ABSTRACT

FOSTER, KARIS R. Factors Influencing the Adoption of 3D Knitting Technologies by U.S. Companies: A Case-Study Analysis. (Under the direction of Dr. Cynthia Istook)

The textile industry is known as a mature industry, with a long-standing established infrastructure and means of production. Even though technological advancements have occurred, the adoption of new technologies into the standard textile production practices is often delayed. The purpose of this research was to uncover the factors which contribute to the organizational adoption of the novel innovation called 3D knitting. By means of a case-study analysis, drivers and barriers to adoption were identified along Roger’s organizational innovation of diffusion process, resulting in a theoretical framework for innovation decision-making. A literature review of the history of knitting, seamless knitting claims, knit production processes, adoption models, innovation decision-making, and case-study research design was explored to ensure an understanding of prior research relating to 3D knitting and innovation decision-making. Based upon this review, a theoretical framework was developed with contributing factors named ‘areas of influence’, prior to field research. A case study design was chosen for this research due to its external validity for an immediate industry issue. Eight companies who had adopted the technology (either currently or in the past) were interviewed in-person, with a total of eighteen respondents. NVivo qualitative data analysis software was used for data coding and the summarizing phases of the research. Driver themes identified through data analysis were: cultural, operational, consumer and demand. Barrier themes identified were: knowledge, operational, management, capital and consumer. An updated theoretical framework was developed to show the identified barrier and driver themes and where along the organizational innovation of diffusion they occurred.
Factors Influencing the Adoption of 3D Knitting Technologies by U.S. Companies: A Case-Study Analysis

by
Karis R. Foster

A dissertation submitted to the Graduate Faculty of North Carolina State University in fulfillment of the requirements for the degree of Doctor of Philosophy

Textile Technology Management
Raleigh, North Carolina

2017

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DEDICATION

To the men in my life, who have all revealed a part of the Father’s heart for me.

Dad, your blind enthusiasm

Salem, your compassion and genuineness

Zion, your tender nature

Tim, your unmatched humor, friendship and pursuit to understand me

Darren, your kindness and unshakable faith
BIOGRAPHY

Karis Foster is a Doctoral Candidate and Lecturer in the College of Textiles at NC State University. She is a rare breed, born and raised and currently lives in the City of Oaks, Raleigh, NC. She has always been enthusiastic about the arts and how form meets function. This is originally what drew her to the field of fashion and textile management in her undergraduate studies at NC State, a field which requires a perfect balance of creative and technical skills. Karis’ technical knowledge grew in her Masters studies in Textiles and a new love of knitwear emerged. She has had the opportunity to work with two leading companies in 3D knitting technologies and hopes that this knowledge will only continue to grow upon completion of her doctorate degree. During her doctoral studies, Karis has also had the chance to experience teaching first-hand. She has developed a love for teaching due to the simple truth that one learns so much more when they teach. Her CAD pattern-making skills have seen tremendous growth during this time and has also sparked her excitement in this area of apparel production. Karis enjoys primarily to answer the 'how' questions in the textile complex; how products are made and how will they be disposed? As simple as these questions are, she believes they lead to some of the most crucial research topics of our time in the field of textiles. Karis’ favorite place to work on her research is sitting next to her apricot colored cat, named ‘Kitty’. Karis Foster is expected to complete her Doctoral of Philosophy in Textile Technology Management in December 2017.
ACKNOWLEDGEMENTS

Many thanks and acknowledgements are overdue for the countless individuals who have helped shape the research that is presented. I would like to thank the members of my committee, assisting me through every step of my graduate career.

First, I must thank Dr. Cynthia Istook, my committee chair and major professor for believing in me from the outset of my academic career. I had the pleasure of working with Dr. Istook the final semester of my undergrad studies and I never would have guessed the impact she would have on my life. If not for Dr. Istook, I would have never been able to attend graduate school or pursue my doctorate without her advocating for my funding. She has managed to make a way for me to pursue this particular form of research which is somewhat unconventional in our field of study. I am overwhelmed by your generous heart, Dr. Istook, and the constant encouragement you have shared with me.

I would also like to thank Dr. Marguerite Moore, for providing valuable insight into this exploration of qualitative research. I could not have managed the strenuous workload that qualitative research takes on one’s brain, without Dr. Moore’s clarity of thought and decisive action. Thank you for your genuine encouragement, Dr. Moore, and the ease with which you can solve some of the most complex problems in an instant.

Dr. Andre West has also provided great encouragement to me during my graduate studies relating to any questions I have had about knitting, of which I am truly grateful. Without him, I would not have been able to have as much time on the 3D knitting machines that we have on campus and would not understand knitting as well as I do today. I am sincerely thankful for you, Dr. West, for your curiosity and passion for knitting, and your unending support in my knitting interests.
Last but not least, I would like to thank Dr. Lisa Parillo-Chapman for her belief in me dating back into my undergraduate studies. It was Dr. Chapman who first counseled me to pursue graduate school and who first inspired my interest in knitting. Without her attention to detail, I would not have the articulated research presentation before you today. Thank you, Dr. Chapman, for your consistently joyful outlook and encouragement in times when I felt hopeless.

There were eighteen informants during this research study, of who I am eternally grateful for their donated time and expert opinions. Thank you also to the eight companies who were willing to participate in the study for the sake of a continued body of knowledge regarding 3D knitting. I would also thank my professors at the College of Textiles, who have helped shape my research interests and given me the skills to undergo such a substantial project.

To my friends who have seen the best and the worst of me over the past four years, thank you for being there to offer your comfort, your advice and your joy. It is the moments that we have shared and the talks that we’ve had that have sustained my spirit these past four years.

Last but definitely not least, I would like to thank my family for supporting me through my academic career and cheering me on during the process. In the midst of the ups and downs of my graduate career, they have been there acting as a sounding board, a rock and a steady source of encouragement. My mother, Carolyn, is responsible for caring for me countless times through this process: emotionally, spiritually and physically. I could not have made it without you, Mom, and I am so thankful that I was gifted with such a generous mother as you. My father, Jim, has given me the gift of hope by offering his excitement in this academic path, and for this I am truly grateful as it has spurred me on to complete the goal. Thank you, Dad, for your unending enthusiasm which I hope to embody one day. To my brothers and sisters, thank you for extending humor into this process and always bringing joy into my life. Blessings to you all!
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CHAPTER ONE
INTRODUCTION

The world has changed at a rapid rate, increasing communication abilities for many industries. Technology developments have grown at exponential rates and the adoption of these technologies has posed a hurdle for businesses in all industries. Similarly, the textile industry has experienced technology developments in the area of knitting, of note is the novel technology called 3D knitting. By means of a case-study analysis, this study has evaluated how 3D knitting technology is currently being adopted by identifying the drivers and barriers to adoption.

Background of the Problem

The textile industry is unique in its slow rate to adopt new technologies. Adoption decisions today still remain a mystery. It is one of the known “mature” (p.56) industries of the world with a long-standing established infrastructure and means of production (Ray, 1983). Yet, improvements have been made to the traditional sewn products industry by means of new machinery, computer-aided systems and supply chain efficiencies. Whether these technological advancements have changed the known textile supply chain is yet to be seen. This research has examined a sub-set of the United States textile industry in knitting technology, specifically related to flat-bed seamless knitting.

Statement of the Problem

There are many drivers and barriers that may impact how a company makes an adoption decision. These factors have an inherent positive or negative influence on the decision-making phase of technology adoption. Identifying these factors could assist business owners to make
informed decisions about the technology they are considering for adoption. All factors must be evaluated with care to result in the best decisive action.

**Purpose of the Study**

The purpose of this study was to identify the decision-making factors that contribute to the adoption of 3D knitting technology. Though this method of knitting has been praised in recent years for its innovativeness, there exists prohibitive limitations to its incorporation into standard production streams. The factors found in this study could assist companies make better informed decisions about their chosen technology adoption. Results of this research could also provide insightful information to machine manufacturers regarding obstacles they could encounter with sales of their technology and potential areas of opportunity.

**Research Objectives**

The objectives of this study were to uncover the barriers and drivers of technology adoption within the Textile and Apparel complex. Organizational factors which influence the adoption of technology were organized into barrier and driver themes. Following the organizational innovation process, a framework was developed which incorporated the findings.

The following research objectives were developed for this study:

**Objective 1:** To identify the drivers for adoption of 3D knitting technologies through the full organizational diffusion of innovations process.

**Objective 2:** To identify the barriers for adoption of 3D knitting technologies through the full organizational diffusion of innovations process.
Significance of the Study

This study contributes to the body of knowledge relating to the diffusion of innovations in the Textile and Apparel industries, most specifically in the area of flat-bed seamless knitting. Little research has been conducted in the past that would provide an insight into the complicated decision-making process related to the adoption of innovation within the Textile and Apparel complex. The results of this study may help bridge the gap between knowledge regarding the capabilities of the technology and the process in which it has been adopted into business operations that are especially relevant to this industry.

Definition of Terms

The following terms have been used throughout this research. A definition is provided here to aid in understanding.

3D Knitting. A term applied to knitted products, of technical or fashion nature, which have all shaping and joining conducted on a flat-bed knitting machine. Other terms which can be used synonymously include ‘integral knitting’, ‘WholeGarment®’ (Shima Seiki trademarked term), ‘knit & wear®’ (Stoll trademarked term), ‘seamless’ and ‘complete-garment’. Trade press articles have used this term as a means to describe the way a product is made (“Fully-fashion and 3D-knitting techniques”, 2017; Legner & Stoll, 2003; “One sleek piece…”’, 2017; “Shima Seiki at Techtextil…”, 2014; “Thursday Finest benefits…”, 2017). It is also a marketing term for the consumer to understand how the innovative technique works without being familiar with knitting principles (Reilly, 2017).

Seamless Knitting. A general term applied to knitted products which have eliminated some seaming of a product. With much discrepancy, ‘seamless’ is often marketed by machine manufacturers for a method of knitting that reduces seaming in a product but still requires
additional making up off of the knitting machine (Karl Mayer, 2017; Santoni, 2017). Appendix A lists and describes the various seamless machines available to the market as of 2017. Due to its ambiguous nature, ‘seamless’ was not chosen as a general term for flat-bed three-dimensional knitting.

**Complete-Garment.** A term applied to three-dimensional knitted garments or knitwear which have all shaping and joining developed while on the knitting machine. Other terms which have been used synonymously used with other terms include ‘3D knitting’, ‘complete-garment knitting’; ‘WholeGarment®’, (Shima Seiki trademark); ‘knit & wear®’ (Stoll trademark); ‘seamless knitting’; ‘one-piece knitting’; and ‘integral knitting’ (Brackenbury, 1992; Choi & Powell, 2005; Kanakaraj & Ramachandran, 2010; Peterson, 2015; Peterson, Larsson, Carlsson & Andersson, 2008; Rao, 2012; Tait, 2008). The term was first established by John Millington (2000), and can also describe generally any garment which is produced mostly on the knitting machine, with minimal processing post-knitting (ex: socks, hosiery, etc.).

**Integral Knitting.** This term has been used to describe “articles which are completely assembled on the knitting machine and require no further making-up operations off the machine” (Spencer, 2001, p. 84). Also known as “whole garments” (Spencer, 2001, p.84). Other sources describe integral knitting as “the combined knitting of more than one component during the knitting sequence of a garment, for example, a body plus trimming and a pocket” (Denton & Daniels, 2002, p. 175). In several instances, ‘integral knitting’ is a general term for the addition of integrated features to a full-fashioned knitted panel, similar to the Denton & Daniels definition (Brackenbury, 1992; Dimkonis and Schminke, 1998; Kanakaraj and Ramachandran, 2010; Larsson, Peterson & Mattila, 2012; Peterson and Ekwall, 2007). Due to this discrepancy in definitions, ‘integral knitting’ will not be used to describe knitting a garment in one-piece.
**Integral Garments.** A term to describe “those (garments) that are essentially knitted in one piece with little or no seam” (Brackenbury, 1992, p. 17). Examples are a tubular knitted sock, gloves and berets.

**Full-Fashioned.** A term applied to “knitted fabrics and garments that are shaped wholly or in part by widening and/or narrowing by loop transference to increase or decrease the number of wales” (Mills, 1965, p. vi; Denton & Daniels, 2002: p.308). Also known as ‘fully-fashioned’ (Denton & Daniels, 2002: 308); ‘shaped knitting’ and ‘panel knitting’. A final stage is required to link or join full-fashioned panels together to make a three-dimensional garment (Brackenbury, 1992).

**Cut & Sew.** A term applied to the traditional garment production systems, where garment pattern pieces are cut from a length of fabric and sewn into final three-dimensional garments. This often results in wasted fabric and an increase in production time. Also called “fully-cut garments” (Brackenbury, 1992, p. 38).

**Reshoring.** A term popularly used to describe the return of manufacturing or sourcing of raw materials to the country of origin of a parent company, specifically the United States (Ellram, Tate & Petersen, 2013). In this research, reshoring will be in reference to the act of bringing manufacturing back to the United States, to take advantage of speed to market opportunities, in addition to providing an opportunity to meet the needs of smaller niche markets. Also known as “insourcing” (Fishman, 2012, p.75) and “backshoring” (De Backer, Desnoyers-James, Menon, & Mouissiegt, 2016, p.7).

**Areas of Influence.** A term coined by the author, to describe contributing factors that might affect the decision process related to the adoption of 3D knitting technology. These hypothesized factors were developed by the author prior to field research and are found in Table
1. The areas of influence served as a starting foundation for the case-study protocol. Expanded explanations of each area of influence can be found in Appendix B.

Assumptions, Limitations and Delimitations

Assumptions

In this research, we assumed that all companies who participated have adopted 3D knitting technology. We also assumed that these companies are headquartered or have manufacturing facilities in the United States.

Limitations

There were several limitations present in this study which are inherent to the use of case-study research. The types and number of companies represented served as a limitation on the research, as only a select few companies were studied. An inherent bias was present in the companies sampled due to their willingness to participate in the study. It can be argued that the companies who participated were also more open to considering the adoption of new technologies simply because of their willingness to speak about the subject.

There was also a limitation of resources and timeline for this study. In order to complete this research in a reasonable amount of time, a select few companies were chosen for

<table>
<thead>
<tr>
<th>Areas of Influence</th>
<th>Managerial</th>
<th>Training/Personnel</th>
<th>Investing/Cashflow</th>
<th>Design Considerations</th>
<th>Size</th>
<th>Inception</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Market/Demand for Product</td>
<td>Diffusion Positioning</td>
<td>Perceived Benefits</td>
<td>Perceived Limitations</td>
<td>Supply Chain Flexibility</td>
<td>Logistics Considerations</td>
</tr>
<tr>
<td></td>
<td>Positioning of Product</td>
<td>Sustainability</td>
<td>Quality Considerations</td>
<td>Production Processes</td>
<td>System Openness</td>
<td>Reshoring</td>
</tr>
</tbody>
</table>

Note: Author’s own.
participation. This exploratory research has opened the door to further research relating to the adoption of 3D knitting technology, rather than explain the global issue in full.

Due to the qualitative nature of this research, this study was also limited by the participants who were interviewed. People are some of the most complex and nuanced variables which can be studied. Insights and findings from this research were based on opinions and pre-conceived notions of these participants which has also served as a limiting factor in the research.

**Delimitations**

Areas of research not covered in this study, purposefully, are any ‘seamless’ knitting technology which cannot be classified as 3D knitting technology, by use of a flat-bed machine. In order to gain a specified insight into this new technology, the scope of the study was narrowed to only the instances where companies have adopted 3D knitting technology.

**Conclusion**

The purpose of the research was to assist business owners in making the wisest decisions possible, by investigating all factors that must be considered to adopt 3D knitting technology. These drivers and barriers to adoption were found after the hypothesized factors, classified under areas of influence, set the foundation for in-depth questioning by company representatives.
In order to provide a foundation upon which to base the efforts of this research, the following topics were evaluated in previous literature: history of knitting; knit product processes; innovation, adoption and decision-making models; and case study research.

**History of Knitting**

A number of knit technologies have been developed in the past that continue to have a significant impact on knit products presently. The following overview of knitting provided clarity on this evolution towards the technology used today.

**Weft Knitting**

A knitted fabric is constructed by the inter-looping of yarns. The first known use of knitting dated back to the Coptic Era of Egypt (Spencer, 2001). The type of knitting achieved during this time is referred to as weft knitting. In this method of creating fabric, loops of yarn are inter-linked in a horizontal row or “course” (Reichman, 1972, p. 82-83; Spencer, 2001, p. 16). With sequential rows of weft knitting, a fabric is produced which grows from the first course up to the last in a vertical orientation.

Weft knitting gained its most important boost in productivity with the invention of the stocking hand frame, in 1589, by William Lee of Nottinghamshire. This invention was so advanced at its inception that the mechanisms for weft knitting remained unchanged for centuries. This stocking hand frame laid the foundation for current methods of weft knitting production: circular and flat-bed. (Spencer, 2001) Key weft knitting developments are displayed as a historical timeline in Table 2 from the inception of knitting to the machines of today.
# Table 2

**Timeline of Weft Knitting Developments**

<table>
<thead>
<tr>
<th>Knitting Development</th>
<th>Time in History</th>
</tr>
</thead>
<tbody>
<tr>
<td>First known weft knitting</td>
<td>Coptic Era-Egypt</td>
</tr>
<tr>
<td>Stocking Hand Frame, by William Lee</td>
<td>1589</td>
</tr>
<tr>
<td>First Circular Knitting Machine (cylinder and dial)</td>
<td>Mid-1800s</td>
</tr>
<tr>
<td>Latch Needle, by Matthew Townsend</td>
<td>1849</td>
</tr>
<tr>
<td>First patented compound needle with sliding latch by Jeacock of Leicester</td>
<td>1856</td>
</tr>
<tr>
<td>Flat-bar machine, by Isaac Lamb</td>
<td>1862</td>
</tr>
<tr>
<td>Heinrich Stoll invented purl split machine with double-ended needles</td>
<td>1890-91</td>
</tr>
<tr>
<td>Rib knitting machine invented</td>
<td>1900</td>
</tr>
<tr>
<td>Automatic narrowing machine, by Stoll</td>
<td>1920</td>
</tr>
<tr>
<td>First motor-driven jacquard flat machine, by Stoll</td>
<td>1926</td>
</tr>
<tr>
<td>First patent for shaped skirts in U.S.</td>
<td>1940</td>
</tr>
<tr>
<td>First three-dimensional knit object (Basque style beret)</td>
<td>1955</td>
</tr>
<tr>
<td>Full-fashioned hosiery knitting machine invented</td>
<td>1959</td>
</tr>
<tr>
<td>Automatic flat knitting machine developed</td>
<td>1962</td>
</tr>
<tr>
<td>First electronic needle selection on rib jacquard circular knitting machine, by Franz Morat</td>
<td>1963</td>
</tr>
<tr>
<td>V-bed full-fashion flat knitting machine developed</td>
<td>1967</td>
</tr>
<tr>
<td>Stitch pressing-down devices (“presser foot”), developed by Frank Robinson and Max Betts of Courtaulds (used by Dubied, Bentley-Cotton &amp; Shima Seiki)</td>
<td>1968</td>
</tr>
<tr>
<td>‘Flechage’ first used in automatic V-bed seamless glove machine by Shima Seiki</td>
<td>1960s</td>
</tr>
<tr>
<td>First fully-electronic/ computerized flat knitting machine developed by Stoll</td>
<td>1975</td>
</tr>
<tr>
<td>Digital stitch control system developed by Shima</td>
<td>1984</td>
</tr>
<tr>
<td>Stoll introduced the CMS series machines with belt-drive system and loop holding sinkers</td>
<td>1987</td>
</tr>
<tr>
<td>Event</td>
<td>Year</td>
</tr>
<tr>
<td>----------------------------------------------------------------------</td>
<td>------</td>
</tr>
<tr>
<td>Shima launched SES122FF with 40-inch needle bed, equipped with</td>
<td>1989</td>
</tr>
<tr>
<td>set-up comb, main roller, auxiliary roller, stitch presser, primary</td>
<td></td>
</tr>
<tr>
<td>and secondary stitch cams and DSCS. (Then soon after introduced</td>
<td></td>
</tr>
<tr>
<td>SES122S with spring loaded sinkers)</td>
<td></td>
</tr>
<tr>
<td>Shima introduced SES 122 RT, having four beds- upper two used for</td>
<td>1993</td>
</tr>
<tr>
<td>loop transfer points rather than needles</td>
<td></td>
</tr>
<tr>
<td>Shima developed a belt-driven 4 needle-bed computerized flat</td>
<td>1994</td>
</tr>
<tr>
<td>knitting machine</td>
<td></td>
</tr>
<tr>
<td>Shima introduced the first WholeGarment® knitting machines, SWG-</td>
<td>1995</td>
</tr>
<tr>
<td>X incorporating four needle-beds and SWG-V incorporating two</td>
<td></td>
</tr>
<tr>
<td>needle-beds.</td>
<td></td>
</tr>
<tr>
<td>Shima introduced their FIRST (full-fashioning, intarsia &amp; sinker)</td>
<td>1997</td>
</tr>
<tr>
<td>knitting machine incorporating the Slide Needle design (enabling</td>
<td></td>
</tr>
<tr>
<td>lateral transfer, split stitch, second stitch, inlay and holding</td>
<td></td>
</tr>
<tr>
<td>techniques), contra sinkers, variable take-down and automatic ‘kic-</td>
<td></td>
</tr>
<tr>
<td>k-back’ for yarn carriers.</td>
<td></td>
</tr>
<tr>
<td>Shima developed SDS-ONE, All-in-One Design System</td>
<td>2000</td>
</tr>
<tr>
<td>Stoll introduced M1 software</td>
<td>2001</td>
</tr>
<tr>
<td>Shima Seiki introduced the SWG 021 &amp; 041 Mini-WholeGarment®</td>
<td>2004</td>
</tr>
<tr>
<td>machines with moveable sinkers, slide needles and optional iDSCS</td>
<td></td>
</tr>
<tr>
<td>and Air Splicer.</td>
<td></td>
</tr>
<tr>
<td>Shima developed the Mach2X and Mach2S WholeGarment®</td>
<td>2007</td>
</tr>
<tr>
<td>machines with four needle-beds. Also develops the SDS-ONE APEX 3</td>
<td></td>
</tr>
<tr>
<td>for the development of WholeGarment® knitting programs</td>
<td></td>
</tr>
<tr>
<td>Stoll introduced M1plus Software system</td>
<td>2008</td>
</tr>
<tr>
<td>Patent applied for sub-roller, pulldown device (Shima Seiki)</td>
<td>2010</td>
</tr>
<tr>
<td>Shima developed SWG-FIRST154 S21, the world’s first knitting</td>
<td>2011</td>
</tr>
<tr>
<td>machine able to knit in 21 gauge</td>
<td></td>
</tr>
<tr>
<td>Stoll introduced the CMS-ADF3 series, with 32 self-sufficient yarn</td>
<td>2013</td>
</tr>
<tr>
<td>feeders</td>
<td></td>
</tr>
<tr>
<td>Patent applied for thread guides arranged along guide bars, working</td>
<td>2013</td>
</tr>
<tr>
<td>independently from the carriage (Stoll)</td>
<td></td>
</tr>
</tbody>
</table>
Table 2 Continued

<table>
<thead>
<tr>
<th>Event Description</th>
<th>Year</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shima introduced SRY123LP with loop presser beds</td>
<td>2013</td>
</tr>
<tr>
<td>Shima introduced SWG-N2, Mini-WholeGarment® machine with increased color capacity and production of industrial textiles</td>
<td>2014</td>
</tr>
<tr>
<td>Santoni introduced MEC-MOR Variatex CMP &amp; HP, seamless circular knitting machines with variable working width</td>
<td>2015</td>
</tr>
<tr>
<td>Shima introduced MACH2XS, a WholeGarment® machine with moveable sinkers on four needle-beds</td>
<td>2015</td>
</tr>
</tbody>
</table>


Circular. Circular weft knitting is conducted on a “rotary machine equipped with dial and cylinder” (Reichman, 1972, p. 81). By the mid-19th century, knitting methods evolved to accommodate rotary mechanisms and circular frames required for this type of knitting (Spencer, 2001). This type of machine produces a tubular fabric that is traditionally used as length yardage for cut and sewn products. There are two main types of cylinder machines: single-cylinder and cylinder and dial. Single-cylinder machines produce a single jersey (single layer of knitting with a technical face and technical back); while cylinder and dial machines are capable of producing a double jersey (a double layer fabric which can have identical technical face and technical back). Circular knitting machines are unmatched in their high speed and production efficiency due to their cyclical nature of knitting. The knitting mechanism is never hindered due to the circular orientation of knitting needles. Circular knitting capabilities later realized their full potential by the invention of the latch needle by Matthew Townsend in 1849 (Spencer, 2001). According to Spencer (2001), “it is now accepted that precision-manufactured latch needles can knit structures of the highest quality” (p. 23). The evolution of knitting over hundreds of years and
improvements on machine parts have greatly impacted the success and adoption of circular knitting in the textile industry.

**Flat-bed.** Flat-bed knitting is conducted on a straight needle-bed, positioned in a horizontal orientation. Isaac Lamb first introduced his “flat-bar machine” (p.207) in 1862 (Spencer, 2001). This design later impacted the development of two types of flat-bed knitting machines: double-bed (V-bed) and single bed (flatbed purl or links-links) (Spencer, 2001). In this method, a knitting carriage which activated needles to create loops, carried a yarn across the length of the needle-bed, stopped, and then traversed back to the original position. Since a stopping motion of the carriage from one side to the other is required, this method is less efficient in producing yardage of fabric than circular knitting (Spencer, 2001). There are also advantages to flat-bed knitting, like its inherent quality and pattern versatility (Millington, 2000a).

Flat-bed knitting is limited by the knitting width of the needle-bed. This greatly impacts the sizes of products that can be created on a given machine (Spencer, 2001). The machine gauge in flat knitting is defined by the number of needles per inch on a needle-bed (Reichman, 1972). This constraint changes the coarseness and fineness of a produced fabric and has an impact on the resulting product.

Flat-bed knitting has seen much growth in its development since the late 19th century from its flexibility in designing of products. According to Spencer (2001), automatic power flat knitting emerged in the early 19th century as inventors made improvements on Lamb’s design. Stoll, a key player in the 3D knitting machine market today, contributed greatly to the progress of flat-bed knitting by inventing, “the first motor-driven jacquard flat machine, in 1926; the first
fully-electronic flat machine, in 1975 and the first of the CMS series machines, in 1987”
(Spencer, 2001, p. 224).

With the age of electronics, knitting methods soon gained much of the productivity that it
had been missing with mechanically controlled knitting machines. Flat-bed knitting
developments achieved great strides in the ability to quickly produce a more complicated knit
fabric like jacquard, intarsia, or incorporating shaping to panels (Spencer, 2001). It was the
advent of ‘electronic needle selection’ that gave flat-bed knitting the ability to activate individual
needles for advanced knit stitches (Millington, 2000a).

Soon, the bounds of flat-bed knitting were stretched by the exploration of creating shaped
skirts; the first known example of this was patented in the United States in 1940 (Hunter, 2004)
According to Billy Hunter (2004), the first successful attempt at knitting a three-dimensional
object by automatic knitting occurred in 1955, as a Basque style beret. This method of knitting
created a new term in knitting known as ‘flechage’, ‘course shaping’ (Brackenbury, 1992, p. 77)
or ‘short-rowing’, where specified needles store an area of loops to later be picked up in a
knitting sequence, which allows for the darting of a knitted fabric (Brackenbury, 1992; Hunter,
2004). This knitting ability would not have been possible without the development of the stitch
presser or “presser foot” by Frank Robinson and Max Betts of Courtaulds which was later used
by Dubied, Bentley-Cotton and Shima Seiki (Spencer, 2001).

The principle of flechage later was actualized by Shima Seiki, in the 1960s with their
invention of an automatic V-bed seamless glove-knitting machine (Spencer, 2001). Hunter
explained that though much research and development of this technique took place through the
1960s, the ability to join knitted tubes together during a knitting sequence was impossible due to
the take-down systems limitations.
Since the 1980s, major developments were made by both Shima Seiki and Stoll, setting the stage for 3D Knitting. Shima Seiki invented their Digital Stitch Control System (DSCS) in 1984, which was later perfected with iDSCS (intelligent digital stitch control system). The iDSCS allows for better efficiency during knitting by pre-determining the necessary amount of yarn for every knitted stitch (Anderson, 2008). It was the Stoll CMS series machine, introduced in 1987, which attained two important developments in flat-bed knitting: loop holding sinkers and reversible motor technology (also known as the belt-drive system) (Hunter, 2004). This allowed for knitting to take place only within the required needle width for a product. Before this innovation, flat-bed machines had chain-drive systems which required the carriage to run the full width of the needle-bed for each course.

It was not until 1995 that Shima Seiki launched the four needle-bed configuration with their SWG-X machine which was able to produce the first WholeGarment® sweater (Hunter, 2004). The four needle-bed configuration allowed for transference of stitches to make a seamless three-dimensional garment using all needles (a task that could only previously be accomplished by knitting in half-gauge). In the same year, Shima introduced the SWG-V, which was a two-bed WholeGarment® machine.

