also employs external designers. For the engineered conductive knit product design, Case study FK3 hired an award winning designer with extensive experience in knitted sportswear. This designer has a master's degree in textile economics. His extensive work experience included being an in house designer for an international sportswear and athletic shoe-wear company, a technical designer for ski-wear, and a technical consultant/designer for self heating extreme apparel. In addition, the company consults with a physician for body mapping of heating elements.

The process for this functional engineered design starts with a computer generated drawing from the design consultant. Once the knitwear company receives this drawing (typically an electronic file via e-mail), their pattern maker creates various sizes for cutting. The pattern sizes, for example a small, medium and large, are cut and sewn together to test fit. These initial prototypes are solely created to test fit and sizing and are not indicative of the knit manufacturing process for the end product which is fully fashioned and linked together. In a parallel process, the knit technician begins drafting the fully fashioned knit garment pattern pieces into the company's technical design software. Adjustments in size are made based on feedback from the pattern maker. The shaped garment pieces are knit on V-bed machines and then linked together. Some trim items are sewn on with an over lock stitch.

When describing the manufacturing process for this functional designed knit, the business manager emphasized that the knit production methods are almost identical to the production methods for the fashion items that the company has produced for a number of

years. The silver wrapped nylon yarns are knitted into strategically placed areas of the functional garments using intarsia knitting. No considerable problems occur when knitting with the silvered yarn, such as tension problems or breakage. In fact, the knit manager stresses that in some instances the manufacturing process for knitting with the silvered yarns is simpler than knitting with some of the complex yarns and knit structures required of some of the company's fashion items.

After the garment is knitted and assembled an electronic monitor is inserted into a knitted pocket of the product and connected to the conductive yarns. The electronic component is outsourced, but the company's knit technician works closely with the electronics' company to program the monitor.

The company uses a silver-coated polyamide yarn that is tear proof, unbreakable, and behaves like a textile product (WarmX 2008). Because the silvered yarns have the same properties of traditional textile yarns the knitted underwear has the same comfort, fit, and aesthetics of the company's fashion items. One example of the material description for one of their products is an undershirt that uses three yarns; a 100% polycron microfiber, a 100% superfine merino wool, and a 50/50 cotton/acrylic. The company's tights are made from a yarn that is comprised of 49% cotton fiber, 9% spandex, 40% polyester fiber, and 2% pure silver. The concentration of silver is increased around the foot areas in order to conduct more heat and also to impart antimicrobial properties to control odor.

FK3 had a well established interface with technologies that facilitate the engineered design process. In addition the members of the product development team

were very experienced in use of these technologies. The company had successfully integrated digital communication tools such as fabric texture mapping, 2D product simulation, and electronic storyboards into their product development cycle. In addition, the company used technologies such as state of the art V-bed machines; computerized yarn tension control, and yarn feeders; as well as technical software and design software for knits. This integration of technologies reduced the learning curve and allowed the team to focus their energy on the development of the new conductive garments.

4.3.3.4. Iteration

The leader and business manager describes their process as highly iterative. Ideas are knitted out, assembled, tested and evaluated. If some aspect of the idea doesn't work, the product is redesigned and produced again. The business manager reinforces the idea of multiple design iterations in the statement below.

We work together with freelance designers. The design process is iterative. First we seek for materials and colors. Afterwards the designer presents us his ideas. These ideas are transformed into samples iterative (programming - knitting - testing - changes) together with our programmers. For medical assistance we have a special physician which has experiences in thermo therapy. The iteration has ended when programmer, designer, physician and I are satisfied with the results.

A product, such as case study FK3's, which is engineered for a functional purpose requires a great deal of trial and error. Case study FK3 committed to this process. Tom Huff (2007) enforces the idea of multiple iterations for product development. "The practice of R&D involves making mistakes, realizations, corrections, and more mistakes. Trial and error is a fundamental part of the process. Too many managers in corporate America learn to avoid invention and new thinking because they have been convinced that their careers depend upon not making mistakes."

The first garment produced required many prototypes. Once the initial research and development yielded a successful product, (i.e., once the garment was able to predictably and consistently conduct heat) then each additional variation on the product required only three to four prototypes. The business manager stated that after the first garment was successfully produced, the company focused on creating modifications of the product to increase style options for the consumer. For instance, the color or silhouette could be changed to create a new garment. This next line of products required minor design modifications and therefore prototyping was reduced.

Part of the prototyping process for this item required wear testing. Members of the product development team wore the initial prototypes and gained first-hand knowledge of the strengths and weaknesses of product. The tester's noted that the aesthetic properties, (such as drape, texture, and silhouette), and functional properties (such as comfort, fit and elastic recovery) of the garments were identical to fashion items. However, a change in humidity or deep crease in the fabric produced a painful and very uncomfortable electrical shock! The new product looked and fit like a product from their traditional

product line, but the garment didn't perform at all as expected. Fortunately the company was vested in the success of this product and relegated the necessary resources to continue development.

Vestment in the success of a new product may be greater for an engineered design than a non-engineered design because typically, the engineered design process requires that the product developer (or product development team) be involved in the process from start to finish. The product development process is closer to the process a craftsman would follow while the traditional product development route is often segmented into different departments. The majority of engineered design experts that were surveyed as part of this dissertation research stated that an engineered design process was more centralized and required greater collaboration of team members. Both of these factors may facilitate the prototyping process by supporting loyalty to the success of a product.

4.3.3.5. Special Concerns

Case study FK3 encountered a number of challenges when developing this new product. Because this was an entirely new product idea, rather than a modification of an existing product, the company spent a considerable amount of resources on research and development.

The greatest challenge within the product development process occurred with the electronic component. Following is an explanation by the business manager of the challenges faced by incorporation of the electronic component.

Electricity is a very exact science and textiles are not, so combining the two fields of study was very difficult. The wires always have to be placed exactly to insure the same resistance. Textiles products are by nature very flexible and move around freely. It is very difficult to predict how textile yarns will move or shift based on the movement of the person wearing the product. The electrical resistance will change due to the wearer's movement.

To solve this product development challenge the company developed software for microprocessors that continually monitors and controls the circuits. This solution for the functional engineered design did not come without a price. The product manager stated that the software development for the controller took two years and comprised 75% of the research and development costs.

Perhaps the greatest hurdle the company faced with was in positioning the engineered functional product in the marketplace. The company clearly envisioned the conductive underwear as an apparel item; however the electronic component often caused vendors to mistakenly place the product in the electronics market. The business manager stated

When we would go to shows to sell our knitted apparel, the apparel buyer for a company would say that they were not authorized to buy the product and we would need to see the company's electronics buyer. For us this was a problem because the markup for apparel is often 2.5 times the cost

of the product while the markup for electronics is only 1.5 to 1.8 times of the cost of the product.

