

ENERGY CONSUMPTION DETERMINANTS FOR APPAREL SEWING OPERATIONS:  
AN APPROACH TO ENVIRONMENTAL SUSTAINABILITY

by

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AN ABSTRACT OF A DISSERTATION

submitted in partial fulfillment of the requirements for the degree

DOCTOR OF PHILOSOPHY

Department of Apparel, Textiles, and Interior Design  
College of Human Ecology

KANSAS STATE UNIVERSITY  
Manhattan, Kansas

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## Abstract

Fashion is the second most polluting industry and accounts for 10% of global carbon emissions. Consuming fossil fuel based electricity, the primary source of energy in the apparel production process, causes a great deal of greenhouse gas (GHG) emissions. Due to ever-increasing apparel demand and population growth, this industry's carbon footprint will only grow bigger. As attention on sustainability issues in our world intensifies, research on environmental sustainability in the apparel manufacturing industry is needed.

The purpose of this exploratory study was to investigate energy consumption (EC) of the apparel sewing process. The objectives are to (a) identify the most influential EC factors and develop a model to capture EC levels, (b) determine factor interrelationships, (c) identify steps to reduce EC, and (d) explore experts' level of concern regarding EC of the apparel manufacturing and its contribution to greenhouse gas emissions and climate change. A mixed method research study was employed in this study: a qualitative method was utilized to assess expert perceptions and a quantitative method was used to measure EC and build a regression model.

This study determined dominant EC and GHG emissions factors from sewing process so that apparel manufacturers can understand which factors need to be controlled to reduce environmental damage. Findings from the study indicated sewing machine motor capacity, sewing speed, and standard allocated minute (SAM) were the most influential EC factors, and shortening the sewing time was found as the best solution to reduce energy consumption in the apparel sewing process. The energy consumption model was found as:

$$\text{Log (EC)} = 9.283 + 0.771 * \log (\text{SAM}) + 0.386 * \text{knit fabric type} + 0.260 * \text{sportswear fabric type} + 0.080 * \text{SPI} - 0.008 * \text{capacity} + 0.004 * \text{seam length} - 0.001 * \text{speed} + 0.495$$

The EC model along with GHG calculator (a tool to convert GHG from EC) will help the industry to determine their EC and GHG emissions level to boost their awareness and to encourage greater impetus for environmental actions. Finally, this study will help designers, retailers, and consumers to pursue environmentally friendly actions in terms of decisions regarding apparel design, sourcing, and purchasing.

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Approved by:

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Dr. Melody L. A. LeHew

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# **Chapter 1 - Introduction**

## **Background of the study**

For many countries, including current advanced industrialized economies, the textile and apparel (TA) supply chain typically becomes the first rung in the climb toward large-scale industrialization. The textile-apparel supply chain is defined by Jones (2006) as “a series of interrelated activities which originates with the manufacture of fiber and culminates in the delivery of a product into the hands of the consumer” (p. 1). Being a fragmented and heterogeneous sector, the TA industries utilize a wide variety of substrates, processes, machinery, components, and finishing steps (Hasanbeigi & Price, 2012), many of which cause significant environmental damages. The production and consumption of TA negatively impacts the environment, with the greatest damage in terms of water pollution and greenhouse gas (GHG) emissions. The collective industry accounts for 10% of global carbon emissions (Conca, 2015), which is second only to the oil industry. Therefore, the TA supply chain is the second most polluting industry in the world (Sweeny, 2015) and is a major player in global climate change (Hiller Connell, 2015). In addition, the TA supply chain is the second largest polluter of freshwater resources on the planet (Conca, 2015).

The textile and apparel supply chain significantly contributes to global climate change, mostly because its primary energy (mostly electricity) source is fossil fuels. From the report of Intergovernmental Panel on Climate Change (IPCC, 2014), the electricity and heat production sector account for 25% of global GHG emissions, which is the largest in comparison to any other economic sector. Apart from water waste and toxicity from fertilizer, pesticides, herbicides, and other pretreatment and finishing chemicals, converting raw fibers to finished apparel requires a great deal of energy. This energy generation emits carbon dioxide (CO<sub>2</sub>), methane (CH<sub>4</sub>), and

other GHGs. The GHG emissions calculator, developed by the Environmental Protection Agency (EPA, 2013), estimates that generating one kilowatt-hour (kWh) of electric energy emits 0.0007 MTCO<sub>2e</sub> (metric ton carbon dioxide equivalent). These GHGs act as a blanket, insulating the earth's surface and trapping heat radiation. A small amount of GHGs in the atmosphere is safe and required for maintaining a habitable planet. Before the Industrial Revolution, CO<sub>2</sub> concentration in the atmosphere was about 280 parts per million (ppm) (Blockstein & Wiegman, 2010). Current CO<sub>2</sub> concentration is about 400 ppm and climate scientists expect it to rise by 2 ppm every year (Wolfson, 2007). If this happens, by the end of the 2100, the world would experience a CO<sub>2</sub> concentration of 550-600 ppm, which would be catastrophic for life systems on earth (Blockstein & Wiegman, 2010).

In comparison to the machine intensive textile industry, the apparel manufacturing sector's processes like fabric spreading, cutting, sewing, ironing, and finishing are thought to be the environmentally cleanest sector of the TA supply chain because of its more human labor-intensive nature and consequent lower energy consumption (Sule, 2012). However, considering collective energy consumption (mostly electricity) and its associated environmental damages in terms of climate change, in reality, the apparel industry is one of the major consumers of the world's energy (Jananthant, Ameer, & Shiyamini, 2006). Also, according to a United Nations Industrial Development Organization (UNIDO, 1992) report, the electricity consumption share in the Japanese TA production process is estimated as 27% for spinning, 15% for weaving, 7% for knitting, 18% for wet processing, and 10% for apparel manufacturing. While the share of apparel manufacturing is mostly lower than other aspects of TA production, this 10% becomes a matter of concern when considering global production levels of apparel products and meeting clothing needs for over 7 billion people on the planet. In addition, this "cleanest sector" fallacy may lead



scholars, policy makers, environmentalists, and governments to overlook the apparel industry's environmental impact. Perhaps this explains why there is a paucity of environmental research focused on the apparel industry. The need for research is evident to understand better the environmental impact of this sector.

The apparel industry is unique compared to other industries: it is the most geographically dispersed as well as culturally diverse. Nearly every country in the world contributes to and benefits from the global TA supply chain. Some nations are more involved in apparel production while others are more involved in apparel consumption. The augmented demand from the ever-increasing population and fast changing fashions makes this industry dynamic on a global scale, attracting new apparel manufacturers intent on capturing a share of the growing market. New manufacturers mean more apparel production, resulting in more environmental damage. In 2013, among the 160 World Trade Organization (WTO) members, 83 members (including 28 countries in the European Union) were actively involved in apparel production (World Trade Organization, 2014). Therefore, the environmental footprint of apparel production is not only a local problem, but also a global one.

Non-renewable sources of energy such as coal, used to generate electricity, are becoming scarce (Robertson, 2014) and when coupled with the climate change realities linked to energy consumption, the global energy crisis is becoming a more urgent topic. From the triple bottom line (i.e., environment, economic, and social responsibility) perspective, the social responsibility aspect of sustainability has garnered much attention, and improvements have been made within the apparel manufacturing industry. However, there is a lack of information regarding environmental consequences associated with apparel production. Across the board – designers, manufacturers, contractors, retailers, and consumers – there is limited understanding about this

aspect of sustainability. Considering the lack of attention on environmental sustainability in the apparel manufacturing along with the global climate change crisis, research regarding the environmental impacts of clothing production is imperative.

### **Statement of the problem**

In reality, the apparel industry's emission of carbon dioxide has significant impact on environmental degradation, and especially on climate change. According to Sule (2012), among all apparel production processes (cutting, sewing, and finishing), the sewing process consumes the largest amount of energy (49.8%) and is a significant contributor to environmental damages including global warming potential (GWP 100), ozone layer depletion, and photochemical oxidation.

With an intensified focus on the TA supply chain, overall sustainability in the last decades, governments, retailers, brands, manufacturers, and individuals have become increasingly aware of the necessity to reduce TA supply chain environmental footprints by reducing GHG emissions. Considering this awareness, one would think there would be a plethora of environmental research focusing on TA supply chain including the apparel industry. However, the apparel industry's energy consumption has not received much attention in comparison to that of the textile industry. When analyzing the research literature base, it becomes evident that social responsibility research received greater attention within the apparel industry. Likewise, environmental aspects of consumers' apparel purchase behavior have been the focus of many studies. Though both apparel production and consumption contribute to environmental damage, very little research has investigated the environmental impacts of apparel production. In order to address the gap in the literature base, this study investigated the energy consumption and GHG

emissions associated with the sewing processes of the apparel industry as well as identified practical pathways for increasing environmental sustainability within this sector.

### **Purpose of the study**

It is evident that throughout the textile-apparel supply chain, the environmental sustainability of apparel production processes so far has received limited attention. Without filling this gap, it will not be possible to attain an overall sustainability within this supply chain. However, it is nearly impossible to incorporate all the apparel production processes (e.g., cutting, sewing, and packing) in a single study for environmental sustainability; therefore, this study will focus on energy consumption and GHG emissions for different sewing operations in the apparel manufacturing industry. The rationale behind conducting an environmental study focusing only on the sewing process is that this process was determined to be the most energy intensive and have the largest environmental footprint in comparison to other apparel production processes such as cutting, finishing, etc. (Sivaramakrishnan, Muthuvelan, Ilango, & Alagarsamy, 2009; Sule, 2012).

The purpose of this study is to capture a clear and comprehensive assessment of the energy consumption associated with the sewing process. The goal is to develop an energy consumption model through analyzing different sewing operations in the apparel industry. The research objectives of this study are –

- To identify most influential energy consumption factors of the sewing process in apparel industry, and to develop a regression model to measure energy consumption.
- To determine the interrelationships among energy consumption factors
- To identify steps to reduce energy consumption within sewing process in apparel industry, and

- To explore the apparel industry experts' level of concern regarding energy consumption, the contribution to greenhouse gas emissions and climate change in the apparel manufacturing.

Research reveals that the production and consumption of TA merchandise can cause a great deal of damage to the environment. Though some researchers claim apparel production process to be the cleanest process, some disagree (e.g., Sule, 2012). However, a wide body of research regarding the environmental footprint of the apparel production process simply does not exist, especially research that captures apparel industry experts' voices on the energy consumption and GHG emissions of the sewing process. Therefore, this study will develop a proposed model of energy consumption and GHG emissions for the sewing process.

### **Conceptual Framework**

Climate change is the result of the atmosphere's increased heat radiation absorption, an increase caused by GHG emissions. This study focused on CO<sub>2</sub> emissions produced from burning fossil fuels. Carbon dioxide is a significant GHG because of its global impacts and higher rate of emission in our industrialized society in comparison to other GHGs.

According to Intergovernmental Panel on Climate Change (IPCC, 2007), by the end of 2100, the world will be 2° F to 11.5° F warmer than it was 100 years earlier. A small rise in the temperature can cause great change. For example, if the earth becomes warmer by only 3-4° F, 20-30% of species will be at risk of extinction (Henson, 2011). Even if we stopped burning fossil fuels (a significant source of GHG emissions) today, the world would still be at least 0.9°F warmer because of the existing GHGs (Henson, 2011). In today's world, burning fossil fuels is the most established and depended-upon source of energy for the manufacturing industry, and

CO<sub>2</sub> concentration has increased about 30-40% since the Industrial Revolution (Houghton, 2009). Similarly, burning fossil fuel is the only reliable energy source for the TA supply chain. On a global scale, in 2008, 60 billion kg of textiles produced used one trillion kWh (kilowatt-hour) of electric energy (Rupp, 2008).

The TA supply chain is energy intensive, requiring 10 times more energy to produce one ton of textiles than does the production of one ton of glass (Draper, Murray, & Weissbrod, 2007). Electricity is one of the most commonly used types of energy (Reddy & Ray, 2011) and one of the key cost factors in the TA supply chain (Hasanbeigi, 2010). The International Energy Agency (IEA, 2012) estimates that final energy consumption in the TA supply chain doubled from 47 Exajoule (EJ)/year to 90 EJ/year (1 EJ= 10<sup>12</sup> MJ and 1 MJ = 0.28 kWh) between the years of 1971 and 2004 (as cited in Palamutcu, 2010).

Despite low technology and labor-intensive process (Scott, 2006), there are a number of factors that affect the energy consumption and GHG emissions from sewing operations. Rogale, Petrunic, Dragcevic, and Rogale (2005) identified various factors such as motor speed, seam length, stitch density, and number of fabric layers as determinants of energy consumption for sewing operations. However, there are numerous unexplored issues (e.g., energy efficiency of the machine, productivity of the operator) as new machinery and new technology are emerging daily in this dynamic industry. Based on investigating energy consumption factors, this study proposes a model that might help apparel manufacturers determine the energy consumption of the sewing process. Also part of this study is the incorporation of apparel industry experts' responses through emerging qualitative approaches for curbing climate change issues.

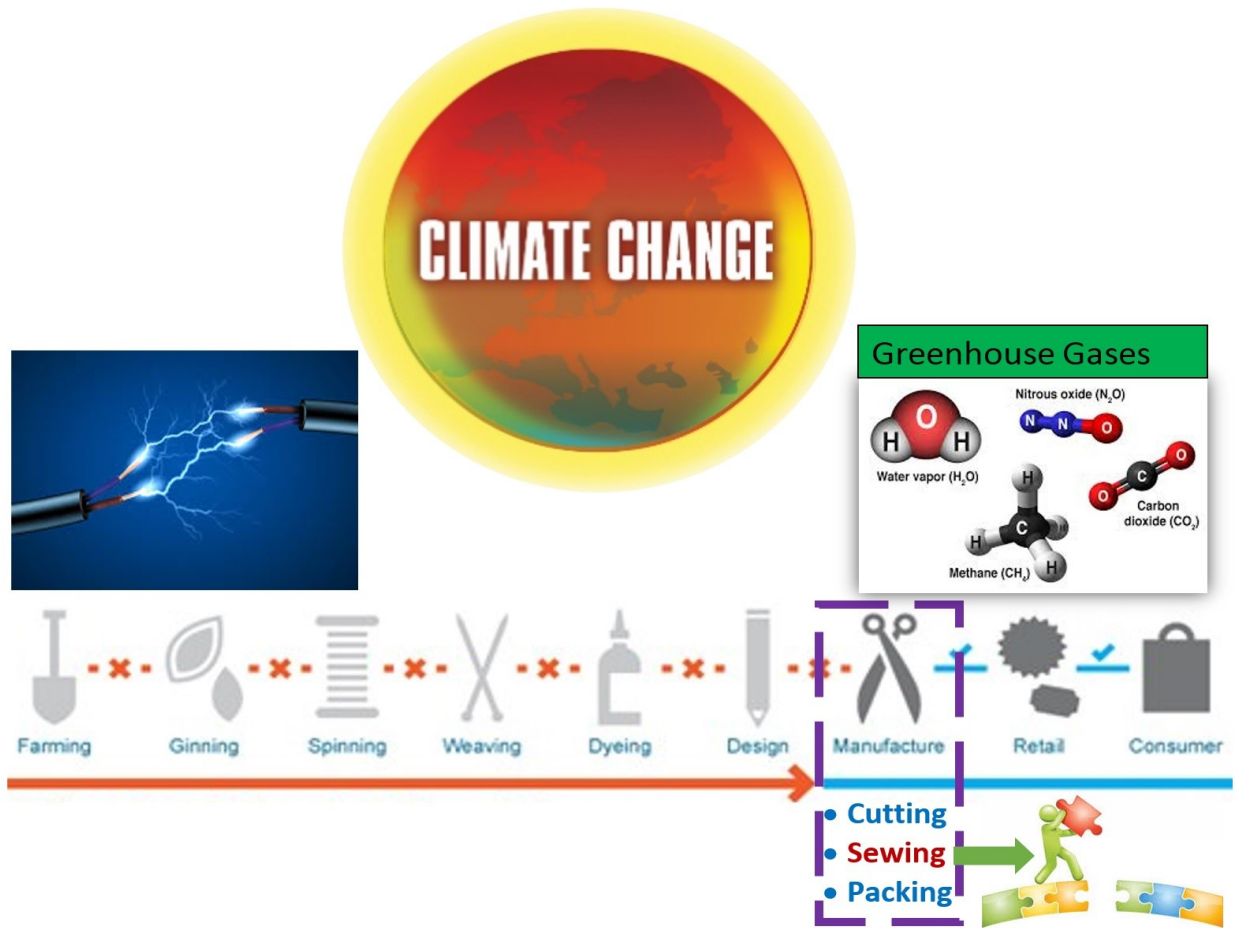


Figure 1.1 Conceptual framework of this study

Most studies on the apparel production process have been with an eye toward improving production efficiency, whereas only a few studies have addressed environmental impacts from the same process. This study addresses climate change by investigating both sewing efficiency and energy consumption of the sewing process to develop an implementable model to encourage life cycle analysis of the sewing process.

## **Significance of the study**

The significance of this study is that it will enlighten apparel manufacturers about different energy consumption factors as well as GHG emissions and will help them to analyze and modify their processes to reduce emissions through conserve energy accordingly. In this age of growing concern about global climate change, identifying a tool that reveals energy consumption in the sewing process may bring greater attention to the environmental impact of production. Companies that address environmental impacts from their processes will better meet the growing demand in the marketplace. Additionally, Phylipsen et al. (2002) argued for using energy consumption and efficiency comparisons as a tool within an industry to assess a company's performance relative to that of its competitors. Designers, retailers, and consumers can then be better equipped to make sustainable sourcing decision and to purchase environmentally friendly apparel.

## **Definition of Terms**

To avoid confusion, definitions and delineations are provided for a number of terms that are frequently used throughout this study.

**Apparel manufacturing:** Processes involved with merchandising, design, product development, production, and wholesale marketing (Glock, 2005).

**Apparel production:** Garmenting process that includes fabric laying up, cutting, sewing, cleaning with air suction, ironing, and transportation. This is a part of apparel manufacturing process, which involves converting materials— including fabrics, findings, trims, and usually thread— into a consumable good. Fabrics are cut, shaped, assembled, and trimmed as they are converted into specific styles to meet customer needs.

