ABSTRACT

PATIL, SANJAYKUMAR ANANTRAO. Impact of New Technologies on Textile Supply Chain. (Under the direction of Dr. William Oxenham and Dr. Trevor J. Little).

Several innovations have transformed the technologies of textile manufacture. There has been growing interest in increased machine speeds, reduction of lead time in manufacturing and savings in materials and other cost. New technologies are justified, they are adopted and at certain time they become obsolete. Few examples of obsolete technologies are mule spinning, scutcher in blowroom, handloom, group drive of shuttle looms, automatic cop changing loom, steam engine and data storage devices such as floppies for computers. It is not only the technology that transform but also the supply chain undergoes transformation. Recently, the motivational factors for those transformations are customization, energy consumption, amount of waste, competitive advantages in the aspect of capital investment, reduction in labor work, a better product and additional savings.

Smart technology in manufacturing is the need of the hour. Here the term smart technology does not indicate the advent of communication technologies but the smart manufacturing technology that is also advantageous for the supply chain. In this research two different technologies viz. spin-knit technologies and digital textile printing technology, which are located at distinct positions in the textile supply chain, are selected for case studies to analyze the impact of those new technologies on textile supply chain. A theoretical framework and model for analysis of new technologies is developed. Different factors for the analysis of new technology are identified and classified according to time dependent, country specific and technology specific factors. The evaluation of spin-knit technologies as per the theoretical model reveals that Corizon® technology can provide reduction of electric power cost by 54 %, spinning labor cost by 48 % and reduces cost of land, interest and depreciation. There are countrywide differences in the cost of cotton fibers. United States can be the most preferred location due to lowest cost of cotton as raw
material since it is cheaper by nearly 100% than the maximum cost. For the determination of capacity utilization and other specific needs of the batch process, Matlab SimEvents® based simulation models are prepared for process capacity utilization and supply chain simulation. It is found that the use of 120 spindle roving frame, which corresponds to the 120 feeders on combined spinning and knitting machine, instead of 192 spindles can provide 100% capacity utilization of knitting in the combined process. The difference in weight of roving bobbin and weight of cones also results in reduced capacity utilization at knitting stage in the combined process.

The advent of single pass digital textile printers has resulted in increased printing speed. The developments in printing head, increase of printing speed, development of printing ink and satisfactory image resolution with 125 to 600 DPI along with elimination of cumbersome operations and reduction in lot changeover time are the strength of this technology. From the supply chain point of view, the ability to economically process smaller batches coupled with drastic reduction in the process timeframe of eleven weeks to few hours for complete process from design idea to final shipment of printed fabrics, has resulted in the emergence of new supply chain models. The power cost is reduced by 64% with digital textile printing. Digital textile printing also offers 42% saving in requirement of floor space area for the plant and machines. It is possible to give up the low wage criteria and instead prefer skilled workforce as criteria and carry out reshoring of production with the new technology. The need of additional operations such fabric pretreatment is the major hurdle which affects the performance of this process. Matlab simulation model for capacity utilization and transportation can be used to determine the process requirements in different manufacturing scenarios.
Impact of New Technologies on Textile Supply Chain

by
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DEDICATION

To my wife Monica and our kids

for their wholehearted support and understanding,

my friends in United States

for their endless support and

our Parents and Teachers

who always inspired me to make a difference and achieve success
BIOGRAPHY

Sanjaykumar Anantrao Patil was born in India. He was born and brought up in a family of farmers in a small town in Maharashtra. He pursued his B. Tech. in Textile Technology from renowned college, Shri Guru Gobind Singhji Institute of Engineering and Technology, Nanded, India. Native form a cotton producing belt in Vidarbha province, he had great aspiration to work for textile industry. He had keen interest in the technology and exploring its ability to transform the lives of people whose livelihood depend on textiles. During his course of studies, he visited several textile industries. He started his career with a reputed textile mill in Mumbai in 1994. Later, in 1995, he joined VJTI, Mumbai for higher studies, Master of Textiles. He graduated from Mumbai University in 1996. He worked for the textile industry and taught in educational institutes for fourteen years. He had genuine interest in teaching and research. In his teaching career he has mentored his students, taught different subjects of textile technology to degree level students of B. Tech Textile. He taught at a textile degree college in Indore for seven years before joining at VJTI, Mumbai as Assistant Professor in Textile Technology in the year 2008. He had an ambition to pursue higher studies at world renowned educational institute. With this ambition, in the year 2015, he joined PhD at College of Textiles at North Carolina State University. After graduation, he plans to continue working for textile and allied industry and academics.
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CHAPTER 1: INTRODUCTION

Technological advancements are continuously changing the textile industry by introducing increased machine speeds, improvements in final product and new machinery features that aim at reducing manual work (TEXDATA INTERNATIONAL, 2016; Mayer & Cie. GmbH & Co., 2017; Schlafhorst, 2015). Different issues arising at different time periods have an impact on those advancements (Ashworth, 2017). Technologies such as ring spinning in yarn manufacture have retained a unique position in textile manufacturing despite several attractive alternatives in the form of new spinning systems (Hearle, 2013). The capital investment in textile manufacturing including yarn and fabric in the United States increased by 75% from $960 million in 2009 to $1.7 billion in 2015 (Land, 2017). The capital-intensive nature of the textile industry poses new challenges in making decisions regarding adoption of a particular technology. While the cost of adopting a failure-prone new technology can lead to great losses, the cost of not adopting a potentially game changer technology may lead to lack of competitiveness in the near future. It is well known that there is growing concern regarding the cost competitiveness of textile manufacturing. The cost competitiveness may not be governed by a single factor. It has always been essential to access the technological advancements from the viewpoint of not only the level of automation and reduced manual efforts in manufacturing, but also its economic impact, effect on the supply chain and end product.

An important aspect of new technology in textile manufacturing can be the ability to provide shortened lead time and small batch size. However, the different models in the area of research on textile supply chain are mainly concerned with production planning, process optimization, agent-based models for demand etc. (Leyton-Brown, Porter, Venkataraman, &
Hence it is essential to use a strategic model to evaluate the new technology in manufacturing as well as determine its impact on the supply chain. This research begins with identification of emerging technologies in textile manufacturing that can have its impact on the textile supply chain. The new emerging technologies selected for case study are Digital Textile Printing and Combination of spinning and knitting. The theoretical framework is prepared for analysis of new technology. Process simulation is carried out by using Matlab SimEvents® model to determine capacity utilization in the batch process and requirements of manufacturing and transportation.

The literature review is covered in Chapter 2 followed by the research methodology in Chapter 3. The theoretical framework for analysis of the new technologies is indicated in Chapter 4. The case study-I consists of process combination of spinning and knitting and covered in Chapter 5. The case study-II consists of Digital Textile Printing and indicated in Chapter 6. The conclusions, limitations and future scope are described in Chapter 7.
CHAPTER 2: LITERATURE REVIEW

The following is the short summary about the organization of this literature review. The technological innovations and their adoption in textile industry are reviewed and a few examples are flying shuttle, knitting machine, ring spinning and improvements in production speeds of modern spinning machines. The production speeds of some major technological innovations that have been adopted in textile manufacturing are summarized. This is followed by a consideration of complete processes and the trends in process integration, coupling and decoupling. Beginning with different types of manufacturing systems the review proceeds with research on supply chain models. It is followed by the review of recent articles on supply chain models incorporating simulation techniques and the goals they have achieved.

2.1 Transformation of the Textile Complex Supply Chain by Technological Advancements

2.1.1 Technological innovations in the machines in different textile manufacturing processes

It is important to consider the capabilities of supply chain that are vital for its efficient operations. The capabilities may be influenced by the level of technology in individual machines as well as the desired goals in manufacturing. If the technological advancements in textile manufacturing are reviewed, it will be found that they are influenced by the issues prevailing at that particular period of time (Ashworth, 2017). In the present review, it is intended to first consider the different machines in individual processes in textile manufacturing. William Lee’s invention of knitting machine (stocking frame) in 1589 and John Kay’s flying shuttle in 1733 have dominated textile fabric manufacturing and they are still not outdated (Hearle, 2013). The technological advancements may have opened up the further possibilities of faster processes and enabled a reduction in the time to manufacture while simulating the manual operations in the machines. The desire to achieve increased speed in ring spinning has resulted in increased spindle speed through
technological advancements in 20th century. The ring spinning maintained its competitive position even after challenges from new spinning systems with shorter routes (Hearle, 2013). It is ironical to note that the flying shuttle was gradually replaced by unconventional weft insertion systems whereas the drafting roller that replaced spinners fingers and thumb in 1758, still persist (Ashworth, 2017). While there are many examples of successful technological innovations these have been seldom viewed from aspect of their impact on the supply chain.

At the level of technological advancements in the 80’s and 90’s, the manufacturing systems had limitations of achievable production speed and the capabilities of material handling technologies. The textile machinery manufacturers are making efforts to increase the operating speeds of different machines at important stages in the manufacturing, as it is evident from ITMA data (Table 2.1). The major development to avoid bottlenecks in the process between spinning and weaving was high speed winding. The winding machine operating at very high speed is now linked with ring spinning machines (“Schlafhorst”, 2015). Developments in the mechanism of package formation have made it possible to achieve such higher speeds.

The one step or two step processes in the manufacture of polypropylene, polyester, recycled polyester and polyamide fibers in small volumes such as 5 tons per day to 300 tons per day also focus on shift in manufacturing concepts. The problems of economic production with smaller manufacturing volumes are being addressed at fiber production stage as it is evident from Oerlikon Neumag’s machines for self- crimping fibers, binding fibers, super microfibers and hollow fibers. One process step includes spinning and drawing with further enhancement in the process with the option of dyeing at the spinning stage. The two-step process is also suitable for bi-component fibers (TEXDATA INTERNATIONAL, 2016).
Table 2.1: Examples of production speed of textile production machines at different stages of production process (TEXDATA INTERNATIONAL, 2016; Mayer & Cie. GmbH & Co., 2017; Shima Seiki, 2017; Schlaflhorst, 2015).

<table>
<thead>
<tr>
<th>Sr. No.</th>
<th>Machine</th>
<th>Production speed linear m/min</th>
<th>For specific example using standard parameters</th>
<th>Manufacturing speed (kg/hr), at maximum efficiency</th>
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</thead>
<tbody>
<tr>
<td>1</td>
<td>Carding machine - Trützschler TC 15</td>
<td>500 m/min</td>
<td>0.13 Ne Sliver</td>
<td>135</td>
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<td>2</td>
<td>Rotor spinning-Saurer Schlafhorst Autocoro 9</td>
<td>300 m/min</td>
<td>40 s Ne Yarn 50 Head machines</td>
<td>13</td>
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<tr>
<td>3</td>
<td>Saurer Schlafhorst AUTOCONER 6 winding machine</td>
<td>2400 m/min 80 winding heads</td>
<td>40 s Ne Yarn</td>
<td>167</td>
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<tr>
<td>4</td>
<td>Air-jet spinning-Rieter J 26</td>
<td>500 m/min</td>
<td>40 s Ne Yarn 40 Spinning units per machine</td>
<td>18</td>
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<tr>
<td>5</td>
<td>Corizon® machine from Terrot</td>
<td>1.39 m/min</td>
<td>For 96 feeder machines, Yarn feed rate 200 m/min, 30°Ne, 120 grams per sq. meter fabric.</td>
<td>23</td>
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<tr>
<td>6</td>
<td>Mayer &amp; Cie Spinitystems® 3.0 E spinning &amp; knitting</td>
<td>1.16 m/min</td>
<td>For 96 feeder machines, 120 grams per sq. meter fabric, 30°Ne, 35 RPM, 30 inches diameter, 2.4 m width.</td>
<td>20</td>
</tr>
<tr>
<td>7</td>
<td>Digital Printing machine SPG Prints Pike</td>
<td>75 m/min</td>
<td>130 grams per sq. meter fabric, 1.2 m width</td>
<td>702</td>
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</table>

In another example, the process shortening is demonstrated by the integration of carding and drawframe in Rieter’s C70 carding machine combined with RSB drawing module (Figure 2.1). This type of system can reduce the processing time.
Here it is evident that efforts are being made to increase manufacturing speeds at final stages in fabric manufacture whereas the fiber manufacturing is heading towards customization. It is also well known that the fiber manufacturing capacities are not flexible to switch from one fiber to the other in case of all types of fibers.

![Figure 2.1: Manufacturing process shortening by combination of carding and drawing in rotor spinning process indicating VARIOline, C70 Card with RSB module and R 60 Rotor spinning. (“Rieter”, 2017).](image)

Thus, if the consumption pattern changes or the technological innovations bring some new process with unique requirements there is no quick fix to the problems of supply chain. The combination of knitting and spinning in Corizon® by Terrot and Spinitsystems® by Mayer & Cie have demonstrated the possibilities of process integration. However, the difficulties such as the need of different form of input material (i.e. roving bobbins) might become an obstacle in the absence of most appropriate supply chain model. It is needed to have a model that can explain the impact of such technologies on the supply chain and provide a mapping of new supply chain.

### 2.1.2 Trends in process innovations in textile manufacturing and supply chain

Now considering the complete individual processes in textile manufacturing comprising of several manufacturing machines. Here the concept of process integration and disintegration comes into focus. It is well known that textile manufacturing process is traditionally a batch process that lacks continuous flow from fiber to finished product. The batch process has typical sequence of spinning, weaving and knitting operations. As per reviewed literature, process integration is increasingly applied in order to achieve benefits such as optimized process, which incorporates easier workflow, reduced raw materials consumption and increased process efficiency (Gloy, Schwarz & Gries, 2016).
But the adoption of process integration or disintegration does not only occur on the basis of factors as mentioned above. Business process has different considerations as compared to the manufacturing process. The example of Sara Lee demonstrates different purpose for disintegration of the business process. In 1998, Sara Lee opted for de-verticalization by selling nine of its twelve textile manufacturing facilities. The company offered contracts of manufacturing yarn and fabric to the buyers of its manufacturing facilities and identified them as suppliers to Sara Lee. This ambitious step released the capital of the company, which was later used for expanding the business. This ensured departure from the capital intensive and low profit margin manufacturing while increasing the availability of capital for the retailing. At the time when vertical integration was considered beneficial due to its ability to protect the confidentiality of innovations, in reality the economic factors were in favor of de-verticalization for this particular textile manufacturing operation (McCurry, 1998). Contrary to this concept, the model adopted by Marks and Spencer provided opportunities to utilize responsive technology driven production techniques to its supplier network. Thus, the vertical networking of suppliers enabled the modernization. This helped in the survival of UK textile manufacturer in the international competition (McCurry, 1998; Toms & Zhang, 2016).

In order to achieve a competitive business goal, it is important to consider the transformations in manufacturing operations and follow the recent trends (Singletary & Winchester, 1996). The application of digitization and smart technologies can change the way textiles are being manufactured. The approach to time compression in textile complex supply chain was based on methods to reduce the lead time, improvements in throughput speed and improvements in material and information flow. Figure 2.2 demonstrates the shortcomings in
achieving minimum time from order generation to delivery of material in different processes (Forza & Vinelli, 2000).

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<td>PRODUCTION OF TEXTILES FOR CLOTHING SAMPLES</td>
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<td>DEFINITION AND PRODUCTION OF CLOTHING SAMPLES</td>
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<td>“IN THE DARK” TEXTILE ORDERING</td>
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<td>RETURN OF EXTERNAL PRODUCTION</td>
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<td>SALES TO THE FINAL CUSTOMER OF PREVIOUS SPRING/SUMMER GOODS</td>
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Figure 2.2: Production stage chart of textile supply chain for spring/summer season (Forza & Vinelli, 2000).

Figure 2.3: Textile Process from receipt of order to consumer (Gloy et al., 2016).

While investigating the scope of process shortening and smart integration of business and manufacturing process as indicated in Figure 2.3 (Gloy et al., 2016), the major considerations and differences in textile processes are ignored. It is evident that only business process and material
and information flow is considered without proper representation of material flow and different possibilities in the flow due to innovations in manufacturing technology. Also, the literature fails to correctly represent the differences in process of spinning and weaving. It would be beneficial to further expand the scope of this integration to achieve the level at which the amount of production can be continuously tuned as per the need. At present, no such effort is found in the studies of advanced manufacturing technologies. Although there are examples of textile process integration and improved communication through cyber-physical systems, they are still an integral part of some process that has already evolved or needs a different approach to evolve. In ITMA 2016, Oerlikon presented modular plant operation center with digital control of all stages in the yarn manufacturing processes. The aim is to improve the process efficiency and transparency through the networking. The networking is achieved through implementation of cloud-based systems in addition to ERP systems. Marzoli’s remote maintenance solution for textile machines enabled continuous information from smart components integrated in the manufacturing machinery. Online data and information can be used for improvements in process efficiency and carrying out predictive maintenance of machines (TEXDATA INTERNATIONAL, 2016). Since the textile industry is capital intensive, it needs a careful approach in selection of technologies as well as the development of technologies for the benefit of supply chain as well as the end customer. In order to successfully exploit the advantages of the technological advancements explained above it is essential to have some criteria to justify the adoption of those technologies. However, there are no major guidelines regarding the adoption of technology and there is a need to investigate how these are influencing the supply chain.
2.2 Relevant research on supply chain models

Supply chain management is expected to be responsive with the capabilities to compress the time in its various components. Research on supply chain models deals with the aspects such as process management, production planning and control, demand uncertainty, agent-based modeling for various purpose etc.

2.2.1 Agent based model of supply chain

A swarm is defined as a set of agents acting in their local environment and communicating in different ways. The set of agents form a collective intelligence system (Jacob, Hushlak, Boyd, Nuytten & Sayles, 2007). The agent-based modeling is based on defining these agents for supply chain models.

The marketplace is a system that does not end in chaotic turbulence. Although the system lacks stability, the action of agents such as consumers, firms etc. create system equilibrium (Brannon, Ulrich, Anderson, Presley, Thommersen & Missam, 2000). It is also important to explain what influences the action of each of the element in the supply chain. The system acts like a complex, spontaneous, adaptive, dynamic, self-organizing system (Brannon et al., 2000).

However, the research of Brannon et al. (2000) was only concerned with individual preferences and purchase decision for apparel and subsequent responsiveness of the particular supply chain. Also, the research does not take into account the influence of technological advancements and changes in capabilities of supply chain. Consumer’s individual preferences and purchase decisions as well as the responsiveness of supply chain are not solely the human factors. The prevailing and emerging technology may have a role in determining the future demand. Different agent-based supply chain models in apparel industry are reviewed in Table 2.2. The
research is mainly concerned with inventory, optimization, information sharing and multi-agent nature of supply chains.

Table 2.2: Agent based supply chain models in apparel supply chain.