Shima Seiki then developed the SlideNeedle®, which was incorporated to the FIRST (full fashioned, intarsia, sinker) machine (Spencer, 2001). The SlideNeedle® allowed for a twelve-way knitting techniques including: lateral transfer, split stitch, second stitch, inlay and holding techniques (Karasuno, 2000). Figure 1 demonstrates the added consistency in knitting with the use of the SlideNeedle® as it positions the yarn symmetrically in the needle-bed groove.
In 1999, Stoll introduced their version of 3D knitting technique, with the TC generation knit & wear® machines. The new machines incorporated Stoll’s multi-gauge knitting technique, also known as flexible gauge knitting (Millington, 2000a). The technique allowed for two gauges to be knit in the same course, made possible by “moveable knockovers” and “spring-borne latch needles” (Flat Bed Knitting Developments, 1998, p.20). Stoll-touchcontrol® was also introduced at the same time, adding to Stoll’s philosophy of flexible manufacturing. The computer touch screen allowed for quick changes of a knitting pattern at the machine.

One of the most important developments enabling WholeGarment knitting, involved the CAD patterning system, known as the SDS-ONE; its most updated version is called the APEX3 (“SDS-ONE,” 2016). Spencer (2001) stated that the Shima Total Design System is a “totally-integrated knit production system that allows all stages- planning, design, evaluation, production, and sales promotion- to be integrated into a smooth work-flow” (p. 144). The APEX3 software

![Conventional latch needles offset in grooves](image1) ![SlideNeedles® centered in grooves](image2)

Figure 1. SlideNeedle® compared to conventional latch needles

Note: taken from Anderson, 2008, p.3
has also made great improvements in added flexibility of template designs, avatar simulations and material simulations (“SDS-ONE,” 2016).

On the other hand, Stoll debuted their M1 pattern preparation system to the public in 2001. This software allowed for the programmer to view technical information and knitted simulations at the same time (“Solutions for,” 2001). Stoll has made improvements to the software with their introduction of the M1plus software in 2008. The upgraded software allowed for the creation of color arrangements, module arrangements and a new design-mode (“Peripheral equipment…”, 2008). The module arrangement assists the knitting programmer by identifying the process order of modules within a given course. Color arrangements are useful in the example of knitting an intarsia pattern by splitting up the knitting efficiently. (“New solution.”, 2009)

**Warp Knitting**

Lee’s invention of the stock knitting frame led to the development of the principles for warp knitting. The first example of this method of knitting was seen in 1769 by Crane and Porter, which established the method of using a series of warp yarns as a grounding agent for embroidery knit on the stocking frame. The first warp loom with a weft knitted ground was patented by Crane in 1775 (Spencer, 2001).

Warp knitting functions similarly to a loom that creates woven fabric. A warp or length of yarns in the vertical direction serves as the grounding agent for the interlinking of diagonal loops of yarn. In this sense, a warp knitting machine typically produces a length of fabric, rather than complete-garments (Reichman, 1972; Spencer, 2001).
There are two categories of warp knitting machines: tricot and Raschel. Tricot fabrics are known to be finer in gauge (28-32 needles per inch), and Raschel fabrics are generally coarser gauges (12-18 needles per inch) (Reichman, 1972). Though this technology has traditionally been used to create sheeting of knitted fabric, warp machine companies like Karl Mayer are developing their own ‘seamless’ knitted options. The first mention of this in trade press occurred in 2009, where Knitting International reported the advent of Karl Mayer’s DJ42 ‘seamless warp knitting model’ that was able to create small ‘seamless’ pieces (Siddons, 2009). In 2012, Karl Mayer introduced the RDPJ 4/2 two-bar Raschel machine, which allowed knitting of two layers of fabric that are bound together at specified areas, creating a ‘seamless’ garment (“Brückner/ Karl Mayer”, 2012). This type of seamless knitting is demonstrated in Figure 2.

Figure 2. Warp seamless knitting before stentering.  
Note: taken from Brückner, 2012, p. 30

**Previous Research: Three-Dimensional Knitting**  
Though 3D knitting is still in its infancy, several empirical studies have been conducted to demonstrate its advantages over other production methods. Most of these studies have dealt with the knitting capabilities of these machines (Choi & Powell, 2005; Ma & Lamar, 2013; Song,
Wu & Wei, 2006), communication issues between designers and technicians (Eckert, 1999; 
Sayer, Wilson & Challis, 2006) and proposing new retail concepts through fast fashion and mass 
customization (Larsson et al, 2012; Peterson, 2015; Peterson et al, 2008; Peterson & Ekwall, 
2007). There remains a void in the body of research relating to 3D knitting technology and how 
it is adopted by knitting companies. Understanding this decision-making process is not only 
beneficial for business owners and investors to make wise decisions, but also for the machine 
manufacturers to know how to best market themselves to potential customers.

The Seamless Conundrum

With the evolution of knitting technologies in recent years, terminology has become 
muddled with various meanings, leaving consumers and academics without a general term for 
flat-bed seamless knitting. Seamless knitting in its truest form would mean a product without 
seams. This translates directly to a product which has all making up conducted on the machine 
itself. However, the term seamless has been marketed by all methods of knitting, including 
circular, warp and flat-bed (Karl Mayer, 2017; Santoni, 2017; Shima Seiki, 2017b & Stoll, 
2017b). An investigation of the machines which are marketed as creating seamless products as 
of 2017 are presented in Appendix A.

The term integral knitting has been used in academic publications regarding a product 
where all making up is conducted on the machine. However, the use of this term in industry 
settings is uncommon, resulting in a lessened external validity.

The capability of knitting a three-dimensional shaped piece is not a new phenomenon. 
This method of knitting is achievable by using only two needle-beds. The caveat to working with 
two needle-beds is requiring the knitting to occur in half-gauge in order to knit a seamless three-
19 dimensional piece. Shima Seiki’s development of the four needle-bed system eliminated the need to knit every other needle. Stoll’s knit & wear® machines are able to achieve a three-dimensional shape, in one piece from the machine but requires the garment to be knit half-gauge (knitting every other needle), resulting in a bulkier knit. Shima Seiki has attained success with WholeGarment® knitting by allowing for the creation of fine gauge knitted garments that would be difficult to join otherwise.

**Knit Product Processes**

The business decision to adopt a new technology is greatly impacted by the production processes that are already in place to create a product. For this reason, a review of the various production processes relating to knitted products is presented. The processes discussed will further explain the advantages and disadvantages that are present in each knit production process.

**Cut & Sew**

The traditional method of creating a knit garment is known as cut & sew, where pattern pieces of a garment are cut from a length of fabric and then sewn or linked together. Cut & sewn

![Figure 3. The cut and sew production method. Developed by author.](image)
garments made of knitted fabric is typically from a circular or warp knitting machine. (Brackenbury, 1992)

Circular machines are classified into two categories: 1. Single jersey, and 2. Double jersey (Brackenbury, 1992, p.10). A visual representation of the cut & sew method is presented in Figure 3. The production sequence of cut & sew production is provided by Brackenbury, in Figure 4.

**Advantages.** The benefits seen with a cut & sew production method are equal to the benefits of circular knitting since most circular knitting types require a making-up process. Circular knitting is known for its unmatched speed of production, due to continuous knitting with a cylinder and dial. This created an advantage for the cut & sew production method, so that more products can be created in a shorter amount of time.

If a company already had cut & sewn manufacturing methods in place, it is likely easier for them to continue in this method of operation. This production sequence required a larger workforce to operate post-knitting steps, and thus could be an advantage to companies who have well established relationships in areas with a cheap labor supply (Peterson & Ekwall, 2007).

**Disadvantages.** There were several disadvantages discovered regarding the production sequence of fully-cut garments. Garment or pattern pieces are always cut from a length of fabric. The surrounding fabric around these cut pattern pieces were usually thrown away. This wasted material translated not only to a loss of usable material and capital, but also added disposal costs. This waste-factor of fully-cut garments could have, “ranges from 17-50%” (Brackenbury, 1992, p.13), for any given product. According to Kanakaraj and Ramachandran (2010), and Peterson et al (2008), as much as 30- 40% of the original fabric may be wasted in this process. Disposing of
these scrap fabrics were costly to the firm in a financial sense, and could also be costly to their marketing image from a sustainability perspective.

This production method was also found at a disadvantage in terms of its ease of manufacturing. Knit fabrics differed significantly to woven fabrics which may be layered on top of each other for cutting of multiple pattern pieces. Due to the extensible nature of knit fabrics, distortion could occur, and edge-curling of the fabric is expected (Reichman, 1972). This unfortunate fact, could create inconsistent cutting of pattern pieces, which in turn created inconsistently finished products (Reichman, 1972). Because of this unstable characteristic of knitted fabric, automation of cut and sewn garments had been unattainable (Millington, 2000a).

Cut and sewn garments were also stated as liable to human error, as they are joined by human operations (the costliest of all production overhead) (Anderson, 2005). This posed a risk to the overall garment quality and potentially the credibility of a brand. Possibly the most

Figure 4. Cut & Sewn Production Sequence, information provided by Brackenbury, 1992, p.12
commonly mentioned disadvantage to the cut & sew method is the existence of post-knitting activities, including cutting and sewing (Choi & Powell, 2005). As shown previously in Figure 2, many steps occur after garment pieces are cut, which require a larger workforce to accomplish these production steps. This dilemma could force a company to continue to seek out the cheapest labor possible, in countries where labor practices have little or no oversight (Peterson & Ekwall, 2007).

Cut and sewn garments were also seen to have a disadvantage in comfort. Areas of a garment that were of annoyance and uncomfortable were the shoulder and underarm seams. For any garment that is created by the joining of seams, the garment is compromised at the joining area and is more likely to break at this junction. (Anderson, 2005)

Dr. Masahiro Shima of Shima Seiki, stated matter-of-factly of his competition, that adaptability and quick-replenishment of product will be the downfall of the traditional cut & sew method (Mowbray, 2002). Though most of the industry used cut & sew production, it is argued that more attention should be paid to this product replenishment issue with quick response strategies (Martin, Horridge & Craig, 1998).

**Panel Knitting**

A large majority of knitwear is created using the panel knitting method, where a rectangular piece of fabric is knit, with an integrated welt finish at the hem. It is also known as “cut-stitch shaped”, “garment blanks” (Brackenbury, 1992, p. 12); and “garment-length” (Spencer, 200, p. 83). Circular or flat knitting machines may be used to knit these panels. Once the fabric is knit, areas of shaping are cut into the fabric, and pieces are then joined together. A
visual representation of the panel knitting production method is presented in Figure 5. The production sequence for this knitting way is demonstrated in Figure 6.

**Advantages.** Panel knitting machines were mentioned to have an advantage over traditional circular knitting machines, as the rib hem of a garment is integrated to the pattern piece on the knitting machine. This reduced two additional processing steps of knitting a rib fabric (on a separate machine) and then joining the rib hem with the body fabric. Though cutting and sewing are required in this production method, the requirements of each are significantly reduced with the integrated hem.

![Figure 5. Panel Knitting production method, Author’s own](image)

**Disadvantages.**

Similar to that of cut & sewn garments, panel knitting was stated to have a disadvantage in its requirement of post-knitting processes. A need for human labor was still present, as rectangular panels must be cut and sewn to account for armholes, collars and sleeves. Comfort of
a garment was also mentioned as a concern with this method, as seams exist around the armhole and shoulders. (Spencer, 2001)

**Full-Fashioned**

Full-fashioned knitting employs flat-bed knitting techniques to shape a garment pattern piece with contained selvedges on all sides. This shaping is achieved by narrowing or widening of the knitting width, through the process of increasing or decreasing active knitting needles (Brackenbury, 1992). Depending on the level of automation present on a flat-bed knitting machine, narrowing, and decreasing of knitting width may be operated by hand or through various forms of mechanical actuators and computer technology (Mills, 1965; Brackenbury, 1992). A visual representation of the full-fashioned method is shown in Figure 7. The production sequence for full-fashioned knitting is shown in Figure 8.

![Figure 6. Panel Knitting Production Sequence, information provided by Brackenbury's 'cut-stitch shaped' sequence, 1992, p. 13]
Advantages. Peterson & Ekwall (2007) stated that full-fashioned knitting is unique in its ability to create pattern pieces that require little or no cutting. This serves as an advantage for this production method, as the pieces that are created are less liable to human error than that of cut & sew garments. Wasted material was also stated as not being a hindrance to this production method, as all used material is contained within the knitted piece. (Brackenbury, 1992)

Inherent to flat-bed knitting on a v-bed machine, full-fashioned knitting was noted for its versatility in knit stitches. This provided an advantage to a knitting company with designing capabilities that could be set-apart from their competition. Many of the high-end retailers of knitwear employed full-fashioned knitting due to its ability to create a superior product in terms of quality and design.

![Diagram of full-fashioned knitted pieces](image)

Figure 7. Full-fashioned production method, Author’s own

Though full-fashioned pieces required the joining of seams, which could hinder the comfort of a garment, typically these seams are less bulky than that of a traditional cut and sew garment. Full-fashioned knitting is often joined using a linking machine, or cup-seaming machine. Linking provides a virtually seamless feeling juncture, as selvedge loops are looped
together with a joining yarn, maintaining extensibility at the seam. Many advancements have been made in the world of computer automated v-bed machines to produce consistent and high quality full-fashioned pieces. It is these advancements that have made v-bed knitting a commercially viable option for knitting companies. (Brackenbury, 1992)

**Disadvantages.** Full-fashioned knitting has its draw-backs as well. This method is less efficient in terms of speed of production due to loop transferring and the physical nature of a flat-bed knitting machine. Unfortunately, this type of knitting must be planned diligently before production so that the final sizing of a product is correct. All steps necessary to create a final garment must be documented so it is easy for a hand operator to create the pieces accurately. There can be little room for error in the production sequence, or sudden changes to silhouette plans. With automated flat-bed knitting, machine operators may also be hindered by a large learning-curve to understand the computer programming knowledge that is required. (Raz, 1991)

![Process Flow Diagram](image)

**Figure 8. Full-Fashioned Production Sequence,** information provided by Brackenbury, 1992, p.16
The major disadvantage of full-fashioned knitting is its requirement for linking or joining of pieces. This sewing function has thus far been a down-side to all traditional methods of production and still serves as a major hindrance to production speed and overhead costs. Linking, which is a highly labor-intensive process, depends greatly on the skill and dexterity of the operator (Mills, 1965). Human labor is still a necessary portion of the full-fashioned production sequence, which increases the overall cost of a product.

**Integral Knitting**

An advanced version of full-fashioned knitting exists, called integral knitting. With this method, shaped pieces have integrated trims which are knit into the pattern piece. Examples of these trims are pockets, button holes and additional knit structures (Anderson, 2008; Kanakaraj & Ramachandran, 2010; Peterson & Ekwall, 2007). Integral knitting employs the use of V-bed knitting and has similar advantages and disadvantages. A visual representation of the integral knitting production method is shown in Figure 9.

**Advantages.** Integral knitting has an advantage over traditional cut & sew production in terms of materials and the need for human labor. Since the trims of a garment may be integrated

![Figure 9. Integral knitting production method, Author’s own](image_url)
into a pattern piece, no longer does a need exist for separate knitting of trims or the human operation to join them. This significantly reduces the post-knitting time required to finish a garment. The overall quality of the pattern pieces, and final product, should also be more consistent as they are created by the machine and not subject to human error. (Kanakaraj & Ramachandran, 2010; Peterson & Ekwall, 2007)

**Disadvantages.** Similar to full-fashioned knitting production, integral knitting requires the post-knitting step of joining seams. Though much of the additional trims are conducted on the knitting machine, a human element is still required which creates an added cost. Of all of the production methods discussed thus far, integral knitting attains the highest production efficiency while still requiring human labor elements.

**3D Knitting/ Complete-Garment/ Seamless**

The most advanced knitting method is 3D knitting. With this method, fashion or technical textiles are created by knitting in one piece with no seams. Complete-garments are created by using a combination of tubular or shaped knitting, which are joined during the knitting process (Choi & Powell, 2005; Kanakaraj & Ramachandran, 2010; Ma & Lamar, 2013; Rao, 2012). This production method employs the use of flat-bed knitting machinery, which allows for loop transference from opposing beds.

The market innovators in 3D knitting machinery today are Shima Seiki of Japan and Stoll of Germany. Each company has specialized in their own particular brand of 3D knitting. Shima Seiki, the first to debut their WholeGarment® knitting machine in 1998 at ITMA, is a constant innovator in WholeGarment® samples. These machines employ four needle-beds for a heightened ability in designing. At their Wakayama base, over 2500 new garments are designed a year (around 50 a week) (“A Decade of Development,” 2005). Dr. Shima believes the potential
for WholeGarment® samples has barely been touched; new discoveries in knitting ways are emerging every day in their Japan headquarters.

Stoll differentiates their knit & wear® technology and has stated their main strength is the flexibility their machines allow for use of different yarn types and thicknesses. This system is ideal for design and versatility, due it its ability to control different areas of a garment to be knit with different stitch construction. Stoll has also designed their CAD system in such a way that is user-friendly, as the technical and knitting simulations are simultaneously present on the computer interface (Anderson, 2008).

In terms of a production method, complete-garment knitting reduces many of the post-knitting requirements of other methods. A visual representation of this method is shown in Figure 10. The production sequence steps for complete-garment knitting are shown in Figure 11.

**Advantages.** Complete-garment production has several advantages over other production methods in a financial sense and market positioning. Since all joining of seams are conducted on
the knitting machine, the production steps of cutting and sewing become unnecessary (Choi & Powell, 2005; Spencer, 2001). Without these steps, additional linking machinery and human labor are no longer a financial burden on the firm. A comparison of all knitting production sequences is present in Table 2.

Three-dimensional knitting is also extremely conservative in its use of raw material. This method of knitting is virtually waste-free with all yarn that is required for knitting comprising the whole product (Choi & Powell, 2005; Peterson & Ekwall, 2007). This can be a great benefit to companies that are using more expensive yarns, to supply a higher quality product without any wasted material during production.

![Complete-garment production sequence](image-url)
A company investing in complete-garment knitting technology, is also likely to benefit from the added value proposition that can be leveraged in the mind of the customer. There are several selling factors that could appeal to an informed customer. One very important factor being the unmatched comfort that complete-garment knitting provides. Without seams, a customer may be willing to spend more on a garment which is more comfortable than those produced with other methods.

Table 3

*A Comparison of Knitting Production Sequences*

<table>
<thead>
<tr>
<th>Cut &amp; Sew</th>
<th>Panel</th>
<th>Full-Fashioned</th>
<th>Integral</th>
<th>Complete-Garment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Circular knitting of fabric</td>
<td>Flat or circular knitting of blanks</td>
<td>Knitting ribs and garment portions</td>
<td>Knitting garment portions, with pockets and trims integrated</td>
<td>Knit garment in one piece</td>
</tr>
<tr>
<td>Scouring, bleaching and/or dyeing</td>
<td>Rough Press</td>
<td>Rough Assembly</td>
<td>Rough Press</td>
<td>Scour, dye, mill, shrink-resist finish Press</td>
</tr>
<tr>
<td>Pressing, calendaring or decatizing or stentering</td>
<td>Cutting</td>
<td>Scour, dye, mill, shrink-resist finish</td>
<td>Assembly</td>
<td></td>
</tr>
<tr>
<td>Laying up (spreading) of fabric</td>
<td>Assembly</td>
<td>Press</td>
<td>Scour, dye, mill, shrink-resist finish</td>
<td>Examine and mend</td>
</tr>
<tr>
<td>Marking and cutting Assembly</td>
<td>Examine and mend Finish Press</td>
<td>Cut, neckholes, etc.</td>
<td>Press</td>
<td>Finish Press</td>
</tr>
<tr>
<td>Examine and mend</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Finish and press</td>
<td></td>
<td></td>
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</tbody>
</table>


Complete-garment products are also inherently of higher quality and able to last longer than those with seams. Since the entire garment is produced using a machine, the quality and consistency of a finished product will remain the same (Peterson & Ekwall, 2007). Time spent in production can also be reduced significantly. Compared to traditional knitting methods, all-in-all
about half the amount of time to create a complete sweater (Millington, 2001). Other methods are hindered by the existence of seams, which are quicker to wear out at these junctures.

Seamless products also have better drape than those with seams, as the drape is not encumbered by a break in the fabric. Garments are less likely to fail because there are no points of stress created by stitching. There is also potential for a wider range of fit for different body types within a size, since there are no limitations to how a garment can drape when it has no seams.

Performance features can also be added to these garments, considering areas of support, compression, ventilation or shaping (Tait, 2008). All of these factors could contribute towards a higher value proposition in the mind of the consumer.

In addition, complete-garment products have an advantage in terms of design capabilities. Patterns and knit structures may be arranged continuously from the front to the back of the garment, over shoulders and down the sleeves when engineered correctly. Functional reversibility could potentially be designed into the garment by the engineering of knit stitches (Tait, 2008).

A proposal for 3D knitting has arisen in recent years, to create a completely vertical supply chain where the raw material of yarn is cultivated. Figure 10 shows the much shorter production sequence that is required of complete-garment knitting, and suggests that a final product could be produced with significantly less demands on labor than other production methods. This could be a major advantage for complete-garment knitting, allowing for knitting companies to have a quicker response to every facet of manufacturing of a product.

Since seamless knitting technologies are computerized there is great potential for small production runs with a wider range of variety. These machines could potentially create custom or made-to-measure garments. Researchers have gone so far as to propose a “knit-on-demand” (p.
89) retail offering, to quickly respond to a customer order of a garment, and produce it within only a couple hours (Peterson et al, 2008). This also aids in a more consistent quality for each piece created repeatedly (Kanakaraj & Ramachandran, 2010; Tait, 2008). This method of mass customization is likely to satisfy the customer more with overall superior fit and comfort.

Production of the product closer to the time of sale allows the manufacturer to make better design decisions with reductions in unsold merchandise. This method has been used by producers like Benetton, who create greige goods that are then dyed to the desired seasonal colors shortly before delivery to the retail outlet to ensure the customer will want the item. Increased customer service potential is also attainable within this method of manufacturing, as customers are easily heard and demand for a particular garment can be tracked (Peterson & Ekwall, 2007).

Complete-garment knitting has been forecasted “to continue growing and could be one of the largest next generation knitting technologies” (Kanakaraj & Ramachandran, 2010, p.1). It is important for investors and potential customers to understand these benefits of complete-garment knitting, and its hope for the future.

**Disadvantages.** Complete-garment knitting is a relatively new method of knitting production that has not been marketed to a large consumer-base. Even though 3D knitting has been around for twenty years, the average consumer is still unaware of the technology and its benefits. The athletic company, Nike, has helped to introduce the consumer world to this technology with their collection of “Flyknit” (p.1) shoes, a feature which they have hinted to extend into other product categories (Rhodes, 2016). Other companies have developed products which implement this technology, yet consumers are not explicitly told which complete-garment machines are being used. The ultimate success of complete-garment knitting relies heavily on
the demand of products which is driven by consumers. Effective marketing is required to ensure the success of the adoption of complete-garment knitting technology.

Stoll and Shima Seiki have found it difficult to convince knitwear companies to adopt this technology because it would up-end an entire production process. The current supply chain of fashion knitwear is heavily reliant on demand as a key driver. This supply chain system would likely need re-configuring to coexist with the current production methods. (Peterson & Ekwall, 2007)

Most knit technicians have issues communicating with designers due to their lack of technical knowledge, creating a knowledge gap (Sayer et al, 2006). Only 30% of designs that are developed can be made into a sample garment at a specified price point due to time constraints. Designers and technicians are ultimately disenchanted by the amount of overtime required to accomplish a goal. In the end, many of the designs that are produced are less than ideal since there is no time for extra sampling (Eckert, 1999). Communication can be a large contributor to the success of complete-garment manufacturing, where designers and technicians must have a great deal of technical knowledge to complete a successful design.

Three-dimensional knitting is also at a disadvantage because it is difficult for the consumer to tell the difference in quality. Dr. Shima admittedly stated that, “It is difficult to make the distinction between conventional cut and sew products and WholeGarment® product unless you know what you’re looking for” (“A Decade of Development,” 2005, p.28).

**Adoption Models & Factors**

The method of production that a firm decides to take, could have substantial consequences on the supply chain. Organizational research has attempted to synthesize the decision-making phases into systematized models, to aid the firm. The purpose of these models
has been to guide the decision-making process, for wiser decisions that weigh all factors. Research which has contributed towards the body of knowledge in the adoption of innovative technologies and related adoption factors were found in the following literature.

**Diffusion & Adoption**

The adoption of technology is a pertinent issue for businesses today. Technology has changed rapidly and has forced researchers to ask which technology could stand the test of time. This curiosity of how a technology is adopted and ultimately diffused into society has developed the theory of innovation diffusion.

E. M. Rogers, the recognized expert in diffusion of innovations has been cited over 88 thousand times in empirical research (Google Scholar, 2017). He is known for his extensive research in the diffusion of innovations and has developed the most widely used models relating to adoption. The categorization of innovation adoption, appearing in Figure 12, has been used in several industries as a simple explanation to understand the market positioning of a brand. He defined diffusion as “the process which an innovation is communicated through certain channels over time among the members of a social system. It is a special type of communication, in that the messages are concerned with new ideas” (p.5). This definition implied an element of uncertainty that is typically studied on a case-by-case basis.

The investigation of the adoption of 3D knitting technology has been spurred on by the unique history of the mature textile industry, where technologies have been adopted slowly. One historical example, that has supplied much insight into the field of diffusion, is the diffusion of the shuttleless loom. Despite knowledge of the unmatched efficiency of the shuttleless loom, manufacturers remained hesitant to implement for over thirty years. (Gruber, 1998)
Ray (1983) argued that the linchpin for the adoption of innovations, relies heavily on the level of investment that is present. Shuttleless looms, for example, were historically an order more expensive that competing shuttle-looms (Gruber, 1998). This barrier to adoption of technology was also found to be true by Yan and Fiorito (2007), in regard to the adoption of CAD/CAM systems in the US apparel industry. Regardless of the benefits that could arise from the adoption of a new technology, the initial investment proved to be a major hindrance.

The adoption of new technologies could also be affected by governmental factors. Gruber’s (1998) findings suggested that underlying policies, such as trade liberalization could have a significant impact on the rate of a technology’s diffusion. In the case of the shuttleless loom, areas of the world with reduced trade liberalization were more likely to have slower diffusion rates.

The textile industry is considered to be a mature industry, with established methods of production which are heavily reliant on the use of human labor. The notion of adopting new technologies into this industry is challenged by the prevalent and abundant cheap labor in Asian countries. Incentive to change has been greatly reduced by this fact. (Ray, 1983)
The human element, was also an important factor mentioned whether a technology will be adopted. Findings from a study in regard to the adoption of CAD/CAM systems in the US apparel industry, stated that the lack of employee skills served as a major deterrent (Yan & Fiorito, 2007). Factors relating to human resources were found to be a barrier to entry.

**Decision Making**

The act of choosing methods and the location of production, marketing strategies, and management style could be crucial to the success of a company. Many small decisions could add up to one large victory, or failure. Existing literature relating to the body of knowledge in decision-making for business management is shown below.

**The Innovation-Decision Process.** One of the most relevant models to determine the factors which contributed to the adoption of new technologies, is the Innovation-Decision Process, developed by Rogers (2003). This process model is represented in Figure 13. Rogers asserted that every decision, is carried through five stages of communication channels: knowledge, persuasion, decision, implementation, and confirmation. Upon the decision phase, a firm had the choice to adopt or reject a technology, by first weighing all of the advantages and disadvantages to implementation (through prior conditions, knowledge and persuasive characteristics). Understanding these decision steps was noted of importance, regardless of how a firm decides to adopt new technologies. For the technology innovator, this model could provide insight to the points of contention a customer may deliberate their technology purchase. For business management, this model also provided a guide to consider the factors that could be affected with a new technology adoption.
To take this model a step further, Rogers created a related Innovation Process model specifically for organizational adoption of an innovation. Figure 14 shows this adapted model. Two phases existed in this process: initiation and implementation. Similar to the Innovation-Decision Process model, the *agenda-setting* and *matching* steps include all factors that accumulated *knowledge* and *persuasion* which contributed toward an adoption decision. The main difference between these models, was an expanded view of the *implementation* step where *redefining/restructuring*, *clarifying* and *routinizing* emerged. For the purposes of this research, both models were used interchangeably as they both offered insight into the innovation process. (Rogers, 2003)

![Figure 13. A Model of Five Stages in the Innovation-Decision Process, by Rogers, 2003, p. 170](image-url)
Location Decision-Making and Reshoring

The concept of reshoring has emerged in the last ten years and has spurred on research to ask questions regarding the location of the manufacturing or the sourcing of a product. Reshoring has been generally defined as shifting the manufacturing and/or sourcing of a product to the parent company’s home-country (Ellram, 2013). According to Fratocchi, Ancarani, Barbieri, Mauro, Nassimbeni, Sartor & Zanoni (2016), reshoring has been a topic of debate among academics and the effects of its use have been studied in many manufacturing fields. The decision to re-shore a business’s manufacturing or sourcing, is a location-decision and must be weighed with diligence and care.

![Figure 14. Five Stages in the Innovation Process in Organizations, by Rogers, 2003, p.421](image-url)
The concept of reshoring of the textile and apparel industry to the United States poses a challenge due to the decimated local supply chain. Employment rates in the textile and apparel sector saw continuous decline in the United States beginning in the 1950s through the 1990s. Mittelhauser (1997) stated that the textile and apparel sector in the United States lost forty percent of its jobs from 1976 to 1996. The apparel sector felt this collapse much more severely than the industrial textile sector. In the case of North Carolina, the local apparel sector lost seventy percent of the jobs from 1996 to 2006 (“Key industries…”, 2007). With the loss of jobs and managing companies, also comes the loss of supply chain infrastructure. Without supply chain partners to rely on, reshoring will face much difficulty in the resurgence of textile and apparel related companies.