The company quickly realized that this new product would need intensive sales effort in order to sell, and so they invested in training for all sales associative. The business manager states that 25% of the cost of the product line is earmarked for sales training and support. One outcome of this training was the understanding that new sales venues would need to be explored. Therefore, instead of marketing to department stores, the company began to show their product at user specific trades shows. These new sales venues included healthcare trade shows focused on consumer products for patients with healthcare problems such as rheumatoid arthritis and kidney failure. In addition trade shows for outdoor sports consumers were also targeted. Currently, one the largest purchasers of these conductive products are hunters.

4.3.4. Case Study Four (FW4): Input to Model

Case study FW4 looked at the instance of the product development process for a functional woven design. The product is a woven garment with embedded electronic components for military application. The development of the product was segmented into phases, with passage to the next phase of product design dependent on certain success factors of the previous stage. Each member of the design team was chosen for their expertise in certain areas. The development team consisted of an electronic company with expertise with wearable electronics; a garment cut and sew operation; a yarn

manufacturer; and an expert of woven fabric, fiber, and yarn with experience in electronic textiles. See Table 16 for the input to model of Case Study FW4.

Table 16. Summary of Case Study FW4 Results

Phase	Case Study FW4 Results: Input to Model
Generation	<ul style="list-style-type: none"> • An important part of the design generation phase was identification of product designers who had required expertise. • The product existed, however the functional design needed significant improvement. • Review of the existing product was critical to assess faults.
Communication	<ul style="list-style-type: none"> • Team members were in different geographically locations, communication occurred by e-mail. • The fabric engineer needed to produce drawings to communicate basic fabric design ideas because other team members had little or no experience in woven design. • Physical samples were needed to establish fabric properties.
Implementation	<ul style="list-style-type: none"> • Dobby and jacquard looms were used to manufacture the woven fabric. • The expert stated the need for more memory on the loom to facilitate storage of woven structures.
Assessment	<ul style="list-style-type: none"> • Because this product was used as a protection device for a consumer, assessment of the functionality of the product was crucial.
Iterations:	<ul style="list-style-type: none"> • The development of the product was segmented into three phases, with passage to the next phase dependent on the success of the previous phase.

4.3.4.1. *Generation*

Because this was a modification, or improvement on an existing product, the product development team began the project with the majority of the design concept already generated. An extensive part of the generation phase though consisted of reviewing of the existing product and also looking at similar products on the market. The interviewee stated that a critical part of this first phase was setting the criteria for the product, and then

4.3.4.2. *Communication*

A challenging part of the product development process was communication between team members. Although each team member had expertise in their particular field, some personnel had little or no knowledge of their team member's field of study. For instance, the interviewee expressed frustration with having to explain what a *float* was in a woven design. In order to convey this concept, the woven experts had to draw a depiction of float, and scan the image so that he could e-mail this picture to his team member. Communication occurred primarily by e-mail and phone due to budget and time constraints. However, a face to face meeting was needed at several points in the process to facilitate communication between team members.

4.3.4.3. *Implementation*

Appropriate personnel and material resources were determined in the generation phase, and the team leader helped to communicate the criteria of the engineered design to all team members. The implementation of the product occurred by delegating the

responsibility of each required manufacturing process to the appropriate team member. For example, the woven design experts began production of the woven fabric while the electronics company worked on all electrical components. At this point in the development process, communication between team members was most challenging, and most critical. Continuous feedback was needed so that the process of one team member could be altered based on discoveries or changes occurring in another process. For example, the woven design expert was experiencing significant problems with yarn breakage, and subsequently machine stoppage, due to the weave structure attempted. The woven design expert determined that in order for the woven fabric to be feasibly produced, the yarn had to be redesigned. The woven design expert and the yarn manufacture worked collaboratively to engineer the yarn properties for the end product.

4.3.4.4. Assessment

Assessment of the engineered design was critical because the garment would be worn by the military to provide vital communication functionality. The ability of the garment to provide communication functions to the wearer could be life saving. Therefore, this engineered design project was segmented into three phases. Phase one criteria consisted of producing a woven cloth that had improved conductive qualities. The current garment on the market only had a 10% success rate of maintaining a continuous electrical current; anything higher than this percentage would be considered an improvement. Initial assessment consisted of evaluating the weave of the fabric to determine if the woven structure would improve conductivity. However, during the sampling process, the yarn

had to be assessed too, as the woven design expert deducted that the type of yarn originally chosen was no longer suitable for the new weave structure. At the end of Phase one, the new engineered woven fabric was assessed to have a 90% success rate of conductivity, a vast improvement over the original design.

The engineered design is currently in Phase two of development. The product will now be assessed on how well the fabric integrates with garment. The product will have to have at least the same comfort, fit, and wear ability properties as current products, and hopefully some or all of these properties will be improved. The woven design expert stated that computer simulation tools would not be valuable evaluation tools for this stage of product design because software “does not adequately simulate any functionality of the fabric and also does to not satisfy the designer’s need to evaluate the fabric by touch”. When asked to elaborate on this shortfall of CAD simulation the interviewee stated that “The hand of the fabric - how crisp or soft, how well the fabric drapes, is best evaluated by seeing and touching and then making a determination if the fabric qualities are suitable for the end product”. The woven design experts felt that CAD systems were good at simulating the surface design of fabric, and provided adequate information for evaluating the color and overall look of the fabric but software was not capable of simulating important fabric properties such as density, shearing, and drape.

If the engineered product passes phase 2 evaluation the product will enter into Phase three: positioning the product into a new market. The new consumer market would be civilians.

4.3.4.5. *Iterations*

The woven design expert went through several iterations of the fabric design in order to suit the requirements of the end product. Five different weave structures were attempted, and two prototypes were needed. The interviewee stated that had the product not been an improvement on an existing product, many more prototypes would have been needed.

4.3.4.6. *Special Concerns*

The interviewee expressed that throughout the project for the engineered design each team member needed to “look at the big picture” of how their part in the product design was meeting the criteria of the product. He felt that communication was the biggest challenge because while each team member worked on the segment of the product design related to their expertise, a change in one aspect of the product affected all other aspects of the products. It became very critical for each member to explain to all other team members any new developments to the product process. For example, a change in the size of an electronic component could affect the garment and weave design. Communication was hindered in some respects because of lack of understanding of each other’s field of work.

The weave design experts felt strongly that communication could be improved by better education at the University level. He stated that we have a “big hole in our education systems” and that students are not educated on the all of technological needs of a product. He further stated that the need to assess the properties of fabric has to be communicated to software developers.