**Climate change:** Climate change refers to any substantial changes in the measures of climate (e.g., temperature, precipitation, or wind patterns, etc.) that occur over an extended period.

**Energy consumption:** Energy (mostly electricity) consumption measured in kilowatt-hour (kWh) from running machinery, heating and cooling control systems, lighting, and operating office equipment, etc., in the TA industry.

**Greenhouse gas (GHG):** Gases found in Earth's atmosphere. GHGs include carbon dioxide (CO<sub>2</sub>), methane (CH<sub>4</sub>), nitrous oxide (N<sub>2</sub>O), and fluorinated gases (Environmental Protection Agency, 2013).

**Sewing machine utilization percent:** It refers to the time a sewing machine is actively used in a sewing operation.

**Sewing operation:** The number of small tasks that make up the entire sewing process. This number is dependent on a specific apparel style.

**Specific energy consumption (SEC):** Amount of consumed energy to produce one unit of output.

**Standard Allowed Minute (SAM):** SAM is a unit that measures the amount of work to be done by an operator in a sewing operation by the number of minutes in which it should be completed (Solinger, 1988).

**Stitch density:** Denoted as the number of stitches per inch (SPI), which represents “the amount of fabric that is advanced under the needle between penetrations” (Glock, 2005, p. 178).

**Textile mill:** Manufacturing facility where yarns and fabrics are produced.

**Textile and apparel (TA) supply chain:** “A series of interrelated activities which originates with the manufacture of fiber and culminates in the delivery of a product into the hands of the consumer” (Jones, 2006, p. 1).



## **Overview of the Dissertation**

This research study is comprised of five chapters. Chapter 1 provides the background of the study, statement of the problem, purpose of the study, definition of terms, significance of the study, conceptual framework, and the assumptions of the study.

Chapter 2 presents a review of the literature, which includes research on climate change, sustainability, greenhouse gases (GHGs), energy consumption in the textile and apparel (TA) supply chain, various energy consumption factors within the apparel industry, and GHG emissions from TA production.

Chapter 3 depicts the methodology used for this study including the sampling techniques, data collection strategy, instrumentation, units of analysis, data collection, and data analysis procedures for both qualitative and quantitative methods of inquiry.

Chapter 4 represents the findings and discussion of the study. It includes an introduction to research participants, descriptive statistics, major findings and discussion of this study, organized by each research question, to attain the four objectives mentioned above.

Chapter 5 summarizes the study and includes an integrated discussion drawn from findings with implications for both academia and practitioner. It also presents the study's limitations and provides recommendations for further research.

## **Chapter 2 - Background Information and Literature**

This chapter includes an overview of sustainability; a focused discussion regarding environmental sustainability in terms of the textile and apparel supply chain; a summary of scientific foundation of climate change in order to understand how energy consumption contributes to greenhouse gas (GHG) emissions; and finally, an overview of key energy consumption factors within sewing operations in the apparel industry.

### **Sustainability**

Sustainability is so broad a topic that no single sufficient definition exists. However, central to the concept is seeing and recognizing the cyclical, dynamic, and interdependent nature of all parts and pieces of life (Robertson, 2014). It is also about becoming educated and involved citizens of this living and changing world and determining what most needs to be done and what we will do to take care of the planet and human systems from our individual corner of the world. The United Nations' World Commission on Environmental Development (WCED, 1987) asserted that businesses and organizations valuing and desiring to practice sustainability should consider balancing the triple bottom line – environment, economics, and social goals –while simultaneously meeting present needs without compromising the ability for future generations to meet their needs. This triple bottom line (TBL) is also sometimes referred to as the 3E's (environment, economics, and equity) (Edwards, 2005) or 3P's (planet, profit, and people).

The first "P" represents the planet and the importance of restoring and preserving the health of living systems. All life on planet earth depends on its complex ecosystem to purify water and air, to pollinate crops, to provide foods, and to circulate the atmospheric gases, chemical elements, and energy. Therefore, it is extremely important to maintain the Earth's ecosystems through the employment of environmental sustainability efforts. The second "P"

represents profit or economic growth and the belief that distribution of economic resources should be equitable so that all humans can meet their basic needs. Meeting basic needs and improving quality of life is sustainable, whereas unlimited economic growth is not (Daly & Farley, 2011). Unlimited economic growth uses natural resources and pollutes air, water, and soil, eventually leading to a decline in quality of life. The third “P” represents people, and more specifically equity, social equity, or equality among people. Equity means freedom from unhealthy living conditions and equal access to food, water, healthcare, education, etc. It also means providing equal opportunity to all members of the society, not just a privileged few, to grow and flourish in their own way (Edwards, 2005). This component of sustainability is concerned with ensuring all people have fair quality of life.

The three related components of the TBL, if in good balance, can help a business become more sustainable. Therefore, if a business entity implements the TBL with equal priority to each component, it will move towards greater sustainability. The environmental aspect of sustainability is about using renewable resources at a rate that they can be replenished and available for future generations. This same is applicable to TA manufacturing. Environmental sustainability in TA production means textiles are produced using raw materials, energy, and other ingredients from renewable sources to preserve these existing resources and help future generations to meet their needs. Sustainable fibers, which are produced from renewable sources of raw materials, chemicals, energy, and other ingredients, play a big role in the TA industry’s sustainability.

The dominant social paradigm puts emphasis on economics (e.g., perpetual growth, financial business performance, etc.) and consequently, the TA supply chain addresses economic growth through ‘the race to the bottom’. The impact of globalization and free trade on the TA

supply chain has led to the shifting of production sourcing from higher-wage countries to lower-wage countries. In addition, after the phase out of the Multi-Fiber Agreement's (MFA) quota system for apparel in 2005, the TA supply chain entered into a fierce competition and all parties involved in the global apparel market were seeking to display their products before customers at the lowest price. In this intense competition of bottom price, outsourcing was a logical solution for meeting low cost in operations, flexible production, and quick response to the changing markets (Shelton & Wachter, 2005). Cheap labor, availability of skilled work force, and richness of natural resources facilitate minimum operating cost. Outsourcing greatly increased competition and created situations where companies and countries try to compete with each other to survive in the market by cutting wages and weakening living standards for workers. These situations are known as 'the race to the bottom' (Ross, 2002); apparel brands and vendors (apparel manufacturers) are racing to source their products for the lowest price. These low prices cause the overflow of apparel product in the market and creates unsustainable demand to the consumer.

Perry and Towers (2009) showed a connection between the rising demand for fashion products with abusive social (e.g., forced labor, child labor, pregnant worker exploitation, gender discrimination, and sexual harassment) and environmental practices. In terms of social abuses, apparel industry workers are considered the most exploitable workers in the world (Bonacich, 1998). With the increasing public awareness and sense of social responsibility related to the aforementioned social issues in the TA supply chain, governments (e.g., Bangladesh), brands (e.g., Reformation, People Tree, Loomstate, Eileen Fisher, American Apparel, Amour Vert, etc.), policy makers (e.g., Fair Labor Association), researchers (e.g., Hyllegard, Ogle, & Yan, 2009; Strong, 1997), and customers have increasingly sought initiatives to curb these social abuses.

Therefore, the TA supply chain has made great strides in giving greater emphasis on social responsibility. However, in comparison to both economic and social sustainability, there has been less progress or less attention given to environmental sustainability, including climate change issues facing the industry.

### **Climate Change and Greenhouse Gases (GHGs)**

Climate is not weather. Weather is the short-term variations of temperature, precipitation, and wind that occur day by day, whereas climate is long-term variation of these atmospheric conditions measured over decades, centuries, or even longer periods (Intergovernmental Panel on Climate Change [IPCC], 2007). Greenhouse gases (GHGs) have a significant impact on climate change. Stated explicitly, with the increasing concentration of GHGs over time, the planet will become warmer because GHGs trap heat radiation reflected by the Earth's surface. Therefore, climate change is the effect of GHG emissions (or, greenhouse effect) in the atmosphere through warming the Earth and resultant wide-ranging impacts (e.g., rising sea levels, melting snow and ice, more extreme heat events, fires and drought, and more extreme storms).

Based on the notion of increases in CO<sub>2</sub> and other GHGs (e.g., methane, nitrous oxide, ozone) atmospheric concentrations, the report of the IPCC (2007) revealed that by the end of 2100, the world would be 2° F to 11.5° F warmer than it was 100 years earlier. A small rise in the temperature may cause great change in climate and the effects of rising temperature are pervasive. Today, the world is experiencing numerous symptoms of climate change such as changing ocean water salinity and temperature, more acidic seawater, rising sea levels, decreasing differences between day and night time temperatures, increasing evaporation rate, increasing intensity of hurricanes, melting polar icecaps, and overall warming of the Earth's surface (Robertson, 2014). From the report of the IPCC (2007), it was also found that the

average seawater level will rise by seven to 23 inches by the end of 2100. A small change in ocean temperature could change the levels of marine planktons, tiny plants and animals on which the ocean food system is dependent. If the planet becomes warmer by 3-4° F, 20-30% of species will be at risk of extinction (Henson, 2011) and the effect of CO<sub>2</sub> emissions into the environment will be irreversible (Chestney, 2012). The damage level is so high that the world still would be at least 0.9°F warmer in comparison to current temperature even if we stopped burning fossil fuels tomorrow (Henson, 2011). This is because the existing GHGs are in play, acting as a warm retainer, and their constant churning in the environment would result in this warming. This churning could cause CO<sub>2</sub> retention in the atmosphere for a century or more (Robertson, 2014).

The average Earth surface temperature is 59° F. If Earth had no atmosphere, all the light coming from the sun would be reflected as infrared radiation and Earth's surface temperature would be 0° F (Wolfson, 2008). The earth, however, does have an atmosphere and the gases of this environment absorb some of the infrared radiation, keeping it from escaping and producing a warmer earth surface. These gases are called greenhouse gases (GHGs), as the process is similar to how a greenhouse traps hot air, keeping it from escaping so that plants can grow even when outside temperatures are low. GHGs trap infrared radiation and keep this radiated heat from escaping, creating warmer temperatures that support life on earth.

Not all gases in the atmosphere have similar infrared radiation trapping capability. Nitrogen (N<sub>2</sub>) and oxygen (O<sub>2</sub>) gases are diatomic or two-atom molecules and they are simple in structure. They do not block much infrared radiation reflected from earth surface. Nitrous Oxide (N<sub>2</sub>O), ozone (O<sub>3</sub>), carbon dioxide (CO<sub>2</sub>), and methane (CH<sub>4</sub>) are larger and more complex molecules acting as GHGs. Among these, N<sub>2</sub>O, O<sub>3</sub>, and CO<sub>2</sub> are triatomic or three-atom molecules. They are complex in structure and can be rotated and oriented in different directions,

which causes significant infrared radiation blockage. Among them, CO<sub>2</sub> was identified as a highly significant GHG considering its drastic rate of emissions due to global industrialization (National Aeronautics and Space Administration [NASA], 2016).

There are some other reasons for identifying CO<sub>2</sub> as an especially threatening GHG. A typical CO<sub>2</sub> molecule remains in the atmosphere for at least five years (Wolfson, 2007). Fifty-five percent of the CO<sub>2</sub> humans put in the atmosphere is stored in the ocean and taken up by plants and soil, and the remaining 45% stays in the atmosphere and mixes with preexisting CO<sub>2</sub> (Henson, 2011). The amount of carbon dioxide emissions from natural sources is only marginally predictable and not controllable (Salby, 2011). The current global average of CO<sub>2</sub> concentration is 400 ppm (parts per million) and this concentration is rising by 2 ppm every year (Wolfson, 2008). Adding CO<sub>2</sub> to the air from any part of the world, it mixes with the air due to constant churning of atmosphere and spreads globally. With the existing carbon cycle, CO<sub>2</sub>'s impact remains for around 100 years (Wolfson, 2007). This means that releasing CO<sub>2</sub> from one part of the world becomes a global problem. It also means measuring CO<sub>2</sub> concentration from one region accurately represents average CO<sub>2</sub> concentration globally. Conversely, reducing CO<sub>2</sub> emissions from one region will positively affect the rest of the world.

According to National Aeronautics and Space Administration's (2015) Global Climate Change report, the temperature change in January 2015 was 0.87° C (or, 1.566 °F) against 399.96 ppm CO<sub>2</sub> concentration measured over a one-year time period. The Intergovernmental Panel on Climate Change (2007) concluded that there is a more than 90% probability that human-produced GHGs (through various activities such as deforestation, industrialization, burning fossil fuel) have caused today's warmer planet over the last 50 years. If this happens in same pattern over the next 50 years, we would see 550-600 ppm CO<sub>2</sub> concentration by the end of

2100, which is high enough to be catastrophic to average global temperatures (Blockstein & Wiegman, 2010).

Methane (CH<sub>4</sub>), another significant GHG, is produced when anaerobic bacteria digest organic matters, emerging from decaying plant matters from marshes, landfills, sewage treatment plants, and mining. The current atmospheric average of CH<sub>4</sub> concentration is about 1800 ppb (parts per billion) (Kump, Kasting, & Crane, 2010). The Intergovernmental Panel on Climate Change developed a unit called Global Warming Potential (GWP), a relative measurement of how much heat a GHG traps in the atmosphere, to compare strength among different GHGs. The GWP of CO<sub>2</sub> standardizes to one so that it compares the heat trapping ability by a certain mass of other GHGs in relation to a similar mass of CO<sub>2</sub>. According to the Environmental Protection Agency (EPA, 2013), CH<sub>4</sub> has a GWP of 28, meaning that CH<sub>4</sub> has 28 times stronger heat trapping ability than that of CO<sub>2</sub>. On a molecule-for-molecule basis, CH<sub>4</sub> is a far more active greenhouse gas than CO<sub>2</sub> (28 times stronger), but also one that is much less abundant in the atmosphere (Robertson, 2014). Therefore, being the most prevalent GHG, CO<sub>2</sub> draws all the attention in discourse on climate change.

The major source of GHGs is from burning fossil fuels. Natural gas, oil, and coal are the three types of fossil fuels. Natural gas and oil are fossilized marine plankton, and coal, the most plentiful in nature, is fossilized terrestrial plant matter. They all are nonrenewable, one-time energy sources. They cannot be regenerated, only depleted. Though coal is the most abundant in nature, when burned it heavily pollutes the environment in comparison to oil and natural gas. Burning coal emits CO<sub>2</sub>, mercury and generates carcinogens such as a variety of sulphur and nitrogen oxides, which results in photochemical smog and acid rain (Martin & Griswold, 2009). On the other hand, burning natural gas causes less environmental pollution (Randolph &



Masters, 2008). For today's industries, including the TA supply chain, burning fossil fuels (and most often, coal) is the most established and dependable source of energy; burning fossil fuels emits a great deal of GHGs and hence, leads to severe climate change. Fossil fuels supply 87% of global energy demands, and coal supplies nearly 30% of those energy demands (Institute for Energy Research, 2013). Therefore, around 30- 40% of CO<sub>2</sub> concentration increased after the Industrial Revolution (Houghton, 2009). The apparel business is booming rapidly over last two decades because of fast fashion, globalization, ease of cheap sourcing, and consumers' unsustainable apparel consumption, and the supporting TA supply chain is growing uncontrollably and hence becomes a source of substantial GHG emissions.

### **Energy Consumption in the Textile and Apparel (TA) Supply Chain**

The TA supply chain has been identified as highly polluting compared to other manufacturing industries (Challa, 2012). Sweeny (2015) identified it as the second most polluting, after the oil industry. The environmental pollution of the TA supply chain is significantly contributing to climate change issues and taking a vast toll on the planet. Most of the TA products have a negative impact on the environment one way or another, through either production, consumption, or clothing waste.

Electricity is the main energy component in the TA supply chain. The share or consumption of energy varies from country to country because energy efficiency varies from country to country (Martinez, 2010). A number of research studies have been completed based in different countries, such as Turkey, China, India, Taiwan, the Netherlands, Iran, Greece, Thailand, Germany, Columbia, Mauritius, Finland, Spain, Sri Lanka, and USA (e.g., Aranda-Uson, Ferreira, Mainar-Toledo, Scarpellini, & Sastresa, 2012; Bhurtun, Kistamah, & Chummun, 2006; Hasanbeigi, 2010; Hasanbeigi, Hasanabadi, & Abdorrazaghi, 2012; Hong, Su, Lee, Hsu, &

Chen, 2010; Jananthant et al., 2006; Kalliala & Talvenmaa, 2000; Kim, Grady, & Hersh, 1983; Kocabas, Yukseler, Dilek, & Yetis, 2009; Martinez, 2010; Ozturk, 2005; Palamutcu, 2010; Palanichamy & Babu, 2005; Phylipsen, Blok, Worrell, & de Beer, 2002; Reddy & Ray, 2011; Schönberger & Schäfer, 2003; Visvanathan, Kumar, Priambodo, & Vigneswaran, 1999; Zabaniotou & Andreou, 2010). While it is important to understand energy consumption on a country-to-country basis, GHG emissions are a global concern. Apart from country specific data, some of the aforementioned studies captured process and sector specific energy information from the TA supply chain. However, there are many unexplored issues particularly because new machinery and new technology are emerging frequently in this supply chain.

With changes in technology and machinery, energy consumption and conservation policies have evolved over time. Energy consumption patterns within industries have already begun changing because of increased energy costs (International Energy Agency, 2012). Government agencies and policy makers regulated firms to consume energy efficiently. To improve energy efficiency levels, individual firm needs to track past trends in energy use, assesses the factors that contribute to changes in energy intensity, and measures the performance of energy-related policies (Reddy & Ray, 2011). With the increasing pressure to address energy consumption in the industry one would think a plethora of research studies including journal articles, conference proceedings, books, etc. would be available. Surprisingly, a limited number of studies address TA supply chain energy issues, especially when compared to other energy intensive industries such as steel/iron mill, cement industry, petro-chemical industry, etc. In light of the ubiquitous nature of the TA supply chain discussed earlier in terms of employment generation, global energy use, and economic impact there is an urgent need for TA supply chain energy consumption research.