It has been argued that the cause of the collapse of the United States textile and apparel manufacturing sector is due to trade regulations and overseas sourcing. NAFTA, the North American Free Trade Agreement, has received criticism for the downfall of the local textile and apparel industry and has been selected by the Trump Administration for renegotiations. However, Platzer (2017) argues that the implications of NAFTA on the textile and apparel industry cannot be directly correlated to production and job losses. She also states that a modification to the existing NAFTA would result in less export revenue by United States companies to Mexico and Canada. In the time since NAFTA’s inception, textile and apparel companies in the United States have been forced to become highly automated and capital intensive. (Platzer, 2017)

Reshoring was mentioned as a response to the downfall of outsourcing, which began over twenty years ago. According to Harry Moser, the founder of the Reshoring Initiative, “about 60% of the companies that offshored manufacturing didn’t really do the math. They looked only
at the labor rate- they didn’t look at the hidden costs” (Fishman, 2012, p.11). The reshoring of the U.S. textile sector has seen much growth in the last couple of years with the implementation of new technology, in the area of domestic sourcing (Friedman, 2015). Investment from Chinese companies has emerged since the year 2000, to establish manufacturing facilities in the United States and take advantage of the reduced local energy costs (Van den Bossche, Gupta, Gott, Levering & Gutierrez, 2015). Walmart has also an example of this shifting and have committed to purchasing $250 billion in American-made goods by 2023 (Thuemer, 2015).

**Advantages.** There were several advantages identified that may prompt a firm to implement a reshoring strategy including: a leaner supply chain, higher quality assurance, an advantaged branding label of “Made in USA”, and improvements in wages, logistics and total ownership (Van den Bossche et al, 2015, p.4). According to the U.S. Reshoring Index, established by AT Kearney, the leading reason for a company to adopt a reshoring strategy was improvement in delivery time (Van den Bossche et al, 2015). Keeping the sourcing or manufacturing of a product in one’s home-country, allowed for a quicker speed to market, as well as quicker product replenishment. This method of production, was best suited for shorter-runs of product, rather than mass-market methods. Consumer behavior has changed significantly in recent years, where consumers expect to receive an order with the click of a button. Reshoring has the potential to meet this new requirement of quick response to keep a customer’s attention (Friedman, 2015).

The reshoring strategy also had a competitive edge by creating a demand-driven supply chain, or an “agile supply chain” (Christopher, Lowson & Peck, 2004, p.369). Traditional textile production methods were notorious for creating overwhelming inventory of product, which later had to be sold. This is referred to as “forecast-driven” (p.369) sales. Reshoring, on the other
hand, allowed for a shorter lead time on a product, so adjustments could easily be made to the quantities produced. Orders for customized products were also a possibility with this strategy, by implementing mass-customization. Overall, it was stated that there was an advantage for added flexibility in the structuring of the supply chain when it is located in the same country as the headquarters. (Christopher et al, 2004)

Another advantage to reshoring was its ability to have high quality assurance of products. Quality inspections can occur with precise attention to detail and more frequently in a lean supply chain. This factor was stated as the second most important reason for a firm to adopt a reshoring strategy by the Reshoring Index (Van den Bossche et al, 2015). There was also potential for products to be of higher quality, due to the implementation of newer technologies. Rosemary Coates, of Blue Silk Consulting, believed that reshoring is a part of a manufacturing evolution that is taking place with new automation including, “the use of robotics, 3D printing and 5-axis milling” (Coates, 2014, p.1).

Products that are created in the United States are also privileged to acquire a unique selling factor, by simply marketing as made in the USA. American consumers have been known to seek out these kinds of products preferring to purchase a product made in their home country which has been spurred on by “economic patriotism” (Coates, 2014, p. 5). The label, made in USA, created instant comradery between the company and the customer, as customers could be assured that their purchase was directly impacting the local economy. Customers can also be assured that these products have been regulated in terms of environmental pollution. This led to an expected price premium of such products, giving reshoring firms a cost advantage. Made in USA products have also become sought after by overseas markets, as this branding created an exclusive positioning in the mind of the consumer (Reichard, 2014).
There were also many advantages identified in literature that are inherent to manufacturing and sourcing within the same country, related to the country’s culture and native language. Production can be much more efficient when language barriers do not exist between upper-management and factory workers. Expectations of employees could also be easier to establish with similar cultural assumptions. Additional factors that positively contribute towards the decision to reshore, are presented by Fratocchi et al’s (2016) interpretive framework in Figure 15.

**Disadvantages.** One of the main disadvantages that companies have faced when considering the implementation of a reshoring strategy, was the loss of cost reduction. Companies who have established relationships with foreign producers could have a sudden increase in labor costs, if manufacturing is moved away from low-wage working countries. (Fratocchi et al, 2016)
Implementing a reshoring strategy for a business could also completely alter a company’s current mode of production. Rather than chasing the lowest wage earning countries for cheap labor, a company would have to invest in methods that are not reliant on cheap human labor, ie. advanced technologies. Capital investment could also be a concern with implementing newer technologies.

Figure 15. Motivation for reshoring strategies: an interpretive framework. Taken from Frattochi et al, 2016, p.110.
The apparel industry is one of the least likely to benefit from reshoring investment, due to the basic skills needed to operate sewing equipment (Reichman, 2012). Experts were not anticipating a large surge to the United States manufacturing sector, because labor can be seen as too expensive. Yet, with the inventions of technologies that reduce the need for human labor, there is a shifting taking place in manufacturing. “Jobs are coming back not for a single, simple reason, but for many intertwined reasons- which means they won’t slip away again when one element of the business, or the economy, changes.” (Reichman, 2012, p.18)

Financial analysts have also argued that the reshoring movement has yet to truly take off. Van den Bossche et al (2015), of AT Kearney, discussed the lackluster results of reshoring to date and stated that other factors come into play when considering a location-decision, like “global currencies, labor rates and energy costs” (Van den Bossche et al, 2015, p.8) There could be a risk of investing in such a strategy, as the rest of the market is steadily increasing in offshore production, leaving a firm trying to swim against the stream. (Van den Bossche et al, 2015)

**Complete-Garment Knitting and the Reshoring Agenda**

The reshoring movement in the United States required the implementation of advanced technologies which lessened the need for human labor. Since the human element must be less critical in order for reshoring to be successful, the implementation of 3D knitting is a prime example of this qualifier. Adoption of 3D knitting technology could be an option for a reshoring strategy due to its reduction of production steps, particularly the joining steps (linking or sewing). Mechanics operating the machines can potentially oversee a larger number of machines than other knitting machines without sequential knitting. A 3D knitting production sequence would require a highly skilled workforce, of which the United States is equipped to supply. Due to the high-quality nature of 3D knitting, a superior product could be manufactured, adding more
A value-proposition to a “Made in USA” product. Many of the benefits mentioned in regard to 3D knitting and reshoring has potential to contribute as drivers to the adoption of 3D knitting technology.

Adoption Factors

Diffusion experts have found several factors that have contributed towards the adoption of a technology. These broad categories may be applied to several industries. The body of knowledge regarding the factors that influenced adoption in a general sense will be discussed, along with the remaining factors that pertained to the textile industry.

General Factors. Since this research focused on a new technology, the question of when it will be diffused into society is too far reaching at this point. The point where 3D knitting rests in time could be considered the “pre-diffusion” (Ortt, 2010, p. 48) phase. According to Ortt, factors which contributed to this phase, fell into three systems- the main organization, the technological system and the market environment. The factors defined by Ortt are listed in Table 4. (Ortt, 2010)

Ortt (2010) explained that the factors found, largely depend on the industry in question and variance can occur from these generic categories. Many of the factors listed were applicable to the adoption of 3D knitting, due to its technological advancement and have served as a starting point for this research. The willingness of an organization to adopt new technology greatly impacted the likelihood that an innovation will be adopted. This willingness, as described by Rogers (2003), as the organizational innovativeness. He described several variables, or factors, which are likely to contribute towards this business decision, in Figure 16. These factors are classified into external and internal characteristics of the company, including leadership, and organizational structure.
Table 4

*Categories of Factors Found to Affect the Pre-Diffusion Phases*

<table>
<thead>
<tr>
<th>The main organization(s)</th>
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<tbody>
<tr>
<td>Fit with mission and other criteria of companies to evaluate the importance of the product for the company</td>
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<tr>
<td>Cheapness for producer/supplier (overview of costs/benefits)</td>
<td></td>
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<tr>
<td>Resources of main actor (to develop, produce and supply)</td>
<td></td>
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<tr>
<td>Expertise (to develop, produce and supply innovation)</td>
<td></td>
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<tr>
<td>Market (Supply) strategy</td>
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<tr>
<td>Number of suppliers for product and technological system; number and resources of suppliers of alternative products/technological systems</td>
<td></td>
</tr>
<tr>
<td>Customer need and other customer-related criteria needed to evaluate the product</td>
<td></td>
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<tr>
<td>Cheapness for customer (overview of costs/benefits)</td>
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<tr>
<td>Resources of customer (ability to adopt and use)</td>
<td></td>
</tr>
<tr>
<td>Expertise (to use innovation)</td>
<td></td>
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<tr>
<td>Adoption strategy</td>
<td></td>
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<tr>
<td>Number of potential customers (market potential)</td>
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<tr>
<td>Network effects on the customers’ or suppliers’ side</td>
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<tr>
<td>Cooperation/competition among different actors</td>
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<table>
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<tr>
<th>The technological system</th>
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<tbody>
<tr>
<td>Relative performance compared to alternative technology</td>
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<tr>
<td>Competition with other new/old technologies</td>
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<tr>
<td>Required and available complementary products</td>
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<tr>
<td>Reliability, certainty and risk of technology</td>
<td></td>
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<tr>
<td>Complexity and network requirements of technology</td>
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<tr>
<td>Availability of knowledge components (newness)</td>
<td></td>
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<tr>
<td>Difficulty in controlling production</td>
<td></td>
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<tr>
<td>Type of technology (basic, general purpose and/or competence-destroying technology)</td>
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<tr>
<td>Visibility of benefits</td>
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<tr>
<td>Unknown applications of technology (newness)</td>
<td></td>
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<tr>
<td>Ease of translation from invention to innovation</td>
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<tr>
<td>Compatibility with similar systems in other regions or with previous systems</td>
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<table>
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<tr>
<th>The market environment</th>
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<tbody>
<tr>
<td>Regulatory environment</td>
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<tr>
<td>Availability of rules and standards</td>
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<tr>
<td>General public attitude</td>
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<tr>
<td>Accidental changes in the macro-environment</td>
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<tr>
<td>Accidents during development/exploitation</td>
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Note: Table information from Ortt, 2010, p. 68
The adoption of 3D knitting is also subject to the target market that would purchase the products created. These knitted garments or products are in a sense, a sub-set of high-tech products, due to the requirement of advanced technology for their creation. Frattini (2010) described seven main variables to consider as a company attempts to introduce a high-tech product to the market: timing, targeting and positioning, interfirm relationships, product, distribution, advertising and promotion, and pricing (p.89). These market factors had the potential to have a large sway in the adoption of new technologies.

Much of the previous research found before the late 1990s suggested that the only hindrance to success was an internal issue relating to machine efficiency (Bailey, 1995).
However, in a volatile economic climate, other factors such as marketing and driving sales could be more important for the modern textile business.

**The Human Element.** Much effort has been paid to increased efficiencies of new technologies and their speed to market productivity. One factor remained, the human resources side of the textile complex. Sampath (2002) argued that, “human resource development is a prelude to modernization. No modernization is complete without commensurate development of human resources” (p.40). This statement pointed to the truth that machines are ultimately maintained and operated by humans. Without taking human interaction with machines into account, new technologies have no relevance to the industry they operate. (Sampath, 2002)

The textile complex functioned much as it has in the past, bargaining with the cheapest unskilled labor to manufacture as much product as possible. This method worked in the rural south up until the 1970s, when manufacturers soon began to turn their production efforts to foreign producers. United States textile manufacturers also found that they had to keep up with a demand for variety they were not accustomed to (Bailey, 1995). Suppliers have consistently outsourcing different areas of their production stream to foreign producers. Many companies within the textile complex have relied solely on this contractual labor demand (Penn, Martin & Scattergood, 1991).

Traditionally, the human resource strategy was to reduce all tasks down to the simplest form so that mechanical memory overrode a need for high aptitude level. This strategy allowed companies to employ large numbers of unskilled workers, with little educational background, to complete manual tasks (like sewing pieces of a garment together) (Bailey, 1995). Some employers were able to go so far as to create coding methods for employees with no prior
knowledge of chemistry, color science or even basic literacy, to create dye bath formulas as accurate as any textile chemist with a bachelor's degree (Sampath, 2002).

Bailey (1995) argued, however, that this has been the downfall of the United States textile industry and provided a clear warning to developing countries where the textile infrastructure is prevalent. If an organization relied on an unskilled workforce, there was little hope for that workforce to adapt to a change of the status quo. A revealing quote from a textile employer stated, “the trouble with my workers was that they couldn’t do a damn thing that they had not done before” (p.164). Without a base knowledge of education pertaining to textiles, the unskilled workforce proved to be more trouble than they were worth. The skills and tasks the workers had acquired had reduced their scope and ability for growth into new positions, or implementation of new technology. Having unskilled labor may get the job done, but it will not take you into the next decade, or even the next few years (Bailey, 1995).

**Software and Users.** Software has also been as much of a deciding factor for adoption of a technology as the hardware itself. It was one of the most challenging notions to business development, because it inherently required some amount of training. Geroski (2000) stated “without good software knowledge, many potential users will not adopt the new technology, however aware they are of its existence” (p.605). This has been seen in the adoption of CAD/CAM systems in the US apparel industry, where manufacturers’ attitudes towards the software was positive, yet the lack of qualified employees with this knowledge served as a deterrent (Yan & Fiorito, 2007).

According to the epidemic model of diffusion, software is best retained by word of mouth (Geroski, 2000). “Although some of the software can be transmitted impersonally through a
user’s manual, much of the software of a particular technology is built up from the experience of using it, and at least some of that valuable knowledge will be tacit” (Geroski, 2000, p.605).

A high level of investment is required for adopting technology that workers are unfamiliar with, which could be a drain on time and overall costs. Some companies have built in a cushion within their timeline to account for “absorptive capacity” (p. 613), which is their ability to learn and dedicate time to learning (Geroski, 2000).

Software understanding was also stated to be of great concern in relation to the adoption of 3D knitting technologies. Programming of this technology requires extensive understanding of knit stitches and operation of the racking needle-beds. A case-study conducted by Sayer, Wilson and Challis (2006), found that this technical skill was so sought after by companies using seamless knitting technology that they did not bother to employ creative knitwear designers. Many of the students who attained a bachelor’s degree in knitting, were ill-equipped to understand advanced technologies and needed additional training. Two of the companies interviewed suggested that a post-graduate program should exist that includes extensive programming to bridge that gap between the designers and technicians. The learning curve for 3D knitting was noted to be very steep and must be taken into consideration when weighing the factors of adoption (Sayer et al, 2006).

When implementing 3D knitting technology, firms must also consider the type of employees that may fill the programmer roles. A topical issue in the field of human resources is the expectations that millennials and generation Z have for their jobs. Millennials consist of people born from the year 1980 to 2000 (Deal & Levenson, 2016). Generation Z, also known as the “I” generation consist of those born from 1995 to 2012 (Stillman & Stillman, 2017).
Millenials were stated to have a lower retention rate than other generations and have a tendency to switch jobs if they encounter obstacles like: work overload, organizational politics, bad management and unacceptable compensation. This poses a particular challenge for 3D knitting programming as the learning curve is commonly agreed to be steep. (Stillman & Stillman, 2017)

On the other hand, a new generation (Generation Z) will soon reside in the workforce and demand their own stipulations in a career. This upcoming generation is skeptical of higher education and prefers the idea of going to trade schools. Gen Z’s are also more attuned to creating a customizable educational journey. The technical and design skills needed for knitting programming could be a perfect fit for some in this group. This could provide an opportunity for higher education to take notice of the efficiency of their educational programs to entice Generation Z students to attain a skill-set in knitting programming. (Deal & Levenson, 2016)

**Research Design Considerations**

The backbone of all research inquiry is the manner in which data is extracted, either in word or numeral form. Qualitative research employs the former, creating a rich and descriptive means of analysis (Robson, 2002). The proposed research will discover factors that contribute to the adoption of complete-garment knitting technology and thus will require extraction of qualitative data. The underlying theory of this qualitative analysis is discussed in the following section.

**Epistemology & Case Studies**

The philosophy of a how knowledge is attained, is known as epistemology. It is important to consider the philosophy of the researcher before any experiment is conducted because this
greatly effects the interpretation of the resulting data. This is especially true for the interpretation of qualitative data (Travers, 2001).

There has been much debate in recent years as to the validity of the case study method. Much of this discrepancy is a result of conflicting research philosophies, so much so that the definition of a case study has been known to have an ambiguous meaning (Piekkari, Welch & Paavilainen, 2009). Eisenhardt (1989) and Yin (2009) are the leading researchers in case-study methodology, both of which take a positivist philosophical stance. This philosophy assumes that everything can be studied from an objective and scientific vantage point (Travers, 2001). Eisenhardt and Yin are both proponents of developing theory which can be generalized to many management issues. The positivist view is the most substantiated case-study research philosophy, and is more accepted as reliable and having representativeness (Travers, 2001). This requires adapting an amorphous data-set, such as is found with case-study research, into variables that can be quantified into causal laws (Piekkari et al, 2009).

A less common epistemological approach to case-studies, is the interpretivist or constructivist philosophy. “Interpretivists believe that the objective of sociological analysis should be to address how members of society understand their own actions” (Travers, 2001, p. 10). The principal to this research approach is to seek understanding of the human experience (Piekkari et al, 2009). This is helpful to consider when proposing a study of people, especially employees, what their opinions are regarding the adoption of a new technology. Though this research is focused on the most prevalent factors leading to adoption of 3D knitting, it is important to consider this philosophy since decisions are weighed by humans and their experiences which could be multi-faceted.
Case Study Justification

Much of the research surrounding the adoption of technology has been focused at the societal diffusion of innovations. This type of research requires historical data and generally is investigated only when a given technology is at full diffusion. Rogers (2003) argued that insightful data regarding the decision-making phase is overlooked with this approach. He also stated that it would be beneficial to conduct field experiments (i.e. case-studies) before the diffusion process is complete, to overcome any “pro-innovation bias” (p.112). The pro-innovation bias is the assumption that a technology should be diffused into the society, without thorough investigation. He explained that diffusion researchers often, “underemphasize the rejection or discontinuance of innovations, (and) overlook reinvention (…) and fail to study anti-diffusion programs design to prevent the spread of “bad innovations” (Rogers, 2003, p.107). that may be present (p.112). In further defense of the use of case-study research in the field of innovation adoption, Rogers stated, (emphasis added by author):

We should increase our understanding of motivations for adopting an innovation. Such “why” questions about adoption have seldom been probed effectively by diffusion researchers. Undoubtedly, motivations for adoption are a difficult topic to investigate. Some adopters may not be able to tell a researcher why they decided to use a new idea, and other adopters may be unwilling to do so. Seldom are simple, direct questions in a survey interview adequate to uncover an adopter’s reason for using an innovation. But we should not give up on trying to find out the “why” of adoption just because valid data about adoption motivations are difficult to obtain by the usual methods of survey data gathering. (Rogers, 2003, p.115)
It is with case-study research that rich data could emerge and uncover hidden motives for technology adoption. Two case studies found in the review of literature, served as justification for this methodology. Park and DeLong (2009), in their case study about rapid prototyping technology, adapted several social frameworks (Roger’s Innovation Diffusion Process in Organizations, Social Construct of Technology (SCOT) and the Technology Acceptance Model) to create a comprehensive framework which includes external variables which affect social groups and results in issues and perceptions of these issues. This study focused mostly on the social framework aspects of technology adoption. Only one company was studied with a web-based questionnaire. The variables which were inquired were limited in scope, likely to hold the attention of the respondent. Figure 17 shows the proposed theoretical framework of this study, which later incorporated TAM as a solidifying framework. Though this is a very close subject-matter to our proposed research, the execution would be inappropriate for exploratory research in identifying factors that contribute to the adoption of new technology.
Fang, To, Zhang and Chang (2014) conducted a case study, similar to our proposed methodology, in regard to information and communication technologies for textile virtual collaboration. An interpretive approach was taken, by gathering opinions from “qualified subjects” (p.5) with in-depth interviews. Their proposed framework, is found in Figure 18. In essence, this framework is constructed first of factors (characteristics of ITC), that are affected by the external environment followed by a selection and adoption of a technology. They concluded that six characteristics of ITCs would influence its adoption. These categories could translate as the proposed areas of influence introduced in Chapter 1.

To further defend the use of case-study methods in this research, we must also consider the obstacles of attaining exploratory research. Three-dimensional knitting is still a niche method...
of production and thus will have limited decision-makers who could respond to this inquiry. The best method to take is face-to-face contact with those who are influential in this area, for breadth of data and assurance of response. Speaking directly with these influencers has allowed a deeper understanding of the barriers and drivers of adopting this novel technology.

Figure 18. Proposed framework of ICTs adoption in the textile virtual collaboration, by Fang, To, Zhang & Chang, 2014, p. 6
CHAPTER THREE
METHODOLOGY

The following chapter describes the methodology used for this dissertation research. A case-study approach with in-depth interviews was conducted of knitting company representatives. Interview protocol, the setting and the data analysis process are discussed along with a theoretical framework of a decision-making process model.

Research Design

All research studies must have a structured plan in order to effectively make a claim on a given issue. This study consisted of a nonexperimental research design, where subjects were observed in their natural state rather than manipulated into testable conditions (Spector, 1981). A case-study design determined the factors that influence the adoption decision of 3D knitting technology. Eight total companies of varying sizes and product categories were studied who have already adopted 3D knitting. Two of the eight companies studied had a change of use of technology and thus have resulted in insightful findings. Due to the nature of the case-study research design, external validity has been shown to be the main benefit to the body of knowledge of textile technology management.

The case study research design was chosen due to its benefits to social sciences. In the case of this research, the benefits are seen within organizational settings. As Robert Yin described, “the distinctive need for case studies arises out of the desire to understand complex social phenomena” (Yin, 2009, p.4). The adoption of new technology is a very complex decision-making process for any organization; the factors that determine a decision are important to understand for any seller or buyer of 3D knitting technology.
Case study design has also been proved to be appropriate for contemporary issues, in which behaviors cannot be manipulated (Yin, 2009). Since 3D knitting technology is still very much in its infancy, a case study approach was found to be most appropriate for investigation into this current topic. Yin also quoted Schramm (1971) in the purpose behind case studies: “it tries to illuminate a decision or set of decisions: why they were taken, how they were implemented, and with what result,” (Yin, 2009, p.17). This view is appropriate for this research and has assisted in illuminating the decision-making process of new technology adoption.

Case-study research also has an added benefit of external validity. By examining an industry issue at the location it occurs, a higher degree of insights may be generated. By conducting the research with company representatives at their chosen facility, a higher degree of participation and commitment was fostered throughout the research process.

The resulting qualitative data from in-depth interviews provided a rich understanding of hidden insights to the business decision to adoption 3D knitting technology. Another benefit of qualitative data was finding more factors which were not previously hypothesized prior to the data collection phase. Due to the open-ended question structure of the interviews, respondents were free to express their opinions in their own words. Barriers and drivers emerged during the data analysis phase which had not been speculated prior to research.

**Theoretical Framework**

In order to establish the factors that contribute to the decision-making process of adopting new technology, a theoretical framework was determined before field research. Roger’s models were used as a starting point for the development of a theoretical framework due to his recognition in the field of technology adoption. He is the recognized expert in this subject area, with over 88 thousand citations in empirical research (Google Scholar, 2017a). The proposed
framework prior to field research is found in Figure 18. Roger’s (2003) Innovation-Decision Model, Innovation Process for Organizations Model, and Park & DeLong’s (2009) theoretical model inspired this framework. An updated theoretical framework after field research is found in Figure 19.

Through many factors found in literature review, an interview script was developed, by addressing the areas of influence which impact technology adoption. These factors were divided into two broad categories, of drivers and barriers. Administrative-level employees and 3D technology users are likely to understand different drivers and barriers depending on their own human experience and exposure to the technology. The most salient drivers and barriers emerged through in-depth interviews conducted with both administrative-level employees and technology-users.

**Research Questions**

The research objectives of this study are to identify the drivers and barriers for adoption of 3D knitting technologies through the full organizational diffusion of innovations process. By means of a hypothesis map in Appendix A, the development of an in-depth interview script for administrative employees and technology user employees was developed, located in Appendix B and C. Each proposed hypothesis, grounded with intuition and prior knowledge based upon research, relates to one or more area of influence which are variables that influence barriers and drivers of technology adoption. In effect, each question in the interview script has a grounded justification for its presence.
Setting

In-depth interview data gathering took place at the participating company’s headquarters, in the United States. Four companies were located on the west coast, and the remaining four companies were located on the east coast. One interview was conducted using Skype.

Participants

Participants of this study were administrative employees, administrative and technology user employees and technology user employees. All participant types have held valuable insight into the decision-making process of adopting 3D knitting technology. Individuals were found to have their own opinions in regard to the technology, so their responses were subject to personal bias. To ensure the anonymity of each participant and to gain as much objective information as possible, individual names and company names were not referenced.
Figure 19. Theoretical framework prior to field research: Drivers and Barriers contributing to Innovation Adoption, Authors Own
Data Collection

Data was collected in a series of in-depth interviews with company representatives of three different groupings: administrative employee, administrative & technology user employee, and technology user employees. Each company was first contacted through email, to attain the most pertinent company representative to contact for the research. A phone call was then placed to follow-up on the email to arrange a day to interview the company’s representatives. On the data collection day, company representatives were asked to sit in a quiet room for interviewing, since the interviews would be video-taped. The purpose of video-recording was for the assurance of accurate transcriptions in the data analysis stage. All video and audio files were stored on an external hard drive, which will be deleted upon completion of the research study.

Data Analysis

Due to the nature of a case study which comprises of in-depth interviews, qualitative data was analyzed. Upon completion of the interviews, each interview was transcribed verbatim to provide the highest level of accuracy in the data analysis process. The data obtained through in-depth interviews proved to be very rich with nuanced insights.

NVivo is a computer software which has the ability to designate rich textual data into groups so as to draw similarities or distinguish trends, called “nodes”. It is the recognized software for analyzing and interpreting qualitative data, having been cited over three thousand times (Google Scholar, 2017b). Each category was then synthesized further to identify common threads among the responses for a particular question or subject. This system also allows for ease of coding and analyzing qualitative data and thus lending itself to greater insight generations.

The first summary after coding in NVivo is placed in Appendix F. Version 11 of NVivo Pro was used for the coding and comparison of data for this study. It has been stated that NVivo
is only as powerful a tool as the researcher using it (Costa, Reis, de Sousa, Moreira & Lamas, 2017); and in this sense, each code group of textual data must be specified by the researcher relying on their ability to identify hidden meanings in a respondent’s answer to a given question. It is stated by Bryman and Bell (2003) that, “the analyst must still interpret his or her data, code and then retrieve the data, but the computer takes over the manual labor involved” (p. 445).

NVivo assisted in the physical task of coding and grouping text together, but the true data interpretation relied heavily on the researcher’s conceptual mapping abilities.

In the data analysis phase, the hypothesized drivers and barriers (areas of influence) to 3D knitting adoption served as an initial starting point for nodes. Filtering through the rich text with NVivo allowed for hidden insights to also be specified as a new node with found commonalities between interviews. Due to the nature of NVivo’s flexibility of use, a larger number of drivers or barriers first hypothesized became more prominent than others. The use of NVivo was used for grouping similar questions together and similar responses to identify trends.

NVivo was used to designate demographic coding by the use of “classes”. In this research, classes captured data relating to a respondent’s job title being either administrative, administrative & technology user, or only technology user. The educational background of each respondent was also captured in this area along with identifying information like the size of the company and the inception of the company.

The data analysis was limited by a strict timeline and the number of researchers with the expertise to synthesize qualitative data. Only two researchers analyzed the data, opposed to three. Typically, qualitative data is analyzed by a larger team of researchers but in the case of this research the constraints resulted in only two interpretive view-points.
Conclusion

Through the use of qualitative research with case-study in-depth interviews of company representatives, insights were generated regarding the factors that contribute to the adoption of 3D knitting technologies. A theoretical framework was developed prior to field research with hypothesized factors called areas of influence. NVivo served as a means to speed up the data analysis process and was reliant on the abilities of the researcher. The results after field research are discussed next.
CHAPTER FOUR
RESEARCH FINDINGS

Introduction

The case study research conducted for this dissertation included eight companies with headquarters in the United States. A total of 18 respondents were interviewed during the case study, including ‘administrative’, ‘administrative & technology user’, and ‘technology user’ employees. Each company also had a main spokesperson who voiced the overall company value system. An exception to this was Company 4 who had two spokespersons. Table 7 describes each company in quick summary of their company type and whether they are currently or have in the past used 3D knitting technologies along with the types of employees interviewed.

Since all companies within this study are currently or have used this advanced knitting technology, it is important to also note their pre-disposition towards innovation and adopting innovative practices. Each spokesperson responded positively regarding the belief that innovation is a value for their company. All spokespersons identified their company as being placed at the innovators or early adopters of the diffusion of innovation bell-curve, found at Figure 11.