4.4. Model Analysis

The engineered design process model provides a graphical representation, categorization, and description of steps, components, and decisions that make up this product development methodology. Harvey (p. 330, 2005) defines process modeling as “the action of mapping or defining a fixed or ordered set of operations that complete an objective. This sequence of operations often contains constraints, back and forth movement and parallel actions.” The engineered design process for textile placement reflects the definition of an engineered design in that it is an iterative process that starts with set criteria that guide the design and manufacturing parameters from the beginning until the end of the product development cycle. This model is specific to the engineered design process for textile placement. This cycle is segmented into four design phases; generation, communication, implementation, and evaluation. The shape of the model is an ellipse to symbolize the holistic approach to an engineered textile design. In holism, an entity is not comprised solely of the component parts, rather the system as a whole determines how all parts function. In an engineered design for textile placement, the end product determines the manufacturing processes, shape or silhouette, as well as the fabric design and properties. The requirement or criteria for the end product is the driver for all of the processes throughout the product development cycle. See Figure 47 for the process model for engineering textile design properties within the shape of a product.

Figure 47. Final high level process model for engineering textile design properties within the shape of a product.

4.4.1. Design Generation

The design generation represents the beginning phase of the engineered design process. At this point, the product is in an impalpable form. The product development team or individual may take varied approaches when generating ideas, however, three main tasks are essential. These tasks are broadly defined as the need to review, envision, and define. Because an engineered design for textile placement is a holistic approach, a thorough understanding of the properties of the end product is essential – even at this very

beginning phase. For this reason the review process takes many forms. One critical part of the review process involves the examination of existing products; both internal and external to the organization or design team. This review of products provides a valuable starting or jumping off point as existing products can be used to compare manufacturing processes, material properties, cost parameters and design criteria. For instance, in engineered design of fully fashioned knitted apparel, the fashioning or shaping sequence is quite complex. In addition, fiber properties of yarns, combined with the type of finishing process can produce a wide range of shrinkage and shape distortion – all of which will need to be calculated prior to beginning the design of an engineered product. For this reason, many product developers “recycle” or reuse existing fully fashioned shapes. Existing fully fashioned shapes already have the fashioning frequency, shrinkage, distortion and machine parameters calculated; therefore product developers can focus on changing aspect of the aesthetic design such as color. In addition, both digital and analog samples of fabrics, colors, design motifs, product shapes, and yarn assist ideation of the product.

4.4.2. Design Communication

Prior to the start of the research, the investigator assumed that the most difficult part of engineering fabric properties within the shape of a product would be the mechanics of implementation. However, based on data analysis of responses from experts, most practitioners felt confident in their ability to design an engineered product, and adequate processes and industrial equipment existed to manufacture engineered products, but

communicating the exact design specifications to team members, or to manufacturing personal was very challenging.

Communication in an engineered design process takes many forms. For example, communication could be in physical form such as sketches, renderings or storyboards; fabric, yarn, and product samples; or written directions and specifications. Communication could also occur digitally, for instance by e-mail; 2D storyboards; simulations of yarn, fabric, and products; or machine specifications such as a cut file for the shape of a product, an image file to print, or a weave or knit file. Designers also stated the need to communicate in person, by either verbal or gestural expressions.

Communication serves three main purposes, to guide the process, relay information, and specify requirements.

4.4.3. Design Implementation

Implementation refers to the refinement of ideas, design of product and/or product components, and the manufacture of the product. The implementation phase can be a point of compromise as this is the part of the process where an intangible idea meets a physical form.

4.4.4. Design Assessment

Evaluation or assessment of a design that has textile properties engineered within the shape of the product often has more criteria to evaluate than a non-engineered product. Assessment of the design occurs throughout the process and acts as a gate for the design to either pass through or be stopped and redirected back to the generation or

implementation phase for refinement or redefinition. An engineered design is assessed as to whether or not the product meets the aesthetic and functional criteria established, and whether or not the design is feasible to produce and market.

5. FINAL ANALYSIS: SUMMARY, CONCLUSION, AND RECOMENDATIONS

The results of this research contributed to the knowledge base of textile and apparel design and development by collecting, analyzing and synthesizing data culled from an extensive literature review, as well as responses of expert practitioners who are engineering textile design properties within the shape of a garment. While a good deal of practical research exists on individual instances of this method of engineered designing, this body of research is the first comprehensive, “big picture” look at this design and development process, and the first investigation to provide a theoretical model.

5.1. Summary

The primary objective of this research was to define and describe the engineering design process for strategically placing fabrication properties within the shape of a product. Outcomes of this objective are a model of the process, a working definition of the process, and a foundation of theory detailing the process.

The objectives were met by conducting a three stage research project. Stage One involved exploratory research comprising a comprehensive literature review of technologies available for engineering knit or print fabric design properties. This literature review established the available technologies for engineering knitted and printed fabric properties. A canvas of software and hardware technologies at ITMA 2007 further assisted in developing the survey instrument for Stage Two of the research. A tabulation of software capabilities for design of knitted, printed, and woven fabric assisted in the survey development.

The literature review also summarized current product design and development models. From this literature review it was determined that an adequate model for engineering fabric design properties within the shape of a product did not exist. However, literature documenting examples of this process did exist. Current design and product development models, practical examples of this engineered design process from the literature review, and the investigators own experience assisted in building theories to test, and helped to build a rudimentary model of this engineered design process for coloration; an aesthetic property.

Results from Stage one assisted in developing the survey instrument for Stage Two. Stage One of the research provided information about engineered designing for aesthetic properties. Stage Two of the research used this data as a base of knowledge to gather more information about engineered designing for aesthetic purposes and to also gather information about engineered designing for functional purposes. The experts who were surveyed for engineered designing of knitted, printed and woven fabric felt that they used this design process to improve both the aesthetic and functional design of a product. Data collected from the survey assisted in describing this highly collaborative, often time intensive design process. The experts surveyed expressed the opinion that advancements in software and hardware technology had facilitated this engineered design process. However, more development was still needed for software simulation. Data analysis of survey results also provided descriptive information about the engineered design process. Participants cited a need for improved communication, and the importance of the product meeting the initial criteria.

Stage three of the research, case study analysis, provided triangulation of results. Case study analysis also allowed observation of an instance of the engineered design process. Cases were chosen for their ability to benchmark successful use of the engineered design process, and to provide a variety in the type of scenario for an engineered design.

5.2. Conclusions

A result of this investigation was the detailed descriptions of the engineered design process via case study analysis. Detailed descriptions of the processes allow viewers to see the possible design and manufacturing routes available for an engineered design. The detailed cases studies were categorized by fabric design method, i.e. knitted, printed, or woven. These descriptive examples are useful for both expert and novice designers, particularly in the generation stage of the design. During design generation, products are reviewed and needed resources are determined. The case study examples will assist designers in making informed decisions as to which production method is most appropriate for the implementation of their engineered design. An earlier decision about the design route will help determine needed resources in terms of personal, raw materials, and design and manufacturing equipment.