Most of the limited existing research has captured energy information from major sectors of TA supply chain; these sectors are spinning, fabric production (knitting and weaving), wet processing (dyeing and finishing), apparel manufacturing, etc. In this regard, several energy analysis models were reported. Jebaraj and Iniyar (2006) attempted to understand and review the various emerging issues related to energy modeling including: energy planning models, energy supply-demand models, forecasting models, renewable energy models, emission reduction models, optimization models, etc. The authors found that efficiency and cost factors were critical parameters in the objective function formulation (energy conservation and GHG emissions reduction); which is an attempt to express a business goal in term of decision analysis through mathematical terms. Again, Philipsen et al. (2002) argued that energy efficiency comparisons could be used as a tool within the industry to assess a company's performance relative to that of its competitors. In contrast, monetary-units based energy analysis led to erroneous policy implications because price related reasons affect the analysis without any real change in efficiency (Martinez, 2010; Reddy & Ray, 2011). Volatility in currency conversion rate over time may be another important reason for this. As mentioned earlier, the share or consumption of energy differed by country to country due to varying energy efficiency in diverse industry (Martinez, 2010). However, a few researchers have tried to provide information in terms of energy cost instead of energy consumption from the textile mills. Researchers found that the proportion of energy cost within total production cost is generally around 5-10% (Kiran-Ciliz, 2003), which devalued the importance of energy consumption reduction as well as the reduction of GHG emissions. So, instead of monetary and energy efficiency based data, this study focuses on energy consumption, especially energy consumption on a particular sector of the TA supply chain.

To understand the energy consumption of the TA production processes, it is important to understand the TA supply chain. Figure 2.1 illustrates the typical textile and apparel chain, found from the study of Schönberger and Schäfer (2003). It categorizes the entire textile-apparel supply chain into four sub-sectors: spinning mill (to produce fiber and yarn), fabric mill, wet-processing mill (to dye and finish fabrics and yarns), and apparel mill. The textile production starts with fiber production and culminates in either grey fabric or finished fabric. Though the authors used ready-made textiles under the apparel mill sub-sector, they actually referred to ready-made garments as they indicated making-up process (which included cutting, sewing, and assembling) before mentioning ready-made textiles. This study focused upon the making up process, more specifically on sewing process.

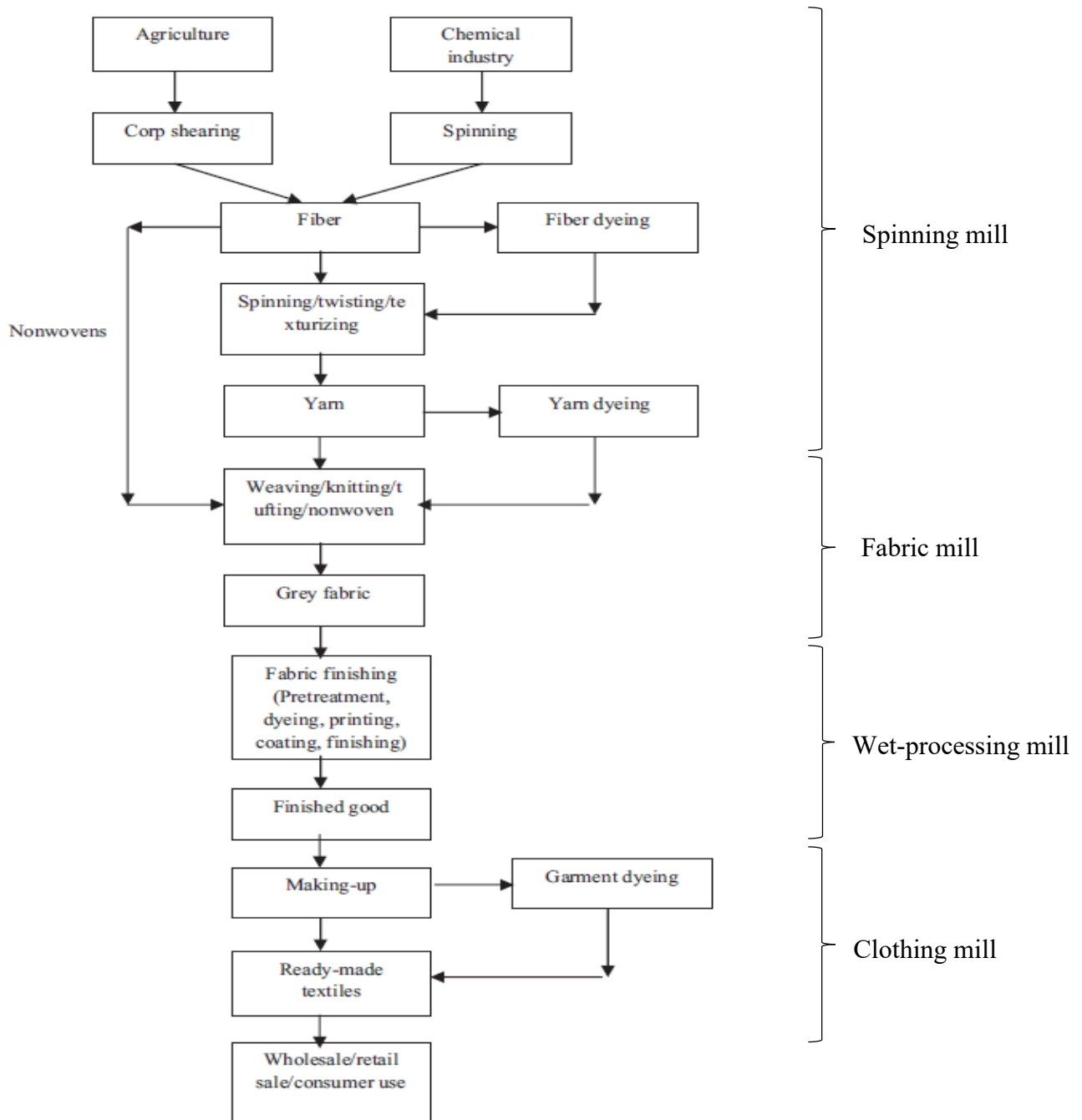


Figure 2.1 The textile and apparel chain

According to the International Energy Agency (2013), there are a variety of units used for energy consumption determination, including Megawatt hour per ton (MWh/ton), kilowatt hour per kilogram (kWh/kg), Gigacalorie per ton (Gcal/ton), Gigajoule per kilogram (GJ/kg),

Gigacalorie per kilogram (Gcal/kg), Gigajoule per ton (GJ/ton), and Gigawatt hour per ton (GWh/ton). Different researchers have used different consumption units. Using a unit converter provided on the International Energy Agency website, one can convert these units into any desired units. Also, during a review of energy consumption literature, the terms “energy intensity” and “specific energy consumption” (SEC) were used to indicate how much energy is consumed. SEC deals with energy units per kg of yarn produced (kWh/kg) or units per kg or meter of fabric processed (kWh/m) or units per 1000 meters of fabric garmented (kWh/1,000m). The International Energy Agency defined energy intensity as total primary energy consumption per dollar of GDP. In addition, from the study of Hasanbeigi et al. (2012), energy intensity is defined as:

$$\text{Energy intensity} = \frac{\text{Energy consumption (kWh or GJ)}}{\text{Production quantity (unit of output)}} \quad (1)$$

The rationale of focusing on energy consumption in the TA supply chain was supported by the findings of several researchers. For instance, Palanichamy and Babu (2005) determined that a 1% reduction in energy consumption could substantially reduce annual production costs in the spinning mill and sewing thread industry in India. They have shown that equipment operational changes, building structural modifications, changes in machinery accessories, and steam heating in place of electrical heating could result in a consumption reduction of 171.10 kWh for every ton of produced textile product. Price, Wang, and Yun (2010) found that the Chinese government’s goal regarding reducing energy consumption in top 1000 energy intensive enterprises, including the TA supply chain, could contribute to somewhere between 10% and 25% of the savings required to achieve a 20% reduction in energy use per unit of GDP by 2010. Reddy and Ray (2011) stated that between 1991 and 2005, cotton yarn had the highest increase in emission compared to gray cloth, jute goods, and polyester chips production. This increase

was due to a transformation from a manual to intensive mechanization process of production where fuel use is very high. They have found substantial improvements in energy consumption in production of textiles (cloth and gray cloth) by changes in energy intensities and specific energy consumption. Steinberger, Friot, Jolliet, and Erkman (2009) have found that a t-shirt accounts for over 70% of the energy used and CO<sub>2</sub> emissions in the consuming country, whereas for a jacket, more than 70% of energy consumption and CO<sub>2</sub> emissions occur in the producing country. On the other hand, Zabaniotou and Andreou (2010) focused on the utilization of cotton ginning waste for energy production as an alternative energy source in the TA industry.

### **Energy Consumption in Apparel Industry**

Apparel or clothing production has been an important industrial activity for many nations like Bangladesh, China, and Vietnam because of its contribution to their gross national products (GDPs), employment rates, and export rates. This industry has become one of the major energy consumers of the world (Jananthant et al., 2006). It uses energy for the production of garments, thermal and visual comfort of the factory occupants, as well as maintenance purposes and office equipment such as computers, printers, and photocopy machines. The energy consumed by the apparel production division consists of large numbers of small-sized companies and their employees in the overall textile mill, is not necessarily low compared to other sub-sectors, but the share percentage of energy cost to the total cost (personnel cost + energy cost + material cost) is relatively low ( United Nations Industrial Development Organization, 1992), which can be deduced from Table 2.1. Also, Figure 2.2 depicts the clothing production processes and their respective energy sources. Clothing production stages, including laying up, cutting, sewing, cleaning with air suction, ironing, and transporting processes, mostly consume electric energy. Only finishing processes (heating and ironing) might require both steam or hot air and electricity

(Palamutcu, 2010). Palamutcu found that specific electric energy consumption of clothing production plants varied between 0.065 and 0.195 kWh/kg for actual SEC and 0.07 - 0.09 kWh/kg for estimated SEC (see Figure 2.3). Possible differences in product properties of fabric weight, product type and model, production quantity, and machine efficiency may explain the varying actual SEC values year round. Sivaramakrishnan, Muthuvelan, Ilango, and Alagarsamy (2009) have studied process based energy consumption for woven apparel production and knit apparel production. As shown in Table 2.2 and Table 2.3, knit apparel production (73 kWh) consumes less energy than woven apparel production does (96 kWh). The machine intensive nature to produce woven fabric is the most probable reason that woven garment production consumes more energy.

Table 2.1

*Energy Cost (in Million Yen) and its Share in the Total Production Cost*

Year	Fiber Production			Spinning			Fabric Production			Dyeing			Clothing Manufacturing		
	Energy Cost	Total Cost	Share %	Energy Cost	Total Cost	Share %	Energy Cost	Total Cost	Share %	Energy Cost	Total Cost	Share %	Energy Cost	Total Cost	Share %
1969	2.8	33.3	8.41%	2.1	80.5	2.61%	1.3	67.8	1.92%	4.7	66.1	7.11%	0.8	68.7	1.16%
1973	4.1	57.9	7.08%	1.8	74.8	2.41%	1.2	66.7	1.80%	4.2	64	6.56%	0.8	65.2	1.23%
1977	10.3	84.8	12.15%	4.2	83	5.06%	2.7	66.3	4.07%	9	70.6	12.75%	1.1	66.8	1.65%
1981	12.6	81.6	15.44%	6.2	81.8	7.58%	3.8	63.4	5.99%	12.8	67.7	18.91%	1.6	64.5	2.48%
1985	10.2	77.3	13.20%	5.6	79.2	7.07%	3.8	66.1	5.75%	10.7	67.2	15.92%	1.4	64.8	2.16%
1989	5.3	61.2	8.66%	5.3	77.7	6.82%	3.1	62.4	4.97%	5.5	60.1	9.15%	1.1	59.1	1.86%

Source: United Nations Industrial Development Organization, 1992

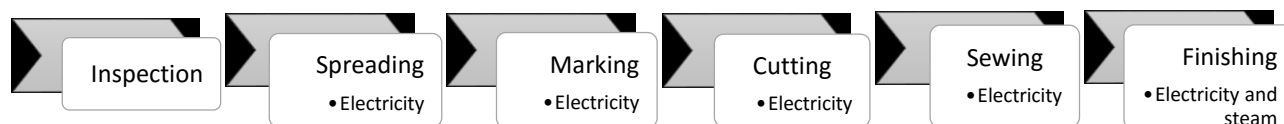


Figure 2.2 Clothing manufacturing process and energy use ( United Nations Industrial Development Organization, 1992)



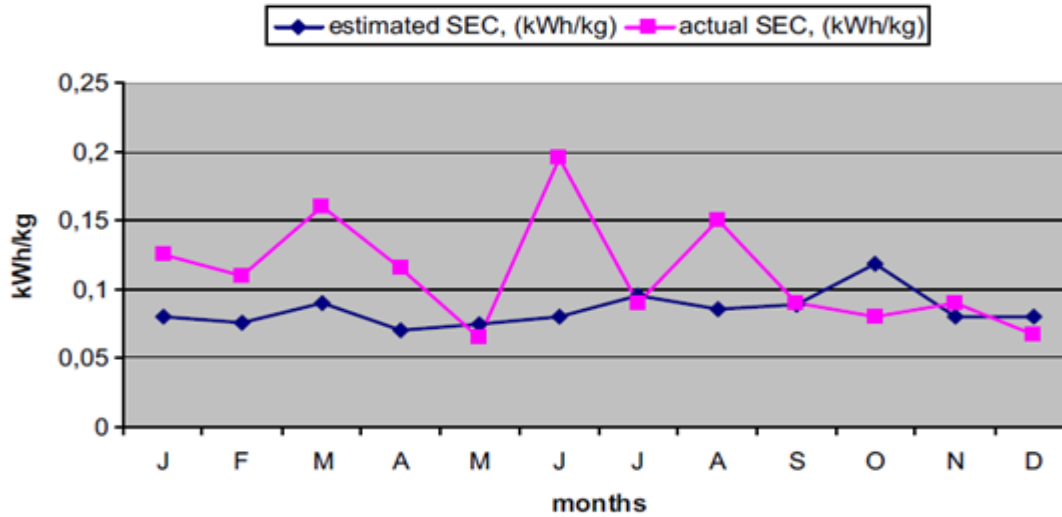


Figure 2.3 Comparison of actual and estimated SEC values of clothing production plant (Palamutcu, 2010).

Table 2.2

*Energy Consumption in Knitted Garment Division (250,000 pieces /month)*

Process	Energy Consumption (kWh)	Percent on total Energy Consumption
Garmenting machine	23	31.5
Compressor	10	13.7
Lighting	19	26
Finishing	21	28.8
Total	73	100

Table 2.3

*Energy Consumption in Woven Garment Division (50,000 pieces /month)*

Process	Energy Consumption (kWh)	Percent on total Energy Consumption
Laying, Cutting and Sewing (150 machines)	45	46.9
Lighting	17	17.7
Finishing	34	35.4
Total	96	100

The finishing process in the garment division holds second position in terms of energy consumption. Bhurtun et al. (2006) determined specific electric energy for clothing production as 0.80 – 1.00 kWh/kg. They did not explain how they determined per kg energy consumption instead of pieces/month based energy consumption. Furthermore, a department-specific and equipment-specific energy consumption share for the apparel industry was determined in the study of Jananthant et al. (2006). They did not provide any SEC information for the apparel industry. Their study (see Table 2.4) found that the sewing department shared the highest energy consumption followed by the cutting department for six factories (F1 to F6). In addition, as shown in Table 2.5, air conditioning equipment consumed the largest amount of energy (46%) whereas sewing machine consumed only 19%. Uses of energy differs from factory to factory as each factory produces different types of garments with different types of fabric.

Table 2.4

*Comparison of Energy Consumption – Functional area (or, Department specific)*

Departments	Energy consumption (%)						Average
	F1	F2	F3	F4	F5	F6	
Sewing	64	51	41	48	51	65	53.33
Cutting	6	33	29	17	19	17.5	20.25
Finishing	8	7	2	3	8	1.5	4.92
Packing/Store	7	2	9	6	5	1.25	5.04
Office area	12	5	3	5	6	6.75	6.29
Other	3	2	16	21	6	8	9.33

Source: Jananthant et al., 2006

Table 2.5

*Comparison of Energy Consumption – by the types of equipment*

Equipment	Energy consumption (%)						Average
	F1	F2	F3	F4	F5	F6	
Air conditioning	51	44	45	42	45	50	46
Lighting	26	16	22	17	25	16	20
Sewing machines	12	13	21	24	17	26	19
Pumps and Fans/blowers	5	6	2	3	2	1.5	3
Compressor	4	4	5	9	7	3.5	5
Other equipment	2	2	4	5	1	3	3

Source: Jananthant et al., 2006

Apparel industry is low technology and labor-intensive (Scott, 2006), and the production process of apparel differs from style to style, country to country, and culture to culture. In addition, time and energy consumption vary significantly, depending on complexity of design

and fabric selection. Total monthly production quantity of a heavy terry towel sewing process may increase (because of simple sewing process), whereas production may decrease for a time consuming sewing process of a lightweight silk dress. Apart from this, 20-30% of sewing time is made up of machine-hand sub-operations (i.e., operations using the machine), whereas the remaining 70-80% is done by hand (Cooklin, 2006; Rogale et al., 2003). Furthermore, reworking garments that did not meet quality standards the first time consumes additional energy and time without further contribution to the manufactured quantity. This might be another important reason for variations in energy consumption throughout the apparel industry (Palamutcu, 2010).

In terms of energy conservation in the apparel industry, several considerations are needed, including: efficient use of finishing and lighting (e.g., the use of a servo stabilizer in the lighting circuit, high efficient fluorescent tubes, reflectors and electronic ballasts); maintaining optimum height for fittings; and in some cases, improved work methods and practices (Sivaramakrishnan et al., 2009). Additional recommendations included: checking for compressed air leakages; insulation replacement of inefficient magnetic ballasts with efficient electronic ballasts; checking the steam leakages in boilers; and introducing good movement and thermal sensors in the air-conditioning systems (Jananthant et al., 2006).