To keep all respondents answers consistent with terminology, all were questioned regarding a general term that could be applied to flat-bed seamless knitting technologies including Stoll’s knit & wear® and Shima’s WholeGarment®. Seven of the nine company spokespersons agreed that 3D Knitting was an appropriate term because it speaks to the ability to knit a three-dimensional shape which is not restricted merely to apparel applications. Other terms that emerged with this query were: true seamless, whole garment and full-garment seamless.
Through qualitative analysis, conducted using NVivo software, several themes emerged among respondent’s answers to the interview questions. These themes are identified as drivers or barriers in Table 6, along with their corresponding definitions. The themes identified as drivers through qualitative analysis were: demand, cultural, operational and consumer. Barrier themes identified were: capital, management, knowledge, operational and consumer.

Table 5

*Driver and Barrier Themes Identified Through Qualitative Analysis, Authors Own*

<table>
<thead>
<tr>
<th>Drivers</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Demand</td>
<td>Associated with product demand outside of the company</td>
</tr>
<tr>
<td>Cultural</td>
<td>Associated with relationships between businesses, company values and business model</td>
</tr>
<tr>
<td>Operational</td>
<td>Associated with equipment and production lines along with their efficiencies</td>
</tr>
<tr>
<td>Consumer</td>
<td>Associated with benefits added to the end consumer</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Barriers</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Capital</td>
<td>Associated with capital investment, available cash flow and financial risk</td>
</tr>
<tr>
<td>Management</td>
<td>Associated with recruiting appropriately skilled personnel</td>
</tr>
<tr>
<td>Knowledge</td>
<td>Associated with lack of knowledge or personnel knowledge</td>
</tr>
<tr>
<td>Operational</td>
<td>Associated with equipment and production lines along with their efficiencies</td>
</tr>
<tr>
<td>Consumer</td>
<td>Associated with the demand of a product and consumer expectations</td>
</tr>
</tbody>
</table>
### Table 6

*Company Profiles for Case Study Analysis*

| Company # | Type                                      | Type of Product                                      | Current or Past use of 3D knitting | Firm Size Class | Years in Business | Admin Employees Interviewed | Admin & Tech User Interviewed | Tech User Interviewed | Shima or Stoll |
|-----------|-------------------------------------------|-----------------------------------------------------|-----------------------------------|-----------------|-------------------|-----------------------------|---------------------------|--------------------|----------------|----------------|
| 1         | Contract Knitter and Research Development | Technical Textiles and full-fashioned knitwear apparel | Current                           | 2               | 2                 | 1                           | 1                         |                    | Shima          |                |
|           |                                           |                                                     |                                   |                 |                   |                             |                           |                    |                |
| 2         | On-Demand Manufacturing                    | 3D knit Fashion Accessories                         | Current                           | 1               | 3                 | 1                           |                           |                    |                |
| 3         | Contract Knitter                          | Cut & Sew, Full-fashioned and 3D knitwear apparel    | Current                           | 6               | 26                | 3 Owner, Designer, Production Manager | 1                        |                    |                |
| 4         | Research and Development                  | Technical textiles                                   | Current                           | 1               | 30                | 2                           |                           | 1                  |                |
| 5         | Fashion Knitwear Brand                    | Cut & Sew Knitwear Apparel                          | Past                              | 9               | 55                | 1                           | 1                         |                    | Both           |
| 6         | Outdoor Brand Sustainability Focus        | 3D knitwear apparel                                  | Past                              | 9               | 44                | 3 Product Line Manager, Designer & Material Development Director |                           |                    | Shima          |
| 7         | On-Demand Manufacturing                    | 3D knitwear apparel                                  | Current                           | 2               | 3                 | 1                           |                           |                    | Shima          |
| 8         | Research and Development Firm             | Technical Textiles                                   | Current                           | 2               | 11                | 2                           | 1                         |                    |                |

*Note: Business firm size class information from “Business Employment Dynamics…”, 2017.*
Seven of the eight companies interviewed have purchased their own machines. Six of those are creating 3D products. Four of the remaining six company’s spokespersons stated that they have already broken-even on their purchase or have paid for their machines in full. Company 3 has not broken-even on the 3D knitting machines they have purchased and their spokesperson stated that they understand it will take double the time to break even on the investment because the machines are three times more expensive than normal knitting machines.

Regarding financial risk, Company 8’s spokesperson commented that they perceived the financial risk as relatively low considering that the machines are in demand and can be resold.

Company 3 administrative employee suggested a solution to this barrier and stated:

I think if they would drop the price, it will definitely increase the adoption a lot faster. And they can make it back on the economy of scale. Because if they produce more machines, their production cost is going to go down, and they’ll be able to sell a lot more machines. They can also increase their market share. (Company 3 administrative employee, personal communication, April 27, 2017)

Management

Recruiting the appropriately skilled personnel is a management issue and has also been found to be a barrier theme in this analysis. Of concern with 3D knitting is the difficulty in finding skilled knitting programmers to develop new patterns and operate these complex machines. Two company’s spokespersons stated that finding such programmers was the biggest risk associated with adopting the 3D knitting technology.
All spokespersons for each company agreed that the labor pool of knitting programmers is very small and those with the skillset are being recruited to larger companies that can compensate higher wages. An even smaller labor pool exists of candidates who have an ability to program three-dimensional shapes and those who understand this type of intricate knitting. Applications in technical textiles are of concern when attempting to find programmers since most experienced knitting programmers have a fashion apparel background.

Since this technology is relatively new in the industry, only three of the companies employ highly-skilled programmers (at least 20 years of experience). One company contracts out the programming and manufacturing. Of the remaining four companies, all programmers are new to programming within the last 5 years. Spokespersons from three companies stated that they expect to train internally for this skill, since it is difficult to find programmers with experience. Company 2’s spokesperson has been unable to find contract programmers and has decided to get personally trained to program the machine. Company 3’s initial challenge in implementing 3D knitting technology was significant resistance from employees to take on the complex machinery. The production manager has had to force the technicians to make machine adjustments and needle replacements, many times. These types of issues demonstrate the importance of employees when implementing this technology.

Knowledge

The most prevalent barrier to the implementation of 3D knitting technology is the lack of knowledge by administrators, technicians, and other personnel. This is an issue with not only the personnel in a company, but also the textile industry at large. There is a significant lack of understanding of the capabilities of the machines.
Eight out of the nine spokespersons interviewed agree that a base-line of knitting knowledge, preferably with hand-knitting machines, is essential before transitioning into programming of the 3D machines. Four of these spokespersons also agree that candidates available in the textile industry who know knitting are very rare and thus are willing to invest in training their employees internally. Two of the technology users interviewed were trained internally at their job and had little background in hand-flat knitting and no prior experience with electronic knitting.

A lack of understanding regarding the raw material components used on the machines is also a knowledge barrier. Company 6 has found that the biggest challenge to 3D knitting technology adoption is understanding what yarns can be used on the machine and at a certain gauge. Company 8 has been exploring 3D knitting machine limitations and have found that certain yarns are incapable of being knit on the machine due to high tensile strength.

All spokespersons agreed that there is a very steep learning curve for understanding programming for a three-dimensional shape, another major hindrance for the adoption of this technology. Of the eight companies interviewed, seven have programmed their own patterns. The consensus among most administrative and all technology user employees is that programmers will need two to five years of programming experience full-time to become proficient and add value to the company. Spokespersons also agreed that the training provided by machine manufacturers will only allow someone to run a perfectly calibrated machine; the real training comes when people can practice on their own, which takes much longer than some companies may expect.

All ‘administrative & technology users’, and ‘technology users’ admit that they are still learning new concepts about knitting, even those who have been knitting for over thirty years.
Two of the three technology users described having difficulty connecting both software program and machine concepts together. Successful operators must have intimate knowledge of not only the operating software, but also the machine itself. It becomes especially difficult to create new iterations of a design when movement between the machine to the software and back to the machine is necessary.

Software architecture and functionality is also a hindrance in adopting 3D knitting technologies. Compared to a typical software interface for design, such as that of Adobe Creative Suite, Shima’s Apex 3 and Stoll’s M1 Plus are primitive in their layout and ease of understanding for the user. The technology user from Company 1 commented on this drawback to the technology. Both software’s are limited in their ability to edit knitting commands outside of modules pre-programmed into the software. Company 4’s spokespersons stated that they had refused to adopt the M1 version of Stoll’s software until the newest iteration of M1 Plus debuted in 2008, which allowed the creation of customizable modules. A suggestion made by Company 7’s spokesperson was to open source the software development so that the architecture can be improved for everyone.

A lack of understanding regarding machine capabilities also impacts adoption of this technology. Two companies’ spokespersons mentioned that there is a great misconception about the capabilities of the technology based on comparisons to a 3D printer, which have been used as a marketing gimmick in recent years. This comparison gives the allusion that products can be created by a simple push of the button, disregarding the development time needed to make a successful product.

Overall, the textile industry does not understand how this technology might be used efficiently to speed up production. Company 7’s spokesperson suggested that this was the
biggest challenge to adoption. Big businesses must be informed of the technology and how it can be used. This has been evident since Stoll’s introduction of the belt drive system, allowing for a carriage to move to a certain area of a needle-bed rather than run the full width of the bed for each course like chain-drive systems. Company 4’s spokespersons witnessed a disconnect between knitting companies use of the newest technology and the flexibility that the belt-drive system allowed for. One of Company 4’s spokespersons explained this dilemma by saying:

The most expensive thing in product development is usually, “we’ve always done it this way”. The most expensive words. And what you have are people that would use this same machine for the same projects. They just got the new machine and were running the full width of the bed. Rather than using for what it best was. (Company 4 administrative & technology user, personal communication, April 28, 2017.)

**Operational**

The second most prevalent barrier identified during this research related to factors contributing to the equipment use and production stream efficiency. This factor also considered how parts of the supply chain might act as a barrier to the adoption of 3D knitting technologies. When problems arise with a machine or the software systems, quick solutions are difficult to find. This has directly impacted production line efficiency and acts as an operational barrier to adopt 3D knitting. Two company’s spokespersons complained regarding the limited troubleshooting resources for operating machines and software. Both are hoping for a “Wikipedia of errors” (Company 2 administrative & technology user employee, personal communication, April 24, 2017), a way to google the solution or at least a communal resource for Shima or Stoll users to crowdsource a solution to their operational problems. Company 2’s
spokesperson also explained that there was a great deal of translation inconsistencies when it comes to errors on the machine, which sometimes made no logical sense.

The maintenance of the machines is also a necessary component to successful adoption. Company 3’s spokesperson stated that being able to maintain the machines is the second largest risk to adoption since the machines are higher precision and the needles are more difficult to change.

Limitations of the machines were also stated as a barrier to adoption relating to operational success. The gauge of machine and needle-bed length are both limiting factors. Company 5 switched their use of 3D knitting machines due to the limitations of the machines to make fancy fabrics and making these fabrics into a complete knitted piece.

Four company’s spokespersons were also skeptical of the future production load for 3D knitting and expect that products will remain as a niche category. Company 3’s production manager expects that production will never exceed 50% full-fashioned knitting/ 50% 3D knitting since the coarser gauge items can be linked quickly in the established production stream. There are also physical limitations of the machines that Company 8 has found by knitting yarns with high tensile strength which have caused broken needles.

Another component affecting production time is the time it takes to program a pattern. Two company’s spokespersons agreed that the programming time is much longer for this technology than other types of knitting. One of Company 4’s spokespersons argued that making a product with little waste requires many hours of programming and can swallow the manufacturing efficiencies attained. All representatives from Company 6 still believe that despite the longer development time, the cause is worth supporting due to the saved raw materials in the knitting process.
The design capabilities of the 3D knitting machines are important to take into consideration since they will directly impact the type of product created, whose retailing success depends on consumer demand. Three company’s spokespersons agree that the 3D knitting machines are only able to make a limited number of styles which are simple in their aesthetic. Company 7 stated that this is a major hindrance for designers to understand:

A lot of designers don’t understand so they’re designing crazy shapes with crazy slopes and crazy patterns that just can’t be done on WholeGarment® at this point (…) We’ll probably figure out a solution in time but right now, it’s just not possible. (Company 7 administrative & technology user employee, personal communication, May 18, 2017.)

When knitting a complete-garment the machines are limited to jersey-based fabrics, meaning they are not able to achieve a double-knit fabric, full-needle or half-cardigan stitch. These types of affects can only be mimicked.

In sweater manufacturing, Stoll machines are unable to create a complete-garment using all needles on the knitting bed, and instead must knit in half-gauge. This creates a bulkier fabric which tends to be in less demand than finer gauge knits. Shima on the other hand can create a complete seamless garment from the machine, but requires an additional investment in this specific machine.

**Consumer**

Three-dimensional knitting technology allows the unique development of garments that consumers might not actually be aware that they need or desire. Two companies creating fashion apparel products have decided to manufacture full-fashioned or cut & sew garments because they
know that their customers want more intricate garments than the 3D knitting machines are able to make. Company 5 was the only company interviewed who had switched from their use of 3D knitting. Their spokesperson stated that their customer expects a couture quality garment that is highly constructed with a lot of shaping or darts, which is not achievable on the current machines. This was the key explanation for discontinuing their use of these machines.

Consumers are not always aware of what makes a quality product. Four company’s spokespersons agreed that a typical consumer has a difficult time identifying the difference in quality between a seamlessly knit product compared to a product joined with seams. Company 6’s production line manager stated that quality could be identified as performance, durability or the life-span of the product. Company 7’s spokesperson stated that the quality of a product is often directly associated with retail price in the mind of the consumer:

Price and quality go hand in hand these days. So, I think when a customer looks at something that is 3D knit versus cut & sewn, they won’t really understand what’s a higher quality knit. They’ll just look at it and see if it fits. And they’ll just go by the reputation of the brand in some sort of way in the price. (Company 7 administrative & technology user employee, personal communication, May 18, 2017.)

Two company’s spokespersons agree that customers are not able to tell the difference in quality of a product, thus making it difficult for them to value the added benefits that seamless knitting may provide. They also agreed that consumers will notice when a product fits better than a comparative product but may still not recognize what is causing the change. One of Company 4’s spokespersons explained the difficulty in communicating value to the consumer:

The issue is always, what does the customer value it at? If you take the example of a garment or a shoe where you can make something fit better, do they really appreciate it?
The girl or guy who’s running in a pair of sneakers and he’s not getting a blister, does he actually think, “Oh, wow!” It’s actually the way the shoe is made that’s stopped him from getting a blister? So, the 3D part of it has a lot to do with the fit. (Company 4 administrative& technology user employee, personal communication, April 28, 2017.)

**Miscellaneous**

**Human factors.** A common issue that poses a difficulty to adoption of knitting technologies is the human interaction between designers and programmers or technicians. The administrator at Company 3 stated that this is not necessarily an issue specific to 3D knitting technology, but it is an issue nonetheless. The one company who could provide perspectives from both roles- designer and programmer commented on this issue. They believe that it takes time to overcome this relational hurdle. The designer interviewed stated, “But then that’s the key, like you have to use some people skills and maybe some friendship to work with them and give them different options, give them some room” (Company 3 administrative employee, personal communication, April 27, 2017).

**Technological.** There are distinct differences between both machine manufacturers and their software platforms. Three company’s technology users agreed that Stoll software is easier to use than Shima. Yet, it is also mentioned by the spokesperson from Company 1 that Stoll’s M1 Plus software has the potential to crash at random times, which is not an issue with Shima’s Apex 3. Company 7’s spokesperson mentioned their trust in Shima’s Apex 3 software because it gives a warning of knitting issues before it is sent to the machine which, “Stoll does not do as much” (Company 7 administrative & technology user employee, personal communication, May 18, 2017).
Drivers

Demand

This type of driver relates to factors which are associated with the demand of a product, the market for the product and external factors outside of the company which are acting on the adoption of 3D knitting technologies. Areas of insight relating to this driver include how a company used the technology, the market demand for a product and new markets that the technology may fit into including technical textiles and mass customization applications.

Two company’s spokespersons stated that their initial purchase drivers to adopt 3D knitting related to demand, specifically the hope of developing a new and innovative product. Five company’s spokespersons also commented on the use of the technology being driven by an added product category or capability.

Three company’s spokespersons stated that they believe that technical textiles are the future for 3D knitting. All companies catering to the technical textile market have seen growth in their client work related to this need. Two company’s spokespersons anticipate that 25% of their client work will consist of technical textiles in the next year.

For two company’s focusing on fashion apparel, their spokespersons have stated that customers have requested finer gauge garments, being 14 gauge or finer. Company 3 has seen that implementing the 3D knitting technology for finer gauge knits is more beneficial to their production stream since the linking part is eliminated. The demand they have seen in this new product offering is just on the rise, with a recent order from a large customer for 5,000-6,000 pieces of one style.

The two companies implementing on-demand manufacturing have seen a significant customer retention rate, where usually around 40% of previous customers purchased again due to
their positive experience. Three companies have also received positive feedback from customers regarding the superior fit and comfort of the products, and surprise of how much they enjoy their product purchase.

Four of the company’s spokespersons also noted that they have attained success with implementation of the technology by driving demand for their products through storytelling marketing. Two of the companies inform their customers that 3D knitting can allow for customizable products either in design aesthetic or fit. Two companies also tell the story that this method of production is inherently less wasteful of materials and thus more environmentally friendly. Other benefits advertised to consumers were the added durability and comfort provided by eliminating seams. New innovative knit structures were also possible with the technology and details regarding this feature were explicitly marketed to customers. Specialized yarn technologies were also a part of one company’s storytelling and its integration into the product was made possible by 3D knitting.

**Culture**

Another consistent factor found through analysis was a driver associated with cultural matching between businesses, company values and resulting business models. Cultural matching means a common ethics or set of beliefs between entities. In this research, the two entities were identified as the interviewed company and their purchased machine brand, who had shared beliefs and thus were attracted to each other to conduct business together. Two of the companies interviewed owned both brands of machines, thus eliminating them from this factor. Cultural matching served as a foundation for the remaining six company’s decision to purchase one brand of machine over the other. For some companies, a prior relationship with the machine manufacturer also served to reinforce the decision to stay with that brand. Four company’s
spokespersons stated that they had received incentives during the purchasing process from their partnering machine manufacturer, which served to better the relationship between the companies.

**Cultural Matching.** Each company and the machine manufacturer they decided to adopt matched culturally by ethos. All company spokespersons agreed that they are intent on making the best product possible. For seven out of the eight companies, building the best product means optimizing manufacturing. The three companies who invested in Shima Seiki machines all had a common mission regarding transparency of their supply chain and striving to make a responsibly created product. The two companies who invested in Stoll machines had a common mission regarding manufacturing optimization, whether that was domestically manufactured or what was best for their customer. The two companies who adopted both brand machines have a common mission of making the highest quality product possible, which in turn disregards the adopted brand of machine. It is important to mention here that a bias exists among the companies studied and their preference towards one machine manufacturer over the other.

**Business Models.** Each participating company’s business model also reflected a pre-disposition to adopting 3D knitting technologies. Two of the companies are contract knitters and have been able to do so in the United States using this technology. Two have adopted a consumer-driven business model, allowing for on-demand manufacturing and customizable features of a product. Three companies are sustained by research and development projects, enabled by adopting the technology.

**Social Compliance.** Many companies today are concerned about social compliance and several companies have commented on how 3D knitting helped with
this issue. Since necessary human operations are taken out of the production process with this technology, the workforce is reduced or virtually eliminated thus removing social concerns. Company 6’s respondents, which values social compliance, noted that using this technology offers an alternative for their company requirements of ethical oversight. Two companies have also found an added benefit by implementing 3D knitting, by maintaining transparency with their customers about how their product is made.

**Sustainability.** A desire to work towards environmental sustainability was also a cultural driver for 3D knitting technologies. Seven of the eight company’s spokespersons stated that they were concerned about business and environmental sustainability and feel that 3D knitting assists in that issue. However, only three of the seven spokespersons could say that it was a determinant in the adoption of the technology. In general, compliance to environmentally sustainable practices are, “a nice thing to hang your hat on” (Company 1 administrative employee, personal communication, March 27, 2017), rather than a main driving factor towards adoption.

**Operational**

Several factors related to the production process have been identified as drivers, including: reduction of the labor component; increased production speed; ease of logistics; scalability; rapid prototyping; quicker speed to market; agile supply chain; in-house manufacturing; manufacturing optimization; and a capacity to create products with a mass customization approach. Other drivers identified related to operations are the added benefit of having adaptable and flexible machinery; having the ability to manufacture in the United States;
having a reliable and consistent product and a reduction of manufacturing costs by retailing primarily online.

Two company’s spokespersons believed that the main benefit to using 3D knitting is the reduction of a labor component to production. It is also thought by one company’s spokesperson that this reduction of labor could allow for the creation of a new business model for the apparel industry.

The companies who used full-fashioned knitting commented on the difficulties involved working with the linking process and the necessary labor pool for this step in production. All companies have had to train their own linkers and admit that this process takes a minimum of 6 months for a new-hire to get up to normal production speed. This issue was the main barrier that drove Company 7 to switch production to 3D knitting. The spokesperson commented that when the company was using linkers, the fastest they could link a sweater was every 2 hours, drastically increasing the overall production time.

Regarding production speed, three company’s spokespersons have commented on the increased production rate. However, there is also a necessary balance that must be taken into consideration. One of Company 4’s spokespersons stated:

And the part of productivity, I would say there is a tremendous balance. Yes, something might take an hour or an hour and a half, but you don’t have all the cutting, you don’t have all the prep. You’re not having to stock all kinds of rolls of fabric. You’re actually making your product at the same time you’re making your fabric (Company 4 administrative & technology user, personal communication, April 28, 2017).
This way of knitting a complete piece directly from the machine in many cases took longer to knit, but it also eliminated many steps along the normal production stream for knitted products. Since Company 6 is using external partners for their manufacturing, their spokesperson also commented that the supply chain could still have bottlenecks if a product needed finishing or additional processes that needed to be completed at a separate facility. From a manufacturing perspective, Company 3’s production manager noticed that their 3D knitting production was usually 30 to 40 percent faster than full-fashioned knitting. This has resulted in a quicker shipping to customers by a week.

Three company’s spokespersons also commented on the ease of scalability that 3D knitting technologies provide. Due to their production-ready nature, products created on a sample scale can easily be reproduced in mass production with enough machines. Company 8’s spokesperson described this seamless transition from prototyping to production:

This brings the knitting out of the factory and into the workspace. Sometimes you can do something on a sample scale (…) but it doesn’t transition to full rate manufacturing. So, you’ve got lots of gaps when you try and make a transition, which is one of the biggest problems in textiles. But with this, we can go straight from the yarn to item and then we know we can duplicate the item in production in thousands of units (…) So there’s no technology gap between prototyping and production and that’s really, very innovative (Company 8 administrative employee, personal communication, June 5, 2017).

Three-dimensional knitting technologies also allowed for quicker iterations of prototypes with rapid prototyping. Three company’s spokespersons mentioned this as a main benefit of implementing the technology. Not only have the machines provided a larger array of stitch
possibilities, but they also allow for a single piece to be knit which eliminates the issue of working with factories and minimum material orders.

Three company’s spokespersons also agreed that the technology provides speed to market advantages. Company 2 has had success with pop-up shop retailing and creating a finished product for a customer within an hour.

Another operational driver was the ability to completely change the standard textile supply chain. There have been mixed reviews about this new ability as it could put certain partners in the supply chain out of work, according to the spokesperson from Company 7. Three company’s spokespersons explained that their supply chain is comparatively simpler than other methods of production like cut & sew and full-fashioned knitting. Implementation has allowed for brands to communicate directly with yarn mills, which has not been the standard protocol for the industry. This is particularly helpful for the on-demand manufacturing companies; it has allowed them to simply stock yarn and adapt their yarn supply to customer orders. For the larger companies, with the normal apparel model all representatives commented that the planning timelines are required to be much longer since they must build in a longer prototype development timeline.

Implementation of this technology has also allowed for the realization of a textile mass customization model. Two companies have implemented on-demand manufacturing as their business model, creating products only as they are ordered through online retailing, resulting in no dead stock or inventory. Adding to the mass customization element, Company 2 offers color customizability and personalization. Company 4’s spokespersons pointed out that the mass customization model had been successful with Stoll machines in the 1980s, which could be used today.
Four company’s spokespersons agreed that being able to keep the machines in-house for manufacturing purposes was a main benefit to adoption. This allows for clear oversight of the knitting process and ensures a responsibly made product. Two company’s spokespersons also noted the advances in energy efficiency that the new machines have. They contend that the implications are that the machines can potentially run on solar panels or anywhere in the world having a reliable electricity connection. One company’s spokesperson stated that the machines use less electricity than a typical household washer and dryer, speaking to the minimal amount of electricity required to operate a machine.

Of a similar note, manufacturing in-house also means that manufacturing can occur domestically in the United States. Of the eight companies, four were manufacturing in the United States. The four companies have had the added benefit of oversight to their production stream. They have also filled a void in the market by providing a service or product to customers who are concerned about the made in America movement. Company 2’s spokesperson commented that manufacturing domestically allows for better logistics and quicker delivery to customers since products are not required to be shipped overseas, further eliminating manufacturing costs.

Two company’s spokespersons commented on the added flexibility that the machines offer for product design. A wide array of products can all be created using the same machine, potentially broadening a product line or research and development projects.

Three company’s spokespersons agreed that the technology creates a consistent product because all making up is completed on the machine. This results in less defects overall if the machine is adjusted correctly. Company 3’s spokesperson explained:

The more human hands that are involved in the production process, the more variations it can have. (…) So you minimize a lot of the variables in the production flow so your end
product is more consistent as long as your machine is adjusted correctly. In WholeGarment®, you could have a dropped stitch in a garment that was not caught and we could have the same issue. But at least you will not have a sewing or linking defect. So you’ll probably experience less defects compared to the traditional method of producing sweaters (Company 3 administrative employee, personal communication, April 27, 2017).

Implementation of the technology has had an added benefit with new retailing venues. Since manufacturing can occur in-house domestically, two companies have retailed primarily online without a brick and mortar store. Company 2, however, has also seen success using pop-up shops to generate traffic to the online store. These in-person experiences have created memorable and magical experiences for the customer and has established brand loyalty. Two company’s spokespersons also commented on the quick initial start-up time for using the machines, contributing as an operational driver.

**Consumer**

There are drivers that have been identified as providing benefits to the end user which have been distinguished as consumer drivers. Added comfort and durability are the two traits that products can have which were mentioned as main benefits to adoption. Two companies have received positive feedback from customers regarding the comfort of seamless 3D knit garments. Two of Company 6’s representatives stated that added comfort of a 3D knitted garment was a main driver to adopt the technology. Their spokesperson stated that this was especially helpful for products that are next to skin:
It reduces waste, it reduces potential quality issues. I mean oftentimes the seams are where we start seeing issues, particularly with base layer and stuff like that. Because next to skin comfort is so critical. Anytime you add a seam in, you have to be really careful to do it in the way that’s not going to introduce a chaff point, a stress point that’s going to limit the stretch of an item, and also, 3D knitting, 3D WholeGarment® knitting really allows you to combine different constructions in a perfect way. (Company 6 administrative employee, personal communication, May 2, 2017)

Complete-garments were stated as having higher durability and were less susceptible to wear since they are continuously knit. Both on-demand manufacturers used this feature as a marketing story and have heard positive feedback from customers.

**Conclusion**

The case study conducted for this research interviewed respondents of eight companies of varying sizes. Commonalities of responses have been drawn in this chapter, revealing barrier and driver themes to the adoption of 3D knitting technologies. The barriers identified were: capital, management, knowledge, operational and consumer. The drivers identified were: demand, cultural, operational and consumer.
CHAPTER 5
CONCLUSIONS, DISCUSSION, AND RECOMMENDATIONS

Introduction

The textile industry is unique in its slow rate to adopt new technologies. It is one of the known “mature” (p.56) industries of the world with a long-standing established infrastructure and means of production (Ray, 1983). Yet, improvements have been made to the traditional sewn products industry by means of new machinery and computer-aided systems that enable supply chain efficiencies. Whether these innovations will be implemented in a way that would change the textile supply chain is yet to be seen. This research has examined a sub-set of the textile industry in knitting technology in the United States, specifically related to flat-bed seamless knitting called 3D knitting. Due to the constraint of only studying United States companies, the perspectives found in the research hold their own form of bias not present in other countries.

There are many drivers and barriers that may impact how a company makes a technology adoption decision. These factors have an inherent positive or negative influence on the decision-making phase of technology adoption. Identifying these factors could assist business owners in making informed decisions about the technology they are considering for adoption.

The purpose of this study was to identify the decision-making factors associated with the adoption of 3D knitting technologies. Implications for this research include insightful information for machine manufacturers and businesses seeking to adopt the technology. After completion of the case-study analysis insights were discovered regarding education of 3D knitting.
Research Objectives

The research objectives for this study were:

**Objective 1:** To identify the drivers of adoption for 3D knitting technologies through the full organizational innovation decision process.

**Objective 2:** To identify the barriers to the adoption of 3D knitting technologies through the full organizational innovation decision process.

Literature Review

The business decision to adopt a new technology is greatly impacted by the production processes that are already in place to create a product. The production processes related to knitted products include cut & sew, panel knitting, full-fashioned knitting, integral knitting, and 3D knitting. In the cut & sew method, pattern pieces of a garment are cut from a length of fabric and then sewn or linked together (Brackenbury, 1992). Cut & sewn garments made of knitted fabric are typically from a circular or warp knitting machine. In the panel knitting method, a rectangular piece of fabric is knit, with an integrated welt finish at the hem. It is also known as “cut-stitch shaped”, “blanks” (Brackenbury, 1992, p.13); and “garment-length” (Spencer, 2001, p.83). Circular or flat knitting machines may be used to knit these panels. Once the fabric is knit, areas of shaping are cut into the fabric, and pieces are then joined together.