The high level model that was created as a result of survey and case study analysis provides the viewer with a broad overview of the entire engineering design process. This macro view of the engineered design process provides a comprehensive overview of the entire process and allows the viewer to grasp the complex interaction of the main components of the process. By segmenting the model into the four phases,

generation, communication, implementation, and assessment and by showing how all of these processes are intricately interrelated and iterative, the viewer begins to grasp the holistic approach needed when attempting an engineered design. The model for this engineered design process is product centric, i.e. the criteria and requirements of the product drive all aspects of the design process.

Another outcome of the research was to establish theory of the engineered design process for strategic placement of textile design properties within the shape of the garment. The experience of the investigator with engineered designing, extensive literature review on digital printing and integral knitting, the review of product development models, and the analysis of technology capabilities at ITMA 2007 provided valuable information for developing theories for this engineered design process. Data analysis of expert practitioners and case study synthesis of an instance of the engineered process proved the hypotheses that i) significant differences exist between the design phases on an engineered design versus a non-engineered design, ii) various levels of difficulty of engineered designing exist, and iii) technology advancements have aided the engineered design process.

Data analysis of expert practitioners' responses proved that engineering the textile properties within the shape of a product requires more collaboration, and is more time consuming than designing a non-engineered product. Centralization of this design process facilitates the process, presumably because of the collaborative nature of the design process. Participants also stated the heightened need to communicate. Because of the holistic nature of an engineered design, any change to one property of the product has

the potential to effect properties of the entire engineered design. For example, in case study WF5, the instance of designing a woven garment with embedded electronic components, when the weave structure was changed, the yarn had to be changed as well, all of which affected the final product design. Communication between each segment of the supply chain was critical.

A further result of the investigation was agreement from the practitioners that various levels of difficulty between engineered design processes. As with any design process, an entirely new design was deemed more difficult than an innovation or improvement on an existing product. Participants also stated that some processes such as placement of textile design properties across a seam or closure was universally more difficult than placement on a flat and unbroken surface of the product. However, data analysis failed to establish, if for instance, a woven engineered design was more difficult than a knitted or printed engineered design. After conclusion of the research the investigator formed the opinion that engineered processes for textile design vary so widely that it is impossible to judge if one type of engineered textile design is more difficult than another.

Research findings conclusively proved that technology advancements have aided the engineered design process. Improvements in design software and computer processing were listed as primary technologies that have aided this design process. A participant echoed this theory by saying “While the engineered design fundamentals did not change, the software packages (CAD, computer codes, etc.) to implement and apply these helped in time reduction and accurate calculations.” However, participants also

stated a need for continued improvement and increase access to virtual simulation software. While respondents generally agreed that simulation would facilitate the engineered design process, most expressed frustration with the inability of the software to truly simulate the properties of fabric.

A final outcome of the study was refinement of the definition. The object of study was given the descriptive name of *Textile Design Engineering within the Product Shape*. The definition for this design process as defined by the author, and collaborated by expert practitioners, is stated as such. *Textile Design Engineering within the Product Shape* is an iterative and often highly collaborative design process within the textile complex. The purpose of this textile engineered design process is to i) improve the performance of the product and/or, ii) to improve the aesthetics of the design. Products engineered for aesthetic purposes can create a seamless design by continuing a motif or fabric structure across a seam, dart or closure, and accentuate shape or movement. Products engineered for functional purposes can improve performance, comfort, fit, and movement, reduce waste, and reinforce areas of high wear.

State of the art software that can be used for engineering textile fabrication within a product shape is fairly sophisticated for aesthetic design such as placement of color, motifs, or structure. However, this same software is lacking for strategic placement of functional attributes within a product. For instance, in knit or woven design, after extensive review, no software was uncovered that simulated how a product shape is effected by placement of elastomeric yarns, or a change in yarn tension, or a change in fabric density. Likewise, in 3D simulation software, case study and survey respondents

felt that available software did not easily or adequately simulate the drape of various fabrics may change how design elements are placed within a product. Engineered design for fabrication placement allows very little room for error, and so software simulation would need to be very exact. Currently, the best method for achieving this precise placement is by trial and error via the physical prototyping process. Based on survey results, the average number of physical prototypes needed is between two and three. The ability to substitute a digital prototype for even one of the physical prototypes needed would result in a substantial savings in both time and money. However, we also see from the survey results, a resistance to adopt the more sophisticated 3D digital simulation techniques – even from expert users of the engineered design process. Some experts stated their frustration of lack of access to such software tools. But, experts who did have access chose not to use these 3D simulation tools because they felt they were “slow and cumbersome”. Certainly much work is still needed in the development of these more advanced simulation tools. The question remains though as to who and what will drive this change. Industry members are bogged down with day to day demands and often don’t have the time to direct the energy needed to push this development. The responsibility to drive this change may lie within academia and other research organizations. Academia has a captive audience and willing audience of new product developers that are in a learning, training, and experimental mode.

The case study that had high integration of technology into their engineered product development process also had the most radically innovative product. Case study FK3, had vast experience with state of art software and knit machinery, therefore more

time could be allotted to the innovation and marketing of the product rather than spending time ensuring that the design idea was translatable to the product manufacture.

5.3. Recommendations

Textile engineered design can be a powerful process for improving the aesthetic and functional properties of a product. Technologies for engineering of knitted, printed, and woven fabric design properties exist and can aid the process. However, the collaborative nature of engineered designing and lack of software tools that aid functional engineered design can impede this design process. It is recommended that further research into this engineered design process concentrate on education and refinement of design software.

Experts in the area of engineered design listed prior software development as the technology that has most facilitated the process, so it stands to reason that further improvement would be beneficial. One case study interviewee stated that software developers are not reaching out to practitioners. He felt strongly that simulation of textile properties could be achieved, but that input from textile technologists was critical.

The collaborative nature of the design process requires greater communication skills. Collaboration and communication skills of designers can be improved with education at the University level. Cross training and an emphasis on a holistic design process, i.e. looking at the design of the entire product rather than design of separate components such as yarn, fabric and silhouette would improve product design. The process, or outcome, of engineering a fabrication design within a shape of a product is a design principle or methodology. Similar to Covey's second habit "Begin with the end in

mind”, this engineering process requires that product developers design fabric with the end product in mind.