<table>
<thead>
<tr>
<th>Author</th>
<th>Topic</th>
<th>Major Findings</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pan et al., 2009.</td>
<td>Optimal reorder decision-making in the agent-based apparel supply chain</td>
<td>Minimizing inventory cost is possible through optimization of vital decisions regarding reorder point and optimum quantity. Genetic algorithm (GA) and optimum quantity fuzzy inference theory can be applied for this purpose.</td>
</tr>
<tr>
<td>Mok et al., 2013.</td>
<td>Intelligent production planning for complex garment manufacturing</td>
<td>Genetic algorithm (GA) can be applied for production planning. The proposed algorithm is verified against real production data.</td>
</tr>
<tr>
<td>Leyton-Brown et al., 2001.</td>
<td>Smoothing out focused demand for network resources</td>
<td>In case of network of agents getting concentrated and inefficient network utilization, demand can be smoothed out using incentives. Thus, improving the sharing of network resources.</td>
</tr>
<tr>
<td>Gupta, A., Whitman, L. &amp; Agarwal, R., 2001.</td>
<td>Supply Chain Agent Decision Aid System. (SCADAS)</td>
<td>Web based SCADAS system is proposed and it enables the highly desirable information sharing to support decision making by mobile agents in the supply chain. Thus, improving the flexibility and at the same time maintaining the conservative information sharing.</td>
</tr>
<tr>
<td>Uppin &amp; Hebbal., 2010.</td>
<td>Multi Agent System Model of Supply Chain for Information Sharing</td>
<td>Multi-agent model of supply chain is proposed with improved functioning through integration of agents. Thus, promoting information sharing for the benefit of all agents.</td>
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</tbody>
</table>

2.2.2 Monolithic and decomposition-based supply chain model

Research on different aspects of the possible bullwhip effect in the manufacturing proposed to investigate on monolithic and decomposability models of supply chain. Lower level of bullwhip effects found in decomposability-based model as compared to monolithic models (Figure 2.4 and Figure 2.5). This may be attributed to the flawed assumption of decomposability (Chatfield, 2013). In the original work on bullwhip effect, Forrester J.W. proposed the beer distribution game and a simulation model for the inventory and production changes according to the patterns of consumer
purchase to understand the behavior of the system as a whole. A group of men around a table represented retailers, postal services, transportation and factory. Considering unit time to represent larger time durations and using a set of rules the time intervals for purchase orders and delivery can be estimated (Forrester, 1958). However, the concept of bullwhip effect may not be valid at all for textile complex supply chain as the assumptions made by Forrester have been drastically changed in the period of time. Communication is improved, and the demand supply status is more visible with orders trying to keep up with uncertain and rapid changes in fashion.

![Diagram of Monolithic supply chain model](image)

**Figure 2.4:** Monolithic supply chain model (Chatfield, 2013).

![Diagram of Decomposition based supply chain model](image)

**Figure 2.5:** Decomposition based supply chain model (Chatfield, 2013).

The supply chain can be two-stage or multistage. In a two stage, there is direct interaction of customer and retailer. However, multistage supply chain can be assumed either continuous or decomposition based. In a decomposition-based model the several stages appear to be firewalled. There is no free flow of information across the entire supply chain as it is assumed to be composed of node pairs. The node pairs are more manageable subsets of the whole supply chain. At each node, there is break in continuity. Contrary to this, a monolithic model represents a single,
continuous and multistage supply chain. The monolithic supply chain model is more appropriate representation of a supply chain as the supply chain is continuous straight process rather than decoupled processes (Chatfield, 2013).

2.2.3 Mathematical modeling tools for textile complex supply chain

The mathematical modeling has been adopted for applications involving optimization of inventory, co-ordination, dynamic pricing, production capacity allocation, financing decision, business model with e commerce, analysis of product complexity considering the disruption cost in fast fashion supply chain (Choi, Yue, Chiu & Chow, 2014).

2.2.4 Models for demand and supply variations in the supply chain

The supply chain needs to aim for reduction of inventory and at the same time handling uncertainties in demand. There can be numerous reasons for the uncertainties. But the demand always impacts the future prospects of organizations. The factors such as the lead-time, delivery time and forecasting accuracy are crucial for a supply chain. Lack of synchronization between demand and supply results in widening the demand supply gap as the product position in supply chain is farther from the end user. Thus, it is an amplification of demand that negatively impacts the profitability (Wangphanich, Kara & Kayis, 2010). But there can be other factors that are responsible for the growing mismatch of demand and supply in the supply chain. The factors such as manufacturing capacities and minimum order quantities can also be falsely interpreted as bullwhip effect. This is more prominent in textile operations that consist of large rigid manufacturing process with very low level of flexibility once it is set up for particular type of products. For example, a spinning mill producing polyester yarn cannot easily switch from manmade to cotton and vice versa. Thus, there are limits on flexibility. Also, even if the demand
pattern is known, it is difficult and uneconomical to tune the manufacturing operations in the absence of a future plan.

The decoupling point and demand supply gap in the supply chain is also studied by considering the decoupling points in the supply chain. Also, it is claimed that the decoupling point decides the form of inventory and the demand that is visible only at the end of supply chain as indicated in Figure 2.6 (Christopher, 2000). The research considers the aspect of uncertainty in the supply chain and concludes that the uncertainty is impacted mainly by demand and supply (Dash & Nalam, 2012). But it still remains unknown as to how the demand and supply uncertainties originate and expand over the period of time. Also, there is no pattern identified that may lead to quantification of lead-time. The technological impact on decoupling is going to be different for different industries.

![Diagram of supply chain](image)

Figure 2.6: Decoupling point and position of held inventory in the supply chain (Christopher, 2000).

In another approach to achieve the demand-based manufacturing a model is proposed that represents fiber, textile, apparel and retail supply chain as liquid pipeline system.
Figure 2.7: Liquid pipeline model of supply chain (Ostic, 1997).

The representation as shown in Figure 2.7 was achieved for pipeline analysis through simulation and analysis of the integrated supply chain. The flow of material was assumed to be similar to the flow of liquid. The analysis of the supply chain for the warm-up jackets was carried out using the pipeline approach (Ostic, 1997). However, the model lacks the manufacturing process and equipment details. Also, the proposed model for co-operation among the different members of supply chain never happened in reality. The progress in information technology and simulation software may enable to achieve the same goals with reduced effort.

The GT (Group Technology) methodology has been previously used to obtain a planning algorithm. The algorithm aimed at developing a production plan to obtain maximum efficiency and minimum inventory in apparel manufacturing. The approach in GT was to combine the design of different products or combining products involving similar processes and achieve reduced level of inventory. The genetic algorithm evolves to achieve the best solution to complex problems. The objective of achieving operator efficiency and timely job completion can be realized with genetic algorithm (Mok et al., 2013).

2.3 Application of software in process simulation and textile supply chain research

Textile supply chain comprises flow of information with product and other related manufacturing aspects such as services and money. As it can be seen in Figure 2.8, ANN is most
widely applied in textile supply chain research. In order to analyze the impact of supply chain dynamics, computer software have been widely used (Ngai, Peng, Alexander & Moon, 2014). Even though the earlier research is aimed at improvements at the supply chain, their main objective remains the demand forecasting as evident from the survey of different techniques applied for textile supply chain research (Figure 2.8).

![Applications of different systems in textile supply chain research](image)

Figure 2.8: Applications of different systems in textile supply chain research (Ngai et al., 2014).

A classification of several aspects into sectors and subsectors as per the business practices and manufacturing activities results in sixteen sub categories. The three sub categories are defined as operational processes between stages of fiber, yarn, fabric and finishing (Figure 2.9). Efforts have also been made to minimize the manufacturers lead time by applying the machine learning techniques for demand forecasting. However, the demand forecasting by application of machine learning techniques is intended at forecasting the distorted demand signals in supply chain (Carbonneau, Laframboise & Vahidov, 2008).
In one of the studies, the simulation of different customized processes for outerwear factory, is carried out. The restructuring of garment manufacturing due to outsourcing of operations to low cost destinations has been identified as the need of the time. This has resulted in new requirements (Figure 2.10). The simulation carried out in this case outlines the targets for important parameters such as lead time, service level etc. in the manufacturing logistics (Zülch, Korucab & Börkircherc, 2011). However, the research takes into account only the existing
technologies and its usefulness is limited to reorganization of existing workplaces. In another research ‘Arena’ simulation software is used to simulate the operations in a yarn dyeing factory (Figure 2.11).

Figure 2.10: Time to market in case of outerwear factory (Zülch et al., 2011).

Figure 2.11: Simulation of workflow in the factory using ‘Arena’ simulation (Brahmadeep & Thomassey, 2014).

The model identifies the links between factors such as decision logic, material movement and variable operator speed, hours and efficiency. The multilevel model also takes into account production floor, machine level and section levels. Yet its applicability to the process flow in case of other operations cannot be assured as it applies to the complex process of yarn rewinding unit of a yarn dyeing factory. The simulation model adopted in this case consider the operative and material movements, it does not consider the manufacturing process flow. Also, the
simulation model logic for workflow is limited as it refers to the particular manufacturing plant (Brahmadeep & Thomassey, 2014).
CHAPTER 3: RESEARCH OBJECTIVES AND METHODOLOGY

3.1 Initial Research Goals

The initial research goals before the start of actual work were the same as the final research objectives. After the review of existing work in different areas and carefully analyzing the various parameters which could need inclusion to satisfy the project’s goals, the fine tuning of objectives was carried out. The methodology was also correspondingly refined by consultation with committee members from time to time. Initially it was considered to explore the different emerging technologies and arrive at final selection of technologies for the case study. Hence an extensive survey was carried out of the work in the area of manufacturing technologies and supply chain models. The drawbacks as well as limitations of the work covered under the surveyed were considered before selecting the technologies for case study. It was initially intended to explore the applications of swarm theory in order to determine its applicability to the present study. However, the most common applications of the swarm algorithm are mainly in the area of consumer demand forecasting. In the era of machine learning and artificial intelligence the accuracy in projected consumer demand may not be satisfactorily established by utilizing a single measure. The theoretical model was planned to consider the enhancements in capabilities of speed, agility, accuracy and efficiency in the supply chain which could be brought about by the introduction of the new technology.

3.2 Preliminary Trials and Selecting the Simulation Software

The preliminary trials for research were aimed at identifying the needs of manufacturing systems and deciding the parameters which should be included in the model. The simulation software which would be utilized needed to be identified as suitable for the manufacturing process and capable of demonstrating the possible integration with supply chain to achieve a real process
simulation. In order to analyze the material flow in the process in the case of spin-knit technologies and workflow in the case of digital printing, different software packages were reviewed.

A lot of the commercially available software for process simulation suitable for various applications have been well reviewed (Capterra, 2017). This review was useful in making a decision about which software to utilize. Based on the review of simulation software commercially available, it was decided to explore the Simio® and Matlab software. The various functionalities of those software and the simulation capabilities were compared from the perspective of the research needs. Both of the software has discrete event simulation capabilities and graphic features.

### 3.3 Simio® for Process Simulation.

Initially the simulation was carried out using Simio® simulation software. The simulation experiments carried out regarding the process under consideration. Simio® has good capabilities in carrying out 3D simulation of process as well as optimization of resources (Simio, 2017). The software is also easy to learn as it has simplified user interface. However, the object-oriented approach of Simio® is more suitable for optimization problems in manufacturing that involves physical objects and their movements such as material transport conveyors, forklifts, manufacturing equipment and various other objects. Any of the objects can be defined as entity for the simulation purpose. Thus, the simulation would be useful if there is only optimization or visualization problem. The simulation is limited in capabilities to quickly introduce new mathematical tools and formulas.

After preliminary trials with Simio® software, using standard entities, as shown in Figure 3.1, it appeared that this software could offer more potential if it were possible to correctly define “material” as “entity” with its own set of parameters and demonstrate the changing materials states.
In textile, the different processes also have parameters such as speed, waste generation, energy consumption, etc., as well as the changing state of material being processed.

3.4 MATLAB for Process Simulation

3.4.1 Possibilities of MATLAB in offsetting limitations of Simio®

MATLAB has Simulink® and SimEvents® modules for process simulation. It is also possible to carry out integration of process data as well as data analysis (MathWorks, 2017). The flexibility in adding mathematical functions to the simulation and defining the attributes of entities can be useful to extend the scope of simulation model. The SimEvents® module is capable of carrying out multi domain model simulation. In order to associate data attributes to the entities it enables customization. The entity generation can also be a discrete event based on the actual needs of the system. It has servers, generators, splitters and various output blocks. The blocks are predefined. Also, the statistical capabilities in calculation and simulation of parameters such as throughput speeds and process capacity utilization can be useful (MathWorks, 2017). Thus, with
the review of present applications of MATLAB and consultation with expert Dr. Michael Kay, it was finalized to use MATLAB for process simulation (Kay, personal communication, 2017).

3.4.2 Identification of Process Parameters and Process Constraints for Simulation

In order to study the impact of changes in technology on supply chain for spin-knit and digital printing, identified important considerations are:

- Individual machines in the manufacturing process, their speed and time to manufacture.
- Material flow in the process.
- Choice of different processing sequence for different applications.
- Waste generation at different stages.
- Major factors impacting cost of manufacturing such as power cost.

3.5 Determination of Research Objectives and Methodology

The research goal of this project is to select new technologies in textile manufacturing and investigate the selected new technologies in textile manufacturing using case study approach. The case study is proposed to be designed to determine the impact of new technologies on textile supply chain. Manufacturing technology can leave its footprints on the supply chain as it might affect the decision making at several stages of supply chain. The selected new technologies are intended to be reviewed for their inherent capabilities that might have positive or negative impact on the supply chain. Here, the research begins with reviewing the approach used in earlier research on different models in the area of technology substitution and technology adoption. From the review of earlier research and considering its drawbacks, it is proposed to adopt a modified and more relevant approach to investigate the technologies and develop the direction in order to achieve the supply
chain and technology model that can be of practical significance. The overall research goal is intended to be achieved through three research objectives and corresponding methodology.

3.6 First Research Objective and Methodology

The first objective of this research is to develop a theoretical framework to predict the impact of introducing a new technology in textile manufacturing and its potential influence on a smart supply chain. Here, the term ‘smart supply chain’ refers to smartness in terms of advancements in manufacturing technology itself and not in terms of merely the advancements in communication technology that supports the supply chain. It was planned that the proposed theoretical framework also takes into account the decoupling points in textile manufacturing process. The objective is to create a guideline for analysis of selected technologies that will also be useful to achieve the final decision model. Here, the specific usefulness also includes its cost competitiveness in addition to the other relevant criteria identified for the selection of technologies.

The methodology opted for the first research objective consists of selecting technologies for case study. After the review of new technologies, earlier literature review, review of available information about new innovations that are yet to be introduced and deliberations with committee members regarding the emerging technologies in textile manufacturing, the following new technologies are planned to be considered for case study.

i) Combination of Spinning and Knitting.


After the new technologies are selected, the next stage consists of identifying the parameters that may be vital for selection of the particular technology in manufacturing. This is followed by identifying the sources of data and collection of data about the new technologies as well as important process inputs for the new technology.
The collection of data and analysis planned to begin with data from different sources, on raw material availability and price fluctuations. Recent data is proposed to be obtained about the cost of cotton fibers at international level and the reported factors behind the short-term and long-term price fluctuations to be noted. This is followed by identifying the top five import destinations for US apparel import.

For the manufacturing process under consideration, it was planned to identify the type of data and sources of data for each case study. The type of data includes data on the elements of manufacturing cost, process parameters in the manufacturing of yarn, knitted fabrics and digitally printed fabrics. The collected data can be utilized, in association with the new model, to carry out a detailed comparison of new technology with the existing technology. The data needs to be most recent and applicable for the detail analysis of how the performance of alternative technologies under consideration would be affecting the supply chain.

### 3.7 Second Research Objective and Methodology

The second research objective is to utilize the theoretical framework to develop a new decision model to study the impact of new technology on textile supply chain using the case study approach for selected technologies. The model is to be developed by adopting criteria as elaborated in the theoretical framework. The developed model should establish the basis for recommendation of particular technology in the manufacturing and conclude whether there can be common criteria for technological advancements.

The derived criteria should aim to identify the goals for manufacturing technology and suggest ways to achieve the desired goals. However, the desired goal can be varying for different technologies. The model should be useful to investigate the impact of process speed, process time, energy consumption, elements of manufacturing cost and position of decoupling points in the
supply chain on the overall performance of the particular technology. The decision model should further strengthen the ability to identify the relative significance of the different elements of cost with reference to the new technology. Data obtained for the technologies, calculations as well as simulation models are planned to be used as tools to explore the new technologies. The model is intended to be designed so that it is further useful for different work environments by making small changes to its parameters and constraints.

3.8 Third Research Objective and Methodology

Utilizing the outcome of first and second research objective it is planned to summarize the detailed analysis of the impact of new technologies and outline the direction in the development of new technologies. It is planned to identify the pros and cons of what has been achieved for the benefit of supply chain by introducing the new technologies in textile manufacturing. The detailed analysis on the impact of new technologies is also planned to be inclusive of the final criteria for selection of the technology in manufacturing.
CHAPTER 4: THEORETICAL FRAMEWORK AND MODEL

Before developing the theoretical framework, different models regarding technology substitution and technology adoption are reviewed. The analysis of their applicability to present situation is carried out by using latest data. Subsequently the different parameters that can have potential impact on supply chain and the cost effectiveness of technology in textile manufacturing are identified by referring to relevant literature as well as obtaining relevant data from different sources.

4.1 Technology substitution model

Fisher and Pry originally developed a model of technology substitution. A mathematical model was established which fitted past data on US consumption of natural vs. synthetic fibers, synthetic rubber vs. natural rubber, plastic vs. natural rubber and detergent vs. natural soap etc. Economic forces and their complex interplay responds to the superiority of new methods and in turn affects the rate of progression of a new substitution (Fisher & Pry, 1971). The model was tested using the past data about different products and at that point in history when the model was introduced, it was found to be valid. The model was intended to be useful for the forecasting of technological opportunities. It was also claimed that the model was useful for recognizing the onset of technologically based catastrophes and investigating the similarities, as well as differences, in innovative change in various economic sectors. Technologically based catastrophes can be the environmental hazards from generated waste and obsolete technology. The model was also claimed to be suitable for investigating the limiting features to technological change and investigating the rate of technical change in different countries and different cultures. The three assumptions of the model as stated by the authors are “(1) Many technological advances can be considered as competitive substitutions of one method of satisfying a need for another. (2) If a
substitution has progressed as far as a few percent, it will proceed to completion. (3) The fractional rate of fractional substitution of new for old is proportional to the remaining amount of the old left to be substituted” (Fisher & Pry, 1971). In another work carried out by Jeong, Park & Yoon (2016), on forecasting technology substitution from incumbent technology and emerging technology, a mathematical model related to hazard rates from reliability engineering was used for forecasting timing of technology substitution. A tool for estimate of timings to develop a new technology was established (Jeong et al., 2016).

The model projection for consumption of natural vs. manmade fibers is presented in Figure 4.1. However recent data on the application explored by Fisher & Pry, leads to the conclusion that the substitution foreseen by the model did not actually take place. Cotton fiber is still being used and the manmade fibers have passed through an entirely different trend of demand. The recent data on consumption of natural and synthetic fibers is presented in Table 4.1.

![Figure 4.1: US Fiber consumption vs. years: Model projection and actual consumption (Fisher & Pry, 1971).](image)

The model fits to the data up to 1971. The model predicted half substitution of natural fibers by synthetics in the year 1969 and takeover with 90% substitution in the year 1998.
However, as per the actual data on US fiber demand (mill use) for the year 2004 was 23.2 % natural fibers and 75.9 % synthetics.

Table 4.1: US mill consumption of cotton, synthetic and other natural fibers.