Full-fashioned knitting employs flat-bed knitting techniques to shape a garment pattern piece with contained selvedges on all sides. This shaping is achieved by narrowing or widening of the knitting width, through the process of increasing or decreasing active knitting needles (Brackenbury, 1992). Depending on the level of automation present on a flat-bed knitting machine, narrowing, and decreasing of knitting width may be operated by hand or through
various forms of mechanical actuators and computer technology (Mills, 1965; Brackenbury, 1992). An advanced version of full-fashioned knitting exists, called integral knitting. With this method, shaped pieces have integrated trims which are knit into the pattern piece. Examples of these trims are pockets, button holes and additional knit structures (Anderson, 2008; Kanakaraj & Ramachandran, 2010; Peterson & Ekwall, 2007). Integral knitting employs the use of V-bed knitting.

The most advanced knitting method is 3D knitting. With this method, fashion or technical textiles are created by knitting in one piece with no seams. Complete-garments are created by using a combination of tubular or shaped knitting, which are joined during the knitting process (Choi & Powell, 2005; Kanakaraj & Ramachandran, 2010; Ma & Lamar, 2013; Rao, 2012). This production method employs the use of flat-bed knitting machinery, which allows for loop transference from opposing beds.

The market innovators in 3D knitting machinery today are Shima Seiki of Japan and Stoll of Germany. Each company has specialized in their own particular brand of 3D knitting. Shima Seiki, the first to debut their WholeGarment® knitting machine in 1998 at ITMA, is a constant innovator in WholeGarment® samples. These machines employ four needle-beds for a heightened ability in designing.

Stoll differentiates their knit & wear® technology, by stating their main strength is the flexibility their machines allow for use of different yarn types and thicknesses. This system is ideal for design and versatility, due it its ability to control different areas of a garment to be knit with different stitch construction. Stoll has also designed their CAD system in such a way that is user-friendly, as the technical and knitting simulations are simultaneously present on the
computer interface (Anderson, 2008). In terms of a production method, complete-garment
knitting reduces many of the post-knitting requirements of other methods.

Little research exists which has examined the current textile industry issue regarding 3D
knitting technologies and the decision-making process related to how these technologies might
be adopted into businesses.

Due to the nature of this research, a case-study approach was chosen. Much of the
research surrounding the adoption of technology has been focused at the societal diffusion of
innovations. This type of research requires historical data and generally is investigated only
when a given technology is at full diffusion. Rogers (2003) argued that insightful data regarding
the decision-making phase is overlooked with this approach. He also stated that it would be
beneficial to conduct field experiments (i.e. case-studies) before the diffusion process is
complete, to overcome any “pro-innovation bias” (Rogers, 2003, p. 112), that may be present.
Rogers argued that all researchers have a pro-innovation bias, which means to favor technology
adoption. Oftentimes the hindrance to diffusion research is a narrow view of adoption, by
“underemphasizing the rejection of discontinuance of innovations” (Rogers, 2003, p. 107).

Park and DeLong (2009), in their case study about rapid prototyping technology, adapted
several social frameworks (Roger’s Innovation Diffusion Process in Organizations, Social
Construct of Technology (SCOT) and the Technology Acceptance Model) to create a
comprehensive framework which includes external variables which affect social groups and
results in issues and perceptions of these issues. This study focused mostly on the social
framework aspects of technology adoption. Only one company was studied with a web-based
questionnaire.
Fang, To, Zhang and Chang (2014) conducted a case study, similar to our proposed methodology, in regard to information and communication technologies for textile virtual collaboration. An interpretive approach was taken, by gathering opinions from “qualified subjects” (p.5) with in-depth interviews. Their proposed framework, is found in Figure 18. In essence, this framework is constructed first of factors (characteristics of ITC), that are affected by the external environment followed by a selection and adoption of a technology. They concluded that six characteristics of ITCs would influence its adoption. These categories could translate as the proposed ‘areas of influence’ introduced in Chapter 1.

Based upon the literature review, a theoretical framework was developed prior to field research as a decision-making model with barriers or drivers contributing to the business decision to adopt 3D knitting technology, found in Figure 18.

Methodology

A theoretical framework was developed prior to field research as a decision-making model with barriers or drivers, based on literature review (presented in Ch. 3, Figure 18). This framework was used as a decision-making model with external areas of influence contributing as barriers or drivers. The ‘areas of influence’, a term coined by the author, (presented in Ch. 1, Table 1) appears in Table 3 performed as hypothesized factors to guide the development of interview questions prior to field research.

A qualitative case-study approach was taken in order to capture the rich and varied experiences relative to adoption of this innovative and disruptive technology. In-person and in-depth interviews produced rich insights, which could translate to other industries. Using the interviewing methodology assured the highest validity of responses and a greater response rate compared to survey studies. During field research, respondents were recorded with video to
ensure the accuracy of data transcription. Video interviews were then transcribed verbatim by the researcher into individual documents to ensure the data’s accuracy. NVivo qualitative analysis software was used to code and sort through each transcribed interview document to identify trends and themes amongst the research. Several iterations of synthesizing commenced; the iteration after initial coding is found in Appendix D. The summarized findings appear in Chapter Four.

**Major Findings**

The first research objective for this dissertation was to identify the drivers of adoption for 3D knitting technologies through the full organizational innovation decision process. Through qualitative analysis, several driver themes emerged as provoking the companies to adopt and keep the 3D knitting technology. The major themes identified were demand, cultural, operational and consumer drivers. The definitions of each theme were presented in Chapter Two, Table 4. Of the driver themes, the most salient of the factors were cultural and operational.

Cultural drivers included those associated with the relationships between businesses, company values and business models. A leading cultural driver was the pre-existing or positive relationship between the company studied and the machine manufacturer of the product they purchased. This was illustrated with cultural matching between the two businesses. Companies were also driven to adopt the technology by the values that were held in place by the upper management of the company, such as building a new apparel model with on-demand manufacturing.

Since all companies interviewed have adopted the technology at one point or another, an important question asked related to the reasons why companies had decided to choose one machine manufacturer over the other. Most of the companies stated their reasoning was
influenced by a prior relationship with the machine manufacturer or a positive relationship in general with them. This points to the fact that relationships between technology provider and technology user are an important factor in the adoption decision process.

Operational drivers were also very common among responses from participants. These include benefits related to the production process including: the reduction of labor, increased production speed, quicker speed to market, ability to scale the technology, rapid prototyping and supply chain agility. Other operational benefits with implementation mentioned were an ability to use a mass customization business model, in-house manufacturing and higher consistency of a finished product resulting in an overall quicker production stream. Adoption also allowed for domestic manufacturing, or anywhere in the world with reliable electricity.

The second research objective for this study was to identify the barriers to the adoption of 3D knitting technologies through the full organizational innovation decision process. Barrier themes were identified as capital, management, knowledge, operational and consumer. Of the barrier themes, the most salient of the factors were knowledge and operational.

Knowledge barriers included those associated with the lack of knowledge or personnel knowledge. This related not only to knowledge necessary in a business but also the industry knowledge of the capabilities of the machines. Most companies agreed that there is a lack of knowledge of candidates who can program and maintain 3D knitting technologies. This new skill set also requires a multi-faceted educational process to provide the best candidates for these necessary roles. All companies also agreed that the learning curve is quite steep for the knitting software’s which pose as a major barrier to entry.

Operational barriers included those associated with equipment and production line efficiency. Machine operating, maintenance of the machines, general machine limitations and
limited troubleshooting resources were all identified as being limiting factors for an efficient production stream using 3D knitting technologies.

**Updated Theoretical Framework**

Considering the driver and barrier themes to adoption found from data analysis, a new theoretical framework was developed. The initial framework was developed based on the speculation that administrative employees influenced the pre-decision phase of the innovation decision process and that technology-user influence was most prevalent in the post-decision phase of the innovation decision process. After interviewing representatives of all three possible roles: administrative, administrative & technology user and technology user, it was found that the innovation decision process was more nuanced than originally hypothesized. The innovation decision process was also found to be more of a holistic process than a linear one.

The proposed ‘areas of influence’ were stated as hypothesized factors which set the foundation for the research design. After data analysis, the ‘areas of influence’ were revealed to have dual implications, both having positive and negative connotations. The ‘areas of influence’ were then synthesized into driver and barrier themes which emerged during the data analysis phase. A visual representation of this synthesis is shown in Figure 19.

It was also discovered during data analysis, where the barriers and driver themes reside along the innovation decision process model. The updated theoretical framework is presented in Figure 20. This framework applies to six of the eight companies interviewed as they have all kept the 3D knitting technology. Also noted in this new theoretical framework is a degree of saliency each barrier or driver holds. Barriers and drivers are listed in descending order of saliency, with the most salient at the top of each phase.
Two exceptions to this framework are found in Figure 21 and 22, where two companies had a change of technology use. What was originally proposed in the first theoretical framework was a recursive decision-making process. This was found to be true only for those companies who changed their technology use.

For the company that had a technology change from 3D knitting to cut & sew production, the company’s core value of innovation seeking drove the purchase of the machines. They soon found that the types of products able to be created were not in line with consumer expectations. It was then impossible for them to justify the expense of the machine purchase for such a limited number of styles which did not fit their design aesthetic. Both consumer and capital barriers led the company to reject the adoption of 3D knitting technology.
Figure 20. Synthesis of 'areas of influence' into driver and barrier themes identified after field research. Developed by Author.
Figure 21. Updated theoretical framework after data analysis with designated barriers and drivers, Authors Own

Figure 22. Innovation Decision Process with a change of technology, from 3D knitting to cut & sew production, Authors Own
The company who had a technology change from full-fashioned knitting, was driven to adopt the full-fashioned technology by an overarching company purpose, a cultural driver. After the decision phase, the company found that full-fashioned knitting posed an operational barrier due to the time-consuming linking step in production. This operational barrier acted as a driver for the 3D knitting technology. With this new adoption, the company was able to maintain their initial cultural drivers. It was 3D knitting that solved their operational barrier issues, thus reinforcing the decision to adopt the technology.

**Additional Insights**

The theoretical framework of this study changed through the process of field research and the data analysis phase. The most salient of drivers towards adoption of 3D knitting technologies
had cultural and operational themes. Cultural matching between machine manufacturer and the participating companies emerged as a driver to adopt. Considering this insight, it suggests that the method in which machine manufacturers approaches potential machine purchasers is significant and establishing a positive relationship from the outset could determine the final machinery purchase. This insight also could suggest that the relationships between people are sometimes more important than the actual abilities of the technology itself. The sales position at machine manufacturers must be very informed not only on the machinery they are selling, but also regarding the core values of their potential customers. A shared vision between machine manufacturers and company users appears to be quite important. With this understanding, machine manufacturers could proactively select certain companies or brands to target for sales inquiries. It is safe to assert that the business decision to adopt 3D knitting technology is nuanced, since human interactions play such a meaningful role in the decision-making process.

The operational drivers relate to benefits attained in the production stream with the adoption 3D knitting technologies. However, in order for the benefits to be recognized, a new production model must to be used. This was represented by the smaller sized niche companies in the case study. Both smaller sized companies implemented an on-demand manufacturing production model.

Flat-bed machine sales have been led by China, Bangladesh, Hong Kong, Turkey and Italy in recent years (“Global machinery..”, 2010; “Circular and flat…”, 2015). The majority of flat-bed machine sales occurring in China. Though the United States comprises a small fraction of the overall machine sales for flat-bed knitting, researching this location has provided additional insights into a collapsed supply chain. (“Circular and flat…”, 2011; 2012; 2013; 2014; 2015)
The main benefit to 3D knitting mentioned by several companies was the ability to hold the manufacturing or prototyping of products in the office or in-house environment. This also spoke to restructuring of the textile industry model by allowing for a more vertically integrated production stream or supply chain. In a time where much of the manufacturing of textile related products has been moved to foreign countries, the technology offers a different approach by manufacturing domestically. Companies considering adoption of this technology will also need to consider the impact on their supply chain. Brands may find it difficult to move to this new model because it could also eliminate jobs relating to forecasting and established relationships with manufacturing partners. According to the results found in this study, smaller niche brands could be the first indication of an industry wide diffusion of technology, with larger brands expected to adopt gradually over time.

The most salient of barriers identified during this research had knowledge and operational themes. The lack of personnel with knowledge of machine operation and software has been seen as a major hindrance to the adoption of the technology. Several participating companies agreed that the candidate pool of qualified individuals that have technical knowledge of knitting or knitting machine operations is very small and must be remedied. Companies also commented on the limited compensation that knitting programmers receive even today when a small availability of candidates exists. Several interpretations could be made from this miss-match of demand versus supply of available programmers: programmers are unaware of how in-demand they truly are and are not confident to seek out higher compensation; the market does not recognize this role as high-tech for higher compensation like a typical software programmer; there are external factors contributing to the lessened compensation, perhaps due to the expected learning curve.
time needed to become an expert in knitting programming; or the status of compensation for any type of technician in the textile industry is not valued.

After the discussion with experts in the field, a compilation of training requirements to overcome the learning curve has been assembled for improvements to curriculum related to 3D knitting technologies. A resounding number of participants agreed that students should have knitting knowledge with a basic understanding of how a flat-bed machine works, preferably with a flat-bed hand machine. Additional requirements include:

1. A student must understand fibers and yarns and how these base elements contribute to the overall success of a 3D knitted product.

2. Students should comprehend how the machines work with hands-on experience. They must know how to troubleshoot when an error appears or needle breaks occur on the machine.

3. Students should recognize how certain yarns will interact with the machine and the risks associated with certain fiber types or yarn count.

4. In order to successfully knit a three-dimensional shape, students must first grasp how to make a three-dimensional shape with a two-dimensional pattern. Because of this, basic patternmaking skills would be required in the curriculum.

5. Students need to possess creativity and spatial visualization abilities. Many of the projects which are being developed currently require knitting to occur in an unusual orientation for sweater manufacturing. Company 4 representative stated that 3D knit programmers have to be inventive by, “thinking outside the box; just because nobody has done it doesn’t mean that it can’t be done” (Company 4 administrative & technology user employee, personal communication, April 28,
2017). This statement hints at the idea that innovation will not be possible without an ability to look at a problem with a diverse perspective.

6. Students must first experience a failure to fully understand the machines. So, it would be prudent to allow students to handle the machines and learn how to fix them when something breaks.

7. Technical textiles pose another level of complexity for curriculum development. Students will not only need to have an interest in knitting but also complex three-dimensional shaping. This group of students will also need to have curiosity for the programming required to operate a machine. Respondents in the technical textile field also commented that programmers must be able to design products with an aesthetic appeal. This will require a multi-faceted candidate, who is technically skilled, interested in knitting and appreciates design fundamentals when developing a new product.

A number of suggestions also emerged for improvements to be made for the usability of the machines and the software. One common complaint among the technology users in this study was the difficulty faced during the iteration process. They found that it was easy to get lost when moving from the software to the machine and back to the software again. This is an issue that arises simply from having two components to a production process. It would be beneficial for both machine manufacturers to consider this in development of new machines and software partnerships. A possible solution to this problem is to create a streamlined process for technicians to adjust a pattern at the machine rather than requiring a stepping back to the software system for edits.
Recommendations for Future Research

The study has presented a new understanding of how businesses make decisions regarding innovation adoption, specifically to 3D knitting technologies. Though the technology has existed for twenty years, the large majority of the textile industry has not adopted the technology yet. The main purpose of this research was to identify the barriers and drivers to adoption for this novel technology. This particular study was limited in its scope by time constraints, funding and the geographic area examined. A larger study of this technology adoption could be done in other countries of 3D knitting manufacturing to see if the factors that impact adoption are similar, on a global basis. Barriers to adoption could also be attained by interviewing or surveying companies who have never adopted the technology but are creating products that could be manufactured with 3D knitting.

Considering some of the unexpected findings during this research, other areas for future research could include:

1. A similar study regarding the factors contributing to 3D knitting adoption in other countries; focusing on China, Turkey or Italy as the highest purchasers of flat-bed knitting machines in recent years.

2. A study investigating the key missing components necessary for implementing a new technology after the collapse of a supply chain.

3. A survey of or interview with 3D knitting programmers to determine their suggested educational methods to prepare future employees for this role;

4. An examination of cultural matching between technology provider and users for other technology types; and
5. An examination of the demand versus supply of knitting programmers, and the impact on compensation.

**Conclusion**

This study contributed to the body of knowledge related to the diffusion of innovations, specifically with organizational innovation decision processes. One major outcome was the understanding of the important role that education plays in preparing the industry for successful adoption of new technologies. Academia, both universities and technical programs, need to be pro-active by preparing the future employees and leaders so that the benefits of disruptive technologies can be capitalized on. This has implications for other technologies that have been or are being developed in other sectors of the Textile and Apparel complex.
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APPENDICES
## APPENDIX A

### Knitting Machines Marketed as “Seamless” as of 2017

<table>
<thead>
<tr>
<th>Name</th>
<th>Description</th>
<th>Knitting Method</th>
<th>Gauges</th>
<th>Size/ Diameter/ Bed Lengths</th>
<th>Feeds/ Yarn Carrier</th>
<th>Carriage Systems</th>
<th>Product Uses</th>
<th>Novel Capabilities</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Santoni</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
| MEC-MOR CMP   | Garment length circular knitting with rib border, Double Jersey | Circular        | E7, E8, E10, E12, E14, E16, E18, E20 | 33”                         | 24 total feeds. (combined knitting transfer systems) 12 knit feeds on 2 technical ways | N/A               | Athleticwear, fancy fabrics (photo-realistic jacquard, blister knits, pointelle) garments with reduced seams | • Each feed has knitting and transfer system  
• Variable working width  
• 4 color stripes  
• Plated effects  
• Pockets  
• Easily knits bare lycra |
| MEC-MOR HP    | Garment length circular knitting with rib border, Double Jersey | Circular        | E7, E8, E10, E12, E14, E16, E18, E20 | 44”                         | 24 total feeds. (combined knitting transfer systems) 12 knit feeds on 2 technical ways | N/A               | Athleticwear, fancy fabrics (photo-realistic jacquard, blister knits, pointelle) garments with reduced seams | • Each feed has knitting and transfer system  
• Variable working width  
• 4 color stripes  
• Plated effects  
• Pockets  
• Easily knits bare lycra |
<p>| <strong>Karl Mayer</strong>|                                                  |                 |                   |                             |                     |                  |                                                                            |                                                                                  |
| DJ 4/2 (EL)   | Narrow double-bar raschel                         | Warp            | E24, E28, E32     | 44”                         | 4 (two) ground guide bars, 2 piezo jacquard guide bars | N/A               | outerwear, seamless foundation wear (pantyhose), bodysuits, innerwear, medical, | Piezo jacquard                                                                     |
| DJ 6/2 (EL)   | Narrow double-bar raschel                         | Warp            | E24, E28, E32     | 44”                         | N/A               |                  |                                                                            |                                                                                  |</p>
<table>
<thead>
<tr>
<th>Model</th>
<th>Type</th>
<th>Machine Type</th>
<th>Knitting Width</th>
<th>Needles</th>
<th>Carriers</th>
<th>Features</th>
<th>Applications</th>
</tr>
</thead>
<tbody>
<tr>
<td>RDPJ 4/2 (EL)</td>
<td>Double-bar raschel Warp E16, E18, E24, E28 138”</td>
<td>N/A</td>
<td>semi-technical applications</td>
<td>Piezo jacquard</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>RDPJ 6/2 (EL)</td>
<td>Double-bar raschel Warp E16, E18, E24, E28 138” (split execution)</td>
<td>N/A</td>
<td>semi-technical applications</td>
<td>Piezo jacquard</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Model</th>
<th>Type</th>
<th>Machine Type</th>
<th>Knitting Width</th>
<th>Needles</th>
<th>Carriers</th>
<th>Features</th>
<th>Applications</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stoll CMS 530 HP knit &amp; wear</td>
<td>3D knitting &amp; full-fashioned knitting</td>
<td>Flat-Bed E 2,5.2- E 7.2</td>
<td>50”</td>
<td>4</td>
<td>12</td>
<td>3</td>
<td>Seamless baby and children garments, accessories (hats, scarves, gloves, etc.) Complete-garments</td>
</tr>
<tr>
<td>CMS 730 T knit &amp; wear</td>
<td>3D knitting &amp; full-fashioned knitting</td>
<td>Flat-Bed E6.2- E7.2</td>
<td>72”</td>
<td>4</td>
<td>16</td>
<td>3</td>
<td>Knit &amp; wear fabrics Tandem knitting of two knit &amp; wear fabrics within the knitting width</td>
</tr>
<tr>
<td>CMS 822 HP knit &amp; wear</td>
<td>3D knitting &amp; full-fashioned knitting</td>
<td>Flat-Bed E2,5.2- E7.2</td>
<td>84”</td>
<td>4</td>
<td>16</td>
<td>3</td>
<td>Complete articles with ultra-coarse stitches</td>
</tr>
<tr>
<td>CMS 830 C knit &amp; wear</td>
<td>3D knitting &amp; full-fashioned knitting</td>
<td>Flat-Bed E 3,5.2, E 7.2, E 9.2</td>
<td>86”</td>
<td>4</td>
<td>16</td>
<td>3</td>
<td>Complete-garments even in extra large sizes</td>
</tr>
<tr>
<td>CMS 830 S knit &amp; wear</td>
<td>3D knitting &amp; full-fashioned knitting</td>
<td>Flat-Bed</td>
<td>Variable stroke. 40” 50” 60”</td>
<td>12 normal carriers</td>
<td>3 (1 knitting + 2 transfer) in 1 carriage</td>
<td>Complete-garments with all needles in action</td>
<td>4-bed configuration slide needle</td>
</tr>
<tr>
<td>Mach 2XS</td>
<td>3D knitting</td>
<td>Flat-Bed 8L, 12S, 15S, 15L (S: Standard hook, L: large hook)</td>
<td>40” 50” 60” 68”</td>
<td>12 normal carriers</td>
<td>3 (1 knitting + 2 transfer) in 1 carriage</td>
<td>Complete-garments with all needles in action</td>
<td>4-bed configuration slide needle</td>
</tr>
<tr>
<td>Mach 2X</td>
<td>3D knitting</td>
<td>Flat-Bed 5S, 8L, 15L, 18L</td>
<td>Variable stroke. 50” 60” 68”</td>
<td>12 normal carriers</td>
<td>3</td>
<td>Complete-garments with all needles in action</td>
<td>4-bed configuration slide needle</td>
</tr>
<tr>
<td>Model</td>
<td>Type</td>
<td>Bed</td>
<td>Strokes</td>
<td>GAuges</td>
<td>Carriers</td>
<td>System</td>
<td>Accessories</td>
</tr>
<tr>
<td>----------</td>
<td>---------------</td>
<td>-------------</td>
<td>---------</td>
<td>--------</td>
<td>----------</td>
<td>-------------------------</td>
<td>----------------------------------------</td>
</tr>
<tr>
<td>Mach 2S</td>
<td>3D knitting</td>
<td>Flat-Bed</td>
<td>8</td>
<td>10</td>
<td>12</td>
<td>Variable stroke. 72&quot;</td>
<td>13 normal carriers</td>
</tr>
<tr>
<td>SWG021N2</td>
<td>3D knitting</td>
<td>Flat-Bed</td>
<td>7</td>
<td>10</td>
<td>13</td>
<td>Variable stroke. 10&quot;</td>
<td>8 Independent motorized yarn carriers</td>
</tr>
<tr>
<td>SWG041N2</td>
<td>3D knitting</td>
<td>Flat-Bed</td>
<td>7</td>
<td>10</td>
<td>13</td>
<td>Variable stroke. 16&quot;</td>
<td>10 Independent motorized yarn carriers</td>
</tr>
<tr>
<td>SWG061N2</td>
<td>3D knitting</td>
<td>Flat-Bed</td>
<td>7</td>
<td>10</td>
<td>13</td>
<td>Variable stroke. 24&quot;</td>
<td>8 Independent motorized yarn carriers</td>
</tr>
<tr>
<td>SWG091N2</td>
<td>3D knitting</td>
<td>Flat-Bed</td>
<td>7</td>
<td>10</td>
<td>13</td>
<td>Variable stroke. 36&quot;</td>
<td>10 Independent motorized yarn carriers</td>
</tr>
<tr>
<td>SWG FIRST 124</td>
<td>3D knitting &amp; full-fashioned</td>
<td>Flat-Bed</td>
<td>S18 S21</td>
<td>4</td>
<td>4</td>
<td>Variable stroke. 50&quot;</td>
<td>12 (2 knitting + 2 transfer+ holding cam)</td>
</tr>
<tr>
<td>SWG FIRST 154</td>
<td>3D knitting &amp; full-fashioned</td>
<td>Flat-Bed</td>
<td>S18 S21</td>
<td>4</td>
<td>4</td>
<td>Variable stroke. 60&quot;</td>
<td>12 (2 knitting + 2 transfer+ holding cam)</td>
</tr>
</tbody>
</table>
APPENDIX B

Explanation of Areas of Influence

Managerial: Relating to the decisions that are intrinsic to management of a particular company and the workplace culture that is established by those in authority positions. An example of this, is the tone-at-the top theory, in which all business’ driving mission or purpose is established first by those with the final say, whether they have the role of ownership over the company, or are the CEO.

Training/Personnel: Relating to all facets that may have to do with the staff of a company, whether it requires more training, or hiring and/or firing of current staff.

Investing/Cash flow: When decisions are made primarily on the basis of available cash flow, or liquid capital investment.

Design Considerations: The design time necessary to create products on new technology; as well as comparable designs to other methods of knitting and perhaps any limitations that may occur in the design phase of production.

Size of Company: May have a direct correlation with available cash flow and capital investment- this may point to increased flexibility, or inflexibility in certain areas of discussion.

Inception of Company: Beginning of a corporate venture; may have a direct correlation with the particular diffusion positioning a company has along the diffusion curve.

Market/Demand for Product: Relates to ability a product has to be marketable to a consumer-base, and if the market will sustain itself overtime.
**Reshoring:** Factors that may relate to place manufacturing in the United States, rather than overseas in foreign countries.

**Diffusion Positioning:** Relates to the area along the diffusion of innovation curve that a company may identify themselves as, and how they leverage that position for their benefit and success.

**Perceived Benefits:** Relates to any idea that may be perceived in the mind of the company in question, that is beneficial to their success.

**Perceived Limitations:** Relates to any idea that may be perceived in the mind of the company in question, that is detrimental to their success, or too risky to undergo.

**Supply Chain Flexibility:** Factors that may contribute towards how a supply chain functions, and whether pieces of the supply chain can be altered at any given time. This also relates to the ability to have a vertically integrated supply chain (where all production functions is localized in one geographic area), and if this is a possibility for the company, given the current state of affairs.

**Logistics Considerations:** Relates to any factors that impact the shipping and receiving of product, either to produce or sell to the customer. The amount of time that a product must travel to different stages in the production process must be taken into account as a time expenditure, as well as reduced time to market, resulting in delayed inward cash flow.

**Positioning of Product:** Advertising principles; relates to the factors that contribute towards the brand positioning a company holds in the minds of their customer. This is where ‘telling a story’ about a product can prove beneficial to maintain the loyalty of customers for repeat purchases.
Sustainability: Any factors that contribute towards a company’s mission of environmental sustainability, whether it be reduced waste, reduction of energy, or reduction of human labor. Sustainability can also relate to the development of processes that will withstand the test of time, by taking into account the needs of the future.

Quality Considerations: Factors which affect the overall structural and aesthetic condition of a product. This can relate to the garment’s ability that a garment has to maintain its shape and initial characteristics over the passage of time and wear.

Production Processes: factors which contribute to the steps required in a production supply chain of a knitted product. These processes may vary depending on the technology used or the requirement of human labor for each step.
## APPENDIX C

### Hypothesis Map for interview question generation

<table>
<thead>
<tr>
<th>Barrier or Driver</th>
<th>Hypothesized Factor</th>
<th>Applicable Area(s) of Influence</th>
<th>Interview Questions</th>
</tr>
</thead>
<tbody>
<tr>
<td>B</td>
<td>Capital Investment</td>
<td>Investing/ Cashflow</td>
<td>To what degree do you feel capital investment has been an issue in regards to adopting 3D knitting technology?</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>How have you solved this issue?</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>What are you doing currently to combat this issue?</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Are there any issues that you have encountered in terms of financing of this technology?</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>To what degree is investment or capital, a concern for your company when it comes to investing in a new technology?</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>What methods have you taken to safely finance the adoption of this technology?</td>
</tr>
<tr>
<td></td>
<td>High Learning</td>
<td>Training/ Personnel</td>
<td>When did you first adopt 3D knitting?</td>
</tr>
<tr>
<td></td>
<td>Curve (experts</td>
<td></td>
<td>What kind of learning curve did your company experience with adopting 3D?</td>
</tr>
<tr>
<td></td>
<td>needed to program)</td>
<td></td>
<td>What kind of challenges have you faced in adopting 3D?</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>How much experience do your employees have with programming?</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Was this experience attained on the job at your company, or previous training?</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>How quickly do you feel your employees have been able to get up to speed with understanding this technology?</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Do you have any complaints about the learning curve associated with this new technology? What are they?</td>
</tr>
<tr>
<td>B</td>
<td>Training Requirements (time associated)</td>
<td>Training/ Personnel</td>
<td>How much training were you given to effectively use this new technology?</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>How do you feel the training has met your needs?</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Do you feel confidently proficient in the technology within the allotted training time that you've had? If not, why?</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>What type of employees do you seek out to fill these programming roles?</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Do you feel there is a good selection of candidates that have these skills before arriving at your company?</td>
</tr>
<tr>
<td></td>
<td>Return on</td>
<td>Investing/ Cashflow</td>
<td>What are some of the risks that you are concerned with when it comes to adopting this technology?</td>
</tr>
<tr>
<td></td>
<td>Investment is slow</td>
<td></td>
<td>Are you confident you’re going to have a good return on your investment? If yes, why?</td>
</tr>
<tr>
<td></td>
<td>or unforeseen</td>
<td></td>
<td>What kind of time-line are you looking at for breaking even on this investment?</td>
</tr>
</tbody>
</table>
What kind of benefits have you seen arise from implementing this technology so far?