### **Greenhouse Gas (GHG) Emissions from Textile and Apparel Production**

The TA supply chain is identified as one of the leading contributors to GHG emissions and accounts for nearly 10% of total global carbon emissions (Conca, 2015). Some large retailers (e.g., Marks & Spencer, Nike) measure their carbon footprints as a step to reduce GHG emissions (Eryuruk, 2012). Figure 2.4 shows Eryuruk's (2012) textile product life cycle and its environmental impact. Additionally, Figure 2.5 depicts the Business for Social Responsibility's (BSR, 2009) percentages of GHG emissions for the entire supply chain of all clothing types.

BSR also performed a comparative study between energy consumption and GHG emissions of denim apparel (Figure 2.6).

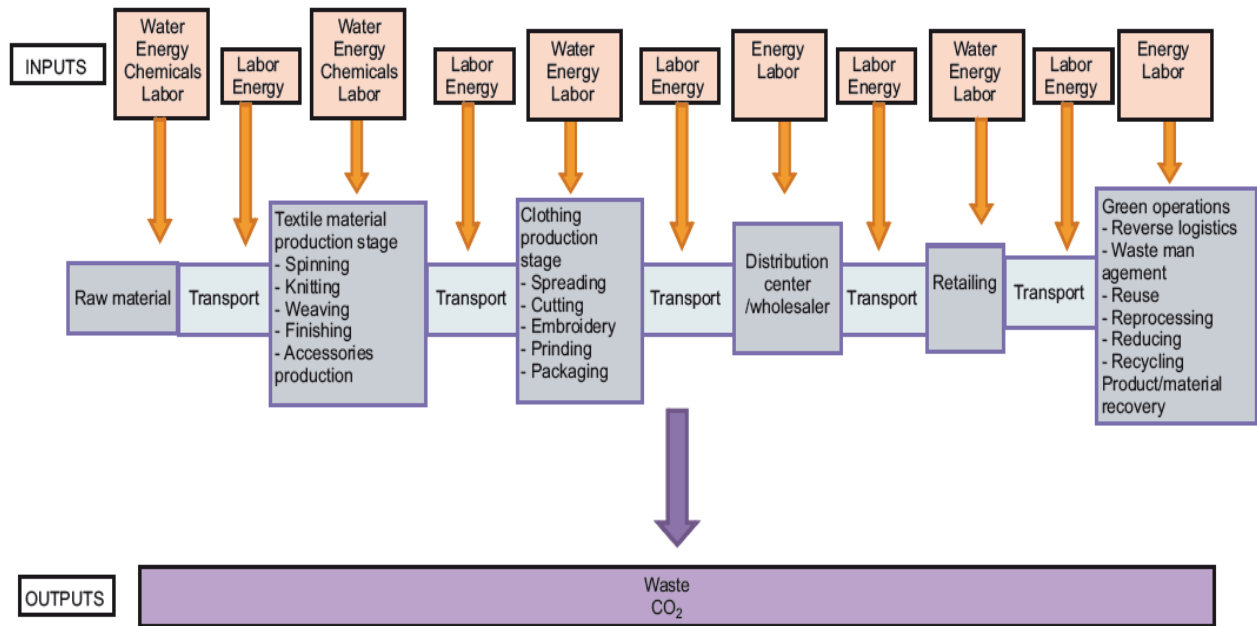


Figure 2.4 Textile product life-cycle and environmental impact (Eryuruk , 2012)

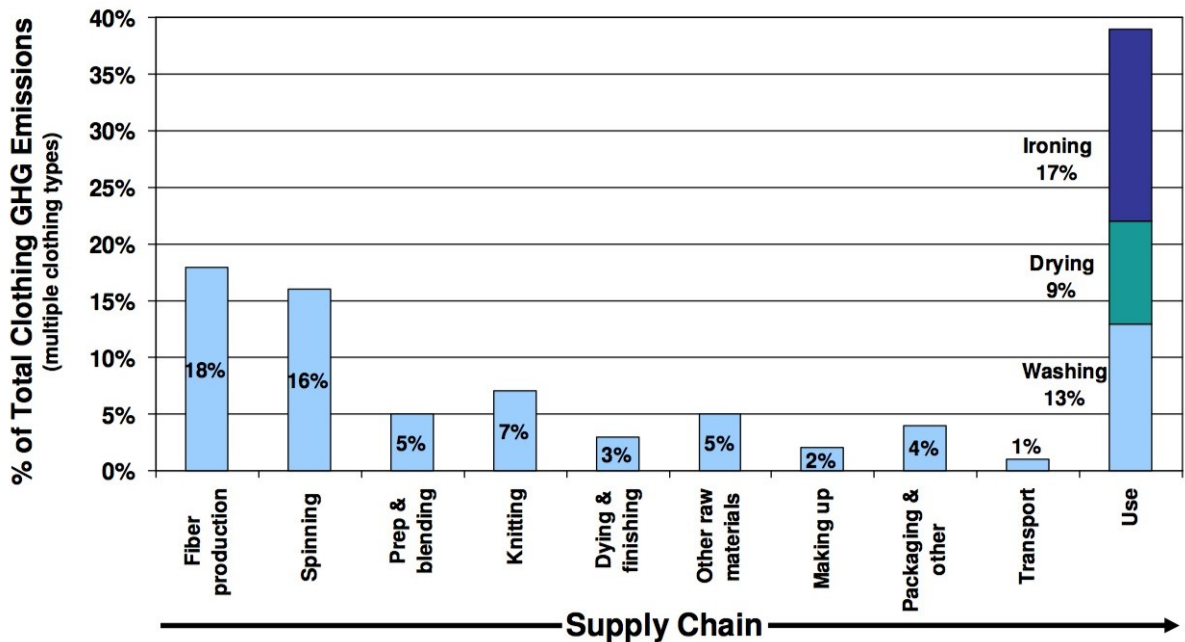


Figure 2.5 GHG emissions percentages throughout the supply chain (Business for Social Responsibility, 2009)

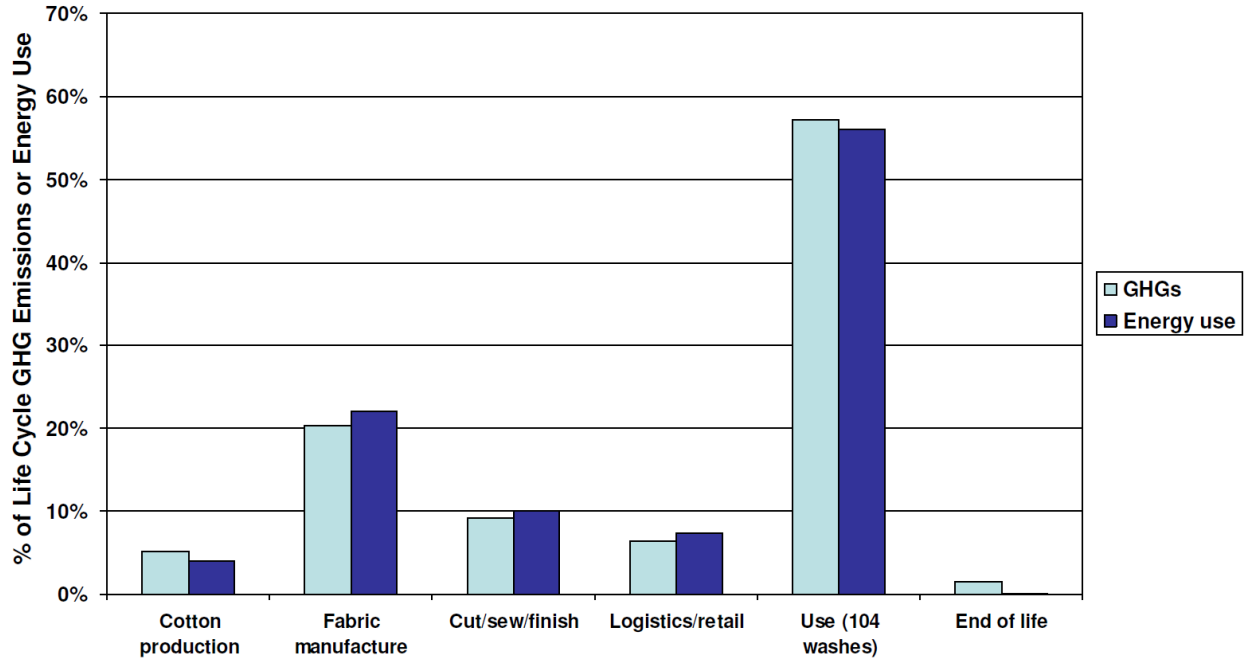


Figure 2.6 GHG emissions and energy use percentages for different processes of Denim apparel (Business for Social Responsibility, 2009)

Hong et al. (2010) observed that annual CO<sub>2</sub> reduction from 1% of energy conservation in the Taiwanese textile industry would represent the annual CO<sub>2</sub> absorption capacity of a 3848-hectare forest plantation. It is declared that the industry has the technical potential (using energy efficient equipment) to decrease its energy intensity and emissions by up to 26% and 32%, providing a striking 8% and 12.4% reduction in total global energy use and CO<sub>2</sub> emissions (United Nations Industrial Development Organization, 1992). The Environmental Protection Agency's (EPA) pollution prevention (P2) program developed a GHG calculator tool to convert standard metrics for electricity, green energy, fuel use, chemical use, water use, and materials management into metric tons of carbon dioxide equivalent, MTCO<sub>2</sub>e, using standard national conversion factors. For example, per kWh energy consumption is an equivalent emission to

0.0007 MTCO<sub>2e</sub> ( Environmental Protection Agency, 2013). Therefore, considering this conversion, the determination of energy consumption is crucial to determine GHG emissions.

### **Energy Consumption Factors in the Sewing Operation**

The study of energy consumption and environmental effects in clothing processes by Sule (2012) found that the energy consumption for cutting, sewing, and packaging of a cotton T-shirt (170 grams) is 0.732 MJ, 1.23 MJ, and 0.51 MJ, respectively. The sewing process alone consumed 49.8% of the total energy consumption and it was the largest contribution from all the clothing processes (i.e., apparel production process). His study also found that the main contribution to a number of impact categories (e.g., global warming, ozone layer depletion) has come from the sewing process even though in general apparel production was thought to be the cleanest process among all TA production processes.

To the best of the researcher’s knowledge, there is no comprehensive review about energy consumption factors for the apparel sewing process in the literature. However, in the study of Rogale, Petrunic, Dragcevic, & Rogale (2005), they observed number of stitches and stitching speed (motor speed) as sewing parameters to investigate their influence on energy consumption in the sewing operation. From their study, a regression analysis was developed that calculated electric energy consumption for sewing straight seams by one specific machine where nominal stitching speed in rpm ( $v_n$ ) and number of stitches ( $N_s$ ) were only two energy consumption factors. However, Rogale et al. (2005) developed the following model:

$$E = e^{[0.441583 - 0.000070 * v_n + 0.003719 * N_s + 0.624983 * \ln(v_n) + 0.198207 * \ln(N_s)]} \quad (2)$$

Their model represented that both speed and number of stitches influenced the energy consumption. This model divulged that speed negatively or inversely influences the energy consumption (i.e., increasing speed reduces energy consumption) and number of stitches

positively influences the energy consumption. In addition, they found continuous seam joining at lower speed results more than three times higher energy consumption than joining the same seam in more layers at higher speed. However, their study included straight seam only, which does not represent the mass apparel production and did not provide any information regarding the explanatory power of their model.

Those with experience in the industry know that determining actual number of stitches in the mass production is a time consuming process and somewhat impractical. Since the total number of stitches is contingent upon seam length and stitch density, this study considered both seam length and stitch density as energy consumption factors. For instance, if a sewing operation has 20-inch seam length and each inch contains 12 stitches, the approximate total number of stitches will be 240. For mass apparel production, using seam length instead of total number of stitches is more practical and easy to determine. In addition, stitch density, also specified as the number of stitches per inch (SPI), is related to the speed of sewing as well as the productivity. It is determined by “the amount of fabric that is advanced under the needle between penetrations” (Glock, 2005, p. 178). Glock explained that the higher the SPI, the shorter the stitch, which results in lower production, and vice-versa. Stitch length can be determined easily from the stitch density regulator of sewing machines, which normally ranges from 7-14 SPI.

The model developed by Rogale et al. (2005) did not incorporate time necessary to perform the operation and percent of sewing machine utilization, though these could greatly contribute to the energy consumption because higher sewing machine utilization reduces the sewing time (Rogale et al., 2003) and associated energy consumption. The percent of sewing machine utilization refers to the time a sewing machine is actively used in a sewing operation. Sewing time consists of both actual machine work time and fabric manipulation time. Therefore,



sewing machine utilization refers to the ratio of actual machine work time to sewing time. In this study, the percent of sewing machine utilization was considered as energy consumption factor and its influence over the energy consumption of apparel sewing operation was evaluated.

Standard Allowed Minute (SAM), also known as Standard Minute Value (SMV), is an industry term representing the time necessary to finish a sewing operation or a garment. Therefore, energy consumption can be coupled with the SAM. SAM is a unit that measures the amount of work to be done by an operator in a sewing operation by the number of minutes in which it should be completed (Solinger, 1988). For example, if the SAM of a sewing operation (e.g., bottom hemming) of t-shirt is two, this operation should take two minutes to complete. SAM could represent standard assembling time for a whole garment or a particular sewing operation. In case of whole garment, SAM represents number of operation and the summation of each operation's SAM. Different garments have different SAM in terms of different number of operations and their respective SAM. Since SAM deals with the time required for sewing operations in the apparel industry as well as the productivity (Babu, 2012), it could be considered an important energy consumption factor for the apparel industry. It is predictable that a higher SAM results in higher energy consumption as well as greater GHG emissions unless this SAM contains extremely high material handling time or fabric manipulation time. However, no study was found which represented the influence of SAM on energy consumption; instead, the focus was on its contribution to productivity. In this study, both number of sewing operations and SAM was considered as factors to evaluate their contribution to the energy consumption.

SAM can be measured through employing the time study engineering tool or using the general sewing data (GSD) software. According to General Sewing Data Limited (1990) student manual, GSD software assigns codes for every commonly occurring human motion in the sewing

process where each code represent a specific time based on the distances moved and difficulty of the motions. The cumulative time for all assigned codes represents the SAM for that sewing process. On the other hand, according to the time study engineering tool, SAM can be determined manually through the average sewing time for an operation multiplied by the respective operator's performance rating factor and allowances necessary for respective operation. An operator's performance rating is a subjective assessment of the operator's rate of working relative to the observer's concept of the rate corresponding to standard pace (Kanawaty, 1992). It is necessary to apply adjustments to the average sewing time to arrive at the time that the normal operator would have needed to do that job when performing the sewing at an average pace. Since performance rating is subjective in nature, it is varied by observer's skill, which is a weakness of time study tool in comparison to using GSD software. Allowances are the provision of additional time for all types of stoppages, interruptions, and the physiological needs of the sewing operator. It is a policy decision by the apparel firm whether to give allowances as a percent of sewing time. Both machine allowances and relaxation allowances were considered in this study. The machine allowances for different kinds of sewing machines are given in Table 2.6. As found by Babu (2012) and shown in Figure 2.7, the SAM determining formula is as follows:

$$\text{SAM} = \text{Average sewing time} * \text{performance rating} (1 + \text{allowances}) \quad (3)$$

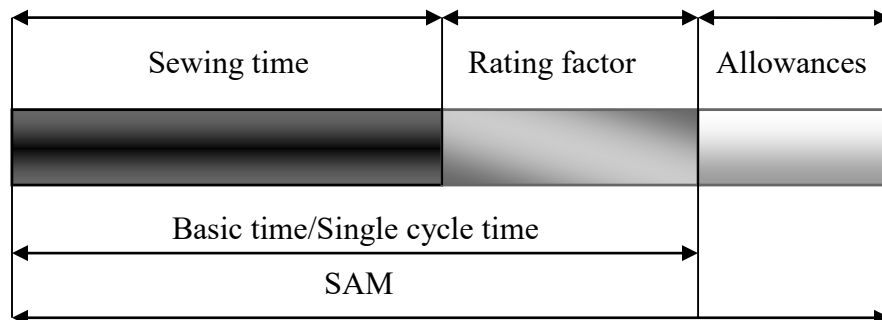


Figure 2.7 How the standard time for a simple manual job is determined

Table 2.6

*Machine Allowance for Different Sewing Machine*

Type of sewing machine according to stitch type	Machine allowance (%)
Single needle lock stitch	12.5
Double needle lock stitch	14
Single needle chain stitch	13
Serger (3 threads and 4 threads OL)	12
Safety stitch (5 threads OL/FL)	18
Multi-needle chain stitch	16
Bartack stitch	12

Source: Babu, 2012

As shown in Table 2.6, machine allowances vary with the number of threads and types of machines. Since machine allowance considers time for thread change, thread and needle breakage, and tension adjustment (Babu, 2012), it might affect the productivity of the sewing operation. Therefore, number of threads was considered as an energy consumption factor in this study. While working in the industry, the researcher found variation in the motor capacity and motor speed of sewing machines with different thread numbers. For instance, a motor used in a three-thread serger machine is different from a motor used in a five-thread serger machine. In addition, the types of stitch represent number of threads. For an example, a lock stitch or plain stitch (a certain stitch type) always consists of two threads: one bobbin thread and one needle thread (Laing and Webster, 1998). Since literature did not provide any energy consumption information based on stitch type and did not answer about which one (between types of stitch and

number of threads) could be a better energy consumption factor, the researcher decided to investigate both as factors in this study.

Rogale et al. (2005) identified number of fabric layers as an energy consumption factor. They found that the sewing machine consumes 2.7% more energy when the number of fabric layers increase from a single layer to four layers with the same RPM. Ideally, each operation consists of different fabric layers. For instance, the shoulder joint operation for a dress shirt consists of three layers of fabric whereas the same operation for a t-shirt consists of two layers of fabric. The dynamic interaction between the fabric and the sewing machine is important to ensure the correct production with right quality. In this context, fabric thickness could be another factor that deals with the energy consumption in the sewing operation of the apparel industry. With the appropriate feed mechanism and right thread, needle size, and sewing speed, increasing fabric thickness leads to higher friction between fabric and pressure foot, requires high needle penetration force to sew (Clapp, Little, Thiel, & Vass, 1992; Hayes & Mcloughlin, 2013), influence the productivity and hence, might contribute to energy consumption. The thickness of each layer of fabric represented the total fabric thickness and hence, the number of fabric layers represents total fabric thickness and vice-versa. Therefore, both layers of fabric and fabric thickness considered as one energy consumption factor in this study.