<table>
<thead>
<tr>
<th>Year</th>
<th>Fiber</th>
<th>(\text{US mill use (Million pounds)})</th>
<th>(\text{Percentage of fibers (%)})</th>
<th>(\text{US mill use (Million pounds)})</th>
<th>(\text{Percentage of fibers (%)})</th>
<th>(\text{US mill use (Million pounds)})</th>
<th>(\text{Percentage of fibers (%)})</th>
</tr>
</thead>
<tbody>
<tr>
<td>2004</td>
<td>3130.8</td>
<td>23.2</td>
<td>10,256.9</td>
<td>75.9</td>
<td>120.7</td>
<td>0.9</td>
<td></td>
</tr>
<tr>
<td>2005</td>
<td>3035.3</td>
<td>22.7</td>
<td>10,196.6</td>
<td>76.3</td>
<td>126.3</td>
<td>0.9</td>
<td></td>
</tr>
<tr>
<td>2006</td>
<td>2,619.4</td>
<td>21.7</td>
<td>9443.2</td>
<td>77.6</td>
<td>111.4</td>
<td>0.9</td>
<td></td>
</tr>
<tr>
<td>2007</td>
<td>2,315.3</td>
<td>20.1</td>
<td>9049.2</td>
<td>78.8</td>
<td>112.4</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>2008</td>
<td>2,067.4</td>
<td>20.4</td>
<td>7935.6</td>
<td>78.6</td>
<td>97</td>
<td>0.9</td>
<td></td>
</tr>
<tr>
<td>2009</td>
<td>1,579.6</td>
<td>18.9</td>
<td>6617.8</td>
<td>79.8</td>
<td>94.5</td>
<td>1.1</td>
<td></td>
</tr>
<tr>
<td>2010</td>
<td>1,829.2</td>
<td>19.4</td>
<td>7433.5</td>
<td>79.7</td>
<td>66.8</td>
<td>0.7</td>
<td></td>
</tr>
<tr>
<td>2011</td>
<td>1,713.0</td>
<td>19.1</td>
<td>7120.0</td>
<td>80.1</td>
<td>60.1</td>
<td>0.7</td>
<td></td>
</tr>
<tr>
<td>2012</td>
<td>1,612.0</td>
<td>17.2</td>
<td>7567.8</td>
<td>82.0</td>
<td>50.3</td>
<td>0.6</td>
<td></td>
</tr>
<tr>
<td>2013</td>
<td>1,715.0</td>
<td>17.6</td>
<td>7819.3</td>
<td>81.6</td>
<td>50.7</td>
<td>0.6</td>
<td></td>
</tr>
<tr>
<td>2014</td>
<td>1693.5</td>
<td>17.0</td>
<td>8010.6</td>
<td>82.2</td>
<td>45.6</td>
<td>0.5</td>
<td></td>
</tr>
<tr>
<td>2015</td>
<td>1,713.1</td>
<td>16.7</td>
<td>8489.8</td>
<td>82.8</td>
<td>38</td>
<td>0.5</td>
<td></td>
</tr>
<tr>
<td>2016</td>
<td>1,261.4</td>
<td>16.4</td>
<td>6396.2</td>
<td>83.1</td>
<td>38.5</td>
<td>0.5</td>
<td></td>
</tr>
</tbody>
</table>

Table 4.2: Data of US Mill Use of Cotton
(Cotton and Wool Yearbook Dataset-89004, 2017).

<table>
<thead>
<tr>
<th>Year</th>
<th>US Mill consumption of Cotton (Million pounds)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1965</td>
<td>4606</td>
</tr>
<tr>
<td>1970</td>
<td>3937</td>
</tr>
<tr>
<td>1975</td>
<td>3480</td>
</tr>
<tr>
<td>1980</td>
<td>2827</td>
</tr>
<tr>
<td>1985</td>
<td>3078</td>
</tr>
<tr>
<td>1990</td>
<td>4155</td>
</tr>
<tr>
<td>1995</td>
<td>5110</td>
</tr>
<tr>
<td>2000</td>
<td>4253</td>
</tr>
</tbody>
</table>
Table 4.2 indicates the historical data for US mill use of cotton fibers from 1965 to 2000. (Cotton and Wool Yearbook, Dataset 89004, 2017). Even if the mill use of cotton fibers is diminishing there can be several reasons that governs this logic and probably not anticipated by Fisher and Pry while they carried out this analysis. Also, from the data it is apparent that, synthetics have not replaced cotton in manufacturing. If we consider the new technologies chosen for case study, it is evident that in case of Corizon® technology, cotton fibers and synthetic filament are both used together to form air jet core spun yarn.

4.2 GDP (Gross domestic product) and per capita fiber consumption growth

Other data, presented by Rieter holding investor relations (Rieter, 2017), establishes the direct link of per capita fiber consumption and GDP growth as evident from Figure 4.2. It shows that the per capita fiber consumption increases with increase in GDP of the specific country. Hence the fiber consumption pattern can also be a country specific parameter.

![GDP and fiber consumption growth](image)

Figure 4.2: Per capita fiber consumption and growth in GDP per capita in India and China (Rieter, 2017).
4.3 Technology Diffusion Model

A model developed by Frank M. Bass relates to the growth of eleven consumer durable products and became popular as the ‘Bass Model’. The widely applied model is basically concerned with diffusion of new technology and new products (Bass, 2004). The ‘Bass Model’ assumes that the probability of purchase at any time and the number of previous buyers have linear relationship. The model is claimed to be capable of long term forecasting of timing and volume of new sales. According to Bass F., “Most substitution models are market share models; indeed, a principal distinction between substitution and diffusion models is that models of technological substitution assume there is a market there to be substituted, and, many times, the size of that market is known, whereas diffusion models make no such assumptions, in general” (Bass, 2004).

The related work on diffusion theory is summarized in Table 4.3.

Table 4.3: Technology diffusion and applications of different models.

<table>
<thead>
<tr>
<th>No.</th>
<th>Major outcomes of the research</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>A model that offers prediction of peak sales volume as well as timings. The model is empirically tested for sales of consumer durable products.</td>
<td>Bass, 2004</td>
</tr>
<tr>
<td>2.</td>
<td>A model for both diffusion and substitution of technology is developed and tested for past data and provides future projections for sales. The model for demand growth and decline for technological innovations is found applicable for the technologies under consideration.</td>
<td>Norton &amp; Bass, 1987</td>
</tr>
</tbody>
</table>

In the Bass model drawn in Figure 4.3, the advertising affects the rate of adoption as initial adopters gain information from advertising. Further the mouth advertising increases and effectiveness of formal advertising drops (Sterman, 2001). However, the diffusion model does not take into account the events such as emergence of new technologies and their impact on the adoption rate of existing technologies. Also, it may not be able to reflect the impact of other factors such as economic conditions and unpredictable events that change the level of demand. Thus, the
model becomes an instrument that only evaluates the impact of advertising in static conditions and applicable solely to the consumer durable products.

Figure 4.3: Bass Diffusion Model (Sterman, 2001).

Thus, even if this diffusion theory and the model forms a basis of many research projects, it may not be reflecting the real scenario.

4.4 Selected technologies for case study and anticipated challenges for the new technologies

The manufacturing technologies selected for the case study are indicated in Table 4.4.

Table 4.4: Selection of manufacturing technology for case study.

<table>
<thead>
<tr>
<th>Manufacturing Technology</th>
<th>Year of first introduction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Digital Printing</td>
<td>1970</td>
</tr>
<tr>
<td>Combination of spinning and knitting</td>
<td>2011</td>
</tr>
</tbody>
</table>

These technologies are at different stages of manufacturing in the supply chain. They are also widely differing in timings of introduction and widespread commercial use as digital printing exist for nearly twenty-six years while the technology combining knitting and spinning exist only for six years and without any major largescale manufacturing units being set up at present. The
spin-knit technology is in its early stages of introduction. It is well known that the traditional processes in textile manufacturing are difficult to be entirely substituted.

One analyst report on ‘The Future of Digital Textile Printing to 2021’ states that the total production volume of digital printing in 2016 was 870 million square meters and $1.29 billion value. The projected growth was attributed to technical innovations and increasing demand (Smithers Pira, 2016).

Another important aspect evident in those technologies is the use of process combinations and process elimination. This may result in a need of the decoupling of already existing textile processes. In this scenario, it becomes important to determine what should be the location of the modified or combined processes in order to achieve maximum benefit for the supply chain such as profitability and smooth flow of material in the manufacturing and supply chain. Another concern with these new technologies might be the in-process material flow. The storage and transportation of material between different manufacturing facilities of the decoupled processes can be another challenge.

4.5 Theoretical framework for analysis of new technologies

4.5.1 Changing needs of the textile manufacturing with new technologies and supply chain

The different models as mentioned earlier have inherent drawbacks and underlying assumptions that may not be valid for current needs of the manufacturing industry and supply chain. With the introduction of new technology, the importance of several aspects, such as process speed, requirements of raw material and final product from quality point of view and needs of process automation may change.

The Textile supply chain is usually comprised of several entities such as spinners, weavers, knitters, which are traditionally separate in existence. They are traditionally manufacturing bulk
volumes of products such as yarn and fabrics. In textile industry, the importance of minimization of lead time in manufacturing is evident from the production stage chart for a particular season (Forza & Vinelli, 2000).

In the case of natural fibers, changes in the countrywide fiber yield, can result in changes in raw material availability and cost. Thus, the raw material is first consideration in the model. An analysis of what is needed as input for the particular technology is to be carried out. In case of spin-knit technologies, the analysis of data on cotton fiber cost and its variabilities is to be conducted. In case of digital printing the special needs of the manufacturing system regarding the technical specifications of the fabric needs to be determined.

This aspect in combination with the rising cost of production due to possible increase in the elements of production cost, further complicates the task of price reduction with the existing technologies. The continuous migration of the industry to low cost destinations is the commonly known evidence that confirms this aspect. However, it can be argued that at this stage it is necessary to reconsider the relative importance of those elements in order to have a realistic vision for the technology. The data on new manufacturing technology regarding the elements of manufacturing cost, raw material availability and cost can reveal greater insight into the future prospects of those technologies. Hence the theoretical framework is an important stage in the development of new model.

4.5.2 Defining inputs for manufacturing process and the new model

The inputs for manufacturing process are machines and materials. Machines represent the capacity of particular manufacturing operations. Here the resources are the raw material as well as energy, labor, floor space and the capital-intensive machinery. Each manufacturing process has multiple technical parameters which needs to be selected as per the need of final product. The
inputs are outlined in Figure 4.4. The entire process in the supply chain incorporates delays due to transportation and several other reasons which are variable from country to country.

Figure 4.4: Different inputs and new model for analysis of manufacturing system and supply chain.

4.5.3 Classification of important aspects in the selection of new technology in manufacturing

Adoption of technology in textile manufacturing is a phenomenon that might be the result of several factors. These can be subdivided into three types as indicated in Table 4.5. The three factors are time specific factors, country specific factors and technology specific factors.

The factors that may change with time are the availability of fibers as raw material, the volume available and the cost. The factors pertaining to specific country are the cost and availability of power, suitability of different labor requirements, requirements of space and cost of land. Also, there are country to country differences in the rate of interest and depreciation (ITMF, 2015).
Table 4.5: Model parameters and their classification.

<table>
<thead>
<tr>
<th>Type of parameter</th>
<th>Classification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Time dependent</td>
<td>Raw material availability.</td>
</tr>
<tr>
<td></td>
<td>Country wise differences in cost.</td>
</tr>
<tr>
<td></td>
<td>Factors affecting yield and cost of fibers.</td>
</tr>
<tr>
<td>Country specific</td>
<td>Electric power cost.</td>
</tr>
<tr>
<td></td>
<td>Labor cost.</td>
</tr>
<tr>
<td></td>
<td>Land cost, interest and depreciation.</td>
</tr>
<tr>
<td></td>
<td>Supply chain for raw materials.</td>
</tr>
<tr>
<td>Technology specific</td>
<td>Operational parameters, Number of processes, capacity of mfg.</td>
</tr>
<tr>
<td></td>
<td>Processing parameters, speed, process sequence and stages, workflow, process time from raw material to finished product and to the final outlet.</td>
</tr>
<tr>
<td></td>
<td>Waste generation, energy consumption, labor requirements.</td>
</tr>
<tr>
<td></td>
<td>Quality of product.</td>
</tr>
<tr>
<td></td>
<td>Requirement of additional processes in order to achieve desired characteristics in final product.</td>
</tr>
</tbody>
</table>

4.5.4 Technological features and limitations of the new technology

The theoretical framework needs to consider the technological limitations. For example, the waste extraction pattern and amount of waste at each process changes as different type of fibers and different manufacturing sequences are adopted. In the case of process decoupling, the factors that needs to be considered are the operational performance, the versatility of the new process, the economic advantages and capital expenditure needed for the new technology. Models for new technology in textile manufacturing consider several features of the entire manufacturing line. The process integration and decoupling have been made possible due to technological advancements, as it is demonstrated in technologies covered in the literature review.
The new technologies under consideration can be analyzed on the basis of

- Energy consumption and labor requirements.
- Possible effect of the process elimination on the technological performance.
- Investigation into the needs of package formation suitable for next process.
- Operational speed, process flow, process selection, waste generation, possible causes of downtime.
- Versatility, suitability for specific fibers or end product.

The case study analysis can reveal the relative significance of those parameters for the particular technology.

4.5.5 Summary of different aspects under consideration

It is important to understand the driving force behind the new technology and how the new technology impacts the supply chain. Whether it is changing the economic needs of capital investment or the requirements of manufacturing capacity in order to achieve the goals of maximizing profitability.

![Elements of Production Cost](image-url)

Figure 4.5: Elements of Production Cost (ITMF, 2015).
Thus, the theoretical framework is presented in Figure 4.5, 4.6 and 4.7. Judicious selection of technology, on the basis of those elements coupled with flawless decision making in the process selection, should ensure the manufacturing making higher profits. At the same time this should not compromise on important constraints such as quality and time.

Figure 4.6: Theoretical framework for Technological Parameters.
4.6 Manufacturing systems, their linkage with supply chain and the position of decoupling point

Different factors to be considered in the analysis of process decoupling are

- Operational difficulties
- Product changes
- Material handling
- Logistics
- Others – adopting to unconventional processes

Here, the different technologies under consideration are positioned at different places in the textile supply chain. Spin-knit technology is at the beginning and digital printing near the ending point in the supply chain. So, the consideration in both cases would be different. In the spin-knit process there are no effluents. However, digital printing needs to be evaluated for its impact on the environments due to various chemical treatment process involved. Now, where to
manufacture will also depend upon the ability to follow the environmental regulations even if all the other factors are in favor.
CHAPTER 5: CASE STUDY I - COMBINATION OF SPINNING AND KNITTING

5.1 Technologies enabling the combination of spinning and knitting

At present, there are three manufacturers providing machines with this technology. These are Spinitsystems® from Mayer & Cie, Corizon® from Terrot and spin-knit from Pai Lung. These systems are using roving and drawn sliver as feed material but the method of “yarn formation” is different for each technology. The process parameters for these technologies are indicated in Table 5.1. Technical data of Pai Lung spin-knit machine could not be available as it has not been published by the machinery manufacturers. From the company there was no response to online queries in this regard.

Table 5.1: Data of machines with technologies based on the concept of combining spinning and knitting (Mayer & Cie, 2017; Terrot, 2015).

<table>
<thead>
<tr>
<th>No.</th>
<th>Parameters</th>
<th>Corizon® from Terrot</th>
<th>Spinitsystems® from Mayer &amp; Cie.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Type of fabric</td>
<td>Plain single jersey, Rib, Interlock.</td>
<td>Plain single jersey, Rib, Interlock.</td>
</tr>
<tr>
<td>2</td>
<td>Diameter</td>
<td>All Dia.</td>
<td>30 inches</td>
</tr>
<tr>
<td>3</td>
<td>Number of feeders</td>
<td>48-120</td>
<td>90</td>
</tr>
<tr>
<td>4</td>
<td>Needle gauge</td>
<td>E 18- E 36</td>
<td>E 28</td>
</tr>
<tr>
<td>5</td>
<td>Type of yarn at the feed, yarn fineness, Roving fineness and Roving bobbin size.</td>
<td>Air-jet Core Spun, Ne 30 - Ne 70, Ne 0.9. Roving bobbin Dia. 180 mm, Height 440 mm</td>
<td>False-twisted, All counts of yarn for 80 grams/sq. meter. to 200 grams/ sq. meter. fabrics. Roving Ne 0.6 - 0.9.</td>
</tr>
<tr>
<td>6</td>
<td>Fiber specifications</td>
<td>Natural, synthetics or blends.</td>
<td>Natural, synthetics or blends.</td>
</tr>
<tr>
<td>7</td>
<td>Delivery speed</td>
<td>200 m/min yarn speed.</td>
<td>150 m/min</td>
</tr>
<tr>
<td>8</td>
<td>Fabric weight</td>
<td>As per Specs.</td>
<td>As per specs.</td>
</tr>
</tbody>
</table>

5.2 Mayer & Cie. Spinitsystems® technology

The Spinitsystems® technology (Figure 5.1) combines the fundamentally different processes of spinning, clearing and knitting. The machine incorporates false twist spinning of yarn from roving as feed material. Also, there is a provision of clearing the thick and thin places in the roving by
using signal from a sensor that prevents the formation of uneven yarn (Mayer & Cie, 2017). The roving bobbin is positioned overhead as indicated in Figure 5.1. Once the feed roving is drafted by the drafting system it enters the air jet spinning nozzles. The false twist is inserted at the spinning nozzles. The fiber strand emerging from spinning nozzle is fed to the needles and knitting takes place.

![Figure 5.1: Spinitsystems® from Mayer & Cie (Mayer & Cie, 2017).](image)

The fiber strand forming the fabric is in twist-less form in the fabric since the false twist has been eliminated. If there is an occurrence of a thick place in the yarn, which is detected by a sensor, the selected knitting needles switches from knit to miss until the slub is cleared from the knitting zone and the needle then reverts back to knit. The inability to feed additional filament such as Lycra®, due to the absence of yarn feeders, impose limitations on the applications of Spinitsystems® technology (Hunter, 2011).
Figure 5.2: Roving fineness and fabric weight in Spinitsystems® (Mayer & Cie, 2017).

The benefits of this technology are:

- Eco-friendly process, since it eliminates ringframe and winding, which may result in reduced energy consumption in addition to the waste associated with those processes.
- Elimination of the need of waxing the yarn because the yarn is not drawn from a package on creel thus avoiding the excessive friction that necessitates waxing.
- Space saving as indicated in Figure 5.3.
- Possibility of obtaining different fabric weights using the same roving (Figure 5.2).
- Cost reduction.
- Fancy module offering knit design flexibility and wide product varieties with all type of fibers (Mayer & Cie, 2017).

As indicated in the process flow diagrams in Figure 5.3, the process demonstrates greater possibilities of recoupling in textile manufacturing operations. The recoupling of different processes can be carried out by using the advantages of increased speed as it is evident from the synchronized delivery speed of air-jet spinning mechanism and speed of yarn feeding at knitting. The shortened spinning process can be an opportunity to link spinning with knitting operations.

<table>
<thead>
<tr>
<th>Roving count</th>
<th>80 gsm</th>
<th>100 gsm</th>
<th>120 gsm</th>
<th>140 gsm</th>
<th>160 gsm</th>
<th>180 gsm</th>
<th>200 gsm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ne0.6 / Nm1.0</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ne0.7 / Nm1.2</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ne0.9 / Nm1.5</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
5.3 Corizon® from Terrot

The Corizon® spinning module is based on the concept of air jet spinning. Here the roving is feed to the machine. After the material is drafted, the yarn formation takes place in the air jet nozzle system. The yarn is core spun with filament yarn being separately fed to the same position. The filament yarn, which goes to the core, can either be texturized or flat yarn. The modular design of Corizon® unit as shown in Figure 5.4 and Figure 5.6 (a), consists of the creel, drafting system, air nozzles and various elements guiding the roving, the filaments as well as for the yarn which is formed at the Corizon® unit.