Has your company ever produced product using full-fashioned knitting machines in the past?

How would you compare the difference in production methods, and which one do you prefer?

On average, how long do you estimate a new style takes to design from concept to program in the knitting software?

Do you see a significant timeline difference from earlier production methods, to 3D technology? Explain.

What kind of features do you inform your customer about your product being 3D?

How do you explain to your customer the value that 3D products have to offer?

What efforts have been made by your company to market the benefits of 3D products?

Have you received positive or negative feedback from customers regarding the quality of your product?

How do you view your competitors in light of using 3D? What kind of positioning do you have over them?

When did your company decide to invest in 3D?

How much of your production stream is 3D to date?

How much of your product line is created using 3D?

How has your company been able to invest in this expensive technology?

Did you receive any incentives from the machine manufacturers to assist in your decision to purchase the 3D machinery?

How do you think the mission and values of the CEO/upper management have impacted the use of adopting 3D?

Was this investment spurred on by their decision, or by other staff?

What type of training have your programmers and/or technicians received in 3D?

How do you view your competitors in light of using 3D? What kind of positioning do you have over them?

When did your company decide to invest in 3D?

How much of your production stream is 3D to date?

How much of your product line is created using 3D?

How has your company been able to invest in this expensive technology?

Did you receive any incentives from the machine manufacturers to assist in your decision to purchase the 3D machinery?

How do you think the mission and values of the CEO/upper management have impacted the use of adopting 3D?

Was this investment spurred on by their decision, or by other staff?

What type of training have your programmers and/or technicians received in 3D?
Where have you sourced your programmers and technicians from?
How difficult has it been for you to find a skilled programmer or technician in 3D?
How many programmers and technicians have you employed?
Do you foresee employing more programmers or technicians in the future?
What kind of qualifications do you look for in hiring a programmer or technician?
How much experience do you prefer a new-hire programmer to have?
How are your knit patterns created- by template system, from scratch or patterns supplied by the machine manufacturer?
If by template- do you feel they adequately fit your design needs as a company?
Why have you chosen to use this method of creating patterns? Easiest, Most flexible, most comprehensive?
How do you feel Machine Manufacturer X could meet your needs better as a programmer/technician?
What difficulties have you faced in working with the knit programming software?
What difficulties have you faced in working with the machines?
How much of a learning curve did you face when first learning the software?
How much of a learning curve did you face when first learning how to operate the machine?
How would you classify your target customer?
How are your customers informed of the benefits that 3D allows?
How much have your sales grown in recent years, of your products that are 3D?
Do you foresee these sales to continue to grow?
Have you noticed any lags in sales related to 3D products that you sell?
When was your company first established?

Inception of Company- may be set in their ways and unwilling to adapt

Where would you place yourself along the innovation curve, as a company? (show picture)
Why do you consider your company to be at this stage of the innovation curve?
When did you first start using 3D technology?
Since it's first implementation, how have things changed in the way that the 3D team operates?
Has the team grown or remained constant?

What percentage of your product-line consists of 3D products?

If very small- why have you not converted to 3D for your other products?

What other knitting methods serve you better for these different products?

How do you inform your customers of the benefits of 3D products?

Do you use the 'newness' of this technology as a selling factor in your marketing?

What kind of marketing venues do you use the most?

How effective do you feel they are at reaching your target customer?

Have you ever noticed miscommunication with customers regarding the novelty of 3D

Where does the manufacturing of your 3D products occur?

Have you ever considered manufacturing your 3D products locally?

What are the deterrents for you, from manufacturing locally?

If, locally- can you explain why you decided to keep your manufacturing local?

What does local manufacturing offer you, that you wouldn't be able to achieve otherwise?

What are the main advantages you've found by manufacturing locally?

Is there any downside to manufacturing locally, that you've encountered?

How do you market your product, as one that is manufactured locally? and is it well received?

Have you ever noticed miscommunication with customers regarding the novelty of 3D

How well positioned do you feel you are to adapt to a changing market?

How well equipped do you feel your staff is to adapt to new technologies?

How would you describe the skill-level of your workforce?

What do you believe are the main benefits that drove you to adopt 3D?
<table>
<thead>
<tr>
<th>Question</th>
<th>Category</th>
</tr>
</thead>
<tbody>
<tr>
<td>How does 3D knitting place you above your competitors?</td>
<td>Diffusion Positioning</td>
</tr>
<tr>
<td>Increased comfort, no seams- selling factor</td>
<td>Quality Considerations, Positioning of Product, Perceived Benefits</td>
</tr>
<tr>
<td>How long after implementing 3D knitting, did you see your profitability increase?</td>
<td></td>
</tr>
<tr>
<td>Have you experienced a good return on your investment so far with 3D? Explain.</td>
<td></td>
</tr>
<tr>
<td>What kind of feedback have you received from customers regarding the quality of your product?</td>
<td></td>
</tr>
<tr>
<td>To what degree would you say that, quality of product is a selling factor for your brand?</td>
<td></td>
</tr>
<tr>
<td>To what degree, is comfort a selling factor for your brand?</td>
<td></td>
</tr>
<tr>
<td>Ability to tell a story about product</td>
<td>Positioning of Product</td>
</tr>
<tr>
<td>What kind of story do you like to tell your customers, about 3D technology?</td>
<td></td>
</tr>
<tr>
<td>What benefits do you highlight the most?</td>
<td></td>
</tr>
<tr>
<td>How do those benefits fit into your own values and mission as a company?</td>
<td></td>
</tr>
<tr>
<td>Has your company ever used full-fashioned knitting to create products?</td>
<td></td>
</tr>
<tr>
<td>Perceived as more versatile in production than full-fashioned</td>
<td>Perceived Benefits, Supply Chain Flexibility, Sustainability</td>
</tr>
<tr>
<td>Unmatched quality in knitwear production</td>
<td>Quality Considerations, Positioning of Product, Perceived Benefits</td>
</tr>
<tr>
<td>How do you feel 3D knitting performs in terms of quality?</td>
<td></td>
</tr>
<tr>
<td>How do you convey this trait to your customers?</td>
<td></td>
</tr>
<tr>
<td>How could it be better in terms of quality?</td>
<td></td>
</tr>
<tr>
<td>Most cost-effective solution for the business product goals (meets expectations for product quality, innovativeness, and speed to produce)</td>
<td>Managerial, Size of Company, Inception of Company, Diffusion Positioning, Logistics Consideration, Positioning of Product</td>
</tr>
<tr>
<td>How does 3D meet your expectations for innovativeness?</td>
<td></td>
</tr>
<tr>
<td>How does 3D meet your expectations for speed to produce?</td>
<td></td>
</tr>
<tr>
<td>In what way has 3D proved itself as being a cost-effective solution for your product goals?</td>
<td></td>
</tr>
<tr>
<td>Least waste of materials in knitwear</td>
<td>Sustainability, Perceived Benefits</td>
</tr>
<tr>
<td>How big of a concern is disposing of wasted material, for you?</td>
<td></td>
</tr>
</tbody>
</table>
How do you think 3D performs in terms of sustainability?

Have you seen a reduction of wasted material, since your implementation of 3D?

In total, how many operators and programmers do you need to handle the machines that you own?

Has this changed since you've implemented 3D?

Has the implementation of 3D shortened your overall production time?

To what degree has implementing 3D changed your production efficiency?

If locally manufactured- Do you also source your materials locally?

If yes- to what degree, do you think this saves you in costs?

If yes, what additional benefits does this provide you?

Where do you think the industry is heading, in terms of new technologies?

Where do you think 3D is heading?

How long do you think it will take for 3D to be a standard practice in the textile industry?

How does your company view environmental sustainability?

How is this demonstrated in your knitted product?

Why do you think someone would decide to choose 3D over full-fashioned knitting?

How do you think 3D fairs in terms of productivity?

How can this be improved?

If made locally- How has your production and delivery time improved with 3D?

Do you market that your products are made in the USA?

How does 3D speed up communication along your supply chain?

Least waste of manpower- more time on machine and less processing steps

Sustainability, Supply Chain Flexibility, Logistics Considerations

D

Ability to produce where the yarn is cultivated and manufactured (less shipping)

Sustainability, Logistics Considerations, Supply Chain Flexibility

D

This is where the industry is heading

Diffusion Positioning, Inception of Company, Market/Demand for Product

D

Can be thought of as a sustainability initiative, reducing wasted materials and processing steps

Sustainability, Positioning of Product

D

Perceived as better investment than full-fashioned knitting

Investing/Cashflow, Perceived Benefits

D

Perceived as having higher productivity than full-fashioned

Supply Chain Flexibility, Production Processes, Logistics considerations

D

Reshoring incentives

Reshoring, positioning of product, sustainability

D

Speeds up communication through supply chain= speeds up

Supply chain flexibility, production processes

D
production of supply chain

Please comment on the nature of communication since you have implemented 3D. Has it improved since implementation? How?

Ability to create a vertical supply chain in the U.S.  Supply Chain flexibility, logistics considerations, resourcing, sustainability

Have you ever considered implementing a vertical supply chain with 3D?

What is holding you back from doing so?
APPENDIX D

Interview Script for Administrative-Level Employees

Introduction

• Thank you for joining me today
• There are no wrong answers, I just want to understand how you decided to adopt your complete-garment technology
• I will be documenting the interview with video & audio. Please sign video/audio release.
• Your confidentiality will remain hidden if you choose to remain anonymous. Recordings are for ease of analysis in later stages of research and for final dissertation presentation.
• If you would prefer to not answer any questions, you are free to do so.
• Any questions?
• Please introduce yourself:
  o Your job title at Company X
  o What does your job entail?
  o How long have you been working for (or in business) Company X?
  o How did you get your job?
  o What is your educational background?
  o What does your typical work day look like- at different times of the day?
  o Where does your job fit into the whole production process?
  o What do you most enjoy about your job, and Company X?

Company Values

• When was your company first established (look up beforehand)
• How would you describe the mission of your company?
• To what degree, do you think Company X is concerned about innovation?
• Where would you place yourself along the innovation curve, as a company? (show diagram of innovation curve)
• Why do you consider your company to be at this stage of the innovation curve?
• What do you think Company X’s attitude towards change is?
• How does CG meet your expectations for innovativeness?
• How does CG meet your expectations for speed to produce?
• In what way has CG proved itself as being a cost-effective solution for your product goals?
• How do you think the mission and values of the CEO/upper management have impacted the use of CGT?
• Was this investment spurred on by their decision, or by other staff?
• How many employees do you have?
• How much of your product line is created using CG?
• How much have your sales from in recent years (weeks or months), of your products that are CG?
• Do you foresee these sales to grow? Explain.
• Have you noticed any lags in sales related to CG products that you sell?

Complete-Garment Adoption

• When did your company decide to invest in CGT?
• How much of your production stream is CG to date?
• What percentage of your product-line consists of CG products?
• If very small- why have you not converted to CG for your other products?
• What other knitting methods serve you better for these different products?
• What kind of learning curve did your company experience with adopting CG?
• Any challenges that you’ve faced in adopting CG?
• What kind of benefits have you seen arise from implementing CG so far?
• How does CG speed up communication along your supply chain?
• Please comment on the nature of communication since you have implemented CG
• Has it improved since implementation? How?
• Have you ever considered implementing a vertical supply chain with CG?
• What is holding you back from doing so?
• Has your company ever created products using full-fashioned knitting machines in the past?
• Are there any products that you believe are better suited for CG over full-fashioned?
• Why was CG chosen over full-fashioned for these products?
• How would you compare the difference in production methods, and which one do you prefer?
• Where does the manufacturing of your CG products occur?
• Have you ever considered manufacturing your CG products locally?
• What are the deterrents for you, from manufacturing locally?
• If locally- Can you explain why you decided to keep your manufacturing local?
• What does local manufacturing offer you that you wouldn’t be able to achieve otherwise?
• What are the main advantages you’ve found by manufacturing locally?
• Is there a downside to manufacturing locally?
• If made locally- How has your production and delivery time improved with CG?
• How do you market your product, as one that is manufactured locally? And is it well received?
• To what degree has implementing CG changed your production efficiency?
• How do you think CG fairs in terms of productivity?
• How can this be improved?

Training
• Since its first implementation, how have things changed in the way that the CG team operates?
• Has the team grown or remained a constant size?
• How quickly do you feel your employees have been able to get up to speed with understanding this technology?
• What type of employees do you seek out to fill programmer/technician roles?
• Do you feel there is a good selection of candidates that have these skills before they arrive at your company?
• If not- do you provide training on CG?
• Where have you sourced your programmers/technicians from?
• How difficult has it been for you to find a skilled programmer/technician in CG?
• How many programmers/technicians have you employed?
• Do you foresee employing more programmers/technicians in the future?
• How much experience do you prefer a new-hire programmer to have?
• How well positioned do you feel you are to adapt to a changing market?
• How well equipped do you feel your staff is to adapt to new technologies?
• How would you describe the skill-level of your workforce?

Marketing Factors
• How would you classify your target customer?
• What efforts have been made by your company to market the benefits of CG products?
• What kind of features do you inform your customer about your product being CG?
• How do you explain to your customer the value that CG products have to offer?
• Do you use the ‘newness’ of this technology as a selling factor in your marketing?
• What kind of marketing venues do you use the most?
• How effective do you feel they are at reaching your target customer?
• How do you view your competitors in light of using CG?
• What kind of positioning do you think you have over them?
• What kind of feedback have you received from customers about your CG product?
• Has any of this feedback related to quality? Explain.
• To what degree is the quality of the product a selling factor for your brand?
• How do you feel CG knitting performs in terms of quality?
• How do you convey this trait to your customers?
• How could it be better in terms of quality?
• What kind of ‘story’ do you like to tell your customers, about CG technology?
• What benefits do you highlight the most?
• How do those benefits fit into your own values and mission as a company?
• What do you believe are the main benefits that drove you to adopt CG?
• How does your company view environmental sustainability?
• How is this demonstrated in your knitted product?
• How much does disposing of wasted materials concern you?
• How do you think CG performs in terms of sustainability?
• Have you seen a reduction of wasted material, since your implementation of CG?

Capital Investment
• How long after implementing CG knitting, did you see your profitability increase?
• Have you experienced a good return on investment so far with CG? Explain.
• What are some of the risks that you are concerned with when it comes to adopting CG?
• Are you confident you are going to have a good return on your investment? If yes, why?
• What kind of time-line are you look at for breaking even on this investment?
• What methods have you taken to safely finance the adoption of this technology?
• Are there any issues that you have encountered in financing of this technology?
• To what degree do you feel capital investment has been an issue for adopting CG?
• How have you solved this issue?
• What are you doing currently to combat this issue?
• Did you receive any incentives from the machine manufacturers to assist in your decision to purchase this CG machinery?
• Where do you think the industry is heading, in terms of new technologies?
• Where do you think CG is heading?
• Why do you think CG is not a mainstream practice yet?
• How long do you think it will take for CG to be a standard practice in the textile industry?
APPENDIX E

Interview Script for Technology-User Employees

Introduction

- Thank you for joining me today
- There are no wrong answers, I just want to understand how you decided to adopt your complete-garment technology
- I will be documenting the interview with video & audio. Please sign video/audio release.
- Your confidentiality will remain hidden if you choose to remain anonymous. Recordings are for ease of analysis in later stages of research and for final dissertation presentation.
- If you would prefer to not answer any questions, you are free to do so.
- Any questions?
- Please introduce yourself:
  - Your job title at Company X
  - What does your job entail?
  - How long have you been working for (or in business) Company X?
  - How did you get your job?
  - What is your educational background?
  - What does your typical work day look like- at different times of the day?
  - Where does your job fit into the whole production process?
  - What do you most enjoy about your job, and Company X?

Training

- How long have you been working with CG programming?
- How long did it take you to feel confident in your training of CG programming?
- Was this experience attained on the job at your company, or previous training?
- Do you have any complaints about the learning curve associated with this new technology? What are they?
- How much training were you given to effectively use this new technology?
- How do you feel the training has met your needs?
- Do you feel confidently proficient in the technology within the allotted training time that you've had? If not, why?
- How do you feel CG knitting performs in terms of quality?
- Are there any products that you believe are better suited for CG knitting over full-fashioned?
- How are your knit patterns created- by template system, from scratch or patterns supplied by the machine manufacturer?
• If by template- do you feel they adequately fit your design needs as a company?
• Why have you chosen to use this method of creating patterns? Easiest, most flexible, most comprehensive?
• How do you feel Machine Manufacturer X could meet your needs better as a programmer/technician?
• What difficulties have you faced in working with the knit programming software?
• What difficulties have you faced in working with the machines?
• How much of a learning curve did you face when first learning the software?
• How much of a learning curve did you face when first learning how to operate the machine?

• Where do you think the industry is heading, in terms of new technologies?
• Where do you think CG is heading?
• Why do you think CG is not a mainstream practice yet?
• How long do you think it will take for CG to be a standard practice in the textile industry?
APPENDIX F

First Summary of Findings after coding in Nvivo

Definitions

What should we call this technology?
- Company 1: 3D knitting
- Company 2: 3D knitting or whole garment
- Company 3: 3D knitting (not just a marketing term, it also represents the technology)
- Company 4: true seamless
- Company 5: WholeGarment® or seamless knitting
- Company 6: full-garment seamless or 3D knitting
- Company 7: 3D knitting
- Company 8: 3D knitting

Production Processes

- Company 1 states that seasonality is very difficult to juggle with fashion apparel applications. They have maximum work from July thru August and less during September and October.
- Company 2 has found that one-off production is the best method to use since their products are customized for an individual customer which means changing yarns is necessary. They have an algorithm as orders come in to the knitting order for a given day to maximize this yarn change efficiency.
- Company 2 does not knit overnight but their production during the day is constant. Their priorities in production are customer orders, prototyping and influencer gifting.
- Company 3 does knit overnight but only holds finishing during the day shift (8-4:30). In their busy season they may have menders and steamers come in on Saturdays or for overtime.
- Company 3 production manager states that production for WholeGarment® is 40% more efficient than normal knitting since it cuts out the linking step. But WholeGarment® must still go through the hand mending process and inspection process just like all products.
- He states that the WholeGarment® process is about 30-40% faster.
- Company 4 states that inefficiencies along your production stream can be cut out with 3d knitting, and save you space in a factory, and time to produce which all can be added back into the product you are making to make it more unique than others in the market.
C: you have to look at the entire bill of materials and the entire cost sheet. So I know that if I’m going to cut and sew the garments that we were talking about before, what it’s going to take. OK, I have lay it out on the table, OK, I have to let the fabric relax. I can’t open next day, then I have to bundle it, I have to take it over to the sewer, and then each action has standard action minutes and how each operation… And then you find that, I take This out, I take this out… I don’t even need the space for laying out the fabric. What am I taking out that they can save? And can I put this into my product, The money, the time, the space I’m saving, that I can make a better product for the same money for my customer. So I can be better rather than the same as everybody else.

- Company 5 primarily uses cut & sew production, but sometimes uses full-fashioned which is produced overseas
- They focus on development in house in California so they can easily transfer knitting files to a factory overseas or in Mexico with no inconsistency between the two
- Anything that is developed in house on a machine must also be produced on the same machine in a factory
- They have discontinued 3D knitting also because of their seasonality demands and their styles are constantly changing
- Company 6 designer states that 3D knitting has required for a closer and more collaborative design process, because all material development, design and fit come together at the same time. So line management, design & development, material development are no longer disjointed jobs on a timeline, but create a dynamic team.

**Sourcing**
- Company 2 states that attaining yarn has been their major bottleneck
- Company 4 comments on the automotive industry and how they are looking into this technology to soon have vertical integration of their materials development. Because so many automobile companies are sourcing from the same factories, there is little differentiation between each company now.
- Company 6 has had issues sourcing an appropriate yarn that fits in line with their brand values of responsibly sourced materials
- Company 7 states that this technology has allowed for a brand to communicate directly with a yarn mill which is very uncommon. They have also been able to source yarns locally from North Carolina.

**Barriers (Negative implications towards adoption)**

**Capital Investment**

**Return on Investment**

- Of the 8 companies interviewed, 7 own their own machines.
- Of those seven companies, 6 are creating products that are three-dimensional in nature in some manner whether they are technical textiles or apparel related
- Company 1, 2, 4, and 7 have already broken even on their machine purchases, or have paid for machines in full.

- Company 3 comments that “WholeGarment® machine on average is about 3 times as expensive as a normal knitting machine. So honestly, the return on investment, it’s a lot longer. It’s typically 5 to 7 years when you break even on the machine. But we did this because we believe this is the future, so we want to start early even when the machine is still very expensive (…) But we want to be on the leading edge. So obviously we want to break even on this investment, but we understand it will take double the time to break even on the machine investment. “

- Company 8 mentions that the return on investment is somewhat an afterthought at this point because it will give them more capabilities of making products they wouldn’t otherwise be able to develop. “I mean, the machine is relatively affordable, even for a small company like ours. And I see it as low risk, because if we decide we don’t want to machine later on, I think it’s very resale-able, as well. So I see it as a low risk proposition to bring it in and use it. And the machines are in demand in that sense.

**Financial Risk**

- Company 3 comments on the overall financial risk barrier: “The machine’s too expensive. It’s three times more expensive. So it will take two or three times, minimum to break even. It’s just too long. (…) So I think if they would drop the price, it will definitely increase the adoption a lot faster. And they can make it back on the economy of scale. Because if they produce more machines, their production cost is going to go down, and they’ll be able to sell a lot more machines. They can also increase their market share.”

- Company 5 has been unable to justify the use of 3D knitting because it does not cover the cost of the machines depending on the products they specialize in: “So for example, underpinning, a shell, a top or whatever. You make it as a whole garment and it can cost you, if it’s an hour knitting, maybe with materials and everything, be between 20 and 30 dollars. And when you do it overseas, it can be between 22 and 32. So there’s a 2 dollar difference, and that doesn’t cover the cost to purchase the machines for us.”

- Company 7 comments on combatting the financial risk: “The apparel industry needs to change first before these technologies are able to be taken up by brands. Because it is more expensive if you look at it in totality. But if you cut out a lot of the supply chain, the costs get down or are reduced.”

**Bottlenecks**

- Company 1 states that their main bottleneck in production relates to fashion apparel products due to the fluctuation of seasonality, combined with having a hard time finding programmers
  - You’ve have the seasonal workloads where you’ve got maximum work between July and August, and then much less work between September/October and then
peaking back up at the end of the year. So it’s just a tough business to balance those cycles. I mean, every business has some seasonality and seasonal variations but fashion and apparel is crazy.

- Company 2’s major bottleneck is working with other vendors along the supply chain, particularly yarn suppliers and getting yarn quickly enough to prototype with
- Company 3 states that the number of programmers is their bottleneck since they are in the private label business and the larger number of samples that can be developed, the more production runs you can do for more customers
- Company 3 production manager also states that linking and pressing are the main bottleneck points. Hand mending has also become a pain point because all products must be yarn finished, whether they are full-fashioned or 3D knitting
- Company 5 has not seen a bottleneck related to programming since they train their programmers on both systems
- Company 7 states that their largest cost in production when they were doing full-fashioned knitting was their linking time
  - But at the same time because we were doing fully-fashioned, we had to link and trying to get linkers and training them took a really long time and that was the largest part and actually largest cost of making a sweater for us. It wasn’t the machine time, it wasn’t the materials, it was actually the linking time.

**Challenges**

- Company 1: working in short time-lines for fashion apparel
- Company 2: No google for troubleshooting problems; Getting yarn in on time; physical difficulties with the machine- moving the carriage and needle changing
- Company 3: At first, a great deal of resistance and hesititation from their staff to use 3D knitting would tend to defer to machine manufacturer technicians rather than dive in and get their hands dirty to make adjustments on the machine or change a needle.
- Company 4: Have had to create their own modifications for the machines because they did not exist from the machine manufacturer themselves.
- Company 5: When working with 3D knitting, they were unable to create a highly fitted garment which is a part of their creative direction as a company. Their customers are expecting something more high-end and so were unable to use it in a 3D knitting sense.
- Company 5 also comments on the process efficiencies that they have implemented in pricing out a swatch before going through production, because one of the biggest challenges they face is creating a swatch that is aesthetically pleasing and contains the right perceived value from the customer. He also states that maintaining quality while making a garment faster is the biggest challenge for them.
  - I think the challenge is how to make a garment faster without sacrificing the quality, the faster the machine can knit, the turn from corner to corner, the transfer speed, the better they make that, the better it is for a manufacturer, time is money.
- Company 6: Understanding what can work on a 3D knitting machine and the yarn specs so that it can be knit on the certain gauge machine you have
- Company 7 states that the biggest challenge for 3D knitting adoption is informing big businesses about the technology and how it can be used
- Company 8 has faced challenges using certain yarns on the machine that are difficult to knit with and are finding the physical limitations of the machine by using unconventional materials

**Misconceptions about Technology**
- Company 1 and 4 both agree that the comparison to printer is a major misnomer for this technology because it gives one the allusion that products can be created by the push of a button

**Overcoming Old Habits**
- Company 4 has experienced that companies also have to understand how new efficiencies in the new technologies will help them and consider adjusting their thinking about the way their production runs.
- “I want to say, the most expensive thing in product development is usually… “we’ve always done it this way”. The most expensive words. And what you have are people that would use this same machine for the same projects. They just got the new machine and were running the full width of the bed. Rather than using for what it best was.
- B: Yeah, so they would buy the new machines to say that they had the new generation. But they didn’t understand it. And if you knew that one body, even though the needle bed is the width of three bodies, but you have a lot of complicated stuff inside that one body, then don’t make three at a time. The stroke of the machine is what gets messed up. So they were all standard at knitting of the way they were knitting on chain drive, and they still didn’t understand- hey, drop the machine down to a small piece, it’s much more efficient that way.

**Training Requirements**

**Knitting Knowledge**
- Company 1, 3, 4, 5, 7 and 8 all agree that a base-line of knitting knowledge, preferably with hand-knitting machines must be established before moving into programming
- Company 2 learned knitting at the same time as programming “better or for worse”
- Company 6 is exempt from this inquiry since they are contracting out the programming
- Company 1, 3, 5 and 8 all comment on understanding that candidates in the field that know knitting are very far and few between and thus are willing to take time to train their employees and give them time to overcome the steep learning curve with programming
- Technology User at Company 1 had simple base-line knowledge of hand-flat knitting before taking position, but never time on electronic machine
- Technology User at Company 3 had design background but transitioned into programming when it was found that she is technically skilled in this area
- Admin & Technology User at Company 7 learned knitting on hand-flat machines with Stoll first, which offered a good base-line knowledge of knitting before adopting 3D knitting from Shima
- Both employees, Admin (Manager) and Admin (Tech User) have base-line knowledge of using hand-flat knitting machines before adopting Mini-WG machine
Learning Curve
- Of the 8 companies interviewed, 7 are programming their own patterns
- All companies agree that there is a very steep learning curve understanding programming for a 3D shape and is a major hindrance to adoption of the machines
- The general consensus is that programmers will need at least 2 years programming full-time to become proficient and add value to their company
- Also, companies agree that the training provided by Shima and Stoll will only allow you to run a perfectly calibrated machine. A programmer must have practice and the practicing takes a longer time than some companies expect.
- Company 1 comments that Shima’s learning curve is steeper than Stoll’s, coming from someone who worked on Shima software for 20 years before transitioning to Stoll
- Company 3 comments that the requirements on a programmer are very specialized because: “You really have to think three-dimensional. And you have to be really creative and maybe changing the direction (of the knitting). Like knitting a shape coming out of the machine, but if you twist it and change it, it becomes a different type of garment. You have to understand the possibility of knitting three-dimensionally.” The implications here is perhaps another necessary skill of understanding patternmaking and how to create 3D shapes, rather than just pure knitting knowledge.
- Tech User at Company 3 states that the most difficult thing about programming is the partnering with a machine and also having to understand what is happening on the machine. This requires intimate understanding of both machine and program.
- Both programmers from Company 1 and Company 3 comment on the difficulty of moving from the software program to the machine and connecting the two. This also becomes especially difficult considering new iterations of a given design, and then moving back to the software to adjust and moving again to the machine to test an adjustment.
- All programmers admit that they are still learning things about knitting, even those who have been in it for 30 years
- Company 2 learned about knitting at the same time as programming, which posed the biggest challenge.
- Company 8 is undergoing a learning curve with certain types of yarns that cannot be knit on the machine (they are too strong and break needles). Understanding the limitations of the actual knitting machine are also important and what can and cannot be knitted.

Requirements to overcome the learning curve:
- Creativity- “thinking outside the box, just because nobody has done it doesn’t mean it can’t be done”
- Understand the base materials - fibers and yarns
- Understand how the yarns will interact with the machine, risks associated with certain fiber types or denier count
Patternmaking for 3D shapes: “And then you’ve got to start thinking about a 3D product. If you want to make a square box, do you know how to make a box? That’s the first question. So a lot of people don’t even know how to build the structure of something, how to bend the fabric. So those lessons come and it takes time.”