Regardless of the industry, the industrial motor uses a significant fraction of total industrial energy consumption. It is evident that electric motors are generally responsible for about 67% of industrial power consumption in each nation and about 40% of overall power consumption (Asia-Pacific Economic Cooperation [APEC], 2008, as cited in Saidur, 2010). This scenario is not different for the apparel industry. Jananthant et al. (2006) revealed that sewing departments shared the highest energy consumption followed by cutting departments in their

analysis of six apparel firms. Since the sewing operation is a machine-man operation, sewing machines are the major energy consumer in the apparel sewing process. For the apparel industry, there is a great diversity of sewing machines in order to perform numerous sewing operations. The motor is the only part that uses electric energy unless there are no energy-consumption working aids such as additional light and compressed air. Work aids are devices built into machines or added to the sewing machine to improve productivity, quality standards, and minimize sewing operators' fatigue (Tyler, 2008). The horsepower (HP) or Watt unit used to represent electrical sewing machine's motor capacity or motor power defines how much energy it will consume. The nameplate on the electrical motors represents their power and RPM (e.g., ½ HP and 3450 RPM). Rogale et al. (2003) provides detailed information regarding motor power of sewing machine and its rotation/revolution per minute (RPM) or main shaft rotation/motor speed. They have found that the sewing motor is constantly under tension and continuously consumes electric energy, whether in active-use mode or not.

Volume of output per unit time also directly affects the productivity. Since Specific Energy Consumption (SEC) for the apparel industry deals with energy units per operation or per number of apparel garments produced and is a measurement of productivity (Bheda, Narag, & Singla, 2003; Glock, 2005), volume of output per hour is an important energy consumption factor for the apparel industry (Rogale et al., 2003). However, some researchers (e.g., Raggi & Barbiroli, 1992; Reitler, Rudolph, & Schaefer, 1987) directly referred to the production quantity as an important energy consumption factor. It was conceivable that a higher volume of output per hour will result in less average energy consumption than a lower volume of output per hour. In addition, a similar term – energy productivity index (the ratio between value of output to value of energy input) – was found in the study of Juan (1998) to describe productivity as the factor of

energy consumption in the apparel industry. It is important to understand that the volume of output per hour, which is also referred to as calculated production, can be measured using SAM.

From the study of Babu (2012), the formula for calculated production was found as:

$$\text{Volume of output per hour} = \frac{\text{Number of operators} \times 60 \times \text{Operator's Efficiency}}{\text{SAM} \times 100} \quad (4)$$

From this formula, it was plausible that the variation between calculated production and actual production is determined by the operator's efficiency because the remaining elements in the formula are constant for a particular garment assembling. Since this study dealt with the energy consumption for actual production, sewing operators' production efficiency was considered as an energy consumption factor instead of dealing with volume of output per hour. In addition, energy consumption is directly related to productivity, hence to the efficiency. Furthermore, sewing operations are repetitive in nature and it is natural that operators' performance of activities or efficiency typically shows improvement when the activities are done on a repetitive basis. Therefore, the researcher believed that an operator's efficiency could be an important variable for the energy consumption.

Sivaramakrishnan et al. (2009) have reported energy consumption for various woven garment production and knit garment production. They found that knit apparel production consumes less energy (73 kWh) than does woven apparel production (96 kWh). Apart from the increased number of machines required to produce apparel, fabric sewability, which deals with productivity, could account for this varying energy consumption. Therefore, types of fabric was another factor for the energy consumption of the sewing operation. Types of fabric could be woven fabric, knit fabric, or sportswear fabric, or according to use, outerwear fabric, innerwear fabric, leisurewear fabric, and so on.

It was evident that sewing machines operate slowly because of wear and tear (Juan, 1998). A sewing machine's age and frequency of maintenance are correlated with slow or smooth sewing operation and can cause delay in production and can also contribute to the energy consumption as well. The apparel firm normally maintains a maintenance record register including the equipment or sewing machines' installation dates.

A thorough review of the literature revealed a definite gap in the understanding of energy consumption in apparel production process. The current study is expected that the current to begin filling this gap. However, it is not possible to determine all energy consumption factors in the apparel sewing operation in one study. Rogale et al. (2003) claimed in their research that higher productivity in the apparel industry has a direct beneficial impact on energy consumption: increasing output units and consequently reducing the energy consumption. Therefore, only the elements directly consuming energy and directly relating to sewing production were considered as factors in this study. In summary, from the literature review these factors are sewing machine's motor speed, motor capacity, seam length, SPI, percent of sewing machine utilization, number of sewing operations, SAM, number of threads, types of stitch, number of fabric layers and thickness, operator's efficiency, types of fabric, sewing machine age, and frequency of maintenance.

## **Chapter 3 - Methodology**

### **Introduction**

This chapter covers the rationale of employing a mixed method of research, qualitative and quantitative, and the approaches of both methods to investigate the energy consumption determinants for different sewing operations in the apparel industry. This methodology chapter outlines the study's research questions, sampling strategy, data collection procedures, and the data analysis process for both the qualitative and quantitative methods.

A mixed method of research was employed based on the purpose of this study as well as to practice pragmatism. Creswell (2009) claimed that the results from one method could help develop or inform the other method to provide comprehensive insights. Qualitative methods emphasize depth through capturing detail, miniscule nuances, and multiple perspectives with vigilant devotion with small sample sizes, whereas quantitative methods focus on breadth through acquiring information from large sample sizes. Recognizing that both quantitative and qualitative methods have different merits and demerits in the context of focusing on depth only or breadth only, this study takes a holistic approach by utilizing on both.

The qualitative method (i.e., expert interview) in this study helps to determine reality-oriented stances about the energy consumption phenomenon. Even though qualitative methods are highly subjective in nature, the added benefit of asking follow-up questions to research participants facilitates a deeper examination of research questions. On the other hand, quantitative methods provide a discrete method of identifying the most influential factors, but do not provide depth of understanding beyond what it measures. Since the energy consumption phenomenon in the apparel sewing process is an unexplored area, the mixed method brings methods triangulation to reveals complementary aspects of the phenomenon (Patton, 2002). In



order to identify the most influential energy consumption factors and their interrelationships in this study, the qualitative method might reveal the deeper understanding of them but would be unable to explain the magnitude of their influences on the energy consumption and the quantitative method might divulge the extent of influence but failed to explain comprehensively. Therefore, implementing a sequential exploratory strategy through mixed method of research is deemed logical considering the pragmatism nature of this study.

The sequential exploratory strategy includes a two-phase approach, a first phase of qualitative data collection and analysis followed by a second phase of quantitative data collection and analysis (Creswell, 2009). The purpose of this strategy includes assisting the interpretation of qualitative findings by using quantitative data and results. Creswell mentioned the primary focus of this strategy is “to initially explore a phenomenon” (p. 211) and energy consumption was the phenomenon in this current study. The mixed method of research ideally places equal weight between the qualitative and quantitative data, but often times in practice, it may be given priority to one or the other (Creswell, 2009). However, it addresses the thorough approach by offsetting one method’s inherent weaknesses with the strengths of the other (Creswell, 2009) as well as overcoming individual method’s intrinsic biasness (Patton, 2002).

## Objectives and Research Questions

The overarching objectives of this study were to understand the phenomenon of energy consumption, and by extension GHG emissions, for different sewing operations in the apparel industry. The objectives were:

1. To identify most influential energy consumption factors of the sewing process in apparel industry, and to develop a regression model to measure energy consumption.
2. To determine the interrelationships among energy consumption factors
3. To identify steps to reduce energy consumption within sewing process in apparel industry, and
4. To explore the apparel industry experts' level of concern regarding energy consumption, the contribution to greenhouse gas emissions and climate change in the apparel manufacturing.

Objectives 1 and 2 were addressed using a mixed method approach, incorporating experts' opinions from qualitative interviews and quantifying each factor's degree of influence (i.e. influencing strength) over energy consumption along with the direction and magnitude of association. The remaining two objectives were answered with a qualitative method of research. Based on the above-mentioned objectives, 12 research questions were developed; these questions along with their respective research method and analysis technique are provided in Table 3.1.

Table 3.1

*Objectives, research questions, method of research, and approaches pertinent to this study*

Objectives	Research Questions	Method and Analysis
1	RQ1: Which apparel sewing operation factors do industry experts identify as being most influential on energy consumption and why?	Qualitative- Realist approach with content analysis and comparative analysis
	RQ2: Which apparel sewing operation factors are identified as most influential on energy consumption through statistical analysis?	Quantitative- Multiple regression analysis
	RQ3: Are the factors identified in RQ2 congruent with the expert findings in RQ1?	Mixed – Sequential exploratory strategy
2	RQ4: What interrelationships between energy consumption factors are identified by industry experts?	Qualitative- Comparative analysis
	RQ5: What interrelationships between energy consumption factors are identified by the statistical analysis?	Quantitative- Pearson correlation analysis
	RQ6: Are interrelationships identified in RQ5 congruent with the expert findings in RQ4?	Mixed – Sequential exploratory strategy
3	RQ7: What potential solutions for reducing energy consumption in apparel industry are identified by industry experts?	Qualitative- Content analysis and comparative analysis
4	RQ8: What level of concern is expressed by industry experts regarding energy consumption in the apparel manufacturing?	
	RQ9: What (if any) energy reduction initiatives have been initiated by the industry experts’ company in order to reduce consumption?	
	RQ10: What type of energy consumption and climate change conversations are industry experts having with other apparel industry professionals?	Qualitative- Content analysis and comparative analysis
	RQ11. How might an energy consumption model be used by apparel industry professionals?	
	RQ12. What level of importance might industry experts give to energy consumption as a decision-making component within apparel production in the future?	

## **Statement of the Use of Human Subjects**

This study utilized an online survey and semi-structured interviews to examine the apparel industry experts' opinions to identify substantial energy consumption factors in the apparel sewing operations, to determine interrelationships among these factors, and to understand approaches used to reduce the energy consumption in the apparel industry. Prior to beginning the research study, the Kansas State University's Institutional Review Board (IRB) board reviewed and approved the study (IRB #8001). "The Institutional Review Board (IRB) is committed to providing a comprehensive and compliant Research with Human Subjects program for researchers, students, and potential human subjects. At Kansas State University the Committee on Research Involving Human Subjects serves as the IRB and is mandated by federal laws and regulations for oversight of all activities involving research with human subjects" (Kansas State University IRB, 2014, para. 1).

## **Qualitative Method of Research**

### **Research Approach**

Qualitative research includes a variety of approaches. Patton (2002) claimed it as "not a single, monolithic approach to research" (p. 76). However, selecting the right approach to develop framework, to lodge plans and ideas is crucial for any research project. For this study, the researcher selected the realist approach was selected as appropriate for the objectives. A realist approach incorporates reality-oriented stances that correspond to the "real world." Reality-oriented stances represent the inclination toward literal truth and pragmatism based on what is practical, more insightful, valid, and useful (Maxwell, 2012). While explaining how to conduct research that will be more insightful and practical, Maxwell mentioned,

I believe that a realist approach can do this by enabling researchers to develop more relevant and insightful theories about the things they study, to plan their strategies and methods to be more productive, valuable, and ethical, and to develop conclusions that more validly indicate what is actually happening in the situations they study (p. 181).

A realist approach focuses on processes and pays close attention to what is actually going on rather than regularities. Since Patton referred to real knowledge as “limited to what could be logically deduced from theory, operationally measured, and empirically replicated” (p. 92), this realist approach aims to search for current facts (i.e., energy consumption phenomenon) from the real world (i.e., apparel production process). It helps to determine current realities from the opinions of research participants by stimulating them to reveal practical knowledge in terms of usefulness. In order to provide the actual information, the participants must have lived experience on that particular fact. Therefore, this study utilized apparel industry experts as participants and engaged them to discuss energy consumption phenomena in the sewing operations from their lived experience.

### **Sampling Strategy**

The power of qualitative research lies in the ability of selecting appropriate sampling techniques and nesting them (Patton, 2002). According to the nature of this study, purposeful intensity sampling strategy was employed. Intensity samples consist of “information-rich cases that manifest the phenomenon of interest intensely” (Patton, 2002, p. 234) and purposeful represents non-random sample selection. In this study, the sampling strategy includes participants who are information-rich along with having intense lived experience with apparel production (especially the sewing process). The samples were apparel industry experts who are capable enough to identify potential energy consumption factors for the different sewing operations. The expert selection criteria included working in the apparel industry for at least four

years; being directly involved with apparel production decision processes; and preferably, holding a managerial post. In addition, a snowball or chain sampling strategy was employed to get connected with more experts from different types of apparel production (e.g., woven-wear, knitwear, and sportswear).

Sample size (i.e., number of experts) was determined utilizing the saturation technique; data collection ended when no new information was reported from the experts. From the recommendations of Romney, Batchelder, and Weller (1986) as well as Guest, Bunce, and Johnson (2006), it was expected that the number of participants would be around 4-12. The final determination of the number of participants was based on the researcher's judgement of when experts were no longer revealing any new information. A total of nine participants were interviewed for the qualitative analysis portion of the study. The targeted apparel industry experts were drawn from production managers, apparel production engineers, vice presidents of apparel sales and production, and general managers, and they were fairly experienced in all types of apparel industry.

The researcher knew three experts in person, having met them at various conferences, seminars, and summer internships. He approached them first for this study and asked for their help connecting with other apparel industry experts in the US. Possible participants were contacted through email with a short description of the project and an invitation to participate. Once they agreed to participate and returned a signed informed consent form, they were interviewed.

## **Instrumentation**

The instrument in the qualitative component of this study was interview questions and the data collection technique was semi-structured, open-ended interviews with oral responses. Immediately before the interview, a Q-sort (i.e., dragging and dropping) technique online survey was distributed via the Qualtrics software platform to the interviewees. The survey consisted of an initial list of energy consumption factors, developed from literature review and research experience. The participants were asked to sort the factors into different groups based on their level of influence on energy consumption (e.g., most influential, less influential). From his industrial experience, the researcher witnessed a lack of concern regarding energy consumption in the apparel production process. This lack of concern might lead to a lack of knowledge and may make experts less competent to provide a holistic picture of energy consumption in the apparel sewing process. Therefore, experts were given the list of energy consumption factors instead of asking them directly which factors contribute to the energy consumption.

The semi-structured interview evolved from the combination of both structured and unstructured questions (Merriam, 2009). The semi-structured and open-ended nature of interviewing allows the participants freedom and creativity in their responses. In addition, this technique offers the interviewer the flexibility to probe, which eventually facilitates information-rich responses to open-ended questions and encourages depth of responses. Semi-structured interviewing also provides hints to the interviewee about the level of desired response (Barriball & While, 1994). At the beginning of the interview, the researcher introduced himself to the participants, followed by a short description of this study. The interview was then initiated with asking an opening question to make the ambience familiar to both experts and interviewer and to develop rapport between the two parties. The same question helped participants to engage with

the subsequent questions related to the energy consumption in the sewing process and elicited the experiences to support their responses.

The interviews occurred via teleconferencing (audio recorded, upon IRB approval and participants' consent) and the researcher utilized an interview guide (see Appendix A). All of the participants were given the same questions. This increases comparability and limits the interviewer effects and bias. All the interview questions were directly related to the research questions and sequentially designed. However, the researcher pursued interesting related topics if introduced by a participant.

### **Data Collection Procedure**

In qualitative research, data must be descriptive in nature. All participants were contacted via email to elicit their participation in this study. Follow-up emails were sent to participants to confirm time and place at their convenience for the interview. All interviewees were provided with an explanation of this study's purposes and intended outcomes. Each participant was guaranteed confidentiality. Participants also were provided the assurance that they could withdraw from the research process at any time without any explanation. For the local apparel industry experts, the interview was conducted face to face by using voice recorder, while for those who were not in vicinity, it was conducted via using online video conferencing service (i.e., Zoom). All the interviews were audio and video recorded according to the consent of interviewees. Participants were contacted again after the interview (based on prior consent) if the researcher deemed it necessary to clarify any issues from the initial interview.



## **Transcription**

Verbatim and denaturalized transcription was used. The denaturalized practice eliminates idiosyncratic elements of speech (e.g., stutters, pauses, nonverbal, gestures, involuntary vocalizations) from the transcription process (Oliver, Serovich, & Mason, 2005). Transcription was conducted by the researcher with the help of NVivo version 11.0 through moving back and forth between recording(s) and transcript(s).

During transcription, the researcher's cultural standpoint and significant power difference in relation to participants could have biased his analysis. The difference in class, culture, and language between the interviewer and the interviewees, along with preconceptions of the interviewees, influenced the transcripts (MacLean, Meyer, & Estable, 2004; Tilley, 2003). However, according to Poland's (1995) recommendation, these limitations were overcome through capturing the utterances as closely as possible as they were audiotaped, and utilizing denaturalized transcription made it easy to perform. Having experience in the apparel manufacturing process, the researcher considered himself as a 'relative insider' in this research, which placed him in privileged position with respect to transcription and interpretation (Witcher, 2010). Since the researcher did not conduct the interviews with a completely blank slate, being a 'relative insider' led to the improvement in transcription quality, in reflexivity, and in maintaining research rigor and trustworthiness.

Sometimes the lack of coherence in the discourse makes it harder to understand (Forbat & Henderson, 2005; Tilley & Powick, 2002). In addition, being a non-native English speaker, some culturally specific words (e.g., unfamiliar accents or colloquialisms) were difficult to understand and the researcher went back to re-listen to the recorded interviews several times. Furthermore, the researcher sought help from his advisor who is a native English speaker to

overcome these problems. However, in spite of requiring more time, overall rigor, trustworthiness, and transcription quality were not compromised. While re-listening to the recorded interviews, the researcher sincerely tried to eliminate transcription errors including missed words, misinterpreted words, and misheard words. Overall, knowing these above-mentioned limitations related to transcription before the interview helped the researcher better ensure transcription quality.