There are two separate creels as shown in Figure 5.5 (a) and 5.5 (b). The two creels are designed to accommodate the roving bobbins and filament packages respectively.
The creel has guides, yarn tensioners and stop motion to stop the machine in the event of a break in the continuity of material being feed. The yarn is then guided to the creel of the knitting machine from where it goes through feeders to the knitting needles.
The drafting system as indicated in Figure 5.6 (b), is three over three roller-drafting. Bottom rollers are fluted steel rollers whereas the top rollers are carrying rubber cots. There are top and bottom aprons. The function and construction of drafting system is the same as in ring spinning. The only difference is that there are two roving feed to the drafting system. An effort to achieve improved uniformity in the yarn by doubling seems to be the possible reason behind the introduction of additional roving end.

Figure 5.7: Spinning limit with different spinning systems (Rieter, 2017).

Figure 5.8: Images of yarn structure (a) Ring yarn (b) Rotor yarn and (c) Corizon® yarn.
There is a difference in machine construction of Terrot’s Corizon® and Mayer & Cie’s Spinitsystems® due to the different methods of mounting yarn formation mechanism. Corizon® technology provides modular machine sections that resembles a large creel and accommodates the roving packages, filament packages, drafting rollers and air jet nozzles (Figure 5.4, 5.5 and 5.6). The provision of separate unit increases possibility of its combined use with different types of knitting machines (gauge, diameter and knit design) as per the need. The spinning limit with different types of spinning systems used in yarn manufacturing is indicated in Figure 5.7 and images of yarn spun with different spinning systems are demonstrated in Figure 5.8 (a), (b) and (c). Both, Terrot’s Corizon® and Mayer & Cie’s Spinitsystems® knitted fabrics are claimed to be possessing soft handle and provides improved dyeing properties (Mayer & Cie, 2017; Terrot, 2017). Although this can be a separate topic of investigation, the impact on fabric properties may be desirable or undesirable depending upon the intended end use of fabric. The display and control panel of Corizon® machine, where important settings can be entered, is shown in Figure 5.9.

5.4 Spin-knit machine form Pai lung

The spin-knit machine by Pai Lung (Figure 5.10), also forms yarn on the knitting machine. It also applies the air jet spinning technology to form the fabric. The fabric is claimed to be soft
and improved fabric handle. This system differs from Corizon® and Mayer’s Spinitsystems in that it uses sliver as feedstock and thus eliminates the need to produce roving, which is regarded as an expensive component of traditional processing.

Figure 5.10: Spin-knit systems by Pai Lung (Knitting Industry, 2015).

5.5 Manufacturing capacity for production with different spinning systems and knitting

The processing parameters and calculated capacity of manufacturing with different technologies in the yarn formation and Corizon® technology are derived from excel sheet model and illustrated in Tables 5.2 to 5.5. The details of production capacity and requirements of feed material for different machines in the production line are indicated in Table 5.3 to 5.6. The data on production rates of machines and processing parameters are obtained from machinery manufacturers’ manuals and other sources such as LCA benchmarking study (van der Velden, Patel & Vogtlander, 2013) and ITMF data (ITMF, 2017). Assumptions are made regarding the size of delivery packages and waste extraction. Here the package size from rotor spinning is assumed to be 3.5 kg (Schlafhorst, 2017). Also, the Knitting fabric output roll size assumed to be 30 kg with roll diameter 0.8-1.05 meter (Terrot, 2017).

For the production with same machinery capacity with same machine parameters and conventional air-jet spinning, 9 air-jet spinning machines and 53 knitting machines would be
required, whereas with Corizon® 53 knitting machines with Corizon® technology would be needed.

Table 5.2: Requirements of feed packages and can capacity for different machines in the manufacturing process for different spinning systems and knitting machines (Rieter, 2017; Schlafhorst, 2017; Murata, 2017; Terrot, 2017).

<table>
<thead>
<tr>
<th>Machine</th>
<th>Creeling requirement (Number of bobbins/packages/cans) at the feed</th>
<th>Minimum size in meters length on bobbin/can/package for material at the feed</th>
<th>Minimum size of bobbin/can/package at the feed (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Blowroom (Aerofeed)</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>Carding</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>Drawframe-1 (Single Delivery)</td>
<td>8</td>
<td>4000</td>
<td>20.6</td>
</tr>
<tr>
<td>Drawframe-2 (Single Delivery)</td>
<td>8</td>
<td>4000</td>
<td>18</td>
</tr>
<tr>
<td>Speedframe (192 spindles)</td>
<td>192</td>
<td>4000</td>
<td>18</td>
</tr>
<tr>
<td>Ringframe (1824 spindles)</td>
<td>1824</td>
<td>6000</td>
<td>3</td>
</tr>
<tr>
<td>Winding (60 spindles)</td>
<td>60</td>
<td>4066</td>
<td>0.08</td>
</tr>
<tr>
<td>Rotor spinning (480 rotors)</td>
<td>480</td>
<td>4000</td>
<td>18</td>
</tr>
<tr>
<td>Air-jet spinning (200 positions)</td>
<td>200</td>
<td>4000</td>
<td>18</td>
</tr>
<tr>
<td>Knitting (single jersey)</td>
<td>120</td>
<td>177846</td>
<td>3.5</td>
</tr>
<tr>
<td>Corizon® Knitting (single jersey)</td>
<td>120</td>
<td>6000</td>
<td>3</td>
</tr>
</tbody>
</table>

Corizon® knitting machine’s waste is assumed to be equal to air jet spinning machine waste. From Table 5.4 and Table 5.5, it can be seen that the total amount of waste extraction with different systems is nearly the same. The difference of one machine is the result of difference in waste extraction at air jet as well as knitting machine in conventional process with separate air-jet spinning and knitting. It reduces the final output of fabric.
Table 5.3: Processing parameters for different machines up to rovingframe in the spinning preparatory process for 30\textsuperscript{s} Ne cotton yarn (Rieter, 2017; Schlafhorst, 2017; Murata, 2017; Terrot, 2017).

<table>
<thead>
<tr>
<th>Machine</th>
<th>Delivered Material fineness (grams/meter)</th>
<th>Speed m/min</th>
<th>Production rate at 100 % efficiency (kg/hr)</th>
<th>Waste for cotton (%)</th>
<th>Minimum capacity for one blowroom (Number of machines)</th>
<th>Machine Efficiency (%)</th>
<th>Production per machine (kg/hr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Blowroom (Aerofeed)</td>
<td>NA</td>
<td>NA</td>
<td>1200</td>
<td>5.4</td>
<td>1</td>
<td>95</td>
<td>1140</td>
</tr>
<tr>
<td>Carding</td>
<td>5.15</td>
<td>300</td>
<td>93</td>
<td>4.5</td>
<td>13</td>
<td>98</td>
<td>91.14</td>
</tr>
<tr>
<td>Drawframe-1 (Single Delivery)</td>
<td>4.5</td>
<td>1200</td>
<td>324</td>
<td>0.8</td>
<td>4</td>
<td>99</td>
<td>320.76</td>
</tr>
<tr>
<td>Drawframe-2 (Single Delivery)</td>
<td>4.5</td>
<td>1200</td>
<td>324</td>
<td>0.8</td>
<td>4</td>
<td>99</td>
<td>320.76</td>
</tr>
<tr>
<td>Speedframe (192 spindles)</td>
<td>0.5</td>
<td>50</td>
<td>288</td>
<td>1</td>
<td>4</td>
<td>95</td>
<td>273.6</td>
</tr>
<tr>
<td>Speedframe (120 spindles)</td>
<td>0.5</td>
<td>50</td>
<td>180</td>
<td>1</td>
<td>7</td>
<td>95</td>
<td>171</td>
</tr>
</tbody>
</table>

Table 5.4: Processing parameters for ringframe, winding and knitting for producing single jersey knitted fabric with 30\textsuperscript{s} Ne cotton yarn (Rieter, 2017; Schlafhorst, 2017; Murata, 2017; Terrot, 2017).

<table>
<thead>
<tr>
<th>Machine</th>
<th>Production rate at 100 % efficiency (kg/hr)</th>
<th>Waste for cotton (%)</th>
<th>Minimum capacity for one blowroom (Number of machines)</th>
<th>Machine efficiency (%)</th>
<th>Production per machine (kg/hr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ringframe (1824 spindles)</td>
<td>65</td>
<td>3.02</td>
<td>17</td>
<td>98</td>
<td>63.7</td>
</tr>
<tr>
<td>Winding (24 spindles)</td>
<td>63</td>
<td>0.5</td>
<td>17</td>
<td>98</td>
<td>61.74</td>
</tr>
<tr>
<td>Knitting (single jersey)</td>
<td>20</td>
<td>3</td>
<td>53</td>
<td>95</td>
<td>19</td>
</tr>
</tbody>
</table>
Table 5.5: Processing parameters for rotor spinning, air jet spinning and Corizon® (Rieter, 2017; Schlafhorst, 2017; Murata, 2017; Terrot, 2017).

<table>
<thead>
<tr>
<th>Machine</th>
<th>Number of Positions</th>
<th>Production rate at 100% efficiency (kg/hr)</th>
<th>Waste for cotton (%)</th>
<th>Minimum capacity For one blowroom. (Number of machines)</th>
<th>Machine efficiency (%)</th>
<th>Total Production per machine (kg/Hr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rotor Spinning</td>
<td>480</td>
<td>171</td>
<td>0.8</td>
<td>7</td>
<td>95</td>
<td>162.45</td>
</tr>
<tr>
<td>Air-jet spinning</td>
<td>200</td>
<td>119</td>
<td>6</td>
<td>9</td>
<td>95</td>
<td>113.05</td>
</tr>
<tr>
<td>Corizon®</td>
<td>NA</td>
<td>20</td>
<td>6</td>
<td>53</td>
<td>95</td>
<td>19</td>
</tr>
</tbody>
</table>

5.6 Matlab simulation of the manufacturing process and material flow in the process

5.6.1 Matlab simulation of the manufacturing and supply chain process

Simulation can be very useful tool to demonstrate the possible outcomes of technological advancements in manufacturing and supply chain operations. It is always desired to achieve maximum benefits by utilizing new technology with reduced manufacturing cost and minimum possible use of resources. The saving in manufacturing cost can be achieved by appropriate capacity planning and maximum productivity by ensuring uninterrupted flow of material in the process (MathWorks 2017).

Matlab Simulink® and SimEvents® tools and capabilities can be used for process simulation. System models can be designed for specific purpose to examine the process performance, process capacity utilization, throughput etc. Further it is also possible to optimize process parameters using simulation technique (MathWorks 2017).

Matlab Simulink® has several predefined blocks, which can be conveniently placed in the model. The model-based approach can be useful for research on manufacturing systems and supply chain as it is also possible to incorporate various factors such as speed, capacity planning and transportation timings (MathWorks, 2017). Matlab_R2017a and Matlab_R2017b versions were
used for the simulation. The drag and drop features of different custom made graphic elements ensures the ease of simulation.

In order to obtain the process simulation model, the outline of input, output and process variables is prepared as shown in Table 5.6. The process variables include machine speed, number of machines, energy consumption and waste extraction.

**Table 5.6: Manufacturing process parameters and process variables under consideration.**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit of measurement</th>
</tr>
</thead>
<tbody>
<tr>
<td>Capacity at each stage</td>
<td>Number of machines at each stage</td>
</tr>
<tr>
<td>Output rate of machines</td>
<td>Machine speed in kg/hr.</td>
</tr>
<tr>
<td>Energy consumption</td>
<td>kwh/kg</td>
</tr>
<tr>
<td>Energy cost</td>
<td>Using input cost in USD/kg for specific country and output total cost at each stage</td>
</tr>
<tr>
<td>Waste extraction</td>
<td>Amount entered as waste % and output as kg amount of waste at each stage</td>
</tr>
</tbody>
</table>

The Matlab SimEvents® has several libraries. The libraries constitute predefined blocks, which represent entity, queues, servers and switches. Entities also carry data in the form of attributes. The possibility of introducing discrete event-based system in Simulink® model makes it more suitable for manufacturing process simulation and logistics applications. The terminology and predefined library functions in Matlab are explained in Table 5.7.
<table>
<thead>
<tr>
<th>No.</th>
<th>Matlab block (Symbol)</th>
<th>Process description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Entity generator <img src="image1" alt="Entity" /></td>
<td>Generates entities. Entities are symbolic of material feed in kg/hr. Entities carry the attributes or process variables such as speed at different stages, Number of machine to be used. Entity generation time is fraction of machine speed of first machine (i.e. 1/machine speed in kg/hr.).</td>
</tr>
<tr>
<td>2</td>
<td>Entity replicator <img src="image2" alt="Entity Replicator" /></td>
<td>Replicates each entity into given Number of times. Used to represent the increased input rate due to more number of machines at the beginning of process.</td>
</tr>
<tr>
<td>3</td>
<td>Subsystem <img src="image3" alt="Subsystem" /></td>
<td>Encloses the individual process or system that may consists of different combinations of servers, functions, output etc.</td>
</tr>
<tr>
<td>4</td>
<td>Resource pool <img src="image4" alt="Resource Pool" /></td>
<td>It defines the total capacity available as resource for manufacturing. Here it is the maximum number of machines.</td>
</tr>
<tr>
<td>5</td>
<td>Resource acquire <img src="image5" alt="Resource Acquire" /></td>
<td>Acquire resource as per the preset definition for resource. Here resource is the machine used for manufacturing.</td>
</tr>
<tr>
<td>6</td>
<td>Resource release <img src="image6" alt="Resource Release" /></td>
<td>Releases the resource and determines the utilization.</td>
</tr>
<tr>
<td>7</td>
<td>Entity server <img src="image7" alt="Entity Server" /></td>
<td>The servers have predefined service time and entity attributes can also be utilized as needed. Here server represents machines and mathematical functions can be set for the action of machines. Servers can also initiate a function.</td>
</tr>
<tr>
<td>8</td>
<td>Function blocks <img src="image8" alt="Function Blocks" /></td>
<td>There are various function blocks that define different functions and provide output values.</td>
</tr>
<tr>
<td>9</td>
<td>Scope <img src="image9" alt="Scope" /></td>
<td>The scopes provide graphical output. They plot the values for corresponding blocks as per the input values. Graphical display labels can be set as per the need.</td>
</tr>
<tr>
<td>10</td>
<td>Terminator or Sink <img src="image10" alt="Terminator" /></td>
<td>End of process and entities are dissolved as there is no further analysis.</td>
</tr>
<tr>
<td>11</td>
<td>Configurable subsystem <img src="image11" alt="Configurable Subsystem" /></td>
<td>It can be utilized as library subsystem set for entering input values at the beginning and the values can be used globally in the simulation.</td>
</tr>
</tbody>
</table>
5.6.2 Matlab process simulation model and process parameters to be entered

The Matlab based models for spinning process, energy and waste are illustrated in Figure 5.11 and 5.12. The elements of Matlab Simulink® models for process combination of spinning and knitting are illustrated in Appendix A. The basic assumptions for simulation model are as explained.

- Entity = 1 kg. fiber material
- One Cycle = 1 Hour process time. (One cycle or more cycles can be selected)

Procedure for entering capacity data is:

- Set entity attributes and enter capacity data at the start: Number of machines and machine speed fractions at each stage.
- Enter the machine speeds in kg/hr.

This is followed by creating a configurable subsystem for entering capacity data that includes number of machines at different stages and machine production rate in kg/hr.

- Configurable subsystem: The configurable subsystem is selected and entered.
- Library: A customized library is to be created for its use as needed.

The simulation blocks used are:

- Entity Generator
- Entity Server
- Connect to Simulink® function
- Functions call

The configurable subsystem library is created as below

- Start
- Open Blank library
- Configurable subsystem
- Mask
- Edit mask: Mask Parameters by using Mask editor
- Icon and Ports
- color('blue');
- disp ('Enter Capacity data Here');

Parameters and dialog, defined variables:

<table>
<thead>
<tr>
<th>Variable</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>No. of blowrooms</td>
<td>Blowroom</td>
</tr>
<tr>
<td>No. of carding machines</td>
<td>Carding</td>
</tr>
<tr>
<td>No. of drawframes</td>
<td>Drawframe</td>
</tr>
<tr>
<td>No. of rovingframes</td>
<td>Speedframe</td>
</tr>
<tr>
<td>No. of ringframes</td>
<td>Ringframe</td>
</tr>
<tr>
<td>No. of winding machines</td>
<td>Winding</td>
</tr>
<tr>
<td>Blowroom speed</td>
<td>BRspeed</td>
</tr>
<tr>
<td>Carding speed</td>
<td>cardspeed</td>
</tr>
<tr>
<td>Drawframe speed</td>
<td>drawspeed</td>
</tr>
<tr>
<td>Speedframe speed</td>
<td>speedfrspeed</td>
</tr>
<tr>
<td>Ringframe speed</td>
<td>ringspeed</td>
</tr>
<tr>
<td>Winding speed</td>
<td>windspeed</td>
</tr>
<tr>
<td>Knitting speed</td>
<td>knitspeed</td>
</tr>
<tr>
<td>Spin-knit machine speed</td>
<td>spinknitspeed</td>
</tr>
</tbody>
</table>

Initialization

Different drag and drop blocks from the library are used and their use is indicated.

- Making blocks - Subsystem for the function.
- Configurable subsystem - For input values making library subsystem
- Math operator - Product
- From spreadsheet - Input values form excel sheet

The model has drag and drop features which enables it to be customized with small modifications for combinations of different types of machines, process sequences, machine capacities, waste extraction and cost.
Figure 5.11: Spinning process, energy and waste model for spinning and knitting as separate process.
Figure 5.12: Spinning process, energy and waste model for process combination of spinning and knitting.
5.6.3 Process simulation results and comparison of graphs for spinning and knitting combined process with traditional process

Using one hour as time unit and considering a minimum of one blowroom line at the beginning of the process, the simulation is carried out. The throughput in kg per hour at each stage of the process is demonstrated in the simulation by considering waste extracted at each stage. There is provision for varying the number of machines or using different systems, by entering data and making use of drag and drop features. The number of machines at each stage can also be calculated using an Excel sheet model as illustrated in Appendix C. The Matlab model enables an analysis of the effect of varying number of machines and using different process sequence in the manufacturing, on the process throughput speed, capacity utilization percentage, waste extracted and total electrical energy cost. Graphs can be plotted which indicates time on the x-axis where the unit time is hour. Simulation can be for any amount of time selected. For comparison one-hour time is selected. The comparison of process throughput and capacity utilization for selected number of machines in knitting and spinning process is illustrated in Figures 5.13 and 5.14. The graphs are plotted for 8-hour duration assuming eight hours shift time. The small curve at the initial part of the graph corresponds to the starting one hour. It appears due to the assumption that one cycle equals to one hour. So, even if the machine utilization is 100 % since the beginning as blowroom is continuously working in this case, the one-hour duration at the start shows the step by step progression of simulation.

The process throughput and capacity utilization % for both the systems is nearly equal for the given set of parameters. The waste extraction with Corizon® knitting machines would be higher when compared to waste at a knitting machine, due to presence of the yarn forming mechanism in the case of Corizon®.
The comparison of electrical energy cost, which is indicated in Figure 5.15 and Figure 5.16 reveals the overall reduced power cost while knitting with Corizon® system and corresponding spinning preparatory machines.
Figure 5.15: Comparison of Electrical Energy cost in USD for manufacture of knitted fabrics for 8 hr run using the specified capacity with different systems in spinning.

Figure 5.16: Energy cost in USD for eight hours run with specified capacity at different stages of manufacture and the associated power cost for different systems in the manufacture of knitted fabric.