- Knitting knowledge and basic understanding of how flat-bed knitting works
- Machine understanding- how to troubleshoot an error, or fix broken needles
- Keeping record of where you are in the development of a product development process (easy to get lost moving from software to machine and back to software)
- Have a failure- learn through making mistakes and having to fix the machine

Limited Troubleshooting Resources

- Company 2 and 7 both comment on needing more resources to troubleshoot problems that arise on the machine.
- Both company 2 and 7 are hoping for a Wikipedia of Knitting Errors (or a way to google the solution), or at least a communal resource for Shima or Stoll users to be able to crowdsource the solution to their problems.
- Company 2 mentions that there is a great deal of translation inconsistencies when it comes to errors on the machines (Shima) and error messages do not make sense sometimes

Machine Operating

- The general philosophy for making sure a program is correct is to knit it down and see what happens with the product is washed, dried and/ or steamed.
- Admin from Company 3: “On the machine side, the machines are a lot more complicated, compared to the traditional machine. It has four beds instead of two beds. And the needles are a lot harder to change. The machine is just a higher precision machine, so you have to adjust the machine really carefully. So those are the main learning curves. It’s the programming side and how do you address and maintain the machine.”
- The machines are more complicated which means the maintenance of the machines is also paramount, perhaps just as important as the programming learning curve.

Time to Feel Confident

- Company 1: 2 years at least
- Company 2: 1 year with training and troubleshooting on own time
- Company 3: 2 or 3 years at least
- Company 4: Still learning, even after 30 years.
- Company 5: Takes at least 3 Months to learn the foundations, but mentions that it is a long process having to understand the machine and how to operate the machine before you start learning programming.
- Company 7: Still not confident, can take 5 years.
  - “I still don’t feel 100% confident, I think no one ever will. But I think once you have the biggest crash on the machine, and fix it, then you know that you can fix anything and I think that was the biggest thing (...) Somebody who trained me, he calculated his time programming sweaters… he was sitting there for 5 years in front of the computer and he’s just not 100% confident on a new thing he hasn’t done before. So it’s hard to feel confident. You get to a point where you feel confident like-ok I feel confident that this will run on the machine but I just don’t know if it will work.. so you’ve just gotta give it a shot.

Yarns and Raw Materials

- Company 4 states that yarn is your most important component in knitting and understanding it’s limitations is the building block for making a successful product. This training must come before any programming or knitting structure education. You have to learn how yarns behave before you can create a product out of them.
- There are also many moving parts when it comes to a knitted product: the fiber, the yarn, the knit structures and how they interact with each other all play a part
  - “We love making things that have very little waste, but actually a lot of the programming that makes that possible to a product.. takes a very experienced person who knows how to program but also understands yarns and structures and how these structures that are put next to each other might distort each other and how they might correct that to get the right shape and the right cut.

Personnel

Communication skills gap

- The one company able to comment on this issue allowed for interviews of the administrator, designer and technician.
  - What a designer wants and what they’re asking for, what the programmer understands and what can be done, and what their interpretation of the tech pack, there’s always a variation and sometimes they don’t match. So it really takes.. It’s a lot of learning between the designer and the programmers to make sure the way they communicate is clear. So I think it’s not just WholeGarment®. Any type of design to a patternmaker...I think the communication, there’s always a ramp up between each individual.
  - “So a lot of times we bring things to them and they will tell us they can’t. We shouldn’t do so. But then that’s the key, like you have to use some people skills
and maybe some friendship and stuff like that to work with them and give them different options, give them some room.”

- People have to get used to each other in order to make this technology work in the long-term

**Programmers**

- Another major barrier is the limited availability of programmers for knitting.
- Two companies state that finding programmers and programming is the biggest risk to adopting 3D knitting
- Company 1 states that finding programming expertise is difficult and finding people that are interested in learning this type of programming also
- Company 3 has only 3 programmers, and one dedicated to 3D knitting programming
- Their dedicated WG programmer has been programming for 5 years total, and training for 1 year.
- Company 4 states that the biggest risk for companies adopting 3D knitting is the capability of their technician. Just because someone has been programming for sweaters or full-fashioned knitting does not mean they will understand the 3D concept.
  - “Yeah, I think that’s the biggest risk, because if your product is developed correctly on the machine, regardless of the brand of the machine, and it worked, then there’s no reason you can’t make it. But if you fail in production, that’s usually a sign of bad planning or bad technical people, bad operators. “
- Company 5 has 3 programmers in initial development, doing trial and error and testing of different yarns and techniques. There are five programmers that work on prototypes and grade patterns and two in training. He states that they always maintain two in training because they are constantly losing people to Nike since their programmers learn both systems.
- Company 7 also states that programming is the biggest risk in adopting WG knitting who can program and also be skilled enough to create as many products as they would like
- Company 8 has two employees that use the knitting machine and one who works on the Apex system for design work

**Labor Pool**

- All companies agree that the labor pool of knitting programmers is very small and those with the skillset have been bought up by large companies who can compensate very well
  - “I don’t understand why programmers who have the understanding of this are coming out and being paid such a low amount. The market is there for them to be paid as much as a software developer coming out of a really great school. Because NC State is a fantastic school. They should be paid really well.. and I see what they’re getting paid and I’m just like- Oh my gosh really? Programmers, there
needs to be more programmers, I guess is my point. And they’ll get paid by companies like us. They’re hard to find. “

- “Quite simply, we can’t find people who are qualified. I mean, I think broad knowledge of knitting is not going to give you the skills you need for 3D knitting. I think they’re different. So understanding what knitting, and circular knitting and industrial knitting isn’t going to tell you how to run a 3D knitting machine (…) And if we want to hire somebody, we’re competing for a very small pool of individuals right now who are trained in it. (…) So we’re really going to have to train internally here to get those skills. And I think a little bit of it is you need a bit more than… you need some problem solving and some design skills as well

- Technical Textiles in knitting will require not only an interest in knitting, but complex 3D knitting and the programming that coincides with that, along with the ability to design with aesthetic appeal

- Programmers need higher compensation to be a sought after job. Students will follow the money if they know they will be compensated, but also stimulated but challenging design problems.

Hiring Requirements

- Company 1 has hired a programmer role with no prior experience on the machine, knowing full well that they will have to be trained on the job
- Company 2 has been unable to find a contract programmer
- Company 3 states that they would prefer to train internally. They send programmers to Japan and Germany also. He also agrees that there just aren’t a lot of people available to hire for this skill
- (did not ask Company 4 about this)
- Company 5 states that knowing who you hire is the most important thing and what they enjoy doing so that they are not stuck in a job that they feel they have to endure.
  - “For knitters, it’s a little tougher. Because first of all there’s not a lot of knitting going on in the U.S. So you would have to train them. I’ve never hired knitters who came with experience. I think people who hire knitters in this area, they come from here, in a way. But for me, I think it’s easier to teach them.
- Company 8 believes that a candidate must know how to use the machine technically but also be good at problem solving and have a good eye for design. They have had a hard time finding people simply because most of the knitting programmers are related to sweaters instead of technical textiles.

Linkers

- Company 1 had to train their linkers because there is no labor pool available of linkers on the East Coast
- Company 3 also comments on the difficulty now in finding linkers. It depends on many character traits for a linker to be good at their job
  - But for the linking, we can try it. But it’s not that easy. Because it really depends on the person and their character and their smartness. Because you need to know how to put a garment together, upside down and the sizes of neck, you try to make evenly, and try to put things properly on the right line, it still takes much much longer. The best people I can say that we’ve trained from the beginning, 6 months is the minimum. You’re just getting started, It’s not even good (yet).

- Company 3 Production manager comments on how it takes a minimum of 6 months to a year, for a linker to become proficient at linking
- They have also been hiring from Asia instead of hiring U.S workers because it is not a skill that the local Hispanic population care to have. They are more familiar with lockstitch and overedge stitching.

- Company 7 also had issues finding linkers for sweaters on the East Coast and that the learning curve for a linker to be really fast at linking can take up to 15 years.
- He also states that when the company was using linkers, the fastest they could link was a sweater every 2 hours.
- Linking was the major bottleneck for Company 7 and thus was the reason why they transitioned to 3D knitting
  - Because you literally need someone who’s been doing it for a really long time and really likes to do it. Because it is hard, it is so incredibly hard. And the skill and craftsmanship of the linker is totally underappreciated. They should be paid more than anyone else at the company. Because it really instills a value when somebody holds a piece and sees it, and if they don’t do it right, it’s the first place that breaks. So for the most part, a brand can live and die by their linker, I think. They’re hard to find in the United States and I think that was one of the big reasons why we decided to go with the 3D knitting machines, the seamless knitting machines than doing fully-fashioned.

- Software

  **Difficulties**

- The software to operate both Shima and Stoll machines has been argued to be cumbersome and inefficient, and also a major hindrance in adopting these technologies
- Tech user at Company 1 states that coming from a graphic design background is difficult to understand a less user-friendly interface, especially since the software may not truly simulate what is happening on the knitting machine. It is always best to knit something down to know if it works. She also comments on the difficulty from going back and forth from computer to knitting machine and losing track of where you are in the iteration process.
- Tech User at Company 3 asserts that there will always be difficulties with these machines, you just have to learn how to avoid the problems you encounter and move forward from there.

- Company 4 states that they would rather have a software that is change-able and does not include too many modules. They refused to adopt the M1 software until 2008 when the M1plus came out which allows the ability to create your own modules.

- Company 7 states that computer programmers who have seen the software for both machine companies are astounded at the primitive nature of the interface. He suggests opensourcing the software development so that the architecture can be improved and streamline the process of creating products.

**Shima vs. Stoll**

- Company 1 states that Stoll’s software tends to be more buggy than Shima- the system will crash randomly, windows updates will interfere with stoll software updates.

- But on the flip-side, they also mention that Stoll’s software is much easier to use, compared to Shima.

- Company 3 Tech User also states that using Stoll is easier. She states that 3D knitting programming is simply more complex and there are more things you have to think about.

- Company 4 is an advocate of Stoll’s software, stating that it is more flexible than Shima’s. That it is as close to open-source as you can get because you can write your own code. (Of course this is coming from someone who has been knitting for over 30 years, and knows very well how to control the machine)

- Company 7 mentions also that the shima software is very helpful because it will tell you before you bring a file to the machine if something will work or not, which Stoll doesn’t do as much.

**Templates**

- Templates sound like a good jumping off point, but by no means are they allowing companies to create innovative products

- Tech User at Company 1 learned first to program from scratch and then was introduced to the template system in Stoll software. She states she is unlikely to use it anyways because it limits your creativity and does not force you to understand what you are doing.

  - “Creating a garment outright from a template, you don’t understand what you’re doing as much. Anybody could essentially do it, which isn’t to say that’s a bad
thing. You just might not know why you’re doing it, or how it’s happening. So if something goes wrong, you won’t be able to fix it, you’ll just have to start it again and you’re not actually learning. Once I was shown that, I still don’t even use it because it really limits your creativity.”

- Tech User at Company 3 uses the template system as a base pattern and then alters the packages a little bit. This helps to speed up the development process.
- Company 7 used the template system to get started, but now has transitioned into programming from scratch to be more innovative with their designs.
  - You can use their templates, which is great and you can do like basic stuff but if you really want to get innovative in the shape and design then you’ve got to learn S Paint. Which is a struggle and one of the reasons why this technology hasn’t seen it’s way to more people.

**Programming Time**

- Company 4 and 6 both agree that the programming time/ development time is much longer for this type of technology
- Company 4 argues that making a product with little waste requires too much programming and you eat up your costs too quickly
  - B: And at 3 hours worth of knitting- that’s easily a $700 cost just for the knitting.
  - C: and about 100 hours worth of programming..
- Company 6 still thinks that the development time is worth it due to saved materials

**Design Considerations**

**As a Driver**

- Flat-bed seamless knitting allows for more flexibility of design in terms of knit structures and variety of products to be made on the same machine
- Company 1 states that: “Flat-bed machines can make all of the stitches. Circular machines can make the stitch that they are purchased with the intent of making. For the most part. Now there are the most specialized circular machines that can may operate similar to flat-bed, but by and large, people don’t have those machines. You want something with a lot of flexibility, I can do any stitch that you want.”
- Company 2: “And the fact that one machine can make all these different products, I think is really incredible. As opposed to flatbed knitting where you have to have someone else be involved and do linking and all of that stuff, and cutting and sewing. I think that is really great about it.”

**As a Barrier**
For sweater manufacturing, you are limited to certain styles that are possible to knit in a 3D way where all joints are connected. Company 3 designer comments: “There’s some restrictions on the WholeGarment®, there’s some trim detail on finishing the sweater, there’s not as many options as the flat-bed machine because you have to do the sleeve and everything together. So for example, WholeGarment® you can’t do a double knit. (...) Like half-cardigan stitch, full needle, those kind of stitches, WholeGarment® cannot do, we can only mimic. And also tubular too.”

Company 3 programmer also comments on the certain styles that cannot be knit the normal way of knitting but can sometimes be achieved by knitting horizontally. Knitting full-needle, or half-cardigan stitch is not possible with 3D knitting.

Company 4 mentions that garments created on a 3D knitting machine are very simple jersey based fabrics with little ability for design or complex knitted structures.

Company 5 Admin mentions that they are creating a highly constructed garment with lots of shaping and darts, which is not achievable on the 3D knitting machines yet.

Depending on the machine manufacturer used, fully-knit garments are not possible on a Stoll machine unless they are in half-gauge knitting, making a bulkier knit.

Shima allows for 3D knitting with finer knitted apparel, but you must adopt their machines.

**Comparison to Full-Fashioned Knitting**

- Since styles are limited using 3D knitting technology, full-fashioned knitting is the next best option for creating a garment with relatively no waste.
- 3D knitting cannot make patterns that have complex shaping yet, Shima is still working on it.
- Company 7 states: “I think the challenge of fully-fashioned.. and what we saw was the linking part. But also just the programming part and understanding what you can and can’t do with WholeGarment®. Because there’s a lot that you can’t do with WholeGarment®, and you’ve got to realize what those things are and your limitations. A lot of designers don’t understand that so they’re designing crazy shapes with crazy slopes and crazy patterns that just can’t be done on WholeGarment® at this point. So I think shima is working.. we’ll probably figure out a solution in time.. but right now it’s just not possible.
- Company 4 states that there is a large misconception about how full-fashioned knitting should be used. They argue that a cup seamer does the same job as a linker and in their own experience using the two, the customer could not tell the difference a cup-seamed garment or a linked one. They state that the only time it is necessary to have a linker is for linking on a trim for a neckline.
- Company 4 also goes so far as to say: “The fully-fashioned knitting is definitely the way to go. If they don’t want to understand it, they’re really in the wrong industry.”
Customer Expectations

- Company 1 states that they have been unable to create complete garments from the machine because their customers want more intricate garments.
- Company 2 also mentions being in the age of Amazon where customers may see the technology working in a pop-up shop, but are soon wanting the products to come out faster.
- In general, most consumers do not understand the concept of waiting for a product anymore and do not make the connection that items have to be made before they are stocked in a store.
- Company 4 agrees that the quality that is coming off of the 3D knitting machines will not meet the expectations of the consumer for the price they will need to charge for each garment (considering programming time to create the garment).
- They also argue that the customer will not be able to tell the difference between a 3D knitting and a full-fashioned garment and it is worth doing a study to find out for sure:
  - The issue is always, what does the customer value it at? If you take the example of a garment or a shoe where you can make something fit better… do they really appreciate it? The girl or guy who’s running in a pair of sneakers, and he’s not getting a blister.. does he actually think- Oh, wow, it’s actually the way the shoe is made that’s stopped him from getting a blister.. not.. So the 3D part of it has a lot to do with the fit.
- Company 5 states that the reason they have not kept the 3D knitting is because their customer are expecting a more fitted and higher-end garment.
- Company 6 comments on how it can be difficult to convince a customer that a heavy knit has better performance than other options in the market.
- Company 7 also comments on how customers tend to focus on fit and the reputation of the brand rather than the quality of a good because they cannot tell the difference.

Machine Limitations

- Company 1 uses a Stoll 14 gauge machine, which means that anything created in 3D knitting must be in half-gauge (7 gauge), producing a chunkier knit. They would not be able to knit full-needle in 14 gauge to do 3D knitting, only panels.
- Company 3 production manager states that the maximum production load will only ever be 50% full-fashioned/ 50% 3D knitting. He states that there are some garments they can still do easily with full-fashioned knitting and the linking is not an issue (coarser gauge knits) 3D knitting will focus on the finer knits which are very difficult to link.
- Company 4 wants machine manufacturers to listen when they need modifications to the machine in order to complete a project.
- Company 5 states that the product they want to make would be impossible to make without cutting with scissors. The technology is not advanced enough at this point to
create fancy fabrics and also knit in one piece. That is why they have discontinued use-
because of the limitations of the machine
- Company 7 claims that opensourcing will solve the issues of technology advancement
  and difficulties with the machines
- Company 8 has found that certain yarns are not compatible with the machine components
  and you are limited in the sense of what materials can be knit on the knitting needles.
  ○ (Development for new knitting needles, stronger materials?)

**Maintenance of Machines**

- Company 3 states that the maintenance of the machines are key to the success of
  implementation, and having the right people to maintain the machine
- Since they are higher precision machines the needles are harder to change and the
  machine must be adjusted carefully
- They are on a regular weekly routine of cleaning the machines inside and out, and
  lubricating all parts
- Company 5 states that the newer machines are less maintenance than the older ones,
  however

**Drivers (Positive implications for adoption)**

**Initial Purchase Drivers**

- Company 1: Relationship with machine manufacturer and the ease of programming
- Company 2: Software System first attracted them. Then the other factors kept them there
  like cultural matching with machine manufacturer to have a quick start-up time for
  business
- Company 3: Initial machines purchased by first owners of the business, so kept in line
  with these established relationships
- Company 4: Overall manufacturing optimization- which machines give the best bang for
  your buck and allowed flexibility
  ○ B: so it’s the little things that people don’t normally look at first. They usually
  look at price, which is not the right thing. And we have stoll customers who
  bought the cheap machine, but it’s a two system machine, but then they run three
  color jacquard andthey need a three system machine. And they’re like, well how
  could I have? Well you could have spent the extra $5000. That’s basically what it
  is and what the Chinese pay for it when they buy 1000 machines. They should
  have spent the extra five, and maybe but 800 machines instead of 1000 And
  they’d be better off.

- Company 5: at first purchased the (3D knitting) machine in the 90s because it was new
  and innovative to create a unique product but found out that it really wasn’t their product.
- It’s not our product, basically. But we do sometimes… I don’t know.. something loose, or whenever a garment comes loose or a poncho, or something that you put on top, then we will have it. But it’s not something that is always on the line and it’s not something that defines us as a company.

- Company 6 implemented the technology only for one product to begin to test the market. Initial driver was to bring something new and innovative to the outdoor market

- Company 7 was initially driven to the 3D knitting machine when they found out about it at a sustainable textile show. They had not heard about the technology at the start of the business so did not know 3D knitting was an option.

- Company 8 adopted the apex software system first and also liked the shima family culture. They also appreciate that the machine can remain in their office, the machine is very flexible in it’s use and it is helpful for rapid prototyping

**Method of Technology Use**

- Company 3 is using 3D knitting, but only for fine gauge knits that are difficult to link. The coarser gauge knits are still knit using full-fashioned knitting techniques because the coarse gauge 3D knitting machines do not exist and also linking is less difficult with chunkier knits.

- Company 4 states that it would be much more efficient for companies to invest in the Stoll twin head machine, rather than 3D knitting because you can run two bodies at once and double the production instantly.

- Company 5 uses the newest technology to develop multiple-gauge swatches and make elaborate fabrics rather than making 3D knitting.

- They also own both systems, Shima and Stoll and thus have more flexibility when developing a new swatch because they are less limited by only have one type of machine.

- They also program for production efficiency, so if a swatch only requires a 2 system machine, they will not be wasting the machine that has 4 systems.

- Company 7 only has one machine for manufacturing in-house.

- Company 8 is developing new products related to electronic textiles using the technology.

**Technical Textiles**

- Company 1, 4 and 8 all believe that technical textiles are the future for 3D knitting.

- Company 1 states the demand for technical textiles is growing: “So i think the technical textiles is what everyone is trying to get into that market. It’s definitely beneficial for stoll and shima both to push the limits as far as they can with the capabilities of the machines. “

- Company 4 focuses on the technical textile market in their client work- 95% of their work is 3D related, the other 5% is flat material development with added tech in the fabric.
Company 4 has also had issues with getting machine modifications from either machine manufacturers for technical textiles and argues that machines have always been made for sweater use and do not consider the other markets.

- Company 8 is also focusing on technical textiles for their client work and they are estimating that 25% of their projects will be related to 3D knitting.
- They also note that the items are not commodity items, at least not yet but could become complex commodity products in the future.
  - Commodity: mass-produced unspecialized product; a good or service whose wide availability typically leads to smaller profit margins and diminishes the importance of factors (such as brand name) other than price.

**Relationship with Machine Manufacturer**

- **Incentives**
  - Company 1 received free machine from Stoll due to good relationship and trust that the machines would be well taken care of.
  - Company 3 received incentive on payment term for multiple machines purchased at once.
  - Company 5 is able to negotiate with both companies to get the best deal on new machines because they have both systems.
  - Company 5 was able to get a better deal with Shima, because Stoll was going to charge to rent the machines, so they chose Shima.
  - Company 7 received no incentives, but did switch machine manufacturers based on product type.
  - Company 8 on a lease to purchase agreement with Shima.
    - C: “Well, I think the.. not necessarily to assist in the decision-making process.. I think the whole package of the support, the training, the opportunity to go to Japan in the future. All of these things are very attractive, they make it.. you know they really want to engage with you and bring you into the shima family, as it were. And they make it attractive to do so.”

**Company Ethos/ Mission**

- Company 1 describes themselves as a “flat-bed knitting capabilities company” focused on domestic manufacturing.
- Company 2 is concerned with an on-demand manufacturing business model, to create products custom-made for the customer who elects to purchase, allowing for “fast-fashion” to be made responsibly.
- Company 3 aims to be the best factory available for manufacturing in the United States.
- Company 4’s mission is to partner with manufacturing partners to optimize their manufacturing practices.
- Company 5 fashion brand creating refined clothing, achieving the best fit and quality of a couture knitted garment.
- Company 6 is concerned about creating the best product with no unnecessary harm, focusing on environmental sustainability and partnering with vendors that can provide sourcing that align with their values
- Company 7 has vision for eliminating inefficiencies in the apparel industry, to create a responsibly made product in the United States
- Company 8 is concerned about solving human-centered design problems and whole systems development and are “agnostic about the technology solution”
- Of the 8 companies interviewed, all are intent on making the best product possible
- For 7 of the 8 companies, building the best product mean optimizing manufacturing, sometimes in the United States

Market/Demand for Product

- Company 1 Admin states that 80% of their customers request something in 14 gauge or finer for fashion apparel related items.
- Company 2 has had increased sales in the short time that they have been in business, generated primarily by word of mouth
- Company 2 has also received a lot of direct positive feedback from customers regarding their customizable sizing of products. They are filling a need with men who are larger in stature and have never had accessories fit them in the past.
- Company 2 also comments that sales for them are primarily based on product marketing and if there are any lags there.
- Company 3 states that their 3D knitting offerings have really only started though they have owned the machines for 3 years now. They have just recently received a large order from a customer for 5,000-6,000 of a style that they developed in-house.
- For companies that are producing in the states, like Company 3, there must be a demand of customers that want to produce here.
- Company 3 hit hard times like many in the textile industry in 2008. “It doesn’t matter how hard we pushed, it’s really up to the customer and their customers to have the demand to produce goods in the U.S.A. I think definitely the turning point was the London Olympics, where you know the Team USA uniforms were made in China, and it there was big press about that. And that’s when the Made in the USA trend really picked up.”
- Company 4 does not believe that there will be great demand for 3D knitting in the sense of making sweaters. They believe that technical textiles will be the future for this technology because the customer simply does not value the product. “In the technical world, it’s nice that they can do it. The reality is, there’s no market for it.”
- Company 7, similarly to Company 2, has had a great return rate (40%) of customers. It is evident that their customers are excited about the customizable nature of their products.
and being able to make something specifically made for you.

- On the machine side of the conversation- Company 7 mentions the company Kniterate and their competition with Shima. Yet Shima does not see this start-up as a true competitor. Company 7 admin believes however, that these small start-ups will drive innovation for companies like Stoll and Shima because they are allowing the ability for anyone to program something which is a major hindrance in adoption.

Diffusion Positioning

- Company 1: Early/ Innovators
- Company 2: Early/Innovators
- Company 3: Early Adopters, as far as machine technology
- Company 4: way before the chart even starts
- Company 5: Early Adopters of new technology, but not necessarily in fashion
- Company 6: Between early adopters and early majority for technical applications. In the outdoor area- innovator panel. Early adopters for functionality reasons (again not fashion trend setters)
- Company 7: Innovators- simply because of taking on so much risk
  - “There are a lot of things that you have to work through to prove that 3D knitting can exist in the marketplace. And so there’s a lot of risks there. In order for a brand to move and shift, they’ve got to know that there’s this 100% positively great thing that can be there for them and that’s just not there yet. We were built on risk, essentially, the reason why I got into apparel was because I thought there was a lot of potential there to, I always say- revolutionize the way clothing is made and the whole industry runs. “
- Company 8: Innovators

Innovation

- All companies studied would consider themselves to be concerned about innovation, regardless of the specific technology they use
- Company 4 adopted the CMS machine in 1987, which was the beginning of the belt drive system that revolutionized machine knitting at the time and that was the moment that all the hand cuffs were taken off as far as restrictions with the machines. They have kept the newest technology available but within reason. They did not adopt the newest software purely because there was a new option. They decided based on how flexible the software was to use and adjustable for their own purposes.
- Company 5 states that they adopt new technology based on what new purpose it can serve in development of a new product. The SRY was adopted because of it’s new capabilities to lay in a yarn and making knits that look like they are woven.
- Company 5 also comments on their focus on innovation really relates to the types of yarns that are used rather than just the way something is created.
- Company 6 sees much potential to use this technology in other product categories and are moving towards those efforts, but must find the right partners in their supply chain first
- Company 8 knows that they would have been unable to make certain products without this new technology, but using it will be better and more efficient in the long run.

**Business Model/ Managerial/ Tone at the Top**

- Company 1 considers themselves to be a flat-bed knitting capabilities company, which means both research and development and being a contract knitter as well as training. (Sharing their knowledge could mean that they are open in general about new product ideas and maintaining adaptability to their entire company mission)
- Company 1 also states that they have adopted a business model committed to creating quality products, which requires linkers to link their garments and taking the necessary time to train them and allow for their learning curve time.
- Company 2’s founder mentions that their main mission is to create a consumer-centric brand, by being transparent in their production methods by doing on-demand products that are created only because you elect to purchase them.
  - A Lot of the companies that are starting to use 3D knitting now are using it for a gimmick. And so we use it for an experience in store, but it’s still foundational to this whole new manufacturing business model. But I think it’s going to take time for a lot of businesses to start adopting it.
- Company 3 mentions wanting to be the best factory in the United States, which means adopting the newest technologies to attract higher-end customers.
- Company 4 being a research and development firm working on technical textiles must use the newest technology to keep on the leading edge of the industry.
- Company 5’s mission is related to couture clothing which does not necessarily translate to new technologies, but despite that have committed to using new tech for the development of innovative fabrics.
- Company 6 has a brand mission of creating products with no unnecessary harm and they are partnering with other factories to make that a reality. They do no foresee owning their own machines because that is not their specialty. They know what they are skilled at and decide to contract out the pain points to others.
  - I think it would be naïve to think that we would have all the information to successfully run the manufacturing. So I think that’s where we take our research and our design skills and we look for the right partners who can help us facilitate those visions. And my guess is that we’ll continue to follow that model. Particularly with an item that requires such high levels of training to really understand and utilize.
- Company 7’s mission is to eliminate inefficiencies in the apparel supply chain, which they accomplished through a transparent United States supply chain at first inception. After switching to 3D knitting, they have eliminated the needed supply chain and can stick to their mission of on-demand manufacturing which can take place anywhere with reliable electricity. He argues that the new apparel business model is the reason to adopt this technology because it is possible when implemented.
- Company 8 is also a research and development firm, so in that sense they are interested in
finding the best solution for a problem regardless of the technology used. They have found that 3D knitting just so happens to be the most efficient in terms of product development for the types of projects they are working on.

**Process/ Production Benefits**

- Benefits found related to production processes include: the reduction of labor, increased production speed, logistics considerations, scalable technology, rapid prototyping, speed to market, and supply chain flexibility and agility.

**Reduction of Labor**

- Company 1 and Company 7 believe the main benefit to using 3D knitting is reducing labor. Company 1 attempts to assemble a product on the machine as much as they can.
- Company 3 tech user also comments on the fact that 3D knitting will be used more in the future because it reduces labor.
- Company 7 also comments on how this reduction of labor allowed for an entirely new business model to emerge in the textile industry.

**Production Speed**

- Company 1 states that full-fashioned knitting is faster than circular knitting, but also more efficient on materials because it only requires a few cones of yarn, opposed to dozens (Set-up time on the machine is faster).
- Company 2 says that the prototyping of a product is very quick, but in normal production they encounter problems with getting the right yarns they need on time, so it is other agents in the production stream that cause problems.
- She also comments on how the knitting time is fast, but when customers see the knitting time in store, they also think it should be able to do it faster in the instant-gratification world we live in.
- Their products tend to take 30-40 minutes to knit, and they can usually run 10-20 products a day on one machine.
- Company 3 uses both 3D knitting and full-fashioned knitting and they have seen that the 3D knitting production run is about a week faster than full-fashioned because the linking step is eliminated.
- The production manager at Company 3 states that 3D knitting is about 30-40% faster than full-fashioned in totality, though 3D knitting takes longer to actually knit.
- Company 4 states that 3D knitting allows for the entire production process to be more agile by eliminating production steps and being able to change the size of things easily on the fly.
  - C: And the part of productivity, I would say there is a tremendous balance. Yes, something might take an hour or an hour and a half, but you don’t have all the cutting, you don’t have all the prep. You’re not having to stock all kinds of rolls.
of fabric. You’re actually making your product at the same time you’re making your fabric. So you’re stocking raw materials. If something’s wrong, or you need to adjust something, or say your customer says I need the pocket to be a little deeper, you can change it right on the fly and the next batch of garments will go straight out and you can change it.. you don’t have to worry so much, you don’t have to change all these markers and you have to tell everybody in the cutting room, or you have to tell everyone in the sewing room we’re doing things differently.. So I think it makes companies more agile to address the needs of the current business and the economy.