Because the data gathered for the qualitative research are voluminous in nature, it could be difficult to handle and organize. In this regard, the researcher followed a pre-plan for managing data. Immediately after an interview, gathered information was transcribed verbatim through reviewing the audio recording. The interviews were scheduled in such a way that the interviewer had 24 hours free after conducting the interview to do this immediate transcription. In addition, the researcher went through field notes to get insights and to determine inconsistencies from the interview to augment the quality of analysis. Throughout the interview process, comparisons of responses provided a sense of the emerging factors and relationships across interviews. Challenges and complications from each interview and its analysis were overcome in subsequent interviews and analyses. The researcher became aware of potential complications in handling interview responses in the form of incomplete field notes, unfinished field notes that were put off to write later, insufficient data collection, a significant gap in the interviewee responses, improper data categorization, and inappropriate labeling.

## **Analysis**

In this study, there were two steps in the qualitative data analysis plan: content analysis to facilitate coding and categorizing the data, and comparative analysis to identify themes. Content

analysis facilitates a flexible, pragmatic method for developing and extending knowledge of the human experience to the researchers. It is described as “the subjective interpretation of the content of text data through the systematic classification process of coding and identifying themes or patterns” (Hsieh & Shannon, 2005, p. 1278). In addition, coding is referred as “the pivotal link between collecting data and to explain these data” (Charmaz, 2014, p. 46). Incident-to-incident coding was utilized in this qualitative analysis. Apart from word-by-word and line-by-line coding, the incident-to-incident coding deals with events or occurrences. The explanation about an energy consumption factor, description of two factors’ interrelationship, and justification of a particular suggestion to reduce energy consumption were examples of an incident in this study. The reason behind using incident-to-incident coding was to facilitate making comparison between incidents. This works better than word-by-word or line-by-line coding to grasp a comprehensive sense of the study contexts (Charmaz, 2014) and addressed the goal of content analysis as “to provide knowledge and understanding of the phenomenon under study” (Downe-Wamboldt, 1992, p. 314).

The qualitative content analysis included searching of key incidents that referred to energy consumption factors, their interrelationships, solutions related to energy conservation, and the experts’ level of concern on global climate change. A coding scheme was developed from the key incidents of expert responses to the research questions. Codes were then sorted into categories based on how different codes are related and linked. In this regard, sensitizing concepts were implemented. According to Patton (2002), a sensitizing concept “refers to categories that the analyst brings to the data” (p. 456). Using sensitizing concepts helped the researcher to determine categories that provide a general sense of reference to both academia and practitioners. It also helped to identify central element of a good description. Since this study is

based on expert interviews from the same industry (apparel manufacturing), the researcher encountered somewhat similar jargon (e.g., SAM) throughout experts' responses. However, the purpose of using qualitative content analysis was to classify voluminous text from the interview into an efficient number of categories that represent similar meanings.

Data analysis started with reading transcriptions repeatedly to obtain a sense of the whole (Tesch, 1990). In addition, the task of discovering themes is the heart of qualitative data analysis and one of the most fundamental tasks (Ryan & Bernard, 2003). A comparative analysis was implemented to identify themes through analyzing similarities and differences written interview statements and incidents within the same interview and among different interviews. While analyzing similarities and differences, word-based techniques— word repetitions and key-words-in-contexts (KWIC) — were applied for theme identification. The frequency of mention was the key strategy to identify factors and their interrelationships. Furthermore, the same technique was applied to identify patterns as well as to utilize saturation technique in this project.

### **Substantive Significance**

The study's substantive significance depends on the consistency and congruency of findings, how the findings are captured, consistency of the findings with others' knowledge, and findings' usefulness (Patton, 2002). Seeking experts' opinion could be another supporting issue for determining substantive significance in this study. All the participants held extensive expertise from the apparel industry and therefore provided in-depth, coherent, and consistent responses reflected from actual apparel production. Witcher (2010) mentioned, “[W]hen working with unique or distinct populations, remaining faithful to the aural record can be difficult and may present the relative outsider with particular challenges to maintaining data quality” (p. 130).

Since this project involves a distinct population (i.e., industry experts), as a ‘relative insider’ (i.e., having experience in the apparel production process) the researcher could play a vital role in maintaining rigor of analysis and interpretation through relying on his own intelligence, judgment, and on his own experience. Since ‘correspondence of findings to reality’ is an important criteria for judging the quality and credibility of a qualitative inquiry (Patton, 2002), the researcher’s ‘relative insider’ status could assist to maintain this criteria.

Most importantly, the findings of research questions were achieved through triangulation. The experts shared energy consumption information about sportswear, woven-wear, and knitwear companies from the US. Apart from the methodological triangulation (i.e., using both qualitative and quantitative method) in this study, including experts from various types of the apparel industry (e.g., sportswear, woven, and knit) addressed the triangulation of data sources; it enhanced the likelihood of capturing all potential energy consumption factors from diverse production units. In addition, triangulation provides greater credibility of data and greater understanding of the findings across different data sources (Patton, 2002). Furthermore, the representation of extensive verbatim transcription of the interviews (e.g., direct quotes) supported the transferability of the data.

## **Quantitative Method of Research**

After the qualitative portion of the project, the study utilized quantitative data collection and analysis. Identified energy consumption factors from the literature were quantified and collected through direct observation. Factors were analyzed to determine explanatory power over energy consumption, investigate correlations among them, and develop an energy consumption model for sewing operation in the apparel industry.

## **Unit of analysis**

Selection of the unit of analysis is a crucial part in any research project and it should be commensurate with the research questions. Based on the specific research questions for this study, the unit of analysis was different sewing operations (e.g., side seam, label attaching) which are common in any apparel industry. At the end of the study, determining influential energy consumption factors for apparel sewing operation was the primary outcome of the quantitative part.

## **Data Collection**

The number of observations for the quantitative part was determined from the guidelines provided by Green (1991) and Maxwell (2000). Green indicated the traditional rule of thumb of having at least five observations or cases per independent variable (i.e., 5:1 ratio) in the multiple regression analysis whereas Maxwell recommended of having 10: 1 ratio (i.e., 10 observations per independent variable). In addition, Vittinghoff and McCulloch (2007) claimed the 10:1 ratio is too strict, even though they found numerous errors associated with ratios of 2:1 to 4:1 at the same time. However, they were indicating that the ratio should be at least 5:1. Ninety-eight observations from 98 sewing operations in three apparel factories— one woven-wear, one knitwear, and one sportswear apparel factories represented the data for this study. These three factories are located in western part of the United States. Each observation consisted of 11 independent variables and one dependent variable (approximate ratio 9:1).

Two high-resolution video recorders, an energy consumption meter, and a fabric thickness gauge were used as instruments to capture real time energy consumption and to quantify factors pertinent to sewing operations. One high-resolution camera was used to capture

sewing activities from the sewing zone of the sewing machine and another camera was used to capture sewing activities from the paddle side under the sewing machine. Therefore, two videos were captured for each operation and before analysis, these two videos were placed side by side and synchronized against their timelines (see Figure 3.1) using Sony Vegas Pro version 12.0 software. The subsequent video editing generated one video for each operation, enabling the researcher to extract data from the video. The energy consumption meter was connected to the sewing machine with a series connection. This way of connection allows the meter to read kilowatt-hour (kWh) information that represents the energy consumption for a particular sewing operation.



*Figure 3.1* Synchronized two adjacent videos against their timelines

## Data Extraction Method

Some data were directly collected from the observations and the remaining data were extracted from the videotaped observations. Sewing machine motor capacity, motor speed, layers of fabric, SPI, number of threads, types of fabric, and seam length per operation per piece were directly collected from the observations. Fabric thickness was measured with a fabric thickness gauge, and energy consumption per operation per piece was collected with an energy consumption meter. SAM, operator production efficiency, and percent of sewing machine utilization was extracted from the recorded video for each operation.

In order to calculate SAM or SMV, first the total sewing time for each operation was extracted from the video. Second, the average sewing time and operator's subjective performance rating were measured, also by video. The percent of allowances (e.g., machine allowance and relaxation allowance) to be utilized in the formula were based on guidelines provided in the literature (see *Equation 3* in Chapter 2).

Operator production efficiency is the ratio between SAM and required SAM (R-SAM). R-SAM represents the actual sewing time per piece in a minute for an operation. R-SAM was extracted and determined from the sewing time recorded.

Percent of sewing machine utilization represents how much time the sewing machine is actually being utilized by the operator. The sewing time for an operation consists of both actual machine running time and fabric manipulation time. The actual machine running time was marked (see Figure 3.2) from the previously extracted R-SAM video clip and determined against total R-SAM value.





Figure 3.2 Determining sewing machine utilizing percent through using markers

Table 3.2

*Summary of Data Collection Procedure*

Factors	Quantifying Method	Measuring Units
Energy consumption	Watt's Up energy consumption meter hooked up to the sewing machine	kWh
Motor speed	Metal nameplate attached on the sewing machine	RPM
Motor capacity	Metal nameplate attached on the sewing machine	HP
Types of fabric	From lot description or direct observation	Ordinal data (Fab 1 for knit, Fab 2 for sportswear and Fab 3 for woven fabric)
Fabric thickness	Fabric thickness gauge	mm
Seam length	Direct observation	inch
Stitches per inch (SPI)	From sewing machine's stitch density regulator	inch <sup>-1</sup>
SAM	Extracted from recorded video	minute
Operator's production efficiency	Extracted from recorded video	percent
Number of threads	Direct observation	
Sewing machine utilization	Extracted from recorded video	percent
Layers of fabric	Direct observation	
Types of stitch	Direct observation	
Frequency of servicing/maintenance	From maintenance record register	year <sup>-1</sup>
Machine age	From maintenance record register	year
Number of sewing operation	Direct observation	

## **Data Variability and Credibility**

Data was directly collected from three apparel production firms in such a way that observations were obtained for different operations, from different operators, and different machines. For example, two sewing operations might be same, performed by same operator but by different machine or, two sewing operations might be different but performed by same operator and machine or, two sewing operations might be same, performed by same machine but by different operator. Therefore, observations had variability, either in operation, operator, or sewing machine. The method of data collection enhanced credibility in the sense that all observations were collected using sewing operations and operators in current apparel mass production facilities. In addition, a careful approach was used in selecting factors to avoid redundancy. For instance, either SAM or the average sewing time could be selected as factors because both are interrelated and can be converted one from the other. However, SAM was selected in this study because it is widely used by the industry. Similarly, any redundant variables and variables that could not be quantified from reliable sources (i.e., lacking of record or evidence) were not included in the quantitative study.

## **Data Analysis**

Data was analyzed using statistical tools in STATA version 12.0. The researcher employed a variety of statistical approaches to analyze and draw conclusions about the variables. The influential energy consumption factors were selected based on higher beta coefficients ( $\beta$ ) and lower significance level of  $T$  ( $p \leq .05$ ) from the multiple regression analysis and were eventually used to determine which factor(s) highly contributed to the energy consumption of the

sewing operation in the apparel industry. The higher the beta coefficients, the higher the factor's (independent variable) influence over energy consumption (dependent variable).

The magnitude (strength of association) and direction of relations among independent variables were determined through employing Pearson's correlation coefficients ( $r$ ) with a significance level of 5% or less ( $p \leq .05$ ). Since there are three strengths of association – weak ( $r = \pm.1$  to  $\pm.3$ ), moderate ( $r = \pm.3$  to  $\pm.5$ ), and strong ( $r = \pm.5$  to  $\pm 1.0$ ) – only the variables with moderate and strong strengths of association were considered in this study and are discussed in Chapter 4. Another reason for using Pearson's correlation coefficients is that it allowed eliminating highly correlated variables to avoid redundancy in the multiple regression analysis.

A regression model was developed using primary data collected from the apparel industry. If the independent variables or energy consumption factors are denoted as  $X_1, X_2, X_3, \dots, X_n$ , and dependent variable or energy consumption is denoted as  $Y$ , the multiple regression model can be represented as:

$$Y = a_0 + aX_1 + bX_2 + \dots + nX_n + e \tag{5}$$

( $a_0$  is an intercept or constant coefficient,  $e$  is the constant error term, and  $a, b, c, \dots, n$  are respective variables' coefficients)

The value of  $a_0, a, b, \dots, n$  of the regression model were determined from coefficients (B), and the value of  $e$  was determined from standard error term (constant). While adjusted coefficient of multiple determination ( $Ra^2$ ) provides an estimate of the strength of the relationship between the regression model and the response variables as well as represents the goodness of fit of the model,  $Ra^2$  value was used to evaluate the model's explanatory power. In addition, using  $Ra^2$  for the multiple regression model is recommended over coefficient of multiple determination ( $R^2$ ) because  $Ra^2$  incorporates the model's degrees of freedom and hence,

increases the independent variables prediction to the dependent variable. Furthermore, since the F-test determines whether the proposed relationship between the dependent variable and the set of independent variables is statistically reliable, the reliability of the model was determined from the F-test of overall significance.

### **Regression Analysis Plan**

**Step 1.** An initial multiple regression analysis was performed to evaluate the influence of all independent variables on the dependent variable (energy consumption). The regression model strength was evaluated based on the  $Ra^2$  value. An  $Ra^2$  value closer to one represents the independent variables' better predictability to the dependent variable in the model.

**Step 2.** A second multiple regression analysis was computed using the independent variables having better explanatory power from the earlier model. Independent variables with better explanatory power were selected based on higher beta coefficient ( $\beta$ ) value. A stepwise regression analysis was performed to crosscheck how many independent variables provide a better prediction over the dependent variable. A comparison between  $Ra^2$  value of the two models: sub-regression model (model from step 2) and original model (model from step 1) was evaluated. If the  $Ra^2$  of sub-regression model increased substantially, it was considered over the original model (after checking that any absolute value of  $r$  was not greater than 0.75).

**Step 3.** Basic multiple regression analysis assumptions (i.e., linearity and additivity, no or little multicollinearity, multivariate normality, homoscedasticity) were evaluated. The method of evaluating assumptions is discussed below.

***Linearity and additivity.*** The regression model assumes that the relationships between the independent variables and the dependent variable are both linear and additive. If the model does

not comply with this assumption, there is a chance that relevant independent variables are excluded, irrelevant independent variables are included, or both (Berry & Feldman, 1985).

Partial regression residual plot and component plus residual plot were applied to detect the nature of the relation. In case of monotonic non-linear relationships between the independent variable and dependent variable, a common rule of power transformation is to be carried out according to Tukey's bulging rule. After power transformation, the new model's strength is compared to the earlier model's strength (based on  $Ra^2$  value). The product-term approach would be implemented to evaluate the additivity assumption of the multiple regression analysis.

***Multicollinearity.*** In order to test the assumption of multicollinearity, the variance inflation factor (VIF) was applied. If the VIF coefficient is less than 4.0 and absolute value of correlation coefficient ( $r$ ) is not greater than 0.75, the model depicts no multicollinearity (Berry & Feldman, 1985). However, if multicollinearity exists, combining two or more highly correlated independent variables into a single variable and then using the composite variable in the place of correlated variables in the regression would be carried out.

***Multivariate normality.*** A skewness test was performed for the variables to detect multivariate normality within the regression model. The acceptable range for skewness is considered between -2 to +2. If the skewness of any variables extends beyond this range, a power transformation would be applied to minimize it.

***Homoscedasticity.*** Finally, the evaluation of homoscedasticity assumption was carried out through plotting the studentized residuals against fitted values. If the pattern of non-constant error variance is linear, then the Breusch-Pagan test would be carried out. Alternatively, if the pattern is non-linear, then White's test would be carried out. For both tests, if the chi-square value for the test is significant ( $p < 0.050$ ), then the model depicts heteroscedasticity and hence,

the White's corrected standard errors (also known as 'robust' standard errors) would be computed and t-test for each independent variable recomputed.

### **Integration of Qualitative and Quantitative Data**

After analyzing quantitative and qualitative data, findings (qualitative and quantitative) were compared to draw conclusions in terms of the study's objectives and research questions. The findings of influential energy consumption factors and their interrelations were compared across the qualitative and quantitative results. These results were then checked against the literature review discussed in Chapter 2. However, the researcher used judgement as to whether the qualitative and quantitative findings corroborated, contradicted, or were not related to each other (Driscoll, Appiah-Yeboah, Salib & Rupert, 2007).

## **Chapter 4 - Findings**

### **Introduction**

Using both qualitative and quantitative research methods, this study investigated energy consumption within the apparel production process, more specifically the sewing process. The qualitative methodology included apparel industry experts' opinions; they were asked about their experiences with apparel production, their opinion about the most influential determinants/factors contributing to energy consumption in the apparel sewing process, their perceptions about the interdependence among these factors, and their experience-based suggestions for reducing energy consumption for different sewing operations. At the very end of each interview, questions were asked about their level of concern regarding energy consumption, the apparel industry's contribution to greenhouse gas (GHG) emissions, and climate change. The interview was recorded and transcribed, and themes (see Appendix B) were identified based upon each research question. The quantitative part of this study included gathering real-time energy consumption data from the apparel sewing process. This chapter presents analysis and discussion of both the qualitative and quantitative data.

### **Introduction to Research Participants**

All research participants in this study were apparel industry experts. A total of nine experts participated in the interviews. These experts were selected through purposeful intensity and snowball sampling. There were six males and three females, and they were all US citizens between the ages of 31 and 63 years. They had noteworthy apparel industry expertise ranging from 4-40 years with the production process along with 4-35 years of direct involvement with management and/or production.



The mean age of the research participants was 53, where the youngest one was 31 and the oldest one was 63. The mean number of years these experts have been involved in the apparel manufacturing process was 27, and the mean number of these years they were involved in management and/or production was 23. Their current designations included Managing Director for Production, Apparel Industry Production Consultant, Senior Vice President of Supply Chain, and Lecturer and Associate Professor in Apparel and Textiles. Though two participants' current position titles were Lecturer and Associate Professor, both had sufficient apparel industry experience to qualify as an expert in this study. See Table 4.1 for all the research participants' demographic information.