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APPENDICES

APPENDIX A

Dear;_____

You have been identified as an expert in the field of engineered designing and your assistance is needed to complete the following survey. The survey results will become part of the published dissertation research conducted by Lisa Parrillo Chapman at North Carolina State University. The Delphi method will be used for conducting this survey. Delphi is a methodology where a small group of experts are targeted and questioned about a new process or technology. The process for engineered designing is currently being researched as a tool for improving product development. Engineered designing is a process where some attributes or all attributes of fabrication are designed purposefully and or simultaneously for the end product. Your candid and thoughtful reply will help aid our research evaluation. Your response and any comments will be treated with utmost confidentiality. After the results are tabulated and compiled, we will issue a report.

Should you have any questions or comments about this survey and if you would like to request a copy of the finished report, please contact Lisa Parrillo Chapman by phone (919) 513-4020, or e-mail lparril@ncsu.edu. The following link will take you to the start of the survey.

http://www.surveymonkey.com/s.aspx?sm=lukfc13EQncpFJwG8eJvrw_3d_3d

Thank you for your help,
Lisa Parrillo Chapman

APPENDIX B

1. Consent Form

1. The purpose of this study is to provide a greater understanding of the various methods of engineered designing, and to build a comprehensive model of this product design and development process. Experts in the use of engineered designing, such as yourself, are asked to complete this survey and assist in defining, describing, and quantifying the complexity levels and methods of engineered designing for textile products. The survey results will become part of the published dissertation research conducted by Lisa Parrillo Chapman.

Your participation in this study is voluntary. You have the right to be a part of this study, to choose not to participate or to stop participating at any time. The information in the study records will be kept strictly confidential. Data will be stored securely on a password protected server accessible only by the principal investigators. SLL encryption will be used for transmitting survey results. No reference will be made in the dissertation which could link you to the study. There is no monetary compensation awarded for participation in this study. However, one benefit of participating in this study is the knowledge that you will have contributed your expertise and experience to a greater body of work on the subject of engineered design. There are no foreseeable risks associated with completing this survey.

If at any time you have questions about your participation, do not hesitate to contact the researchers Lisa Parrillo Chapman or Trevor J Little at the College of Textiles, Box 8301, NCSU, Raleigh NC 27695-8301 or, 919-513-4020.

If you feel you have not been treated according to the descriptions in this form, or your rights as a participant in research have been violated during the course of this project, you may contact Deb Paxton, Regulatory Compliance Administrator, Box 7514, NCSU Campus(919/515-4514), or Joe Rabiega, IRB Coordinator, Box 7514, NCSU Campus (919/515-7515).

By checking the "I accept" box I acknowledge that I understand the above information. You may print a copy of this agreement for your records.

- ☐ I accept
- ☐ I do not accept

2. Contact Information

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

Name:
Company:
Address:
Address 2:
City/Town:
State:
ZIP/Postal Code:
Country:
Email Address:
Phone Number:

2. What is your job title?

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

4. How long have you been employed in your current position?

5. What type of products (ex. sweaters, dresses, rugs, car seats, etc.) do you produce using engineered design methods?

1.
2.
3.
4.
5.
6.
7.
8.
9.
10.

3. Definition of Term

1. One objective of this survey is to establish a recognized definition for engineered design. Experts such as you will assist in defining this term. Please read the following definition and check whether or not you agree with the definition. If you disagree please make corrections to the definition in the space provided.

"An engineered design, as defined by the author, is a process or product where the fabric formation and/or design is produced simultaneously and/or purposely for the end product. The purpose of an engineered design is to i) improve the performance of the product and/or, ii) to improve the aesthetics of the design. Products engineered for aesthetic purposes can hide seams, accentuate shape or movement, divert attention from an area of the body, or continue a motif or pattern across a seam, dart or closure. Performance engineered design can reinforce areas of high wear, reduce waste, or improve comfort and fit. For example, to improve performance, a sweater could be engineered to have a more elastic structure knitted into areas of high stress. In contrast, a print design with a large, central motif that is strategically placed on the garment to accentuate the body would be considered an engineered design for aesthetic purposes. Examples include, but are not limited to; design placement, logo placement, stripe/plaid engineering, intarsia design placement, print/knit/woven motif, structure or pattern placement."

- ☐ Yes, I agree with the stated definition
- ☐ No, I disagree in part with the definition
- ☐ No, I disagree entirely with the definition

Changes to definition

2. Is the purpose of your engineered design for improvement of the aesthetic or functional aspects of the end product? Please check all that apply.

- ☐ Aesthetic improvement
- ☐ Improve function
- ☐ Improve both aesthetic and functional properties

3. Please rate the importance of the following aesthetic attributes you hope to achieve with engineered designing.

	Extremely Important	Important	Minor Consideration	Not Important	N/A
Accentuate shape	☐	☐	☐	☐	☐
Accentuate movement	☐	☐	☐	☐	☐
Accentuate a motif or pattern by strategic placement	☐	☐	☐	☐	☐
Create a seamless design with a motif or pattern	☐	☐	☐	☐	☐
Hide seams	☐	☐	☐	☐	☐
Divert attention from an area of the body	☐	☐	☐	☐	☐
Other	☐	☐	☐	☐	☐

If Other (please specify)

4. If engineered designing is used for functional purposes, please rate the order of importance of the following properties.

	Extremely important	Important	Minor consideration	Not important	N/A
Reinforce areas of high wear	☐	☐	☐	☐	☐
Reduce waste	☐	☐	☐	☐	☐
Improve fit	☐	☐	☐	☐	☐
Improve comfort	☐	☐	☐	☐	☐
Improve performance	☐	☐	☐	☐	☐
Other	☐	☐	☐	☐	☐

If Other (please specify)

5. Do you feel that an engineered product has a superior appearance to a product that is non-engineered?

- ☐ Yes
☐ No
☐ Unsure

4. Experience

1. In what capacity are you creating engineered designs? (you may check multiple responses)

- ☐ Art-to-wear
- ☐ Couture
- ☐ Customized
- ☐ Ready-to-wear
- ☐ Sampling
- ☐ Scholarly research

Other (please specify)

2. How long have you been working with engineered designs?

- ☐ One to three years
- ☐ Three to six years
- ☐ Nine to twelve years
- ☐ Twelve to fifteen years
- ☐ Greater than fifteen years

3. How many years have worked with engineered designing in your current position?

4. Do you feel that adequate literature and training material exist for engineered designing? Please check all that apply.

- ☐ No, I learned by trial and error
- ☐ No, I would still like training
- ☐ No, I can't find published material on engineered designing
- ☐ Yes, my educational experience prepared me
- ☐ Yes, my past or current company trained me well
- ☐ Yes, there are well documented strategies on the web for engineered designs
- ☐ Yes, there are books and papers that explain how to engineer a design
- ☐ Other (please specify)

5. In your opinion, over the past ten years, have any technologies, market influences, or design processes contributed to a change in engineered designing processes? Please explain.