- Company 5 states that the machines themselves are faster, speeding up production
- Company 6 also agrees that there is potential to improve productivity by eliminating production steps but there are still bottlenecks when you are using different partners along your supply chain
  - R: Currently, it’s a tricky question to answer.. because you certainly have fewer steps, but those steps are more time intensive on their own. I would say, it’s certainly still faster, the trick can be that oftentimes the same facility that knits the garment doesn’t fully finish the garment. It might have to go to another facility for some sort of wash, or softening or a chemistry application, so it’s not like you’re taking a process that traditionally involves knitting goods, dyeing goods, finishing them, rolling them and sending them to a factory and cut and sewing. You still have multiple steps, but I would say all in all, very likely that 3D knitting is still faster.
- Company 7 comments that typically the idea of using 3D knitting is lost when considering the timeline comparison to full-fashioned being produced in another country, but perhaps this technology is not meant for the traditional apparel model
  - But if you take that supply chain and significantly reduce it, I may have this on-demand process, 3D knitting is way more profitable and cost effective. And in terms of the speed, when it comes down to it, the cost is much better. You just really have to rethink the apparel model.

**Logistics Considerations**

- Company 2 comments that 3D knitting allows you to produce in the United States rather than overseas and thus reducing a hefty environmental footprint

**Scalable Technology**

- Company 4 states that scalable technology is one of the main benefits to 3d knitting adoption
- Company 7 is now in the process of figuring out how to scale the new apparel business model by automating the process with as little human intervention as possible and bypassing the programming step
- Company 8 also states that this technology will help in the transition from prototyping to larger production. This brings the knitting out of the factory and into the workspace.
sometimes you can do something on a sample scale- that somebody will have a sample machine or you might have a weaving loom where you would hand weave something, but it doesn’t transition to full rate manufacturing. So you’ve got lots of gaps when you try and make a transition, which is one of the biggest problems in textiles. But with this, we can go straight from the yarn to item and then we know we can duplicate the item in production in thousands of units, if somebody wanted to buy thousands of units. So there’s no technology gap between prototyping and production and that’s really very innovative.

**Rapid Prototyping**

- Company 1, 2 and 8 mention that these technologies are very flexible in rapid prototyping.
  - (Company 1) So I think that some companies that are smart are starting to see it as it’s easier to develop; it’s easier to develop things quickly, to test it for ideas. Flat-bed machines can make all of the stitches. Circular machines can make the stitch that they are purchased with the intent of making. For the most part.
- Company 8 also comments that the sampling process is much more efficient because material is not wasted and the capabilities of these machines are completely unique to others, giving a wide variety of options in product development

**Speed to Market**

- Company 1, 2, & 4 agree that the technology provides speed to market advantages
  - Company 2 uses pop-up shops to have customers order a product and have them made within an hour. They also have an algorithm that lets their production know which items should be knit in what order everyday to minimize changes of yarn. They have been able to ship out orders the same week for online orders and within an hour at the brick & mortar store. They are also able to prioritize customer orders if they are in a rush, for a gift or a wedding deadline.
  - Company 4 comments on the economy of scale when it comes to saving time on knitting time. Knitting time affects how quickly you can get to market, so saving 20 seconds on a job can become exponential in mass production. The time factor is great for prototyping but also if you can program well, it can save you a great deal of time and speed up your production.

**Supply Chain**

- Company 1 states that they have a completely different supply chain than conventional cut and sew operations, it is much more simplified. Because they are a contract knitter, they do not source yarns except for the prototype yarns that they use to test out the knit ability of a certain denier count.
- Company 2’s supply chain is also very simplified. They purchase stock yarn from their yarn suppliers and were fortunate that the stock yarns matched each other. With a customizable on-demand manufacturing business model they are able to adapt to their supply of yarn quickly. The main bottleneck for their production processes is from other players in the supply chain.
  o Well I think that everything else slows it down. So I think that it’s super fast and efficient. It’s just that the prototyping is so fast, like even with other partners that we’ve spoken to, the fact that you can program right there especially when it’s made in the U.S. That process is really fast. And it’s the other business practices and business models that slow us down

- Company 3’s supply chain has not been affected by 3D knitting implementation because their yarn suppliers have remained the same and they are uninterested in having a vertical supply chain- they would rather continue to innovate in the sweater market

- Company 4 states that 3d knitting makes your product at the same time as you’re making the fabric, so you only need to stock raw materials and suggests that you can have a very agile supply chain implementing this technology:
  o B: I mean, that’s the best thing. Stock the yarn. If you have yarn storage, stock that and when someone calls you and says- hey I want a long sleeve sweater, you can do it. If you have to wait for the yarn company, it could be months.

- Company 6’s supply chain has been affected by 3D knitting by pushing back farther in time for their plan sheets. They have had challenges finding the right kind of yarn, ethically made and finding the right partners for production that align with their core values. They are also uninterested in owning the manufacturing portion of the production process because it becomes very difficult to handle.
  o I think it would be naïve to think that we would have all the information to successfully run the manufacturing. So I think that’s where we take our research and our design skills and we look for the right partners who can help us facilitate those visions. And my guess is that we’ll continue to follow that model. Particularly with an item that requires such high levels of training to really understand and utilize.

- Company 7 at first inception, created it’s own supply chain to be sourced and produced entirely in the United States. This process took an entire year to vet out and get running but soon found that even a transparent supply chain left them with left-over inventory due to forecasting errors. It was this point that they began looking into other forms of efficient production.

- Company 7 is a strong advocate for 3D knitting because it can significantly reduce the supply chain, which in turn will reduce many of your costs associated with manufacturing and risks involved with making a product that is forecasted. “You just have to rethink the apparel model.”

- Company 7’s supply chain now consists of just the yarn supplier. He comments that this
kind of relationship is quite rare in the apparel industry and not what the mill is used to but they have very good relationships with their suppliers now. (Perhaps helps the human relationship dynamic again)

- Reducing the supply chain is also the second main benefit that he mentions in adopting 3D knitting

**Mass Customization**

- Company 2 and 7 have on-demand manufacturing business models where products are only created as they are ordered online, resulting in no dead stock or inventory
- Company 2 has also offered color customizability and the ability to add personalization to some of their products with added text
- Company 4 comments on a mass customization project they worked on with French Rags in 1989. They were able to create custom-made, made to measure sweaters on the Stoll machine by simply adjusting length and width for panels of full-fashioned knitting
- French Rags was very successful at the time, but the owner had no one to pass the business on to
  - B: you know, everyone talks about mass customization today, and she was doing it. There was no question that she was doing it, and making pretty decent money at it. And it was made in the USA, you can’t get any better than that.
  - C: she is in textbooks. It’s one of those things that I’m able to adjust and control because of the computer being on the machine, I think gives more versatility.
- Company 7 decided to eliminate the issue of forecasting by enacting on-demand manufacturing, he also asserts that they are trying to solve the apparel industry manufacturing problems, so whether that be customization, mass customization or standardization.

**Manufacturing Optimization**

- Company 4’s main mission is to maximize manufacturing optimization which covers all the necessary inputs to create a sustainable product. They also assist their clients with laying out their factories efficiently and eliminating any time where human hands touch a product during manufacturing.
- They also argue that modifications to machines are a necessary part to saving a customer money on knitting time but they have had difficult convincing the machine manufacturers of this
- Company 4 has found that it’s best to listen to your customer’s needs first and then help them find the most efficient solution
B: I think at the age of 20, I was make sure a customer bought the right machine for what he wanted to make. And it used to get me in trouble at Stoll, because they didn’t have stock. But I’m like- he doesn’t need that machine, he needs this machine. And I’d get in trouble all the time. But we could have sold 5 of those, but yeah.. he only needs 2 of those. So, it was just life.. So I already started from the very beginning on how to pay attention to what people need. It’s just a different way of thinking, I think.

- Company 6 designer notes that the 3D knitting factories in HongKong are unlike any cut and sew operation she’s ever seen, with only machines and they’re very clean.
- On-demand manufacturing falls into this idea too

**Product Benefits**

**Quality**

- Company 1 sells themselves on quality made full-fashioned products so they have trained linkers to finish the garments
- Company 1 tech user states that 3D knitting could be better than full-fashioned knitting due to eliminating human error. Their problem with quality is working with full-fashioned assembly of pieces and have had problems with their linkers and making sure that the trims are attached correctly.
  - But I think to knit an entire garment all outright, once we have the capabilities of the getting right people to be able to do that, to program it. I think it would be much better quality, much faster, and just better for the industry overall. It’s just trying to find the people to put the time into learning that type of programming.
- Company 2 has been able to create a “fundamentally better product” by eliminating seams and shaping their products on the machine. She also comments that sometimes quality issues can come into play if you use cheap yarns due to the severe racking that takes place for shaping a 3D object, but they have decided to use the highest quality yarn possible to avoid these issue.
- Company 3 admin states that the quality for 3D knitting is better as long as the machine is adjusted properly, so that the defect rate is lower than other sweater products. He also comments that the quality is always contingent on how the machine is adjusted, so once this is corrected your production run will go very smoothly.
- Company 3 tech user also states that the quality is better for 3D knitting, but has limited styles you can create and cannot achieve certain stitches.
- Company 4 talks about how the quality of the machines themselves have allowed for very cheap yarn to be run on them. The prototypes that are being developed really must have the same quality yarn used during production but this is often where brands like to cut costs and save money. What they have seen is a total misunderstanding of how knitting works in regards to manufacturing solutions- a company must use good yarn, otherwise they will have to slow down the machines and increase knitting time and then the weight
of their cost lies on the actual knitting time rather than other factors.

- C: Yeah, so the customer’s actually making that decision to buy a lesser quality yarn, slow the machine down…their yarn is actually not the real expense, it’s their knitting time. So if they’re not educated to understand that if I bought a better yarn, maybe it costs me ten, twenty cents more a pound. I can actually save three or four dollars in terms of knitting time.

- Company 4 also mentions that other machine manufacturers with lesser quality parts are not even worth considering for a purchase because they do not stand behind their product. Especially when working with 3D knitting needs, it is best to start with a quality machine that you are certain is reliable.

- They also state that knitting components of a product on the machine allow you to take out risk factors during the normal cutting and sewing production process, eliminating human error to create a higher quality product.

- They also feel that 3D knitting does not necessarily match in terms of making a perceived quality garment on their machines you much knit in half-gauge and are limited in your design capabilities so the type of garment you make does not look like a high-end garment.

- C: And the quality is kind of a miss-match, for the quality that is a result versus how much you have to charge for the piece. You can’t sell it to a wal-mart, although it’s a Walmart quality.

- Company 5 states that quality is of high importance to their brand and not limited to just the knits but also the yarns used to make them. He states that the new machines are very good in terms of quality because they require minimal maintenance and are faster.

- D: I think the challenge is how to make a garment faster without sacrificing the quality, the faster the machine can knit, the turn from corner to corner, the transfer speed, the better they make that, the better it is for a manufacturer, time is money. Everywhere. And that’s of course, you need new gadgets, new way of doing stitches, but speed is very important.

- Company 5 tech user also mentions that 3D knitting can achieve great quality in mass production because it takes 2 or 3 garments to perfect the machine adjustments.

- Then when you tune the machine, you can run thousands and thousands of pieces. That’s the benefit. But not if you’re making 10 or 20 pieces. And change the machine, no. That’s why we’re not using it. Because it’s constant changes.

- Company 6 brings up the point that quality can be an ambiguous word because that could mean- durability, performance or the life-span of the product. Their company focuses on having a life-time warranty and “worn-wear” by repairing a product instead of throwing it away, so figuring out how to repair seamless knits have proved to be challenging.

- They also state that quality is contingent on design and figuring out where can you make sacrifices. Educating the customer is also important for proper care of the garment to maintain the quality throughout the product’s life cycle.

- Company 7 states that consumer perceptions of quality are very skewed and are primarily influenced by price, the fit of the garment and the reputation of the brand.

- M: I think what’s hard is that people don’t know what quality is. And I think for the most part, consumer are trained to identify quality by the price. So when we
were selling wool t-shirts that we made to the highest quality, we were using
crazy engineering within our t-shirts.. that no one traditionally uses because it gets
too expensive and we knew our t-shirts wouldn’t break down. We were trying to
sell that at a price below what’s marketable and what Icebreakers and Ibex was
doing.. customers were just like- how do we know this is higher quality? And we
were like- because we took out all the other stuff and realized what they were
putting into it and realized that these things don’t last longer and we were actually
producing a higher quality shirt. So they were just like- it should be priced higher,
and I’m just like- it doesn’t need to be priced higher.. so they were like- yes, it
does, that way we know it’s quality.. so that was the hardest part, right? Price and
quality go hand in hand these days. So I think when a customer looks at
something that is 3D knit versus cut & sewn, they won’t really understand what’s
a higher quality knit. They’ll just look at it and see if it fits. And they’ll just go by
the reputation of the brand in some sort of way in the price.

- Company 8 also things that 3D knitting creates a high quality product that is flawless.
  They also mention the great advent of having minimal finishing work and the pieces
come off the machine mostly finished off the machine.

**Comfort**

- Company 3 tech user states that the seamless nature of 3D knitting will be a selling
  feature, but only certain styles can be used
- Company 6 received positive feedback from their customers who bought the complete-
  garment sweaters and stated how comfortable they were with no seams which allowed for
  no chaffing
- Company 6 also states that the comfort factor was the biggest benefit to using this
  technology to create a seamless garment
  - It reduces waste, it reduces potential quality issues, I mean oftentimes the seams
    are where we start seeing issues, particularly with baselayer and stuff like that.
    Because next to skin comfort is so critical. Anytime you add a seam in, you have
    to be really careful to do it in the way that’s not going to introduce a chaff point, a
    stress point that’s going to limit the stretch of an item, and also, 3D knitting, 3D
    WholeGarment® knitting really allows you to combine different constructions in a
    perfect way.
- Company 7 has not received any direct feedback about the comfort of seamless sweaters
  but makes the point that people may feel that the garment is more comfortable but still be
  unable to recognize why compared to other garments they have. (Perhaps the solution
  here is to educate the customer and bring attention to these details so that it clicks with
  your customers why the product is better)

**Durability**

- Along with Company 6’s mission to make a guaranteed product for life- 3D knitting
  sweaters are difficult to mend and pose a challenge
R: Yes, there’s a beauty in the rub with them. When they’re good, they’re good, when they get damaged they can be really tricky to fix. And that’s something we’ve been working with, full disclosure with our repair center in Reno. Like how do we address a break in a merino air? Do we hand stitch it, do we try and patch it in some manner? Or if we do something, is it going to ultimately make the garment less functional?

- Company 7 uses durability as a marketing story for their brand
  - Durability is a big thing too because I think that a lot of people find that people want their stuff to last forever, anyone would. So because you’re not doing any linking and potentially cutting threads or yarns in there, it ends up being a higher quality knit.

Main Benefits to Adoption

- Company 2, 3, 7, 8 all comment on how machines can be kept for in-house manufacturing. Allowing for clear oversight of the knitting process and responsibly made products by reducing the labor component and bringing the factory into the office.
- Company 1: Reduction of labor; simplification of the supply chain (versus cut & sew); speed to market; rapid prototyping; flexibility of design (compared to circular); minimal waste
- Company 2: flexibility in product creation (multiple products on one machine); easily translates to on-demand manufacturing and customization; can do manufacturing in-house; Shima’s support through the process
- Company 3: Enabling a new product offering for customers to produce in the United States
- Company 4: Consistency of knitting (eliminating human error); Scalable technology- uses minimal electricity, manufacturing can be optimized, contained and controlled.
- Company 5: Offered something new and unique for new types of fabric development; Offers inspiration for other older machines and new and different stitches
- Company 6: Comfort (lack of seams, lack of chaffing); Minimal waste; Innovation in the outdoor retailer space; Joining yarn technology with fabric making technology; Ability to change stitch density strategically without having to hybridize a product
  - “It’s kind of those points I made before, about being able to take yarn technology and knitting technology and kind of remove those shackles of traditional cut and sew construction
- Company 7: In-house manufacturing; Ease of developing a company by selling online and ship direct to consumer; 1. Labor reduction; 2. Reduction of supply chain; 3. developing a new apparel business model.
- Company 8: Able to keep machine in-house, small-size and short set-up time, quiet to run. “It’s accessible”. Flexibility; Software system; Easily translate patterns to production somewhere else.
  - C: So it really brings knitting out of the factory and into our workspace much more easily. And because we can then, if we do produce something that has a commercial value, we can have a factory do it because there are places you can go
to who have banks of these machines. Or we could just buy a lot of machines if we wanted to. We’re less likely to do that, we’re more likely to contract someone to make it. So the integration of the technology into the development process is relatively quick.

Shima Vs. Stoll

- Of the 6 companies that have decided on using only one of the main machine manufacturers (Shima and Stoll), all commented on their relationship with the manufacturer and sometimes a long-term history with the company. Of particular interest is the cultural matching element- that these business owners need to feel they are a part of a family, so to speak and have similar vision for their company that the machine manufacturer must share.
- Company 1: Relationship with machine manufacturer
- Company 2: Cultural matching
  o “Well from a business standpoint it felt like they really understood where the industry was going. And they are really interested in doing the custom clothing and the whole idea of one-on-one manufacturing. Their whole system is really built for that. And so I think as a business they really embraced what we were trying to do. And helped support us along the way. That’s a huge part of just being able to start a new kind of mission driven business, is that additional support that you get. So that was really clear from the moment that we met with them. “
- Company 3: Own both; chose them because they have proved to be the most innovative and reliable machines in the market. His parents originally purchased Shima and then also Stoll so they have decided to keep them.
- Company 4: Long-term history with machine manufacturer
- Company 6: Referral through yarn manufacturer had connections with Shima contract knitters
- Company 7: Cultural matching- train you so you can be independent. Assisting in the beginning to get you started as a business, and train as much as needed and adjust patterns if they need correcting.
  o “So I think there’s a lot of things they’re doing already to have that be possible. I think that Shima is doing that way better than Stoll was when we were working with them into development.”
- Company 8: cultural matching (relationship with machine manufacturer)
  o I think it was just we enjoyed the whole process of meeting them and talking to them and I think their approach fitted us so we honestly didn’t go look farther than that.
  o I think the whole package of the support, the training, the opportunity to go to Japan in the future. All of these things are very attractive, they make it.. you know they really want to engage with you and bring you into the shima family, as it were. And they make it attractive to do so.
Adaptability of Machine
- Company 4 states that Stoll is better in terms of providing adaptable features to a product because of the computer that is on the machine. This is especially helpful for any type of mass customization project because the controls on the machine can easily be changed rather than moving from the machine to the software to edit programs.
- This is especially helpful for technical textile knitting where the controls on the machine need to be changed often to rapid prototype a product.
- They also mention that Stoll can do everything but Shima sells specific machines for specific tasks like intarsia or laying in yarns.

Manufacturing Location
- Company 1: North Carolina
- Company 2: New York
- Company 3: California & China
- Company 4: (Research & Development) California
- Company 5: Development- California, Manufacturing- Mexico
- Company 6: Hong Kong
- Company 7: North Carolina & sourcing from United States
- Company 8: (Research and Development) Rhode Island

Reshoring
- Of the 8 companies, 4 are manufacturing production runs in the United States
- Two of the 8 companies are using the technology in a strict research and development sense and the manufacturing of the products they develop is not up to them
- Company 1 believes that manufacturing locally is possible, it will require people to be open with their knowledge and share with others
  - We’re trying to bring all of the work back with more people that can bring work back and do work here and we think it’s better, it’s going to grow the whole pie, or whatever you would say in academia. So we’re willing, we’ve trained our competitors here. People that are also doing fully-fashioned knitwear, we’ve trained them here. Who cares? (we’d) rather have someone doing quality work at a good price. And that way everyone can keep work in this country. Versus doing a shitty job and then people will say- oh, can’t make it here. Nope, can’t do it.
- Company 2 comments on the benefit to having production locally is that there can be full control over that process and overseen by them. It also allows for the brand to be open and honest with their customers about how their product is created.
- Company 3 states that manufacturing domestically depends on customer preference and there must be a demand for it. He did not see a resurgence in demand for domestic production until the London Olympics when the Team USA were criticized for having
uniforms that were made in China.

- Company 7 believes that a simple way to have a contained and responsible supply chain is to hold it in the United States. They have focused on developing products that will address most of the marketplace and demand (80%) of sweaters in the styles produced. He claims that it is possible with this technology to affordable create products which are more cost effective and profitable than those made abroad.

**General Drivers**

**Flexibility**
- Company 2 and Company 8 both comment on the nature that many products can be created on the same machine, allowing for flexibility of a product range
- Company 8 also comments that the Apex design system is also very flexible and allows for quick presentations of ideas (which they adopted first)
- One of the key drivers for Company 8 to adopt is the flexibility

**Reliability/Consistency**
- Company 3, 4 & 5 all agree that 3d knitting technologies offer a more consistent product.
  - Company 3 states that you will experience less defects that the traditional sweater production methods
    - I mean, you probably know, the more human hands that are involved in the production process, the more variations it can have. So on WholeGarment®, once the garment comes off the machine, there’s really no more human involvement, well.. The tucking of the thread at the end, the washing, the pressing and the package. So you minimize a lot of the variables in the production flow so your end product is more consistent as long as your machine is adjusted correctly.
    - In WholeGarment®, you could have a dropped stitch in a garment that was not caught and we could have the same issue. But at least you will not have a sewing or linking defect. So you’ll probably experience less defects compared to the traditional method of producing sweaters.

**Retailing Venue**
- Company’s 2 and 7 both primarily retail through online selling
- Company 2 has been successful also in pop-up shops to give customers a “magical” experience
  - So really I think it’s about, for us, the area that we see is important is having that conversation about the responsibility of the consumer and the manufacturer for manufacturing. And creating magical experiences, online and off-line. And so that’s what we’re excited about.

**Social Compliance**
- Since 3D knitting does not need as much of a labor component, it is inherently more socially compliant compared to cut & sew factories or full-fashioned knitting that requires labor forces to join and finish garments. Company 6 designer comments on the conundrum:
  - There are so many factories out there that don’t treat their workers right, and it’s hard to always work with people you feel good about. And I don’t know if that’s the total answer, because there just aren’t that many workers. But it is a little bit easier for us to get through our four-fold process, and get them approved. Because we know that they’re not treating their workers bad, and there’s nothing shady going on. It’s always very clean, very efficient, there’s like not that many outstanding issues.

- One of company 6’s core missions relates to social compliance and understand that undergoing these regulations are limiting within themselves, but 3D knitting does offer an alternative to constant oversight.

- 3D knitting also eliminates tedious and monotonous tasks that can be taxing on a human body

- (Again, you are eliminating the job to begin with, rather than solving for the actual issue of employing people and taking care of them)

**Sustainability**

- 7 out of 8 companies are concerned about business sustainability and environmental sustainability and feel that 3d knitting assists in that

- Only 3 companies of the 7 could say it was a determinant in the adoption of the technology

- In general, compliance to environmentally sustainable practices are a nice “thing to hang our hat on”, rather than a main driving factor towards adoption.

- Company 5 had no comment on this issue and said that the company does not talk about it

- Company 4 also comments that being efficient with your supply chain already helps with sustainability and that full-fashioned knitting is the best option to save on material waste
  - As far as knitting things the most efficient way is already saving electricity. Even if it was a cut and sew garment. Just in being how you made a cut and sew garment was important to us. Then when you’re going into the fully-fashioned world, you’re already saving the yarn. Why do you want to throw away yarn that you paid to have dyed? You can imagine, if you’re going to knit a cashmere sweater, you’re going to cut it? You’d have to be crazy.

- Company 4 also states that the hours of programming that it takes to make a product with little waste is not sustainable
- Company 3 states that the customers they have that invest in 3D knitting products are advertising to their customers that it is environmentally friendly and they can tell a story behind it.
  - customers who are becoming more aware of WholeGarment, and they would like to promote WholeGarment® as more environmental friendly, because of less waste and supposedly also, I think it fits better without the linking construction limitation. So that’s on the marketing side. They can create a story behind 3D knitting.
- Company 6 was initially drawn to the technology for it’s exceptional ability to save on wasted material and they have noticed a significant reduction in material waste during implementation

**Flexibility**

- Company 8’s key decision factor was the flexibility of the mini 3D knitting to make many products
- True also for company 2
- Company 8 also notes that the apex design system is flexible for their uses and allows for quick presentations of ideas

**Transparency**

- Company 2 and 6’s core values are maintaining transparency with their customers about how their product is made
- Company 2 is transparent about when the product is made, and customer receive an email when the product gets made and when it gets shipped so they are in touch with the manufacturing process
- Company 6 discontinued the use of 3D knitting due to issues with their supply chain and needing to maintain transparency of the supply chain

**Storytelling/ Marketing Story**

- Company 2 states that product sales are very dependent on the way they are storytelling their product to customers
- Company 2 likes to tell the story to their customers of having a one-of-a-kind product that is specifically made for you, perfectly fit for you. This combines convenience of instead of shopping around to being able to get a product that you know will fit and you will want.
- In this way, Company 2 can have an open dialogue with their customer about the manufacturing process and responsibly made products
- Company 3 states that their customers who are adopting 3D knitting goods are telling the story to their customers about it being an environmentally friendly option due to its minimal waste in production.

- Company 6’s story about 3D knitting described the innovative 3D knit structure that was developed for added warmth next to skin; the yarn technology used (a polyester core spun yarn with exploded merino) for additional micro dead-air space; and the minimal waste during production.

- Company 6 also states that they are not promoting this garment as they could be, they are simply adopting the technology because it makes sense. They argue that more players in the market will need to get involved and promote it more.
  - I would say the story is going to be fairly similar to what we’re telling the consumer now, and that is the ability to change knits without seams, it’s the ability to avoid potentially limiting seams in the garment, reduced the environmental impact of the manufacturing cost and ultimately provide an item that kind of checks all those boxes.

- Company 7 comments that they have found that customer’s primary drivers are not responsibility or sustainability- but fit and price.

- They have found that telling the story of making a custom-fit sweater resonates, and they tell the story of the item being more durable and more comfortable.

**Marketing Venues**

- Company 2 uses PR as a primary driver of sales- articles written about them, pop-up shops, speaking events, online marketing- email, paid social media marketing and influencer gifting
- Company 7- word of mouth. But have noticed times where articles or bloggers wrote about them and how products were flying off the shelves

**Initial Start-Up Time**

- Company 2 and 8 agree that the initial start-up time for using the machine was very quick including the training provided by Shima

- Company 1 warns that machines are not a printer.
  - It’s just now they’ve got to understand it’s not a printer. Not yet. It’s not click and put an image on it and then run it. You can’t plug it in and fire it up on the same day. It’s not gonna work like that.

**Recommendations- Future of Knitting**

**Expectations for the Textile Industry**

- For 3D knitting to become a standard/mainstream practice:
  - Company 1: Depends on the products and uses that we find for the technology and investment on company’s part to train their employees.
Company 2: Will take awhile due to limiting factors like cheap labor, limited expertise in the U.S.

Company 3: Much more widely used in other countries (Italy, Korea and China), unsure about United States though
  - Tech User believes at least 2 or 3 years (but she may not have understood the question)

Company 4: Not in their lifetime, believes it is best used for specialty items. And argues that if the sweater industry would adopt full-fashioned knitting everyone would be doing a lot better

Company 5: Don’t think it will ever happen, it will only be used for a specific product
  - Tech User thinks that it will be the future because you do not need a workforce to finish the piece

Company 6: More brands coming on board and investing in technology

Company 7: Education about the technology to big companies and what can be achieved

Company 8: In the technical textiles segment, 5 years, maybe more.
  - Yeah, I think it’s just going to take, having more prominence in terms of what people see on a day-to-day basis for how to accomplish this. And then it goes through your chart there, right with the innovators, the early adopters, it’s going to have to follow that timeline before there’s enough people that are willing to say- oh yeah, I can make this work, there’s a real future for it.

- Education in knitting -

- Company 1 is attempting to tackle this issue by holding training in M1 plus software. The future will depend on people being willing to communicate and share their expertise and also companies investing to make the training happen

- Company 4 does not believe there is very much knitting knowledge present anymore, combined with a lot of misinformation and buzzwords so that people do not understand the complexity of 3D knitting. They have had to train their clients in baseline textiles knowledge because their clients do not know.

- Company 7 states that more education is key to the success of this technology and the people who are able to program should be compensated highly because the market is there to be

- Company 8 were only exposed to hand knitting machines in school, nothing electronic, so their learning curve is better than most but it still exists

- Future of Knitting -
- Company 3 and 5 believe the step forward is to combine the 4-bed knitting of Shima and the controllable carriers from Stoll.
- Future will be revolve around different ways to 3D knit something—maybe it is turned on its side or upside down instead.
- Company 7 thinks that opensourcing the software will open the doors wide to the possibilities.