### 5.7 Comparison of energy consumption

The energy consumption is an important aspect to be considered, as it is evident from the data obtained from different sources. The minimization of yarn cost needs reduction in several
components of cost associated with the raw materials, waste, power, labor and floor space (Oxenham W., 2015). Additionally, the energy consumption in the entire manufacturing process adds the environmental burden (van der Velden et al., 2014). The following considers the electrical energy consumption beginning with the spinning process. The core yarn formation in Corizon® also needs additional feed of a filament (Terrot, 2017). The technology in manufacturing yarns and fabrics from synthetic filaments begins with fiber manufacturing. Hence the calculation also includes corresponding power consumption in fiber manufacture. The data is obtained from different sources including the technical data from machinery manufacturers (Rieter, 2017; Schlafhorst, 2017; Murata, 2017; Terrot, 2017), ITMF data (ITMF, 2017), Emerging Textiles (Emerging Textiles, 2017) and reference to different studies carried out in this area (van der Velden et al., 2014; Koç & Kaplan, 2007).

5.7.1 Energy consumption and cost in knitted fabric manufacturing with Corizon® technology and comparison with conventional knitting and ring spinning

The contribution of different processes in the total electrical energy consumption in the modern yarn manufacturing process with ring spinning is indicated below (Rieter 2017).

\[
\begin{align*}
E1 &= \% \text{ Contribution of ringframe machines} = 58 \% \\
E2 &= \% \text{ Contribution of winding machines} = 14 \% \\
E3 &= \% \text{ Contribution of rovingframes} = 9 \% \\
E4 &= \% \text{ Contribution of spinning process up to drawframe before roving} = 19 \% \\
E5 &= \% \text{ Contribution of spinning process up to roving} = E3 + E4 = 28 \%
\end{align*}
\]

As per the ITMF (ITMF, 2017) data, different elements of total cost of manufacturing are defined for the spinning process. In those elements of total cost, the electrical energy constitutes 23.3%.
Here

P1 = Power consumption at Corizon® unit.

P2 = Power consumption of filament yarn production.

P3 = Power consumption of filament texturizing

T2 = Proportion of fiber material by weight coming from roving in the yarn

T4 = Proportion of core filament by weight in the yarn

C1 = Power cost of ring spinning.

C2 = Power cost up to roving formation in the spinning process

C3 = Power cost for Corizon®

C4 = Power cost in the filament production

C5 = Power cost of knitting machine

C6 = Total power cost of knitting process with Corizon® including preparatory Processes

C7 = Total power cost of knitting machine including the conventional preparatory processes and ring spinning

For knitting machine with Corizon®

V = Yarn Speed

G = Fabric weight.

W = Width of fabric

N = Number of Feeders

Ne = Yarn Fineness in English count

R = Corizon® unit Production rate (assumed at 85 % efficiency)

Assuming the power cost is for USA, which is 0.053 USD per kwh. (ITMF, 2017).
C1 = Power cost of ring spinning = 0.28 USD/kg, i.e. 23.3 % of the total cost of manufacturing yarn (ITMF, 2017).

Power consumption for ring spinning of 30s Ne yarn is 5.28 (kwh/kg). Since feeding roving bobbins to knitting machine eliminates the ringframe and winding processes, the resultant power cost in spinning would be C2 as calculated here.

Power cost up to roving formation in the spinning process is

\[
C2 = C1 \times \left( \frac{E5}{100} \right) = \frac{0.28}{100} \times \frac{28}{100} = 0.0784 \text{ USD per kg}
\]

Now, calculating the power cost for Corizon® unit with knitting machine.

Power consumption per meter of fabric (kwh/kg) = \( \frac{\text{Power Consumption in kw}}{\text{Production Rate in kg per hr}} \)

Power consumption of Corizon® unit = \( P1 = \) 16 kw (Terrot, 2017)

Calculating the rate of production of knitted fabric with the following specifications on a knitting machine equipped with Corizon® (Terrot, 2017).

\[
\begin{align*}
V &= \text{Yarn Speed} = 200 \text{ m/min} \\
G &= \text{Fabric weight.} = \frac{230}{1.92} = 119.8 \text{ g/ m}^2 \\
W &= \text{Width of fabric} = 192 \text{ cm} \\
N &= \text{Number of Feeders} = 96 \\
Ne_1 &= \text{Yarn Fineness} = 30^s \text{ Ne (19.7 Tex)} \\
\text{Production rate with Corizon® unit (85 % eff)} = R
\end{align*}
\]

\[
R = V \times \text{Tex} \times \left( \frac{1}{1000} \right) \times N \times 60 \times \left( \frac{1}{1000} \right) \times 0.85 \text{ kg/hr/machine}
\]

\[
= 200 \times 19.7 \times \left( \frac{1}{1000} \right) \times 96 \times 60 \times \left( \frac{1}{1000} \right) \times 0.85 \text{ kg/hr/machine}
\]

\[
= 19.29 \text{ kg/hour/machine.}
\]
\[= (19.29 \times 1000) \div (G \times W \div 100)\]
\[= 19.29 \times 1000 \div 230\]
\[= 83.87 \text{ m/hr.}\]

Power consumption per unit production of fabric \(= P1 \div R\)

Power consumption per meter production of fabric \(= 16 \div 83.87 = 0.1907 \text{ kwh/meter}\)

Power consumption per kg production of fabric
\[= 16 \div 19.29\]
\[= 0.83 \text{ (kwh/kg)}\]

Power cost for Corizon® unit in USD per meter
\[= 0.053 \times 0.1907 = 0.0101 \text{ USD per meter at the cost of power 0.053 USD/kwh}\]

Power cost for Corizon® unit in USD/kg. = C3
\[= 0.053 \times 0.83 = 0.0439 \text{ USD per kg. at the cost of power 0.053 USD/kwh}\]

The yarn formed on Corizon® machine is air-jet spun core yarn. The filament in the core can be texturized or flat as per the need. Assuming that the Corizon® unit is feeding the knitting machine with core yarn having 5.2 Tex textured filaments in the core. So, calculating the relative proportion of filament by weight in the Corizon® core-spun yarn.

\[
\text{Filament} = 5.2 \text{ Tex} \\
\text{Yarn} = 19.7 \text{ Tex} \\
\text{Proportion of filament} = T4 = (5.2 \div 19.7) \times 100 = 26 \% \\
\text{Proportion of fiber material from roving in total yarn production} \\
= T2 \\
= 100 – T4 = 100 - 26 \\
= 74 \%\]
Therefore, for each 1 kg yarn produced in Corizon® unit, the power cost contribution from earlier process in filament and roving manufacturing will be 26 % and 74 % respectively.

As calculated earlier:

Power cost of spinning process without ringframe and winding, up to roving

\[ C_2 = \text{0.0784 USD per kg.} \]

So, the power cost contribution per kg of yarn for material from spinning process up to roving = \[ C_2 \times T_2 = 0.0784 \times 0.74 = 0.058 \text{ USD/kg of yarn} \]

The power consumption in filament yarn production can be calculated from the available data. Process parameters for textured filament yarn production are indicated in Table 5.8.

Table 5.8: Textured filament yarn production process parameters (van der Velden et al., 2014).

<table>
<thead>
<tr>
<th>Elements</th>
<th>Specifications</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fiber Spinning Line</td>
<td>Barmag, 2011, PTA and MEG to filament (&quot;direct spinning line&quot;)</td>
</tr>
<tr>
<td>Yarn parameters</td>
<td>FDY 75 denier, 83 Dtex</td>
</tr>
<tr>
<td>Fiber spinning power consumption (P2)</td>
<td>0.8 kwh</td>
</tr>
<tr>
<td>Texturing machine</td>
<td>Barmag, 2011. Filament to textured filament</td>
</tr>
<tr>
<td>Textured yarn parameters</td>
<td>DTY (75/1.6&gt;47 den), Textured filament, 47denier, 52Dtex.</td>
</tr>
<tr>
<td>Texturing power consumption (P3)</td>
<td>0.7–0.9 kwh</td>
</tr>
</tbody>
</table>

Power consumption in filament production

\[ = P2+P3 = 0.8+0.8 \]

\[ = 1.6 \text{ (kwh/kg)} \]

Assuming the power rate is 0.053 USD/kwh.

Power cost in filament production
\[ C_4 = 0.053 \times 1.6 = 0.0848 \text{ USD/kg}. \]

So, the power cost contribution per kg of yarn for power consumption in filament production

\[ T_4 \times C_4 = 0.26 \times 0.0848 = 0.022 \text{ USD/kg of yarn} \]

Power cost of knitting machine \( = C_5 \)

\[ = 0.002 \text{ USD per meter} \]
\[ = 0.008 \text{ USD per kg (For 119.8 g/m}^2 \text{ fabric)} \]

Total power cost of knitting with Corizon® unit (C6):

\[ = \text{Power cost up to roving production} + \text{Power cost of Corizon® unit} + \text{Power cost of filament production} + \text{Power cost of knitting machine} \]
\[ = (T_2 \times C_2) + C_3 + (T_4 \times C_4) + C_5 = 0.058 + 0.0439 + 0.022 + 0.008 \]
\[ = 0.1319 \text{ USD per kg.} \]

Calculation of total power cost of conventional knitting process with ring spinning:

Power cost of preparatory process including ringframes and winding (C1):

\[ = 0.28 \text{ USD per kg} \]

Power cost per meter for knitting machine (C5):

\[ = 0.002 \text{ USD per meter (ITMF, 2017).} \]
\[ = 0.008 \text{ USD/kg} \]

Total power cost of knitting with conventional ring spinning and knitting (C7):

\[ = C_1 + C_5 \]
\[ = 0.28 + 0.008 \]
= 0.288 USD/kg

Now, calculating the percentage reduction in power cost with Corizon® technology as compared to knitting with conventional ring spinning process.

% Reduction of power cost with Corizon® technology as compared to knitting with conventional ring spinning process

= \frac{(C7 - C6)}{C7} \times 100

= \frac{(0.288 - 0.1319)}{0.288} \times 100

= 54.2 %

5.7.2 Energy consumption and cost in the knitted fabric manufacture with rotor spun yarn and comparison with Corizon® as well as conventional knitting technology

The contribution of different processes in the total electrical energy consumption in the modern yarn manufacturing process with ring spinning is indicated below (Rieter, 2017).

In case of rotor spinning the preparatory processes are up to drawframe.

E1 = % Contribution of ringframe machines = 58 %

E2 = % Contribution of winding machines = 14 %

E3 = % Contribution of rovingframes = 9 %

E4 = % Contribution of spinning process up to roving = E1+E2+E3=81 %

E6 = % Contribution of spinning process up to drawframe = 100 - E4 = 19 %

As per the ITMF data (ITMF, 2017), different elements of total cost of manufacturing are defined for the spinning process. In those elements of total cost, the electrical energy constitutes 23.3 %.
Here

P1 = Power consumption of Corizon® unit

P2 = Power consumption of filament yarn production

P3 = Power consumption of filament texturizing

T2 = Proportion of fiber material from roving in the core yarn

T4 = Proportion of filament by weight in the core yarn

C1 = Power cost of ring spinning

C2 = Power cost up to roving formation in the spinning process

C3 = Power cost for Corizon®

C4 = Power cost in filament production

C5 = Power cost of knitting machine

C6 = Total power cost of knitting process with Corizon® including preparatory processes

C7 = Total power cost of knitting machine with conventional preparatory processes and ring spinning

C8 = Total power cost of knitting machine with conventional preparatory processes and rotor spinning

C9 = Power cost up to drawframe in the spinning process

C10 = Power cost of rotor spinning machine

For knitting machine with Corizon®

V = Yarn Speed

G = Fabric weight

W = Width of fabric
N = Number of Feeders

Ne₁ = Yarn Fineness in English count

Tex = Yarn fineness in tex.

R = Corizon® unit Production rate (85 % eff)

C₁ = Power cost of ring spinning

= 0.28 USD/kg i.e. 23.3 % of the total cost of manufacturing yarn (ITMF 2017).

Therefore, if the ringframe, winding and rovingframe processes are eliminated by using rotor yarn on the knitting machine, following would be the resultant power cost in spinning.

Power cost up to drawframe in the spinning process

= C₉ = C₁ × (E₆ ÷ 100)

= 0.28 × (19/100)

= 0.0532 USD/kg.

Power cost of rotor spinning machine = C₁₀

= 0.079 USD/kg.

Power cost per meter for knitting machine = C₅

= 0.002 USD per meter (For 192 cm width)

= 0.008 USD per kg.

Total power cost of knitting with conventional rotor spinning and knitting

= C₈

= C₉+C₁₀+C₅

= 0.0532+0.079 + 0.008

= 0.1402 USD/kg.
Now, the power cost for Corizon® unit with knitting machine as calculated earlier.

Total power cost of knitting with Corizon® unit = C6

= 0.1319 USD per kg.

The total power cost of knitting with conventional ring spinning and knitting = 0.288 USD/kg.

Table 5.9: Power consumption with ring spinning and knitting.

<table>
<thead>
<tr>
<th>Department</th>
<th>Total Production Per Machine (kg/hr)</th>
<th>Individual Process Machine Power consumption (kwh/kg)</th>
<th>Energy Consumption (%)</th>
<th>Total Energy Consumption (kwh/kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Blowroom (Aerofeed)</td>
<td>1140</td>
<td>0.13728</td>
<td>2.6</td>
<td>3.13424</td>
</tr>
<tr>
<td>Carding</td>
<td>91.14</td>
<td>1.04016</td>
<td>19.7</td>
<td></td>
</tr>
<tr>
<td>Drawframe-1</td>
<td>320.76</td>
<td>0.1584</td>
<td>3</td>
<td>5.43</td>
</tr>
<tr>
<td>Drawframe-2</td>
<td>320.76</td>
<td>0.1584</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>Speedframe</td>
<td>273.6</td>
<td>0.24288</td>
<td>4.6</td>
<td></td>
</tr>
<tr>
<td>Ringframe</td>
<td>63.7</td>
<td>3.15744</td>
<td>59.8</td>
<td></td>
</tr>
<tr>
<td>Winding</td>
<td>61.74</td>
<td>0.38544</td>
<td>7.3</td>
<td></td>
</tr>
<tr>
<td>Knitting</td>
<td>19</td>
<td>0.15</td>
<td>100</td>
<td></td>
</tr>
</tbody>
</table>

The comparison of power cost with different systems in manufacture is indicated in Table 5.9 to Table 5.13 and Figure 5.17.

Table 5.10: Power consumption with rotor spinning and knitting.

<table>
<thead>
<tr>
<th>Department</th>
<th>Total Production Per Machine (kg/hr)</th>
<th>Individual Process Machine Power consumption (kwh/kg)</th>
<th>Energy Consumption (%)</th>
<th>Total Energy Consumption (kwh/kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Blowroom (Aerofeed)</td>
<td>1140</td>
<td>0.13728</td>
<td>4.6</td>
<td>3.13424</td>
</tr>
<tr>
<td>Carding</td>
<td>91.14</td>
<td>1.04016</td>
<td>34.9</td>
<td></td>
</tr>
<tr>
<td>Drawframe-1</td>
<td>320.76</td>
<td>0.1584</td>
<td>5.3</td>
<td></td>
</tr>
<tr>
<td>Drawframe-2</td>
<td>320.76</td>
<td>0.1584</td>
<td>5.3</td>
<td></td>
</tr>
<tr>
<td>Rotor Spinning</td>
<td>162.45</td>
<td>1.49</td>
<td>49.9</td>
<td></td>
</tr>
<tr>
<td>Knitting</td>
<td>19</td>
<td>0.15</td>
<td>100</td>
<td></td>
</tr>
</tbody>
</table>
Table 5.11: Power consumption with air-jet spinning and knitting.

<table>
<thead>
<tr>
<th>Department</th>
<th>Total Production Per Machine (kg/hr)</th>
<th>Individual Process Machine Power consumption (kwh/kg)</th>
<th>Energy Consumption (%)</th>
<th>Total Energy Consumption (kwh/kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Blowroom</td>
<td>1140</td>
<td>0.13728</td>
<td>6.8</td>
<td>2.17924</td>
</tr>
<tr>
<td>Carding</td>
<td>91.14</td>
<td>1.04016</td>
<td>51.2</td>
<td></td>
</tr>
<tr>
<td>Drawframe-1</td>
<td>320.76</td>
<td>0.1584</td>
<td>7.8</td>
<td></td>
</tr>
<tr>
<td>Drawframe-2</td>
<td>320.76</td>
<td>0.1584</td>
<td>7.8</td>
<td></td>
</tr>
<tr>
<td>Air-jet spinning</td>
<td>20.9</td>
<td>0.535</td>
<td>26.4</td>
<td></td>
</tr>
<tr>
<td>Knitting</td>
<td>19</td>
<td>0.15</td>
<td>100</td>
<td></td>
</tr>
</tbody>
</table>

Table 5.12: Power consumption in knitting with Corizon®.

<table>
<thead>
<tr>
<th>Department</th>
<th>Total Production Per Machine (kg/hr)</th>
<th>Individual Process Machine Power consumption (kwh/kg)</th>
<th>Energy Consumption (%)</th>
<th>Total Energy Consumption (kwh/kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Blowroom</td>
<td>1140</td>
<td>0.13728</td>
<td>7.9</td>
<td>3.12712</td>
</tr>
<tr>
<td>Carding</td>
<td>91.14</td>
<td>1.04016</td>
<td>59.9</td>
<td></td>
</tr>
<tr>
<td>Drawframe-1</td>
<td>320.76</td>
<td>0.1584</td>
<td>9.1</td>
<td></td>
</tr>
<tr>
<td>Drawframe-2</td>
<td>320.76</td>
<td>0.1584</td>
<td>9.1</td>
<td></td>
</tr>
<tr>
<td>Speedframe</td>
<td>171</td>
<td>0.24288</td>
<td>14</td>
<td></td>
</tr>
<tr>
<td>Spin-knit</td>
<td>19</td>
<td>1.39</td>
<td>100</td>
<td></td>
</tr>
</tbody>
</table>

Table 5.13: Comparison of power cost of knitting with Corizon®, conventional ring spinning and rotor spinning.

<table>
<thead>
<tr>
<th>Sr. No.</th>
<th>Technology used in manufacturing</th>
<th>Power cost for fabric production (USD/Kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Ring spinning and knitting</td>
<td>0.288</td>
</tr>
<tr>
<td>2</td>
<td>Rotor spinning and knitting</td>
<td>0.1402</td>
</tr>
<tr>
<td>3</td>
<td>Corizon® technology with knitting machine</td>
<td>0.1319</td>
</tr>
</tbody>
</table>

Thus, the percentage reduction in power cost while knitting with Corizon® technology as compared to conventional ring spinning is 54.2 % while the same reduction while knitting with rotor spinning is 51.31%. The difference in power consumption while knitting with rotor spinning and knitting with Corizon® technology is 5.92 %.
Thus, it is found that Rotor spun yarn in the knitted fabric production can offer about 51% saving in power consumption of the total process as compared to conventional ring spinning and knitting. Although the rotor spinning comes with a limited range for yarn count and distinct product characteristics, further advancements in rotor spinning cannot be ruled out. The Corizon® technology offers about 54% saving in electrical energy consumption as compared to conventional ring spinning and considering the complete process beginning with fiber manufacture and spinning. The fiber manufacture needs to be considered as the Corizon® technology incorporates synthetic filament in the air-jet core spun yarn. Knitting with Corizon® technology offers only marginal 5.92% saving in electrical energy as compared to conventional rotor spinning and knitting process.