5. Engineered Design Method

This next section of the survey will be broken up into three parts; knit engineered design, printed engineered design, and woven engineered design. Based on your response to the following question, you will be directed to the appropriate survey segment.

*** 1. What method of engineered design and product development are you involved in?**

- ☐ Knitted
- ☐ Printed
- ☐ Woven

6. Knitted Engineered Design: Archiving and Data Storage

1. Do you have access to analog or digital libraries? Please check all that apply.

- ☐ Knit structures: digital format
- ☐ Knitted structures: fabric samples
- ☐ Yarns: digital format
- ☐ Yarns: physical samples
- ☐ Garment shapes: digital format
- ☐ Garment samples: physical samples
- ☐ Other (please specify)

2. If knit structures are in digital format, how are the structures represented?

- ☐ Coded representation of knitted structures
- ☐ Photographic representation of knitted structures
- ☐ Three-dimensional representation of knit structures
- ☐ Other (please specify)

3. Do you use archiving software for digital libraries?

- ☐ No
- ☐ Yes (please specify)

4. Do you have any problems or issues storing imagery, motifs, patterns, or product information due to file size?

- ☐ No, I have adequate storage
- ☐ Occasionally I have issues with not having enough storage
- ☐ I never have enough storage space, I routinely delete files

Comments

5. Ten years ago, did you have any problems or issues storing imagery, motifs, patterns, or product information due to file size?

- ☐ No, I always had adequate storage
- ☐ Occasionally I had issues with not having enough storage
- ☐ I never had enough storage space, I routinely deleted files

Comments

7. Knitted Engineered Design: Process

1. Please check all of the items that you use engineered designing for.

- ☐ Intarsia
- ☐ Knit structure
- ☐ Jacquard design
- ☐ Stripes
- ☐ Elastomeric properties
- ☐ Conductive properties
- ☐ Other (please specify)

2. What type of equipment are you using for engineered designs? Please check all that apply.

- ☐ Circular seamless body-size
- ☐ Circular cylinder and dial
- ☐ Straight bed
- ☐ V-bed

Other (please specify)

3. Please list any software you use for engineered designing?

1.
2.
3.
4.
5.
6.

4. How were you trained for the above listed software?

	Majority of my training	Provided me with moderate training	Provided me with some training	Did not prepare me at all
Trial and error	☐	☐	☐	☐
Education in College or University	☐	☐	☐	☐
Training provided by software company	☐	☐	☐	☐
On the job training	☐	☐	☐	☐
Books and papers	☐	☐	☐	☐
Online resources	☐	☐	☐	☐
Other	☐	☐	☐	☐

If Other (please specify)

5. Using your best estimate, on average, how much additional time is needed to produce an engineered design versus a non-engineered knit design?

- ☐ No additional time is required
- ☐ One to three additional hours are needed
- ☐ Four to six additional hours are needed
- ☐ Seven to nine additional hours are needed
- ☐ Ten to twelve additional hours are needed
- ☐ Additional time is greater than twelve hours (please specify)

6. Using your best estimate, on average, is there an additional cost to produce an engineered knit design versus a non-engineered knit design?

- ☐ No additional cost
- ☐ 1% - 5% additional cost
- ☐ 6% - 15% additional cost
- ☐ 16% - 25% additional cost
- ☐ 26% - 40% additional cost
- ☐ Additional cost is greater than 40%

If cost is greater than 40%, please specify

7. How you grade a fully fashioned engineered design for apparel.

- ☐ The apparel item is first graded, then the knit structure, intarsia, or jacquard design is created for each garment size.
- ☐ The knit structure, intarsia, or jacquard design is created and engineered within a garment shape, and then the apparel item is graded.
- ☐ Other (please explain)

8. If you are producing engineered knitted designs for apparel, furniture or other products that require a cut pattern, are you able to pull your marker (cutting layout) directly into your graphics program?

- ☐ Yes
- ☐ No

Comments

9. Please rank the order of importance for the following design elements.

	Most important	Very important	Fairly important	Least important	N/A
Silhouette	☐	☐	☐	☐	☐
Fiber/Yarn type	☐	☐	☐	☐	☐
Knit structure	☐	☐	☐	☐	☐
Coloration	☐	☐	☐	☐	☐
Other	☐	☐	☐	☐	☐

If Other (please specify)

10. For the following types of engineered designs, please rank the level of difficulty.

	No difficulty	Minimal difficulty	Moderately difficult	Highly difficult
Placement only, not on a seam or closure	☐	☐	☐	☐
Placement across a straight seam	☐	☐	☐	☐
Placement across a curved seam	☐	☐	☐	☐
Placement across a dart	☐	☐	☐	☐
Placement across a closure	☐	☐	☐	☐
Other	☐	☐	☐	☐

If Other (please specify)

11. When positioning graphics, imagery, motifs, logos or repeat patterns for an engineered design, please check all design considerations that apply.

- ☐ Knit structure or imagery is centered on the body or product
- ☐ Knit structure or imagery lines up across the shoulder seam
- ☐ Knit structure or imagery matches up across the side of the body seam
- ☐ Knit structure or imagery follows the shape of the garment/ body, or product lines
- ☐ Knit structure or imagery forms a pattern within the garment shape
- ☐ Knit structure or imagery lines up across all seams
- ☐ Other (please specify)

12. For the last five engineered designs you produced, on average, did the garment shape determine or drive the knit design, or did the knit design dictate the garment or product shape?

- ☐ The silhouette was designed, and then an appropriate knit design was chosen or created that would best complement or accentuate the garment or product shape.
- ☐ The knit design or imagery was conceived and then an appropriate garment or product shape was determined that would best complement or accentuate the knit design.
- ☐ Both the garment shape and the knit design were co-designed.

Comments

13. Do you think creating an engineered design requires the product development process to be more centralized or less centralized than a non-engineered design?

- ☐ More centralized
- ☐ Less centralized
- ☐ No difference

Comments

14. In the past ten years have any technologies or new processes helped improve work flow or increased the speed of manufacturing an engineered print design?

	Greatly Improved	Moderately improved	No impact
Improved design software	☐	☐	☐
Digital stitch control	☐	☐	☐
Increased computing ability	☐	☐	☐
File storage	☐	☐	☐
Other	☐	☐	☐

If Other (please specify)

15. For the engineered knit design methods listed below, please check whether the process is automated, or if the process requires a person's input. An automated process generally means that a software program automatically executes a command without need for manual manipulation.