Table 4.1

*Research Participant Demographics*

Participant #	Age	Apparel manufacturing process experience (years)	Management and/or production decision responsibility (years)	Current position title	Gender
1	63	32	25	Managing Director for Production	F
2	58	35	30	Owner of a Textile and Apparel Consulting firm	M
3	59	33	31	Lecturer	F
4	Unknown	22	10	Associate Professor	M
5	63	40	30	Director	M
6	61	39	35	Consultant	M
7	31	4	4	Production Manager	M
8	53	34	34	Director of Product Development and Production	F
9	37	5	5	Senior Vice President of Supply Chain and Sales	M

After introducing himself to the participants, the researcher initiated interview with an opening question: “In your opinion, what comes to your mind when I ask you to talk about the energy consumption in the apparel industry?” All participants provided insights about the apparel industry’s production process and its energy consumption while they were responding to this first question. They mostly stated the current situation of the apparel industry. Participant 1

stated, “There is probably room for improvement. A lot of factories are operating like they used to for the last 30 years.” The term “probably” and the reference to traditional operation in her response suggest a lack of certainty regarding the reduction of energy consumption in the apparel industry as well as the industry’s lack of attention to sustainable apparel assembling.

In this opening question, even though participants 4 and 8 acknowledged the energy intensive nature of the apparel industry by stating, “apparel industry consumes a lot of energy”, contrasting responses were given by other participants. Participant 2 mentioned, “I don’t know that it [energy consumption] was as much of an issue as it is now.” The most astonishing thing happened when participant 5, with 40 years of experience in the apparel industry, mentioned,

I'm gonna be very candid with you ... It's really nothing in terms of the assembly, the sewing operations that I have ever really given consideration to, it's never been a discussion point with my vendors, the factories that I worked with, etc. ... But in all honesty, I as a professional and the people that I've associated with over the years this is never in the sewing operation being a point of discussion. Honestly speaking, it is the first time I have been exposed to it and am thinking about it...

This response was not surprising to the researcher, who has industrial experience and witnessed a lack of concern regarding energy consumption in the apparel production process. This finding supports the decision to provide a list of energy consumption factors in a Qualtrics survey to encourage a thorough discussion of energy consumption factors in the subsequent interview.

## **Descriptive Statistics**

A total of 98 sewing operation observations were directly gathered from three different apparel manufacturing factories in the US. These 98 observations consisted of 62 sewing operations, performed by 39 sewing operators using 47 sewing machines. Each observation collected quantitative data for a single component of the sewing (or assembling) process such as

energy consumption, sewing time (converted into standard allowed minute [SAM] later), seam length, number of fabric layers, fabric thickness, performing sewing machine’s motor capacity, sewing speed, percent of sewing machine utilization, stitches per inch (SPI), number of threads, types of fabric, and operator’s production efficiency. Among 98 observations, 16% of observations were collected from the knitwear assembling process, 41% from the woven-wear assembling process, and the remaining 43% from the sportswear assembling process (see Table 4.2).

Table 4.2

*Frequency of Apparel Sewing Operations Based on Product type*

Product type	Frequency	Percent	Cumulative Percent
Knitwear	16	16.33	16.33
Sportswear	42	42.86	59.18
Woven wear	40	40.82	100.00
Total	98	100.00	

In terms of sewing machine type, 43.88% of observations were collected from single needle lock stitch machines (also known as a plain machine), 12.24% from covering chain stitch (also known as flatlock stitch) machines with three threads, 3.06% from covering chain stitch machines with five threads, 8.16% from serging stitch (also known as overlock stitch) machines with three threads, 25.51% of observations from serging stitch machines with four threads, and the remaining 7.14% from serging stitch machines with five threads (see Table 4.3).

Table 4.3

*Frequency of Apparel Sewing Operations Based on Sewing Machine Types*

Sewing machine types	Frequency	Percent	Cumulative percent
Single needle lock stitch machine	43	43.88	43.88
Covering chain stitch machine (3 thread)	12	12.24	56.12
Covering chain stitch machine (5 thread)	3	3.06	59.18
Serging stitch machine (3 thread)	8	8.16	67.34
Serging stitch machine (4 thread)	25	25.51	92.85
Serging stitch machine (5 thread)	7	7.14	100.00
Total	98	100.00	

**Influential Energy Consumption Factors for Sewing Operations**

The first research objective includes identifying the most influential energy consumption factors of the sewing process in the apparel manufacturing industry and developing a regression model to measure energy consumption. In order to attain this objective, three research questions were developed and both qualitative and quantitative research methods were integrated. The three research questions were:

RQ1: Which apparel sewing operation factors do industry experts identify as being most influential on energy consumption and why?

RQ2: Which apparel sewing operation factors are identified as most influential on energy consumption through statistical analysis?

RQ3: Are the factors identified in RQ2 congruent with the expert findings in RQ1?

### **RQ1: Energy Consumption Factors Identified as Most Influential by Industry Experts**

A list of factors was initially developed from the review of academic literature and researcher experience in the apparel industry. The list of factors was sent to the research participants in the form of an online survey via Qualtrics software. Participants were asked to help refine the list by dragging and dropping these factors into any of the following four groups:

- A. Most influential energy consumption factor in the apparel sewing process
- B. Factor that falls between groups A and C
- C. Least influential energy consumption factor in the apparel sewing process
- D. Factor that does not contribute to energy consumption in the apparel sewing process

Apart from the factors mentioned in the Qualtrics Survey, respondents were also asked to identify any additional factor(s) they think might be influential energy consumption factor(s) in the apparel sewing process. Table 4.4 summarizes the participants' responses to the Qualtrics survey.

Table 4.4

*Sorting of Energy Consumption Factors by Experts*

Energy Consumption Factors	Categorization by Research Participant									Number of Responses in Each Category			
	1	2	3	4	5	6	7	8	9	A	B	C	D
Types of fabric	C	A	C	C	C	D	C	C	C	1		7	1
Number of sewing operations	A	A	A	A	A	A	C	A	A	8		1	
Standard Allowed Minute (SAM) or Standard Minute Value (SMV)	A	A	D	A	A	A	A	A	A	8			1
Types of Stitch	C	A	C	A	B	B	C	A	C	3	2	4	
Number of threads in stitch	C	D	C	A	B	B	C	D	C	1	2	4	2
Seam length in assembling operation	C	C	A	A	B	B	A	D	C	3	2	3	1
Number of stitches per inch (SPI)	D	D	C	A	B	B	C	C	C	1	2	4	2
Layers of fabric and fabric thickness	C	A	C	C	B	D	C	C	C	1	1	6	1
Sewing machine's motor capacity	A	C	A	A	A	B	C	A	C	5	1	3	
Sewing machine's speed	A	C	A	A	B	B	A	A	C	5	2	2	
Frequency of sewing machine maintenance	D	A	C	C	C	B	A	C	C	2	1	5	1
Operator's production efficiency	C	A	A	A	A	C	A	C	A	6		3	
Sewing machine age	A	D	A	C	A	B	A	C	C	4	1	3	1
Percent of sewing machine utilization	A	B	A	A	A	C	A	D	A	6	1	1	1

Note: A = most influential factor; B = factor that falls between groups A and C; C = least influential factor; and D = does not contribute to energy consumption

The experts were asked to explain their reasons for selecting different sewing processes as highly contributing energy consumption factors from their Qualtrics survey response. Due to the exploratory nature of this study, the researcher sought explanations in the interview only for the most influential energy consumption factors. As each factor was selected as most influential (A) by at least one participant, the researcher determined the most influential factors as mentioned by the majority (at least by five out of the nine participants). The researcher conducted an intensive search for factors and their relationships. Having incongruent responses during semi-structured interviews is somewhat predictable, so this sense-making effort reduced the chance of erroneous analysis and helped to identify core-consistencies and meanings as well as similarities and differences between the participants' responses. As shown in Table 4.4, the participants identified the most influential energy consumption factors as: number of sewing operations, Standard Allowed Minute (SAM) or Standard Minute Value (SMV), sewing machine's motor capacity, sewing machine's speed, operator's production efficiency, and percent of sewing machine utilization.

**Number of sewing operations.** Assembling apparel deals with a series of sewing operations, and eight participants identified number of sewing operations as the most influential energy consumption factor in the apparel sewing process. The complexity and design of a garment determine the sequence and the number of sewing operations. Participant 1 described the sewing complexity of a garment by stating "there's a huge range of complexity from simple garments to a jacket. The jacket would definitely take a lot more sewing time and have a lot more stitches in it than a simple garment." Each sewing operation requires a certain time to accomplish. The total assembling time for a particular garment can be determined from the sum of each operation's sewing time. The sewing time also determines how long the sewing



machines need to run. Hence, it is logical that both assembling time and energy consumption would be higher with the increasing number of sewing operations. Participant 5 pointed to this link by stating, “Concerning the number of operations is gonna speak to how long that product is gonna be in assembling. To me, the longer it's gonna be in assembling going back to energy, a lot more energy it's gonna consume to finish the process.”

The participants illustrated their assertion that sewing operations were the most influential energy consumption factor with examples. Participant 3 gave an example of a t-shirt and a lined wool coat and said, “Obviously if you have like (sic) a simple t-shirt ... that's gonna require much less energy than if you're making like a lined wool coat with many many operations and stuffs.” Similarly, participant 8 offered this example:

Number of sewing operations is how long that garment is on the machine....A very simple garment that just uses one machine and just has a few operations will have fewer minutes of a machine running, taking less electricity than let's say for example apparel leggings, which basically have an inseam and have a rise seam and then have an elastic and hem. Basically four operations in two different machines. It's only going to probably be directly on the sewing machine for 6 minutes whereas if you have a full length coat, you have several machines, many operations, then you have buttons and button holes and it is probably on a machine nearly 40 minutes of total sewing time. So, that total sewing time is the amount of time that sewing machines were up and running and using electricity.

These participants' opinions and examples put forward a clear relationship between the number of sewing operations and energy consumption. The responses of participant 4 and 8 made clear that the number of sewing operations was related to Standard Allowed Minute (SAM) or Standard Minute Value (SMV). Participant 8 stated, “So, number of operations directly ties into SAM. Those are probably the most significant factors.” Participant 5 stated, “I think that the number of sewing operations also has a direct impact on the SAM.” Participant 4 mentioned,

So, more the operations you have, the more machines you have to utilize depending on the SAM and SMV to balance the line. So, these have a direct relationship. I mean they

are pretty much interconnected. The more operations you have, you have to use more energy with more machines.

However, this factor was not included in the quantitative part of the study because quantifying energy consumption for a whole garment was not feasible considering the data collection process. Additionally, mass apparel production deals with different operators using different sewing machines for different operations. While collecting data, the researcher found different garments were in the sewing line at the same time. Therefore, it was more practical to collect energy consumption data from one sewing operator in a specific time period. If the particular manufacturers in this study had a tailoring system of production, where one operator sewed all the operations of a garment at a time, number of sewing operations could have been included in the quantitative study.

**Standard allowed minute (SAM) or standard minute value (SMV).** SAM or SMV is the standard time for accomplishing a sewing operation by a trained operator (Babu, 2012). It consists of both machine time and fabric handling/manipulation time to facilitate the sewing operation. In the garment industry's sewing process, the production managers and/or the industrial engineers use this term to determine time for each operation as well as to set targets for daily production for that operation. The accumulation of the SAMs of all operations determines the SAM for the whole garment. If a garment consists of complex elements in sewing, it requires a higher SAM than for a garment that consists of simple elements.

When selecting SAM as the most influential energy consumption factor, the experts emphasized time to finish the garment, overall cost, and SAM as a mechanism to reduce idle time. Participant 8 mentioned SAM as “the dictator of how much energy is gonna go in.” All the experts pretty much mentioned the same thing about SAM in term of its influence on the energy consumption. Participant 5 stated, “I think that the number of operations also has a direct impact

on the SAM, meaning the more operations, the more minutes that garment is going to require, the more achievement in the machine, the more energy it's going to consume.” Similar statements were made by participants 2, 6, and 7. Participant 6 stated,

Basically with a higher SAM, the more complex the assembly of it is. And the more complex the assembly of a garment is, the more time you can have machines sitting powered on, but not actually sewing. Because there's a lot of handling and so forth that goes on to the garment.

Participant 9 gave an elaborate explanation of why he sees SAM or SMV as the most influential energy consumption factor in comparison to other factors. He linked SAM or SMV with the sewing efficiency and reducing idle time. He stated,

I think all the things that were listed you can make an argument for being important in some way but I think it is the total impact to reduce the amount of energy consumption. It's really about making the system as efficient as possible and that's being very well engineered and having well trained people who understand the tasks and the tasks are laid out very clear and the process is simplified to avoid unnecessary manufacturing time and unnecessary idle time because I feel like there is a lot of wasted minutes in the sewing operation. So, that was my theory and the things that I selected as being most important. They were more about well-engineered processes that reduce idle time.

**Sewing machine motor capacity and sewing machine speed.** Sewing machines are run by an electric motor and the capacity of the motor is indicated in terms of horsepower (or sometimes watts). The machine speed is denoted as revolutions per minute (rpm). Both capacity and speed are written on the nameplate attached outside of the motor. All experts mentioned that both motor capacity and sewing machine speed are interdependent. Participant 5 stated,

Yes, contingent upon the capacity of the motor is how fast the sewing machine will function. The faster the machine, more than likely the less time the operator will spend on it and albeit I don't know this definitively, my thought is, my opinion is that it would probably consume less electricity if we got it off the machine faster and that's why I gave that response.

Similarly, participant 4 said, “[sewing machine speed] is tied up to the motor capacity, I believe.” He used a V6 and V4 car engine analogy to establish motor capacity as an energy consumption factor. He stated, “I’m just thinking, in terms of V6 versus V4 engine for a car...you might need to burn more gas for V6 than V4... I exactly don't know what the real relationship would be. But I think motor capacity has a relationship to energy.”

Likewise, participant 8 mentioned her home sewing machine experience while explaining sewing machine speed as the most influential energy consumption factor. She mentioned, “When I run my home machine on high, I can actually see the lights in the house dim. I know it’s using more and more electricity.” She also stated, “machine speed obviously uses more energy.” In addition to that, she asserted that both motor capacity and sewing machine speed varied by fabric types (heavy fabric vs. light fabric). She mentioned,

Some sewing machines are special for heavy fabrics and they have a stronger motor capacity than others. So, some types of machines use a lot more energy than others. It has to deal with the stitches, how many stitches, how many needles it’s forcing, and the layers of fabric. Although layers of fabric may not dictate the type of machine, the type of fabric does. Definitely, the type of stitch definitely dictates the machine. So, if we are sewing denim for example, it's gonna take a heavier duty engine, heavier duty machine, the motor capacity has to be stronger and it's gonna use more electricity.

Participant 4 echoed this idea, saying “I believe the motor has to run faster and that way it might be consuming more energy.” However, the participants gave no objective explanation for this idea; they just assumed it to be true. While explaining motor capacity and sewing machine speed as the most influential energy consumption factors, they used sentences such as, “just a supposition,” “I don’t know whether it’s really significant,” “I’m not an electrician, I really don’t know,” and “I think this is just conjecture but I would imagine that...” Though experts mentioned higher speed consumes more energy, a counter argument could be that because higher speed reduces the time to sew an operation, it consequently reduces energy consumption. In addition,

as discussed in more detail in the next section, even though a machine can run in a higher rpm, if the operator is not skilled enough to run the machine at that speed, energy consumption will be impacted. In this regard, participant 1 mentioned, “The capacity of sewing machine, some machines can go a lot faster than others and they are varied by experience then she can get a lot more done in the same amount of time and that influence the energy consumption.” The researcher deemed it necessary to investigate further this relationship between sewing machine motor capacity and sewing machine speed in regards to energy consumption quantitatively during the factory production observations phase of the study, discussed in RQ3.

**Operator production efficiency.** Six among nine participants selected sewing operator production efficiency as the most influential energy consumption factor in the apparel sewing process. Participant 2 stressed that “operator efficiency is critical in every aspect of the sewing process.” Experts linked this efficiency factor to manufacturing cost, speed, quality, and eventually waste. Participant 5 clarified the connection among operator efficiency, sewing speed, and energy consumption by stating,

It [operator production efficiency] speaks to the amount of time that the product is going to be in the sewing machine. An operator who is much more highly efficient than their colleague spends less time on the machine and although I don't have any data to support this my instinct is that the faster a product gets out of the machine, the less energy it will consume. I have observed operators sewing for instance, let's say a bottom hem, one could do it in half the time of the other. My assumption is that the person who does it quickly will consume less electricity than the person who is keeping the motor running, sewing at a slower speed. The speed of the sewing by the operators is a direct function of the energy consumption.

In addition, participant 3 linked machine rpm and machine downtime with the operator's efficiency, saying, “an efficient operator is going to be operating at higher rpms and it's gonna have much less downtime than an inefficient operator.” Furthermore, a connection between operator training and operator efficiency was discussed by participant 4: “So, the more trained

the operator that means the efficiency is high so that they finish the operation faster and therefore, they will consume less energy.”

In terms of quality control associated with operator efficiency, it is expected that the sewing output from an inefficient operator will not be as error-free as it should be from an efficient operator. An inefficient operator is unproductive in terms of both speed and quality. A portion of her work might need to be reworked which results in further energy consumption and a portion of her work might end up as scrap material, which will eventually end up as waste. In this regard, participant 9 divulged,

It's the skill of the worker that matters. You can have a well-engineered line but if you have somebody that doesn't understand what is being asked of them then there's a lot of reworking involved and then, not just consuming more energy you have to go back and fix something. So the training and skill of the worker I think plays a very important role. You want to get everything out as error-free as possible, as fast as possible.

Participant 9 also connected operator efficiency to cost savings, saying, “I'm going to go a little bit to the side with the operator efficiency because in my industry I deal with it costing a lot.” He came back to connecting efficiency to energy consumption, though, and said,

I always found that operator efficiency, getting the better operator, most experienced operator, you may spend more [in wages] but in the end you will save more and gain efficiency which means, you know, conservation of energy. So, if you can squeeze the process, you lower consumption of energy.

**Percent of sewing machine utilization.** In a typical apparel sewing operation, a portion of time is known as machine work time and another portion of time is known as fabric manipulation time. Machine work time includes when the machine is on, the paddle is engaged, and all the mechanical gears are engaged (in short, when stitching). Machine utilization percent is the percent of machine work time in the total operation time. Six experts selected percent of sewing machine utilization as the most influential energy consumption factor for the apparel

sewing process. Participant 4 connected machine utilization percent with energy consumption as follows:

I know when the machine is on, the motor runs always. When you engage the paddle, the mechanics will get engaged and then might need more energy. I think there's a difference, between just the motor running and when the machine is run with the mechanical gears and everything engaged. I think that's the difference, but I don't know how much that difference is. So therefore, I think sewing machine utilization, how much time the machine is on versus how much time it's actually sewing, has a relationship. I think there's different energy consumption in that case.