5.8 Manpower requirements with new technologies in the process combination of spinning and knitting

The ring spinning process needs operatives to carry out tasks such as mending end breaks on ringframes, which is still manual. The production labor requirement of spinning is high due to
inherent process features. Moreover, the hourly wages for skilled and unskilled operatives and other labor personnel varies from country to country. The labor cost (for the year 2016) for spinning 30s Ne yarn in USA is 0.458 USD/kg, which is 29.8% of the manufacturing, cost. Also, the labor cost is 18.7% of total cost of production for knitting with ring yarn. (ITMF 2016). The labor cost and different categories of labor required for textile mill in USA are indicated in Table 5.14. Depending on the needs of the manufacturing capacity, the labor cost can be determined.


<table>
<thead>
<tr>
<th>No.</th>
<th>Category</th>
<th>Average wages (USD/Hour)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>First-line supervisors/managers of production and operating workers</td>
<td>26.21</td>
</tr>
<tr>
<td>2</td>
<td>Inspectors, testers, sorters, samplers, and weighers</td>
<td>15</td>
</tr>
<tr>
<td>3</td>
<td>Textile bleaching and dyeing machine operators and tenders</td>
<td>13.42</td>
</tr>
<tr>
<td>4</td>
<td>Textile knitting and weaving machine setters, operators, and tenders</td>
<td>13.79</td>
</tr>
<tr>
<td>5</td>
<td>Textile winding, twisting, and drawing out machine setters, operators, and tenders</td>
<td>13.05</td>
</tr>
</tbody>
</table>

5.9 Space consumption with the new technology

The cost of land and its associated interest on capital investment is also prime considerations as it is a part governing the location decisions of manufacturing plants. Any saving in machinery and plant space requirement is going to benefit by the way of more opportunities for expansion and increase of manufacturing capacities. However, the comparison of different alternatives will depend upon the available options for plant locations. Therefore, in the present study the cost of land is not calculated as the decision can vary from situation to situation.

Also, in the case of logistics cost associated with different locations, a separate simulation model can be prepared for available alternatives to arrive at the least cost option that will benefit from reduced land cost as well as any possible increase in transportation costs.
5.10 New technologies and the waste extraction in process

Waste minimization in the process is very important in order to avoid the drain of high cost fiber material into the waste. The waste generated by at ringframe is in the range of 3 to 4 % depending on the yarn count and type of fibers used. The waste generated at air-jet spinning machine is in the range 4-8 % depending on type of fibers and yarn count. It is nearly double the % at air-jet spinning machine. Also, the actual amount of waste extracted may vary depending on machine settings and quality of raw materials used (Karthik & Thilagavathi, 2016; Murata, 2017).

5.11 Simulation and comparison of supply chains with different systems in the manufacturing by using Matlab Generic Model for the supply chain

A generic model is developed for simulation of manufacturing plants and finished goods transportation activities that can be integrated with demand generation pattern. Projection of demand can be another topic of research, therefore here the model is provided input by making assumptions. Entering the right estimate of demand can further enhance the capabilities to predict utilization of available capacities.

The important assumptions and defined variables are:

1 cycle = 1 entity = 1 order.

order size = order_size_kg.

FIFO queue\[\sum\] Manufacturer 1 to M.

Manufacturer 1 to M,

Service time = entity.order_size_kg*(1/(Number of machines*machine speed))

If there are ‘n’ processes- Process 1 to n

For each process service time for unit production in kg:

Service time1 = 1/ (Number of machines(n1) * machine speed(s1))
Total service time for n processes = \[ \sum \frac{1}{(n_i * s_i)} \]

Server-1:
Manufacturer

Server -2:
Transportation Time

FIFO Queue

For each order, there is a queue

Entity
Event actions
Insert pattern

Repeating sequence
Random number

The model in Figure 5.18 can be customized for spinning and knitting as separate processes or for spinning and knitting combined process, by selecting the entity attributes and server parameters. The elements of the model and other details are illustrated in Appendix B. The results of process simulation are indicated in Figure 5.19, 5.20 and 5.21. Assuming a batch of material that equals to one batch at the end machine of each process, the production and the operational time for a batch is considered for the simulation run in each case. The batch size in case of traditional spinning process followed by knitting is 360 kg (12 knitted fabric rolls, each of 30 kg). The batch size in case of spinning and knitting combines process is 420 kg (14 knitted fabric rolls, each of 30 kg). The batch size corresponds to the number of feeders and package size in each case. Assuming production for six-day week and 17.5 shift (8 hour each shift) operational time, total 140 hours are obtained. The model simulation results for 140 hours runtime with minimum capacity indicate that the capacity utilization percentage of spinning preparatory machines remains the same with the use of combined process in spinning and knitting. The traditional process and new
combined process can offer the same capacity utilization for transportation operations of knitted fabrics. The transportation capacity utilization will depend upon the order size and locations. The transportation of roving bobbins can be introduced in the model if the locations of manufacturing operations are different. Return of empty roving bobbins can also be introduced by addition of another transportation cycle to the model. Here the standard data is referred to get transportation capacity utilization assuming a dedicated transport system.
Figure 5.18: Simulation model with spinning and knitting processes.
However, the capacity utilization of knitting is reduced in combined process while operating with same capacity in the earlier spinning preparatory process. This can be attributed to the differences in batch sizes arising due to difference in weight of individual cone as compared to roving bobbin as well as different number of spindles in roving frames as compared to number of positions on winding machines. The difference in speed as well as number of spindles per roving frame as compared to number of winding positions per machine creates difference in the size and frequency of batch. If the number of spindles on roving frames are 120 which corresponds to the number of feeders on Corizon®, it is found that the capacity utilization at knitting can be 100% as shown in Figure 5.20(c). The same result can be obtained if there are 192 feeders on Corizon® unit.

Figure 5.19: Capacity utilization in spinning in the supply chain with (a) traditional process and (b) combined process.
Figure 5.20: Capacity utilization of knitting in the supply chain with 
(a) traditional process. 
(b) combined process (4 rovingframes with 192 spindles each). 
(c) combined process (7 rovingframes with 120 spindles each).

Figure 5.21: Capacity utilization of transportation in the supply chain with 
(a) traditional process and (b) combined process.
5.12 The decision model

The decision model can be derived from the available data for the technology and supply chain. Various aspects considered in this case study and their inter-relationships can be considered to develop the final model from the factors already discussed. In the entire case study, there are different sub-models as indicated here.

- Raw material availability, special needs of the process and associated cost.
- Country specific parameters
  - Model for electrical energy consumption.
  - Cost of labor and requirement of trained workforce.
  - Space needed for the plant and machinery and related cost.
- Capital Investment in plant, machinery and land.

5.12.1 Sub-model for fibers as raw material for new technology

The selection of particular fiber for manufacturing will depend upon the demand at that specific time. The fiber cost is clearly a time dependent parameter and there are high fluctuations from fiber to fiber as well as period to period and across different countries.

In the knitting of ring yarn fabric, the contribution of raw material cost in terms of USD per meter varies between 0.157 USD/ m² (42.8 % of total cost) for USA to 0.314 USD/ m² (65.9 % of total cost) for Egypt. Thus, it is essential to review the fluctuations in fiber cost and its availability across countries. The data can be helpful in determining whether the cost benefit in several other factors, gained due to augmented performance of technology can be realized or the rising cost of raw materials swallows the gain. The range of fiber cost is indicated as the lowest and highest cost in Table 5.15 (ITMF, 2016).
Table 5.15: Variation in the cost of cotton as raw material across different countries (ITMF, 2016).

<table>
<thead>
<tr>
<th>No.</th>
<th>Type of yarn</th>
<th>Min. Fiber Cost (USD/kg) and Country</th>
<th>Max. Fiber Cost (USD/kg) and Country</th>
<th>Difference %</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Ring Yarn 30's Ne combed ring yarn</td>
<td>1.313 USA</td>
<td>2.623 Egypt</td>
<td>99.77</td>
</tr>
<tr>
<td>2</td>
<td>Rotor Yarn 20's Ne carded rotor yarn</td>
<td>1.235 USA</td>
<td>2.556 Egypt</td>
<td>106.9</td>
</tr>
</tbody>
</table>

The fiber cost for manufacturing a standard parameters single jersey knitted fabric with rotor yarn is the least expensive option in case of USA as compared to all other countries. The cost of manufacturing knitted fabric from ring yarn is more challenging as there is stiff competition in pricing among different countries, which includes US, India, Brazil, Korea and Turkey (Dhandhania V. K., 2015).

The data also shows that the cost of cotton fibers is lowest for United States as there is about 100 % difference between the minimum and maximum cost. The important findings from the sub model are listed in Table 5.16.

Table 5.16: Sub-model for fibers as raw material for new technology in the process combination of spinning and knitting.

<table>
<thead>
<tr>
<th>Type of parameter</th>
<th>Classification</th>
<th>Findings</th>
</tr>
</thead>
<tbody>
<tr>
<td>Time dependent</td>
<td>Raw material availability</td>
<td>Cotton fiber yield is highly variable with its impact on pricing.</td>
</tr>
<tr>
<td></td>
<td>Country wise differences in cost</td>
<td>Cotton fibers cost variability are high due to several reasons that depend on the time fibers are purchased. From country to country the causes are entirely different.</td>
</tr>
<tr>
<td></td>
<td>Factors affecting yield and cost of fibers</td>
<td>The yield is affected by environmental parameters, spread of diseases on cotton plants and resulting is cost escalations.</td>
</tr>
</tbody>
</table>
5.12.2 Sub-model for country specific parameters

Despite several advantages it needs to be confirmed whether process combination is the superior alternative to achieve the benefits such as energy saving, waste reduction and cost reduction through other savings. The cost of power and availability of power is changing from country to country. Theoretically Corizon® technology offers the lowest power cost per kg. of knitted fabric production. The preference of technology and various country specific parameters are indicated in Table 5.17. For all the technology specific parameters listed in theoretical framework, Corizon® and spin-knit technology appears to be preferred technology.

Table 5.17: Country specific parameters and decision points.

<table>
<thead>
<tr>
<th>Type of parameter</th>
<th>Classification</th>
<th>Preference</th>
<th>Comparative advantage over the traditional process</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electric power cost</td>
<td></td>
<td>Corizon®</td>
<td>Lowest cost as compared to all other processes. 54% less as compared to ring spinning and knitting.</td>
</tr>
<tr>
<td>Labor cost</td>
<td></td>
<td>Corizon®</td>
<td>48% saving in spinning labor cost</td>
</tr>
<tr>
<td>Land cost, interest and depreciation</td>
<td></td>
<td>Corizon®</td>
<td>Although it varies from location to location, the reduction in manufacturing capacity can offer proportional saving in cost of land, buildings and depreciations.</td>
</tr>
<tr>
<td>Supply chain for raw materials</td>
<td>United States</td>
<td>Low cost of cotton which is about 100% less than the maximum.</td>
<td></td>
</tr>
</tbody>
</table>

5.12.3 Sub-model for capital investment

As described in the case study, the elimination of ringframe and winding process results in the reduced machine capacity requirements for the same volume of production in combined process. This can be an opportunity to achieve saving in capital investment costs. The depreciation and interest rates are also variable form country to country. In such scenario, any advantage in reduced investment cost and depreciation can offer competitive advantage in manufacturing.
5.12.4 Final model for new technology in textile manufacturing with specific reference to combination of spinning and knitting

The final model and interrelationship between various aspects discussed earlier in this Chapter with reference to the combination of spinning and knitting is indicated in Figure 5.22. The symbols are indicated in Table 5.18.

Table 5.18: Symbolic codes of the model for new technology.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Symbol</th>
</tr>
</thead>
<tbody>
<tr>
<td>Parameters influenced by markets and demand</td>
<td></td>
</tr>
<tr>
<td>Parameters related to the manufacturing technology</td>
<td></td>
</tr>
<tr>
<td>Parameters depending on the country</td>
<td></td>
</tr>
</tbody>
</table>

Finally, the analysis leads to the direct and indirect interrelationship between various parameters investigated. The primary motivation for new technology appears to be the waste reduction, increase of process speed and saving in capital investment due to reduced number of machines. Further analysis reveals that the savings in energy consumption in the process and reduced labor requirement are also important parameters in evaluation of the technology. The advantages further results in reduced total energy cost and transportation cost with the choice of suitable destination.
Figure 5.22: Graphical representation of model for new technology in textile manufacturing and supply chain.
CHAPTER 6: CASE STUDY II - DIGITAL TEXTILE PRINTING

6.1 Digital textile printing - historical facts and present status.

The history of inkjet printing begins with Lord Rayleigh’s investigation into the physics of inkjet technology in nineteenth century. However, commercial digital textile printing began in 1970, with its use in carpet printing by Milliken (Ujie, 2006). The combination of punch card system for pattern generation patented by jacquard in 1801 and process of weaving resulted in greater woven design possibilities for textiles. However, digital printing using hardware and software in addition to improved color on the fabric has ushered a new era of quick and efficient printing. The textile printing which began as block printing in ancient times has evolved from manual screen printing in 19th century to automated flat screen printing in 1950s followed by Rotary screen printing in 1960s and high speed digital printing in 2011 (Expand Systems LLC, 2017). The volume of fabric printed with inkjet printing is estimated to increase from 870 million m\(^2\) in 2016 to 1.95 billion m\(^2\) in 2021 at 17.5 \(\%\) compound annual growth rate (Smithers Pira, 2016). The value of global digital textile printing ink business was $ 698 million in the year 2016. With compound annual growth rate of 17.2 \(\%\), from 2017 to 2023, the global digital textile printing ink business is expected to reach $ 2114 million in 2023 (Allied Market Research, 2018). In 1990 Cannon developed a digital textile printer and in the year 1998, Encad introduced modified plotter for digital textile printing. The developments in the year 2000 to 2008 were marked by different modifications of plotters. Since 2008, companies such as MS Printing, Konica Minolta and Atexco developed machines with different types of print-heads. The most remarkable development was the launching of first single pass digital printer ‘LaRio’ by MS Printing Solutions in 2010. The LaRio with incredible delivery speed was found to be suitable for high speed manufacturing of
digitally printed fabrics (Expand Systems LLC, 2017; Carden, Susan, 2016; MS Printing Solutions, 2018).

6.2 Process for digital printing of fabrics

6.2.1 The different manufacturing stages and main decision parameters of digital printing process

These are indicated in Figure 6.1. Digital printing necessitates fabric pretreatment to make the fabric suitable for desired print resolution and avoid migration of the printing ink. The printing ink is to be selected according to the type of fiber in the fabric. Fabric post treatment also varies according to the type of ink selected which ultimately depends upon fiber material in the fabric. The fabric post treatment results in desired print fixation.

![Figure 6.1: Different stages in the manufacture of digitally printed textiles.](image)

6.2.2 Digital textile printing machines

The differences between analog printing and digital printing processes that results in shortened process time are visible from Figure 6.2 and 6.3. There is a difference in the number of stages in printing. The design process gets simplified and faster with digital printing. Currently many manufacturers offer digital printing machines for textiles. There are fundamentally two types
of printing systems. These are continuous type and drop-on-demand type. The drop-on-demand type printers utilize piezoelectric type print heads (Abe, 2012). The technical features of some of those machines are summarized in Table 6.1.

![Diagram of printing process flow](image)

**Figure 6.2:** Analog printing process flow with time duration 1-2 months (Seiko Epson Corporation, 2017).

![Diagram of digital textile printing process](image)

**Figure 6.3:** Digital textile printing process with time duration of 1-2 days (Seiko Epson Corporation, 2017).

On the basis of mechanism of printing head, the digital printing technologies can be classified as shown in Figure 6.4.
Figure 6.4: Classification of inkjet technologies for fabric printing (Tyler, 2005).

Figure 6.5: (a): Print designs with 600 DPI. (b): Print designs with 600 DPI. (c): Print designs with 300 DPI. (d): Print designs with 125 DPI. (e): Print designs with 72 DPI. (Kisspng.com, 2017; Cockerham, 2017; DeviantArt, 2018; Exhibit Factory LLC, 2018).

The speed of digital printing machine is different for different DPI (dots per inch) resolutions of the print design. However, the DPI resolution of 600 X 600 or less such as 172 X
172 DPI for designs as indicated in Figure 6.5, can provide more than satisfactory image quality for the design on fabric.


<table>
<thead>
<tr>
<th>Technical Specifications</th>
<th>MS Printing Solutions</th>
<th>MS Printing LaRio</th>
<th>Konica Minolta Passenger PRO 1000</th>
<th>Single Pass Pike inkjet Printer</th>
<th>Mimaki TX300P-1800</th>
<th>Mutoh ValueJet 1938TX</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Production Speed</strong></td>
<td>99 – 960 m²/hr up to 8 colors</td>
<td>14400 m²/hr</td>
<td>1000 m²/hr</td>
<td>333-4440 m²/hr</td>
<td>68 m²/hr in 4 color mode.</td>
<td>85 m²/hr</td>
</tr>
<tr>
<td><strong>Production Speed CMYK</strong></td>
<td>180–1472 m²/hr</td>
<td>----</td>
<td>-------</td>
<td>-------</td>
<td>68 m²/hr in 4-color mode.</td>
<td>-------</td>
</tr>
<tr>
<td><strong>Printing heads</strong></td>
<td>4-32</td>
<td>25</td>
<td>81 Drop on-demand piezo inkjet technology</td>
<td>43 On-demand piezo, four print heads in an in-line configuration</td>
<td>Two, Drop on demand piezo</td>
<td></td>
</tr>
<tr>
<td><strong>Dpi resolution</strong></td>
<td>600 x 600 dpi</td>
<td>600 x 600 dpi</td>
<td>540 X 360 (360-1400 dpi range)</td>
<td>1200 x 1200 dpi</td>
<td>60, 540, 720, 1080, 1440 dpi</td>
<td>1440 dpi</td>
</tr>
<tr>
<td><strong>Drop Size</strong></td>
<td>4-72 picoliter</td>
<td>4-72 picoliter</td>
<td>2–10 picoliter</td>
<td>5-25 picoliter</td>
<td>-------</td>
<td></td>
</tr>
<tr>
<td><strong>Printing width and roll size</strong></td>
<td>180 cm-320 cm</td>
<td>320 cm</td>
<td>185 cm</td>
<td>185 cm</td>
<td>192 cm, 88 lbs. max.</td>
<td>190.5 cm, 220 lbs. max.</td>
</tr>
</tbody>
</table>

La Rio digital printer (Figure 6.6) is different than other printers. It has a digitally controlled printing head which dispenses printing ink on the moving fabric. In other digital printers it is the printing head that goes back and forth. This first single pass digital printer can provide improved print quality due to the robust design of the machine (MS Printing, 2017). The Single
Pass ink-jet printer, ‘Pike’ provides Reactive C, M, Y, DK, orange, blue, red, gray and penetration fluid for expanding up to nine colors. Gas-heated dryer is provided with option of 2, 3 or 4-sections including a frequency-controlled exhaust fan for the selected dryer. The drying temperature range is between 70°C and 150°C in 1 or 3 passages.

![Image](image.jpg)

Figure 6.6: MS Printing- La Rio Digital Textile Printing Machine.

### 6.3 Supply chain and the workflow in digital printing

The difference in the production routes and saving in time due to quicker sampling are demonstrated in the outline of conventional screen printing vs. digital fabric printing process in Figure 6.7.

Depending on the roll size, the time needed for digital printing will vary. Assuming roll size of 100 yards (91.44 meters) with 1.85-meter width, printing with Pike single pass ink-jet printer at speed of 4440 m²/hr will complete in two minutes. In addition to this the time for print fixation is another variable. The new business models in digital printing of fabrics makes it easier and quicker to achieve the desired fabric with customized print. This has reduced the total time in order completion to few minutes or hours depending on the lot size.