	Automated process	Requires manual input	N/A
Marker layout	☐	☐	☐
Grading	☐	☐	☐
Logo placement	☐	☐	☐
knit structure placement	☐	☐	☐
Marker cutting	☐	☐	☐
Intarsia design placement	☐	☐	☐
Jacquard design placement	☐	☐	☐
Other	☐	☐	☐

If Other (please specify)

16. For the following types of imagery used for engineered designing, please rate the level of difficulty.

	No difficulty	Minimal difficulty	Moderately difficult	Highly difficult
Single motif or logo with intarsia	☐	☐	☐	☐
Single motif or logo with jacquard	☐	☐	☐	☐
Stripe	☐	☐	☐	☐
All over tossed repeat pattern with jacquard across seams/fashionings	☐	☐	☐	☐
All over tossed repeat pattern with intarsia across seams/fashioning	☐	☐	☐	☐
Other	☐	☐	☐	☐

If Other (please specify)

17. Do you think creating an engineered design requires less or more team collaboration than a non-engineered design?

- ☐ Less collaboration
☐ More collaboration
☐ Equal amount of collaboration
☐ No collaboration is needed

Comments

18. Are you responsible for designing, or overseeing, the design of the silhouette, knit structure, and any graphics, or are these processes delegated to separate departments? Please explain.

19. Please explain how you map or decide placement of a graphics or knit structures onto the body of a garment or product. Please check all that apply.

- ☐ Trial and error with prototypes
- ☐ Texture map on a 2D image
- ☐ Texture map on a 3D image
- ☐ Draw or project imagery or knit structures onto a prototype
- ☐ Draw or project imagery or knit structures onto flat pattern pieces
- ☐ Other (please specify)

20. Please explain any problems or special concerns associated with manufacturing an engineered design.

8. Knitted Engineered Design: Communication

1. How do you communicate information about silhouette, product shape, color, and knit structure within your organization or design team? Please check all that apply.

- ☐ Verbal: in person
- ☐ Verbal: by phone
- ☐ Visual: written specification
- ☐ Visual: pictorial representation
- ☐ Digital Communication: Written (e-mail, etc.)
- ☐ Digital Communication: Graphic (sending pictures, imagery in digital format)
- ☐ Other (please specify)

2. How do you communicate information about silhouette, product shape, color, and knit structure to your manufacturer? Please check all that apply.

- ☐ Verbal: in person
- ☐ Verbal: by phone
- ☐ Visual: written specification
- ☐ Visual: pictorial representation
- ☐ Digital Communication: Written (e-mail, etc.)
- ☐ Digital Communication: Graphic (sending pictures, imagery in digital format)
- ☐ Other (please specify)

3. Have you experienced a noticeable improvement in speed and ease of sending larger graphic files in the past ten years?

- ☐ Yes
- ☐ No

Comments

4. What technologies or processes do you use that have improved the ease with which you are able to send larger graphic files? Please check all that apply.

- ☐ File compression
- ☐ High speed internet
- ☐ File server
- ☐ FTP server
- ☐ Peer to peer file sharing
- ☐ Other (please specify)

5. Do you currently experience any problems sending knit design information due to file size? Example of common problems include: slow upload time; failure to send data; or a need to resize data to less than desirable resolution in order to send the file.

- ☐ Yes
- ☐ No

Comments

9. Knitted Engineered Design: Calibration

1. What technologies and processes do you use to insure that the correct color is achieved for knitted items? Please check all that apply.

- ☐ Pantone colors
- ☐ Spectrophotometer
- ☐ Calibration of computer screen
- ☐ Calibration of printers
- ☐ Fabric sampling
- ☐ Printed knit simulations
- ☐ Other (please specify)

2. Do you feel that you generally are able to achieve the correct color?

- ☐ Yes
- ☐ No

Comments

3. Are there any steps you are taking, or plan to take, to facilitate color communication?

4. Are there any tools or processes that you would like to see developed, or used more often, that you feel would improve color communication?

10. Knitted Engineered Design: Prototype/Simulation

1. Do you produce virtual prototypes of engineered knit garments or actual prototypes?

- ☐ Virtual prototypes only
- ☐ Actual (physical samples) prototypes
- ☐ Both virtual and Actual (physical samples) prototypes

Comments

2. How long does it take to make and receive a prototype?

3. For the last five engineered knitted designs you created, how many prototypes were needed before you were satisfied with your design?

- ☐ No prototypes were needed
- ☐ One prototype
- ☐ Two prototypes
- ☐ Three prototypes
- ☐ Four prototypes
- ☐ Five or more prototypes

If five or more, please specify

4. In your opinion, would the ability to create a virtual prototype, using your specified yarns, silhouettes and knit structures, help to facilitate your prototyping process?

- ☐ Yes
- ☐ No

Comments

5. Do you use 3d visualization software to create a virtual prototype, using your specified yarns, silhouettes and knit structures?

- ☐ Yes
- ☐ No

6. Why don't you use 3D visualization software to simulate your design. Please check all that apply.

- ☐ I was not aware that 3D visualization software existed
- ☐ No access to 3D visualization software
- ☐ 3D visualization software is too difficult to learn
- ☐ I don't feel that 3D visualization software is helpful
- ☐ 3D visualization software doesn't integrate well with my current software
- ☐ 3D visualization software doesn't work well
- ☐ 3D visualization software is too slow
- ☐ Other (please specify)

11. Printed Engineered Design: Archiving and Data Storage**1. Do you have access to analog or digital libraries? Please check all that apply.**

- ☐ Print patterns: digital format
- ☐ Print patterns: fabric samples
- ☐ Artwork: digital format
- ☐ Artwork: physical samples
- ☐ Garment shapes: digital format
- ☐ Garment samples: physical samples
- ☐ Other (please specify)

2. Do you use archiving software for digital libraries?

- ☐ No
- ☐ Yes (please specify)

3. Do you have any problems or issues storing imagery, motifs, patterns, or product information due to file size?

- ☐ No, I have adequate storage
- ☐ Occasionally I have issues with not having enough storage
- ☐ I never have enough storage space, I routinely delete files

Comments

4. Ten years ago, did you have any problems or issues storing imagery, motifs, patterns, or product information due to file size?

- ☐ No, I always had adequate storage
- ☐ Occasionally I had issues with not having enough storage
- ☐ I never had enough storage space, I routinely deleted files

Comments

12. Printed Engineered Design: Process

1. Please check all of the items that you use engineered designing for.

- ☐ Logos
- ☐ Stripes
- ☐ Repeat patterns
- ☐ Photographic Imagery
- ☐ Non-repeating graphic patterns
- ☐ Other (please specify)

2. What type of printing equipment are you using for engineered designs? Please check all that apply.

- ☐ Hand screen print
- ☐ Rotary screen print
- ☐ Transfer print
- ☐ Digital print
- ☐ Other (please specify)

3. Please list any software used for engineered designing.

1.
2.
3.
4.
5.
6.