The level of customization is evident from the possibilities in selection of design, fabric material and printer itself. Spoonflower LLC and Expand systems are few examples of such business model in digital fabric printing.
The new process reduces the eleven-week timeframe to few hours which also includes the shipping time. Only the time needed for shipping and actual fabric printing, is the time needed to complete the order (Spoonflower Inc., 2018; Expandsystems, 2018).

Sample preparation is an important stage in order processing. Digital printing does not need physical sample preparation as the sample can be visualized on computers. The RIP (Raster Image Processor) software is widely used for printing to achieve faster processing of files. The software provides flexibility in design preparation can handle different file types and file sizes. RIP software from Onyx, Colorburst, Image Print, EFI, MatchPrint, Wasatch, Caldera and Ergosoft are commonly used. The ability of computers to accurately display the shade and color is instrumental in this process.
The traditional screen printing processes needed several operations that were time consuming (MS Printing Solutions, 2017). The operating experience on digital printing machines indicates that there is considerable saving in lot changeover timings between inks. The changeover time is just 10 minutes instead of 120 minutes needed for traditional screen printing. The ability of digital printing to process small lots can be partly attributed to the saving in lot changeover time and partly to the elimination of operations such as color kitchen and preparation of screens (MS Printing Solutions, 2017). The strength of some digital printing machines lies in their capability to process small batches. The newer digital printing machines such as MS LaRio can operate at speeds of 75 meters per hour. The supply chain, that earlier consisted of manufacturers and distributors of printing ink, fabric producers, pre- and post- treatment finishes, printing and finishing equipment, color calibration tools, printers, and retailers, has undergone revolutionary changes. The advent of single pass digital printers operating at very high speed about 240 m²/min and capable of economic runs as small as 1000 meters will be instrumental in widespread use of digital fabric printing technology.

6.4 Process stages and variables to be selected in the manufacture of digitally printed fabrics.

6.4.1 Printing ink selection, fabric pretreatment and print fixation

According to the type of fiber in the fabric, there are different types of printing ink to be selected as mentioned in Table 6.2.

Table 6.2: Type of fiber in the fabric and selection of dye or printing ink. (Impression Technology Pty Ltd, 2016; Mimaki, 2017; ZIMMER AUSTRIA- Kufstein, 2017).

<table>
<thead>
<tr>
<th>No.</th>
<th>Fiber</th>
<th>Preferred Type of Digital Printing Dye</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Cotton</td>
<td>Reactive dye, pigment ink, Vat dye</td>
</tr>
<tr>
<td>2</td>
<td>Silk</td>
<td>Acid dye, pigment ink</td>
</tr>
<tr>
<td>3</td>
<td>Wool</td>
<td>Acid dye, pigment ink</td>
</tr>
<tr>
<td>4</td>
<td>Polyester</td>
<td>Disperse dye (sublimation), pigment ink, Vat dyes</td>
</tr>
<tr>
<td>5</td>
<td>Nylon</td>
<td>Acid dye, pigment ink</td>
</tr>
</tbody>
</table>
The fabric finishing is necessary in order to achieve the dye fixation after digital printing. Different types of inks used for different fiber material needs customized processes for fixation of the print on fabric as indicated in Table. 6.3. In case of disperse dye and pigments, the print fixation is achieved by heat treatment (Mimaki, 2017). Fixation of printing ink needs steam-wash-dry and dry-heat application according to the type of printing ink used. The customization requirements in pretreatment, post treatment and selection of printing ink as per the fiber in the fabric are the important features of this process. The need of specific fixation technique, the requirement of drying, pretreatment which consumes water and electricity are factors that further increase the requirements of the shortened process.


<table>
<thead>
<tr>
<th>Sr. No.</th>
<th>Type of printing ink</th>
<th>Pretreatment</th>
<th>Fixation method</th>
<th>Temperature</th>
<th>Process Time</th>
</tr>
</thead>
</table>
| 1       | Acid                 | Pretreated fabric | Steam-wash-dry | 212-214°F  | Atmospheric steamer – 20 minutes  
Pressurized steamer – 40-60 minutes |
| 2       | Reactive             | Pretreated fabric | Steam-wash-dry | 212-214°F  | Atmospheric steamer – 8-10 minutes  
Pressurized steamer – 20-30 minutes |
| 3       | Pigment              | Pretreated fabric | Dry-Heat       | 325-350°F  | Curing in oven-30-90 Seconds |
Direct print on fabric-Needs curing and washing |
| 5       | Vat                  | Pretreated fabric | Steam-wash-dry | 230-266°F  | Steaming for 1-10 minutes,  
Thermosol for polyester |
6.4.2 Selection of fabric and effect of fabric surface

The application of digital printing is not limited to apparel fabrics. It is also widely used in printing technical and industrial textiles as well as home furnishing products. The fabric surface properties are important to achieve required shade, color and resolution of designs.

Digital printing needs the fabric surface to be anti-bleeding to achieve these goals. To reduce the bleeding of ink on the fabric to be printed, plasma modification of fabric surface is investigated by Zhang and Xiaoping (2015). They found improvement in bleeding properties without any effect on fabric properties. The supply chain for fabrics needs to fulfill those requirements of fabrics. The additional processes may increase the cost of fabric.

6.4.3 Printing cost and cost of digital printer

The cost of digital printer is another constraint that may limit the profitability of the manufacturing unit. The initial cost of Mutoh America Inc. digital textile printer 1938-TX is USD 39,995 (in 2017) and its wide range of applications includes soft signage, custom apparel, high fashion, flags, scarves, upholstery, interior décor, fine art, trade show graphics, light boxes and sportswear (Mutoh Inc., 2017). Also, the leasing option makes it very convenient for the investors to buy such machines. Thus, the cost of digital printing machines may not become a hindrance at the destinations where the investment comes at low interest rates. The capital interest rates are indicated in Figure 6.8. The interest rate ranges from 4.25 % for USA to 14.24 % for Brazil (ITMF, 2014). The traditional screen printing needs screens and cylinder cleaning which consumes around 500 liters of water and also needs wastewater disposal. This coupled with the cost of fabric preparation, maintenance operations and associated downtimes in case of traditional screen printing, results in cost increase that may be the savings in case of digital printing.
6.5 Energy consumption and total power cost

Energy consumption in digital printing includes the energy needed for pretreatment as well as post treatment. Pretreatment by adding thickener enables to achieve print resolution by preventing the dye migration from substrate and improves fabric handle. The low viscosity of ink in digital printing necessitates the pretreatment to prevent wicking. Post Treatment usually consists of dye fixation by steam. The choice of pre-treatment and post-treatment depends upon intended end use (Tyler, 2005).

Now, calculating the power consumption for Konica Minolta Nessenger SP-1, single pass digital textile printer with 6400 m²/ hour speed as per the data from machine manufacturer. The printer includes scanning unit and a fabric transport unit (Konica Minolta Inc., 2018). The power supply consists of AC 200-240 V, 125 A.

Power consumption for digital textile printing machine

\[
\text{Power consumption} = \text{Voltage} \times \text{Current}
\]

\[
= 220 \times 125
\]

\[
= 27500 \text{ W} = 27.5 \text{ kw (Assuming power factor =1)}
\]
Power consumption for dryer

\[ = 50 \text{ kw (Maxi-D from MS Printing Solutions)} \]

Total power consumption in digital textile printing including dryer

\[ = \frac{(27.5+50)}{6400} \text{ kwh/m}^2 \]

\[ = 0.01211 \text{ kwh/m}^2 \]

The cost of electricity in US is 0.053 USD/kwh. So, power cost per square meter of fabric is

Power cost for digital textile printing = \[0.01211 \times 0.053 = 0.000642 \text{ USD/ m}^2\].

Rotary screen printing machine requires 70-115 kw power and the speed is 4-80 m/min with printing width 125-325 cm (SHREE LAXMI Precision Engineers, 2017). For 185 cm width and 80 m/min speed the machine can print 148 m\(^2\)/ min.

The power consumption in rotary screen printing = \[\frac{115}{148 \times 60}\] = 0.01295 kwh/ m\(^2\)

The cost of electricity in US is 0.053 USD/kwh. So, power cost per square meter of fabric is

Power cost for rotary screen printing = \[0.01295 \times 0.053 = 0.000686 \text{ USD/ m}^2\].

Electricity, steam and natural gas consumption in conventional dyeing and finishing operations for

Knits preparation and yarn dyeing

\[= 0.174 \text{kwh/kg (Cotton Inc., 2012)}\]

Cost @0.053 USD/kwh \[= 0.0092 \text{ USD/kg}\]

\[= \frac{0.0092}{8.33} \text{ USD/ m}^2 \text{ (Assuming 120 grams per square meter fabric weight)}\]

\[= 0.0011 \text{ USD/ m}^2\]
Knits preparation and batch dyeing

\[ \text{Cost} = 0.216 \text{ kwh/kg} \]

Cost @0.053 USD/kwh

\[ = 0.0114 \text{ USD/kg} \]

\[ = \frac{0.0114}{8.33} \text{ USD/m}^2 \text{(Assuming 120 grams per square meter fabric weight)} \]

\[ = 0.001137 \text{ USD/m}^2 \]

Thus, the power cost of digital textile printing process is 6.4 % less as compared to rotary screen printing.

Power cost in case of rotary screen printing including the knit preparation and yarn dyeing

\[ = 0.000686 + 0.0011 = 0.001786 \text{ USD/m}^2 \]

Power cost in case of rotary screen printing including the knit preparation and batch dyeing

\[ = 0.000686 + 0.001137 = 0.001823 \text{ USD/m}^2 \]

Power cost for digital textile printing is 64 % less as compared to rotary screen printing including the knit preparation and yarn dyeing. Considering knit preparation and batch dyeing in traditional process the saving in power cost can be 64.8 % with digital textile printing. Energy requirements for producing textile fiber are indicated in Table 6.4.

Table 6.4: Total energy consumption in the production of fibers (Dawson, 2012).

<table>
<thead>
<tr>
<th>No.</th>
<th>Fiber</th>
<th>Energy (GJ/ton)</th>
<th>Energy (kwh/kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Flax</td>
<td>10</td>
<td>28</td>
</tr>
<tr>
<td>2</td>
<td>Organic cotton</td>
<td>15</td>
<td>42</td>
</tr>
<tr>
<td>3</td>
<td>Cotton</td>
<td>55</td>
<td>154</td>
</tr>
<tr>
<td>4</td>
<td>Wool</td>
<td>65</td>
<td>182</td>
</tr>
<tr>
<td>5</td>
<td>Viscose</td>
<td>100</td>
<td>280</td>
</tr>
<tr>
<td>6</td>
<td>Polypropylene</td>
<td>115</td>
<td>322</td>
</tr>
<tr>
<td>7</td>
<td>Polyester</td>
<td>125</td>
<td>350</td>
</tr>
<tr>
<td>8</td>
<td>Recycled Polyester</td>
<td>65</td>
<td>182</td>
</tr>
<tr>
<td>9</td>
<td>Acrylic</td>
<td>175</td>
<td>490</td>
</tr>
<tr>
<td>10</td>
<td>Nylon</td>
<td>250</td>
<td>700</td>
</tr>
</tbody>
</table>
Energy required for production of textile fiber can be added to the calculation of total energy consumption. The energy requirement in production of yarn and fabric will depend upon the manufacturing technology used.

6.6 Manpower requirements for the new technology in textile printing

The new technologies may have limited scope to reduce the labor cost. This is evident from the fact that the new equipment and technology is costlier than the analog printing. Also, the replacement costs in case of any part damage can be very high. To avoid the occurrence of damages due to lack of expertise it is always preferable to train the workforce and opt for skilled workforce even if the wage cost increases. Thus, reducing the low skilled operator requirement and increasing high skilled operatives and other employees can be the viable option. The labor cost also highly variable among different countries. A new world bank report ‘Trouble in the Making? The Future of Manufacturing-Led Development’ recommends focus on three dimensions for a new policy agenda that will enable developing countries to benefit from the change resulting from manufacturing development. The agenda should be focused on competitiveness by using new technology and giving up the low wage criteria, capabilities improvement by skilled workforce availability combined with necessary infrastructure and connectedness by removing trade restrictions on manufactured goods coupled with improving logistics.

The reshoring of production of shavers by Philips, Netherlands and production of sneakers by Adidas are examples of how the cost saving by new technology enabled reshoring of production and overcome the high wage cost disadvantage (World Bank Group, 2017).

6.7 Economical advantages in floor space consumption by using digital printing technology

The traditional rotary screen printing machine consists of rotary screen equipment and dryer as indicated in Figure 6.9. The diagram indicates a machine with twelve printing heads and
60 m/min. speed. Here ‘A’ indicates length of printing device, ‘B’ indicates total length of machine, ‘C’ is the printing width. ‘D’ is the machine width and ‘E’ is the width including side spaces.

The space requirement of different digital fabric printing machines is indicated in Table 6.5. Konica Minolta NASSENGER SP-1, Single Pass Printer Layout is indicated in Figure 6.10. The total area in square meters per machine for digital printing machine in this case is (26.180 x 5.435), 142.29 M$^2$ while the area for traditional rotary printing machine is (31.985 x 7.655), 244.85 M$^2$. Thus, digital printing saves 42 % floor space area for the installed machines.

Figure 6.9: Traditional rotary screen printing process which requires 244.85 M$^2$ area (Mitter GmbH & Co., 2017).
Table 6.5: Digital Printing machine space requirements (Konica Minolta, 2017; Mitter GmbH & Co., 2017; Mimaki, 2017).

<table>
<thead>
<tr>
<th>No.</th>
<th>Machine make</th>
<th>Dimensions (LxWxH) Meters</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Konica Minolta- Nassenger single pass printer (Including dryer)</td>
<td>26.180 X 5.435 X 2.540</td>
</tr>
<tr>
<td>2</td>
<td>Mitter GmbH DYR-21 Rotary screen printing machine</td>
<td>31.985 X 7.655X 3600</td>
</tr>
<tr>
<td>3</td>
<td>Mimaki Tx300P-1800B Dryer Ecovapor steamer for fixation Mimaki ecovapor 210</td>
<td>3.197 x 1.798 x 1.845</td>
</tr>
</tbody>
</table>

Figure 6.10: NASSENGER SP-1, Single Pass Printer Layout which requires 142.29 M² area (Konica Minolta, 2017).
6.8 Environmental concerns due to wastewater and other contaminants

The wastewater in the textile dyeing has high BOD/COD and other contaminants including the color (Wang, Xue, Huang & Liu 2011). The process of rotary printing as well as digital printing consumes water and steam. The process of washing releases pollutants in the atmosphere. In the process of rotary printing, suspended solids, solvents, foam, metal, color are released, and these contaminates the water resources where they are drained. It is important to achieve the goal of reduced pollution by taking proper measures such as selecting right ingredients in the process, training employees and making changes in the design of process and equipment. Also, alternatives to urea need to be investigated in order to reduce nitrogen release (Karthikeyan & Alexander, 2008).

With the advancement of digital printing, the elimination of color kitchens and printing screens reduce the atmospheric pollution by reducing the contaminants in the wastewater. However, the washing process and cleaning process still release chemicals in the wastewater. Also, the pretreatment and post treatment on the fabric consumes energy and water.

6.9 Simulation model for digital textile printing process flow

The Matlab SimEvents® based model of digital textile printing process flow is demonstrated in Figure 6.11. The process simulation model can be run for desired time units. The model inputs are process speed, time and outputs are capacity utilization, no. of orders processed, and utilization of transportation. The model can also be further extended to include any new parameters under consideration. The supply chain and manufacturing plants with finished goods transportation activities can be integrated with demand generation pattern. Projection of demand pattern can be another topic of research; therefore, the model used here is input with assumptions.
Entering the right estimate of demand can further enhance the capabilities to predict utilization of available capacities.

The assumptions used here are:

1 cycle = 1 entity = 1 order

order size = order_size_meters

FIFO queue∑

Process 1 to 6 and transportation of finished fabrics.

Service time (Hours) = entity.order_size_meters / machine speed (m/hr)

There are six processes- For each process service time for unit production meter:

Service time1 = 1/ (no. of machines*machine speed)

Server-1- 6 represents six different stages in the process.

Server 7 represents transportation and corresponding transportation Time

FIFO Queue:

For each order, there is a queue.

Finally, the plots for orders processed and capacity utilization are obtained and can be compared for different alternatives available.

The order generation pattern can be identified and inserted at the beginning of the simulation to get the actual projections.

Entity

Event actions

Insert pattern

Repeating sequence

Random number
Figure 6.11: Simulation model for digital textile printing process flow.
Considering on example:

<table>
<thead>
<tr>
<th>Operation</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Order size</td>
<td>10,000 meters</td>
</tr>
<tr>
<td>Fabric pretreatment</td>
<td>80 m²/hr (2-meter width)</td>
</tr>
<tr>
<td></td>
<td>40 m/hr (linear meter)</td>
</tr>
<tr>
<td>No. of pretreatment machines</td>
<td>120</td>
</tr>
<tr>
<td>Digital printing</td>
<td>75 m/min</td>
</tr>
<tr>
<td></td>
<td>60 × 75 m/hr</td>
</tr>
<tr>
<td></td>
<td>4500 m/hr (For 320 cm width)</td>
</tr>
<tr>
<td>Transportation speed</td>
<td>8 hr/lot</td>
</tr>
<tr>
<td>Transportation capacity</td>
<td>1 order (10 orders maximum as per norms for weight from Federal Highway Administration U.S. Department of Transportation, 2015).</td>
</tr>
</tbody>
</table>

Assuming production for six-day week and 17.5 shift (8 hour each shift) operational time, total 140 hours are obtained. Simulation results for 140 hours run time are indicated in Figure 6.12 (a), (b) and (c) for 120 machines for fabric pretreatment and one digital printing machine with above specifications.

All the previous operations such as image and design preparation, image loading is not interrupting the production process. The supply chain model should be able to utilize the appropriate machines with suitable production rates and continuous operation without any need of fabric pretreatment. Thus, the supply chain model with separate entities in pretreatment and digital printing can be feasible option to achieve short runs of designs.
6.10 Other approaches in process combination with digital printing and their limitations

The combination of digital printing and weaving is a demanding approach as it gives rise to the necessity of evolving a suitable sizing agent as well as the subsequent finishing process. The solutions prepared from water, sodium carbonate, urea, thickener, and silica were proposed to be utilized as sizing as well as print fixing agent. But the efforts to obtain a sizing agent that can also function as print fixative agent in printing with reactive dyes, achieved limited success and thus combination of weaving and printing haven’t been commercialized (Ujiie, 2006). Thus, it appears that there is a need of systematic approach towards advancement
of technologies as the success of one technology ensures the success of another one as well as the entire manufacturing and supply chain. Individual efforts in isolation would limit the success of technologies.

6.11 Model for new technology in textile manufacturing with specific reference to digital printing

The various symbolic codes used in the graphical representation are indicated in Table 6.6. The various aspects discussed earlier in this Chapter are summarized in the model indicated in Figure 6.13.

The further analysis reveals that the major benefit in the process shortening is achieved by elimination of color kitchen, screen preparation, ink changeover, design changeover, fabric changeover and space requirement for the machines respectively.