4. How were you trained for the above listed software?

	Majority of my training	Provided me with moderate training	Provided me with some training	Did not prepare me at all
Trial and error	☐	☐	☐	☐
Education in College or University	☐	☐	☐	☐
Training provided by software company	☐	☐	☐	☐
On the job training	☐	☐	☐	☐
Books and papers	☐	☐	☐	☐
Online resources	☐	☐	☐	☐
Other	☐	☐	☐	☐

If Other (please specify)

5. Using your best estimate, on average, how much additional time is needed to produce an engineered design versus a non-engineered print design?

- ☐ No additional time is required
- ☐ One to three additional hours are needed
- ☐ Four to six additional hours are needed
- ☐ Seven to nine additional hours are needed
- ☐ Ten to twelve additional hours are needed
- ☐ Additional time is greater than twelve hours (please specify)

6. Using your best estimate, on average, is there an additional cost to produce an engineered print design versus a non-engineered print design?

- ☐ No additional cost
- ☐ 1% - 5% additional cost
- ☐ 6% - 15% additional cost
- ☐ 16% - 25% additional cost
- ☐ 26% - 40% additional cost
- ☐ Additional cost is greater than 40%

If cost is greater than 40%, please specify

7. How do you grade an engineered design for apparel?

- ☐ The apparel item is first graded (modify for other garment sizes), then then the print pattern is created for each garment size.
- ☐ The print pattern is created and engineered within a garment shape, and then the apparel item is graded.
- ☐ Other (please explain)

8. If you are producing engineered printed designs for apparel, furniture or other products that require a cut pattern, are you able to pull your marker (cutting layout) directly into your graphics program?

- ☐ Yes
- ☐ No

Comments

9. Please rate the order of importance of the following design elements.

	Most important	Very important	Fairly important	Least important	N/A
Silhouette	☐	☐	☐	☐	☐
Print design or imagery	☐	☐	☐	☐	☐
Coloration	☐	☐	☐	☐	☐
Other	☐	☐	☐	☐	☐

If Other (please specify)

10. For the following types of engineered designs, please rate the level of difficulty.

	No difficulty	Minimal difficulty	Moderately difficult	Highly difficult
Placement only, not on a seam or closure	☐	☐	☐	☐
Placement across a straight seam	☐	☐	☐	☐
Placement across a curved seam	☐	☐	☐	☐
Placement across a dart	☐	☐	☐	☐
Placement across a closure	☐	☐	☐	☐
Other	☐	☐	☐	☐

If Other (please specify)

11. When positioning graphics, imagery, motifs, logos or repeat patterns for an engineered design, please check all design considerations that apply.

- ☐ Imagery or pattern is centered on the body
- ☐ Repeat pattern or imagery lines up across the shoulder seam
- ☐ Repeat pattern or imagery matches up across the side of the body seam
- ☐ Repeat pattern or imagery follows the shape of the garment or body
- ☐ Repeat pattern or imagery forms a pattern within the garment shape
- ☐ Other (please specify)

12. For the last five engineered designs you produced, on average, did the garment shape determine or drive the print design, or did the print design dictate the garment or product shape?

- ☐ The silhouette was designed, and then a print design was chosen or created that would best complement or accentuate the garment or product shape.
- ☐ The print imagery was conceived and then an appropriate garment or product shape was determined that would best complement or accentuate the printed imagery, motifs or pattern.
- ☐ Both the garment shape and the print design were co-designed.

Comments

13. Do you think creating an engineered design requires the product development process to be more centralized or less centralized than a non-engineered design?

- ☐ More centralized
- ☐ Less centralized
- ☐ No difference

Comments

14. In the past ten years have any technologies or new processes helped improve work flow or increased the speed of manufacturing an engineered print design?

	Greatly Improved	Moderately improved	No impact
Improved design software	☐	☐	☐
Improved digital printers	☐	☐	☐
Increased computing ability	☐	☐	☐
File storage	☐	☐	☐
Other	☐	☐	☐

If Other (please specify)

15. For the engineered print design methods listed below, please check whether the process is automated, or if the process requires a person's input. An automated process generally means that a software program automatically executes a command without need for manual manipulation.

	Automated process	Requires manual input
Marker layout	☐	☐
Grading	☐	☐
Logo placement	☐	☐
Textile pattern placement	☐	☐
Marker cutting	☐	☐
Other	☐	☐

If Other (please specify)

16. For the following types of imagery used for engineered designing, please rate the level of difficulty.

	No difficulty	Minimal difficulty	Moderately difficult	Highly difficult
Single motif or logo	☐	☐	☐	☐
Plaid	☐	☐	☐	☐
Stripe	☐	☐	☐	☐
All over, packed, repeat pattern (very little ground color)	☐	☐	☐	☐
All over tossed repeat pattern	☐	☐	☐	☐
Photo realistic imagery	☐	☐	☐	☐
Other	☐	☐	☐	☐

If Other (please specify)

17. Do you think creating an engineered design requires less or more team collaboration than a non-engineered design?

- ☐ Less collaboration
- ☐ More collaboration
- ☐ Equal amount of collaboration
- ☐ No collaboration is needed

Comments

18. Are you responsible for designing or overseeing the design of the silhouette and print design, or these processes delegated to separate departments. Please explain.

19. Please explain how you map or decide placement of a graphic onto the body of a garment or product. Please check all that apply.

- ☐ Trial and error with prototypes
- ☐ Texture map on a 2D image
- ☐ Texture map on a 3D image
- ☐ Draw or project imagery onto a prototype
- ☐ Draw or project imagery onto flat pattern pieces
- ☐ Other (please specify)

20. Please explain any problems or special concerns associated with manufacturing an engineered design.

13. Printed Engineered Design: Communication

1. How do you communicate information about silhouette, product shape, color, and print graphics within your organization or design team? Please check all that apply.

- ☐ Verbal: in person
- ☐ Verbal: by phone
- ☐ Visual: written specification
- ☐ Visual: pictorial representation
- ☐ Digital Communication: Written (e-mail, etc.)
- ☐ Digital Communication: Graphic (sending pictures, imagery in digital format)
- ☐ Other (please specify)

2. How do you communicate information about silhouette, product shape, color, and print graphics to your manufacturer? Please check all that apply.

- ☐ Verbal: in person
- ☐ Verbal: by phone
- ☐ Visual: written specification
- ☐ Visual: pictorial representation
- ☐ Digital Communication: Written (e-mail, etc.)
- ☐ Digital Communication: Graphic (sending pictures, imagery in digital format)
- ☐ Other (please specify)

3. Have you experienced a noticeable improvement in speed and ease of sending larger graphic files in the past ten years?

- ☐ Yes
- ☐ No

Comments