Table 6.6: Symbolic codes of the model for new technology.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Symbol</th>
</tr>
</thead>
<tbody>
<tr>
<td>Parameters influenced by markets and demand</td>
<td></td>
</tr>
<tr>
<td>Parameters related to the manufacturing technology</td>
<td></td>
</tr>
<tr>
<td>Parameters depending on the country</td>
<td></td>
</tr>
</tbody>
</table>

The major hurdle in the process continuity is the fabric pretreatment. Without fabric pretreatment, the process throughput increases in the continuous process. Although, there is use of water in the digital printing process, the reduction in release of effluents is achieved by eliminating processes that were indispensable, in rotary screen printing. The ability to process small batches due to absence of time consuming changeover operations is the major advantage that enables reduced lead time.
Figure 6.13: Graphical representation of important considerations in the model for new technology in textile manufacturing and supply chain.
CHAPTER 7: CONCLUSIONS, LIMITATIONS AND FUTURE SCOPE

7.1 Conclusions

The case study approach was adopted to investigate the impact of new technologies on textile supply chain. The two emerging technologies finalized for case study were spin-knit technologies and digital printing. Both these technologies are introduced in manufacturing at different time period and they are at different stages in the manufacturing operations of textiles as well as at different stages of their adoption in the textile industry. Spin-knit technology is at the beginning while digital printing is near the ending point in the entire manufacturing process. These are distinct sequential positions in the textile supply chain. One process is at the start and the other is near the end of supply chain. In both cases the requirements are different. Raw materials are having different constraints. In case of knitting combined with spinning, the constraint is type of fibers. However, in case of digital printing, the process constraint is the need of fabric pretreatment. Both factors are affecting the respective processes.

A theoretical framework for analysis of new technology has been established. Inputs are defined for the manufacturing process and new model. Outcome of the model establishes a basis for selection of the new technology.

7.1.1 Conclusions for Case Study-I: Process combination of spinning and knitting

In case of spin-knit technologies the availability and cost of cotton fibers as a raw material is highly variable with time. There are countrywide differences in the cost of cotton fibers due to several factors such as variations in yield and government policies. The data of supply chain for cotton fibers indicates that united states is the most preferred source since the cost of fiber is the lowest among all other major cotton producing countries.
The country specific factors were analyzed to arrive at the decision regarding selection of technology. It was found that Corizon® is the game changer technology as it requires:

- 54 % reduced power cost.
- 48 % less labor cost in spinning.
- reduced land cost, interest and depreciation cost in spinning.

The additional capital investment is another consideration that is affected largely by interest and depreciation cost which are variable from country to country.

The simulation of manufacturing and supply chain process using Matlab SimEvents® software is found useful in determining the process capacity utilization, optimum capacity and size of batches in the batch production. Further the simulation using Matlab SimEvents®, can be used to predict the need of transportation capacity for different scenarios in the manufacturing operations. The Matlab model can also be used to determine the effect of reducing or increasing the number of machines at different stages on the throughput and capacity utilization at different stages in spinning and knitting as well as combined spinning and knitting. An excel sheet model was developed to include all the variables in spinning and knitting process and determine minimum number of machines at every stage beginning with blowroom. The Matlab model can be useful to determine batch sizes possible with different process variables. Another Matlab model indicating two different processes and transportation, was prepared and customized for spinning and knitting as separate operation and combined operations.

The analysis of the batch process reveals that:

- The use of roving bobbins instead of cones results in differences in feed package sizes at knitting as a result of differences in roving bobbin weight and cone weight.
• Another difference is the batch size as a result of difference in number of feeders on the combined spin-knit (Corizon®) machine and number of spindles on the roving frames.

• The use of number of spindles of roving frames equal to the number of feeders on the spin-knit machine provides maximum capacity utilization due to matching batch sizes. Presently the Corizon® machine is having maximum 120 feeders, so the roving frame should be with 120 spindles.

7.1.2 Conclusions for Case Study-II: Digital Printing

The advancements in digital textile printing are reviewed in this case study. The advancements such as single pass digital printers operating at very high speed, has brighten the future prospect of this technology. Beginning with Milliken’s digital carpet printing machine ‘Millitron®’ in 1970 to the introduction of single pass high speed digital textile printer LaRio by MS Printing Solutions in 2010, the capabilities of digital textile printing have undergone tremendous improvements, but it required substantial time period of four decades.

The theoretical framework is applied to investigate the impact of this technology on textile supply chain. The power cost is found to be reduced by 64 % if we consider knit preparation and yarn dyeing. Addition of the energy required in fiber and yarn production can be helpful in determining the overall reduction in energy cost.

Digital textile printing may result in 42 % savings in machine floor space. The requirement of less in number but high in skill operatives can be an opportunity as it will make it possible to give up the low wage criteria improving the chances of success of the new technology even in the high wage countries.
The Matlab simulation of digital textile printing supply chain can be carried out by using Matlab SimEvents® and it is possible to determine the machine capacity utilization as well as transportation capacity utilization. New supply chain model in the digital fabric printing such as Spoonflower Inc., have resulted in shrinking of timeframe required for completion of an order. The convenient design process using software, elimination of time consuming operations and the high speed of machines are all pointers to the success of digital textile printing technology.

Improvement in the lead time with digital printing is the result of elimination of time consuming operations in the conventional rotary printing process. The reduction in lot changeover time, high speed of digital textile printing machines and their ability to process smaller batches in reduced time are the strength of digital textile printing. The ecological footprints are reduced due to elimination of processes that tends to release harmful contaminants in the wastewater. Digital fabric printing technology is advancing rapidly with the introduction of advanced printing heads and developments in printing ink. If it becomes possible to avoid fabric pretreatment and post-treatment, it will further reduce use of water as well as release of atmospheric pollutants from the process, in addition to reducing the energy cost.

The factors such as need of fabric pretreatment, post treatment and roll size in digital fabric printing are variables, which may affect the actual performance of the process. These variables are depending on the type of fabric and size of orders as well as roll size in digital printing.
7.2 Limitations and future scope

In this work data is obtained from various sources including machinery manufacturers manuals, research journals, reports from reputed international organizations and data from government and world bank websites. The data is assumed to be accurate and all the sources of data are mentioned. The data collected from different sources were also found to be indicative of their methodology.

The Corizon® and spin-knit technologies have not yet been widely adopted in the industry. So, the operating experience is not reported by any organization. The total energy consumption includes the energy requirements for air conditioning, illumination and compressors etc. which are not taken into account as these are highly variable. The reduction in power consumption in case of Corizon® knitting due to reduced illumination and air conditioning is not appearing in the calculation of power cost.

The power consumption may slightly change due to the need of reduced number of spindles per machine on the roving frames and increased number of roving frames in case of Corizon® knitting. Corizon® machines are spinning yarn using air jet spinning technology. It is assumed that the waste generated in the Corizon® spinning unit will be the same as air-jet spinning. Data on air jet spinning waste is an assumption that is based on theoretical reports. However, the optimization of waste may result in lower levels of waste extraction and further depends on the type of fibers. Cotton fibers have high variabilities.

Indicators of operational performance of the process are speed, efficiency, utilization of capacity in manufacturing and supply chain and waste generated in the process. In the calculation for particular yarn count and fabric parameters the actual processing variables may be slightly different than the theoretical considerations due to different needs of processing
parameters for different varieties of fibers. The process speeds can be different for different fiber materials and types of yarn. In order to obtain correct estimates with different set of variables, the values of processing variables can be entered in the model and the Figures can be recalculated. Bobbin flow in the process combination of spinning and knitting can be different at different plants and different cases, thus affecting the actual performance of the process.

An evaluation can be further carried out to examine whether the process could further shorten the spinning line by eliminating roving and use sliver instead of roving. Also, in the spinning process, there is a need of some new concepts in the short staple spinning that will enable to overcome the limitations due to package size, the matching of delivery speeds of different machines and variabilities in natural fiber length. Advancements in fiber manufacturing and attaining improved fiber properties as well as developments in spinning machinery can open up new possibilities in process combinations and continuity in the process. A continuous and shortened process can further bring changes in the supply chain.

The new technology generates new requirements such as need of dyed roving bobbins for spin-knit machines in case it is needed to use dyed yarn in knitting. In this case machines will be needed for dyeing of roving.

In digital fabric printing there are number of process variables and unique requirements of different types of fabrics made from different fibers. The necessity of fabric pretreatment for the fabrics may increase the energy consumption in the process which will be different in different cases. The minimum and maximum possible range of fabric roll size can be different with different machines. These may affect the minimum possible order size.
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Appendix A

Details of Matlab SimEvents® based model for spinning process, energy and waste in the process combination of spinning and knitting

Figure A.1: Simulation of capacity utilization and waste in the process in the Matlab model for process combination of spinning and knitting.

Figure A.2: Function for calculation of throughput of process in the simulation.

Figure A.3: Process waste function block.
Figure A.4: Function for calculation of process waste and linking waste data from excel sheet to the model.

Figure A.5: Block for energy cost in the process.
Figure A.6: Function for energy cost.

Figure A.7: Subsystem block for all scopes.

Figure A.8: Scopes for plotting energy cost.
Figure A.9: Scopes in the respective subsystem block for plotting process capacity utilization, throughput and waste.

Figure A.10: Configurable subsystem block for entering the data about number of machines and machine speed.
Appendix B

Details for the Matlab SimEvents® based simulation model for manufacturing process and transportation

B.1 Full Matlab Model Hierarchy

Table B.1: Configurable subsystem details.

<table>
<thead>
<tr>
<th>Simulation Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solver</td>
<td>VariableStepAuto</td>
</tr>
<tr>
<td>RelTol</td>
<td>1e-3</td>
</tr>
<tr>
<td>Refine</td>
<td>1</td>
</tr>
<tr>
<td>MaxOrder</td>
<td>5</td>
</tr>
<tr>
<td>ZeroCross</td>
<td>on</td>
</tr>
</tbody>
</table>

Table B.2: Display block properties.

<table>
<thead>
<tr>
<th>Name</th>
<th>Format</th>
<th>Decimation</th>
<th>Floating</th>
</tr>
</thead>
<tbody>
<tr>
<td>Orders Transported</td>
<td>short</td>
<td>1</td>
<td>off</td>
</tr>
</tbody>
</table>

Table B.3: Entity generator block properties.

<table>
<thead>
<tr>
<th>Name</th>
<th>Generation Method</th>
<th>Time Source</th>
<th>Period</th>
<th>Intergeneration Time Action</th>
<th>Generate Entity at Simulation Start</th>
<th>Attribute Name</th>
<th>Attribute Initial Value</th>
<th>Number Entities Departed</th>
<th>Pending Entity in Block</th>
<th>Average Intergeneration Time</th>
<th>Entity Type</th>
<th>Entity Priority</th>
<th>Data Initial Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Order Generation</td>
<td>Time-based</td>
<td>Dial og</td>
<td>1</td>
<td>dt = rand (1,1);</td>
<td>on</td>
<td>order_size_kgs</td>
<td>transportation_time</td>
<td>100</td>
<td>10</td>
<td>off</td>
<td>off</td>
<td>Structured</td>
<td>Ord</td>
</tr>
</tbody>
</table>

135
### Table B.4: Entity queue block properties.

<table>
<thead>
<tr>
<th>Name</th>
<th>Capacity</th>
<th>Queue Type</th>
<th>Priority Source</th>
<th>Sorting Direction</th>
<th>Entity Arrival Source</th>
<th>Multicast Tag</th>
<th>Number Entities Departed</th>
<th>Number Entities in Block</th>
<th>Average Wait</th>
<th>Average Queue Length</th>
</tr>
</thead>
<tbody>
<tr>
<td>Entity Queue</td>
<td>25</td>
<td>FIFO</td>
<td>PriorityAttribute</td>
<td>Ascending</td>
<td>Input port</td>
<td>A</td>
<td>off</td>
<td>off</td>
<td>off</td>
<td>off</td>
</tr>
<tr>
<td>Entity Queue1</td>
<td>25</td>
<td>FIFO</td>
<td>PriorityAttribute</td>
<td>Ascending</td>
<td>Input port</td>
<td>A</td>
<td>off</td>
<td>off</td>
<td>off</td>
<td>off</td>
</tr>
<tr>
<td>Entity Queue2</td>
<td>inf</td>
<td>FIFO</td>
<td>PriorityAttribute</td>
<td>Ascending</td>
<td>Input port</td>
<td>A</td>
<td>off</td>
<td>off</td>
<td>off</td>
<td>off</td>
</tr>
<tr>
<td>Entity Queue3</td>
<td>inf</td>
<td>FIFO</td>
<td>PriorityAttribute</td>
<td>Ascending</td>
<td>Input port</td>
<td>A</td>
<td>off</td>
<td>off</td>
<td>off</td>
<td>off</td>
</tr>
</tbody>
</table>

### Table B.5: Entity server block properties.

<table>
<thead>
<tr>
<th>Name</th>
<th>Capacity</th>
<th>Service Time Source</th>
<th>Service Time Value</th>
<th>Service Time Attribute Name</th>
<th>Service Time Action</th>
<th>Permit Preemption Based on Attribute</th>
<th>Sorting Attribute Name</th>
<th>Sorting Direction</th>
<th>Write Residual Time to Attribute</th>
<th>Residual Time Attribute Name</th>
<th>Number Entities Departed</th>
<th>Number Entities in Block</th>
<th>Pending Entity Present in Block</th>
<th>Number Entitie s Pending</th>
<th>Average Wait</th>
<th>Average Utilization</th>
<th>Number Entities Preempted</th>
</tr>
</thead>
<tbody>
<tr>
<td>Process1</td>
<td>1</td>
<td>LAB action</td>
<td>1</td>
<td>Service Time</td>
<td>$dt = entity.order.size_kgs*[1/(1*C(1)*C(10))+(1/(C(2)*C(11))+(1/(C(3)*C(12))-(1/(C(4)*C(13)))+((1/(C(5)*C(14))+((1/(C(6)*C(15)))+(1/(C(7)*C(16))))];$</td>
<td>off</td>
<td>Preemption Priority</td>
<td>Ascending</td>
<td>off</td>
<td>Residual Time</td>
<td>on</td>
<td>off</td>
<td>off</td>
<td>off</td>
<td>on</td>
<td>off</td>
<td></td>
</tr>
<tr>
<td>Process2</td>
<td>1</td>
<td>LAB action</td>
<td>1.0</td>
<td>Service Time</td>
<td>$dt = entity.order.size_kgs*[1/(C(8)*C(17))];$</td>
<td>off</td>
<td>Preemption Priority</td>
<td>Ascending</td>
<td>off</td>
<td>Residual Time</td>
<td>on</td>
<td>off</td>
<td>off</td>
<td>off</td>
<td>on</td>
<td>off</td>
<td></td>
</tr>
<tr>
<td>Transportation</td>
<td>C(19)</td>
<td>Attribute</td>
<td>5</td>
<td>transport_time</td>
<td>$dt = rand(1,1);$</td>
<td>off</td>
<td>Preemption Priority</td>
<td>Ascending</td>
<td>off</td>
<td>Residual Time</td>
<td>on</td>
<td>off</td>
<td>off</td>
<td>off</td>
<td>on</td>
<td>off</td>
<td></td>
</tr>
</tbody>
</table>
Table B.6: Message viewer block properties.

<table>
<thead>
<tr>
<th>Name</th>
<th>Variable Step Time Precision</th>
<th>History</th>
<th>Show Events</th>
<th>Show State Info</th>
<th>Show Functions</th>
<th>Show Messages</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sequence Viewer</td>
<td>3</td>
<td>5000</td>
<td>on</td>
<td>on</td>
<td>on</td>
<td>on</td>
</tr>
</tbody>
</table>

Table B.7: Block type count.

<table>
<thead>
<tr>
<th>Block Type</th>
<th>Count</th>
<th>Block Names</th>
</tr>
</thead>
<tbody>
<tr>
<td>Entity Queue</td>
<td>4</td>
<td>Entity Queue, Entity Queue1, Entity Queue2, Entity Queue3</td>
</tr>
<tr>
<td>Entity Server</td>
<td>3</td>
<td>Process1, Process2, Transportation</td>
</tr>
<tr>
<td>Terminator</td>
<td>1</td>
<td>Terminator</td>
</tr>
<tr>
<td>Subsystem</td>
<td>1</td>
<td>Configurable Subsystem</td>
</tr>
<tr>
<td>Message Viewer</td>
<td>1</td>
<td>Sequence Viewer</td>
</tr>
<tr>
<td>Entity Generator</td>
<td>1</td>
<td>Order Generation</td>
</tr>
<tr>
<td>Display</td>
<td>1</td>
<td>Orders Transported</td>
</tr>
<tr>
<td>CMBlock (m)</td>
<td>1</td>
<td>Model Info</td>
</tr>
</tbody>
</table>

Table B.8: Model variables.

<table>
<thead>
<tr>
<th>Variable Name</th>
<th>Parent Blocks</th>
<th>Calling character vector</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>C</td>
<td>Process1</td>
<td>C</td>
<td>[1 13 4 4 4 3 16 53 0 1140</td>
</tr>
<tr>
<td></td>
<td>Process2</td>
<td>C</td>
<td>91.14 320.76 320.76 273.6</td>
</tr>
<tr>
<td></td>
<td>Transportation</td>
<td>C</td>
<td>392.98 69.58 19 0 5</td>
</tr>
</tbody>
</table>
Appendix C

Calculations of spinning and knitting machines production, energy consumption and waste

Table C.1: Excel-sheet model for calculation of minimum number of machines and energy consumption at each stage for traditional process.

<table>
<thead>
<tr>
<th>Process</th>
<th>Machine size (No. of positions)</th>
<th>Machine speed at 100% efficiency (kg/hr)</th>
<th>Machine Speed (meter/min) for all deliveries</th>
<th>Grams/ meter of delivered material for 30s Ne</th>
<th>Waste (%) Cotton</th>
<th>Feed-Creeling requirement (no. of packages/cans)</th>
<th>Feed-Minimum Can/Package Capacity (meter)</th>
<th>Feed-Minimum Can/Package Capacity (kg)</th>
<th>Minimum capacity (No. of machines)</th>
<th>Machine efficiency</th>
<th>Total Production Per Machine (kg/hr)</th>
<th>Total Production required (kg/hr)</th>
<th>Energy Consumption %</th>
<th>Total Process Power Consumption (kwh/kg)</th>
<th>Individual Process Machine Power consumption (kwh/kg)</th>
<th>Total Energy Consumption (kwh/kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Blowroom &amp; Aerofeed</td>
<td>1 1200 NA NA NA 5.4 NA NA NA 1 95</td>
<td>1140 2.6 5.28</td>
<td>0.1372</td>
<td>5.43</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Carding</td>
<td>1 93 300 300 5.15 4.5 NA NA NA 12 98</td>
<td>91.14 1088.7 19.7 5.28</td>
<td>1.0401</td>
<td>5.6</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Drawframe-1</td>
<td>1 324 1200 1200 4.5 0.8 8 4000 20.6 4 99</td>
<td>320.7 6 1080 3 5.28 0.1584</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Drawframe-2</td>
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Table C.2: Excel-sheet model for calculation of minimum number of machines and energy consumption at each stage for the process with rotor spinning and air-jet spinning.

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<th>Machine Speed (meter/min) for all deliveries</th>
<th>grams/ meter of delivered material for 30s Ne</th>
<th>Waste (%) Cotton</th>
<th>Feed-Creeling requirement (no. of packages/cans)</th>
<th>Feed-Minimum Can / Package Capacity (meter)</th>
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<th>Minimum capacity (No. of machines)</th>
<th>Machine efficiency</th>
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<th>Total Production required (kg/hr)</th>
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Table C.3: Excel-sheet model for calculation of minimum number of machines and energy consumption at each stage for combined process.

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