From the participants' opinions, it was found that machine aids (additional features or functions that are available to the sewing machine to facilitate sewing operations) influence this machine utilization factor. It also reduced the manual time spent by operators. Participant 1 exemplified this as follows:

Some machines have more functions than others. Like cutting the threads, sometimes there's even machines that don't cut the thread. So, somebody would have to cut that or it would be a manual function. If the machine does that it would save time and it would be a function of the machine. So the higher the machine utilization, it will consume more energy.

Both participants 7 and 9 urged better capacity and professional planning to reduce the time the sewing machines sit idle (since they still consume energy), and maximize the efficient use of the machine. Similarly, participant 3 mentioned, "if you have a style that has higher utilization of your existing machine and you got 80% of your machines running gonna have a higher energy consumption." Participant 5 also made a connection between percent of sewing machine utilization, number of sewing operations, SAM or SMV, the complexity of garment, and energy consumption, stating,

Yes, obviously it [sewing machine utilization] is significant and this may be also related to the standard allowed minutes. The more machine is being utilized and the more equipment that's being utilized to construct the garment, I think that is a significant contributing factor to the consumption of energy or electricity. The complexity of the

garment, the number of operations and how often the machines are utilized to do that if that makes it clearer.

**Factors by industry type.** In addition to being asked about the most influential energy consumption factors for the apparel sewing process in general, participants were also asked about these factors as they relate to specific types of apparel manufacturing such as woven, knit, and sportswear. Participants 1, 4, 5, and 8 said the energy consumption factor they identified as most influential would remain same regardless of fabric. Participant 1 stated, “Whether it’s knit or woven, yes, I think the factors would be the same.” Participant 4 said, “Of course, they [most influential energy consumption factors] will. They will act in the same way irrespective to what the industry is.” Participant 8 agreed that energy consumption factors remain same regardless of the product. She said, “I would say the factors that you have included which directly relates to the sewing process, the answers to those questions are identical across all aspects of the apparel industry.” She stressed that the number of operations and the SAM (or SMV) dictate energy consumption rather than fabric type. However, it is conceivable that both number of sewing operations and SAM might change with product differentiation. Participant 5 elaborated on this point:

I don't think that the product differentiation between different market segments is going to have an impact. I think it's pretty much going to be the same throughout the products that you discussed and it all gets back to the matter of the other criteria that we said. In other words, a woven or knitted garment depending on how many standard allowed minutes there are in each of those products is gonna be the direct function as to the consumption of the energy. I don't think the products matter as much as what is involved in assembling those products.

On the contrary, participants 2, 3, and 8 thought the most influential energy consumption factor might vary according to the specific segment of apparel industry. These participants identified variables such as product complexity, operator efficiency, fabric handling difficulty



(heavier fabric vs. thinner slippery fabric), and stitch and seam intricacy. For example, participant 2 explained that the sportswear industry uses a wide variety of fabrics, from thinner, more slippery fabric to thicker pile fabrics and said that an operator's efficiency in handling these fabrics plays a role in how much energy is consumed. Participant 3 provided this observation:

I think that probably there is a difference whether you're running knits or wovens regardless of it being sportswear or outerwear or innerwear or careerwear, I think there's gonna be less energy consumption for knits because they don't require as complicated of a stitch and seam classes and they are a little bit easier, quicker to assemble in my opinion anyway.

**Additional factors identified by industry experts.** A follow up interview question asked if participants wished to add any additional factor(s) that might contribute to energy consumption of the apparel sewing process. Participant 2 stated, "Your list is pretty broad. Some of the areas I never actually thought about, some of the areas to me are very consistent." Participant 3 said "I think you pretty much done a good job of covering everything." Participant 8 mentioned, "In just the sewing process, you are very thorough."

Participants mentioned a number of additional factors that were influencing energy consumption to the apparel industry as a whole instead of the sewing process only. These factors related to production (direct and supportive elements) and waste. Factors related to direct production elements were running machines for cutting, finishing, and packaging (participants 3 and 4), operating handling equipment such as conveyors and trollies (participant 4), production display units such as monitors to illustrate workflow, product information, and production rate (participant 4), and creating steam for pressing (participant 5). Energy consumption factors related to production supportive elements were heating and cooling to maintain appropriate room temperature (participants 1, 3, and 4), lighting (participants 3 and 4), equipment for

administrative work (participants 3, 4, and 9), and sometimes cooking (participant 1). Participant 9 referred to direct production elements as specific construction issues and production supportive elements as tangential issues. He encompassed many of the abstract thoughts expressed by other participants in this statement:

I think the list covers the specific issues but I think that there's tangent issues so like facility energy requirements while you are doing that...so, you have to heat or cool the room and there is energy requirements associated with that or even just sustaining of the people you have restroom facilities or the lounge and refrigerator all those other things, copiers. Computers are used in the process, in order to make that happen you have to have the people available and there are things that support them being able to do their job. The specific construction elements I think you covered in here.

Participants 7 and 8 added factors related to waste. Participant 8 said, “Waste is a huge factor in this industry.” She also mentioned, “It’s truly waste that is (sic) I see as our largest problem in what we spend time and energy making garments that nobody buys and end up going on sales.” Participant 7 linked quality control issue with operator skill and scrapping garments. He mentioned, “You’re also wasting whatever energy went into sewing them [scrapped garments].” Since the list of factors included operator efficiency (a quantitative way of measuring operator skill) as an energy consumption factor, the researcher believed that waste as an energy consumption factor was indirectly covered in this study. However, waste that results from overproduction, dealt by sales forecasting and production-planning departments, was an issue that will need another study to address.

## **RQ2: Most Influential Energy Consumption Factors Identified by Statistical Analysis**

As explained earlier, number of sewing operations was not included in the quantitative analysis. In addition, types of stitch, sewing machine age, and frequency of maintenance were not included. Types of stitch was not included as a factor because each sewing operation would

be completed using a particular stitch on a single machine. So, the number of threads on a specific sewing machine represented a specific type of stitch and hence, stitch type would be a redundant variable. For instance, a serger machine with three threads represents a 3-thread serging stitch (a stitch type) whereas the same machine with four threads represents a 4-thread serging stitch (another stitch type). Moreover, instead of types of stitch, number of threads was easy to analyze because of its quantitative nature. Though it was found from the literature that both sewing machine age and frequency of sewing machine maintenance influence the apparel production (Juan, 1998) and hence, energy consumption of a sewing machine, these two variables were not included in the data collected. This decision was made because the three factories did not maintain maintenance records and were unable to provide any reliable information.

On the other hand, number of fabric layers and total fabric thickness was combined as one factor in the qualitative study, but they were used as separate variables in the quantitative part. Initially, they seemed redundant. However, while collecting data, the researcher found examples of two different fabrics with different thickness being sewn together. Both thickness and layers made the fabric manipulation complex, thereby influencing energy consumption in different ways.

In the quantitative analysis, energy consumption was considered a dependent variable and other factors (e.g., sewing machine motor speed, motor capacity, seam length, SPI, number of threads, SAM, operator production efficiency, machine utilization, layers of fabric, fabric thickness, and type of fabric) were considered independent variables. By using statistical software STATA version 12.0, a multiple linear regression analysis was computed.

Some variables (e.g., type of fabric, motor capacity, energy consumption, operator efficiency, and sewing machine utilization) were converted to quantitative data or transformed into similar units of measurement (e.g. watts) to ease comparison prior to statistical analysis. Since type of fabric (e.g., knit, woven) had no quantitative value, a dummy variable was implemented to convert type of fabric into a numeric value. This dummy variable created three variables: knit (Fab 1), sportswear (Fab 2), and woven (Fab 3). In the statistical analysis, one fabric type must be held constant (omitted) in order to test the effect of the other two. In addition, an energy consumption unit and motor capacity unit were converted from kilowatt-hour (kWh) to watt-minute (Wmin) and horsepower to watts, respectively, in order to maintain unit consistency. Finally, operator production efficiency and percent of sewing machine utilization were converted from percentages to decimal values. An example of quantitative data set was given in Appendix C.

An initial multiple regression analysis was performed to test the influence of all 11 independent variables (including one dummy variable) on the dependent variable (energy consumption). This analysis also indicated how much better the function predicts the dependent variable from the adjusted coefficient of multiple determination ( $Ra^2$ ) value. The results of the regression model are shown in Table 4.5.

Table 4.5

*Summary of Regression Analysis for Variables Predicting Energy Consumption*

	Coefficients	Standard Error	Beta	T	Sig.
Speed	-0.043	0.031	-0.193	-1.41	0.162
Capacity	-1.503	0.244	-0.474	-6.16	0.000
Seam length	2.415	0.619	0.362	3.90	0.000
SPI	19.543	5.739	0.222	3.41	0.001
Thread	-14.974	21.933	-0.086	-0.68	0.497
SAM	36.518	12.639	0.243	2.89	0.005
Efficiency	-16.939	93.628	-0.012	-0.18	0.857
Utilization	-90.823	155.743	-0.042	-0.58	0.561
Layers	-13.233	17.489	-0.067	-0.76	0.451
Thickness	20.585	25.245	0.080	0.82	0.417
Knit (Fab 1)	81.988	45.928	0.167	1.79	0.078
Sportswear (Fab 2)	125.3	41.963	0.341	2.99	0.004
Woven (Fab 3)	0	(omitted)	0		
Constant	694.935	227.649		3.05	0.003

A significant regression equation was found [ $F(12, 85) = 16.22, p = .000$ ], with an  $Ra^2$  of 0.653. Within the multiple regression, sewing machine motor speed ( $\beta = -0.193, t = -1.41$ ), number of threads ( $\beta = -0.086, t = -0.68$ ), operator production efficiency ( $\beta = -0.012, t = -0.18$ ), sewing machine utilization ( $\beta = -0.042, t = -0.58$ ), number of fabric layers ( $\beta = -0.067, t = -0.76$ ), fabric thickness ( $\beta = 0.08, t = 0.82$ ), and knit fabric type ( $\beta = 0.167, t = 1.79$ ) did not have a significant influence on the energy consumption of apparel sewing operation. These factors might violate the basic assumptions of multiple regression analysis or may not have a significant

influence on the energy consumption at all. On the other hand, other factors or independent variables such as motor capacity ( $\beta = -0.474, t = -6.16$ ), seam length ( $\beta = 0.362, t = 3.90$ ), SPI ( $\beta = 0.222, t = 3.41$ ), SAM ( $\beta = 0.243, t = 2.89$ ), and sportswear fabric type ( $\beta = 0.341, t = -2.99$ ) had a significant influence on the energy consumption. Since type of fabric was a dummy variable and there was collinearity among different types, woven fabric type was omitted by the analysis.

It is known that beta coefficients ( $\beta$ ) represent explanatory power of each independent variable and measure how strongly each independent variable influences the dependent variable. Based on higher absolute  $\beta$  value, a sub-regression analysis was performed to test the influence of six independent variables (e.g., motor capacity, seam length, sportswear fabric type, SAM, SPI, and sewing machine motor speed) over the dependent variable (energy consumption). In the case of motor speed, literature (Rogale et al., 2005) directly supported its influence on energy consumption and the higher  $\beta$  value explains its explanatory power even though motor speed was found to have non-significant influence ( $p > .05$ ) on energy consumption. This indicated that the non-significant influence of motor speed may be occurring due to noncompliance with basic assumptions of multiple regression and hence, it was included in the subsequent regression model along with testing assumptions. The remaining factors depicted very small effect size (i.e., lower absolute  $\beta$  value), did not hold stronger explanatory power and hence, were not included the subsequent multiple regression analysis. The stepwise regression analysis validated the choice to use these same six independent variables. The results of the sub-regression model are shown in Table 4.6.

Table 4.6

*Summary of Regression Analysis for Variables Predicting Energy Consumption*

	Coefficients	Standard Error	Beta	T	Sig.
Speed	-0.048	0.017	-0.214	-2.83	0.006
Capacity	-1.447	0.209	-0.457	-6.91	0.000
Seam length	2.735	0.546	0.410	5.01	0.000
SPI	17.914	5.520	0.204	3.25	0.002
Sportswear (Fab 2)	113.087	29.507	0.308	3.83	0.000
SAM	33.2	11.336	0.221	2.93	0.004
Constant	634.705	118.925		5.34	0.000

A significant regression equation was found [ $F(6, 91) = 30.83, p = .000$ ], with an  $Ra^2$  of 0.649. Within the multiple regression, sewing machine motor speed ( $\beta = -0.214, t = -2.83$ ), motor capacity ( $\beta = -0.457, t = -6.91$ ), seam length ( $\beta = 0.41, t = 5.01$ ), SPI ( $\beta = 0.204, t = 3.25$ ), SAM ( $\beta = 0.221, t = 2.93$ ), and sportswear fabric type ( $\beta = 0.308, t = 3.83$ ) had a large and significant influence on the energy consumption of apparel sewing operations.

An ad-hoc method was implemented by adding other fabric types (knit and woven) with the variables used in the last model and a subsequent sub-regression analysis was performed. This was because sportswear, woven, and knit fabric together represented the dummy variable, type of fabric. Woven fabric type was omitted because of collinearity. The results of this sub-regression model are shown in Table 4.7.

Table 4.7

*Summary of Regression Analysis for Variables Predicting Energy Consumption*

	Coefficients	Standard Error	Beta	T	Sig.
Speed	-0.025	0.019	-0.112	-1.32	0.190
Capacity	-1.516	0.206	-0.478	-7.36	0.000
Seam length	2.465	0.544	0.369	4.53	0.000
SPI	18.134	5.382	0.206	3.37	0.001
SAM	38.564	11.274	0.257	3.42	0.001
Knit (Fab 1)	95.728	39.877	0.195	2.40	0.018
Sportswear (Fab 2)	151.394	32.894	0.412	4.60	0.000
Woven (Fab 3)	0	(omitted)	0		
Constant	541.078	122.315		4.42	0.000

A significant regression equation was found [ $F(7, 90) = 28.63, p = .000$ ], with an  $Ra^2$  of 0.666. Within the multiple regression, motor capacity ( $\beta = -0.478, t = -7.36$ ), seam length ( $\beta = 0.369, t = 4.53$ ), SPI ( $\beta = 0.206, t = 3.37$ ), SAM ( $\beta = 0.257, t = 3.42$ ), sportswear fabric type ( $\beta = 0.412, t = 4.60$ ), and knit fabric type ( $\beta = 0.194, t = 2.40$ ) had a significant influence on the energy consumption of apparel sewing operations. However, sewing machine motor speed ( $\beta = -0.112, t = -1.32$ ) did not have a significant influence on the energy consumption of apparel sewing operations within this multiple regression. Though a significant model was found, one independent variable did not have a significant influence. The equation could be a result of having non-compliance with the basic assumptions of multiple regression analysis. Therefore, further analyses were computed according to the multiple regression assumptions checking steps described in Chapter 3.



A skewness test was performed for the variables used in the regression model of Table 4.7. The skewness is considered normal when the range is between -2 to +2. Results indicated two variables, energy consumption and SAM, not complying with the assumption of multivariate normality and both depicted high skewness. Therefore, a power transformation was applied on both to minimize their skewness. The results of the skewness test are shown in Table 4.8.

Table 4.8

*Summary of Skewness Test for Variables*

	Variance	Skewness
Energy Consumption	33358.22	2.063
Speed	658958.8	.299
Capacity	3322.375	.912
Seam length	749.059	1.415
SPI	4.314	1.126
SAM	1.483	2.729
Knit (Fab 1)	.138	1.822
Sportswear (Fab 2)	.247	.289

From the histograms by power transformation in Figure 4.1 and Figure 4.2, it was found that a log based power transformation on both energy consumption (i.e., logEC) and SAM (i.e., logSAM) will reduce their skewness. It ensured the model compliance with the basic assumptions of multiple regression analysis and hence, enhanced this model's data predictability.

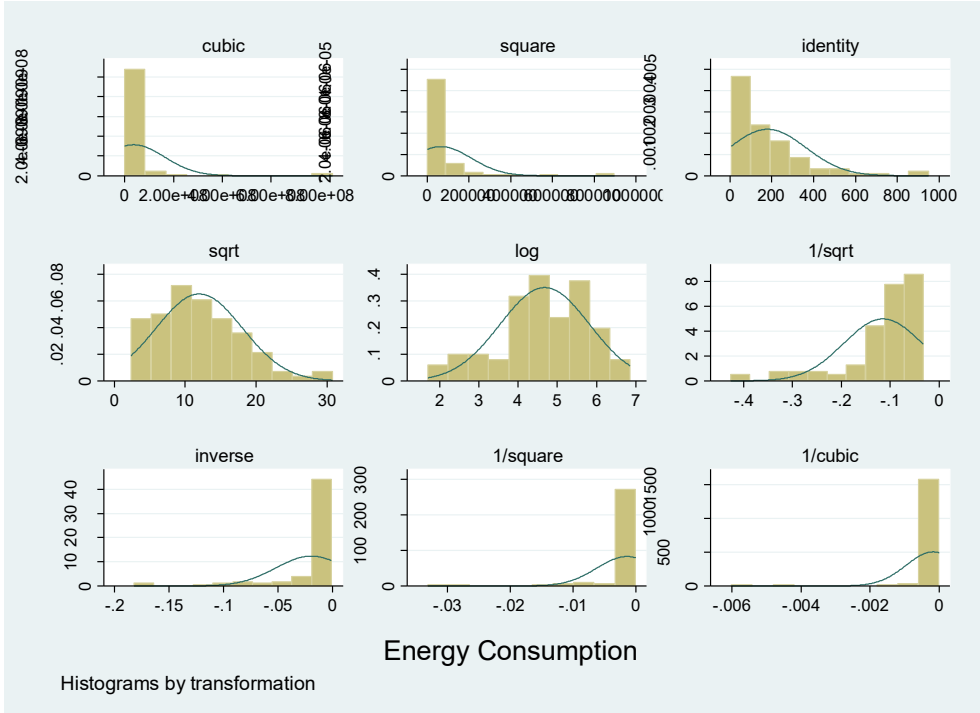


Figure 4.1 Histograms by power transformation for energy consumption

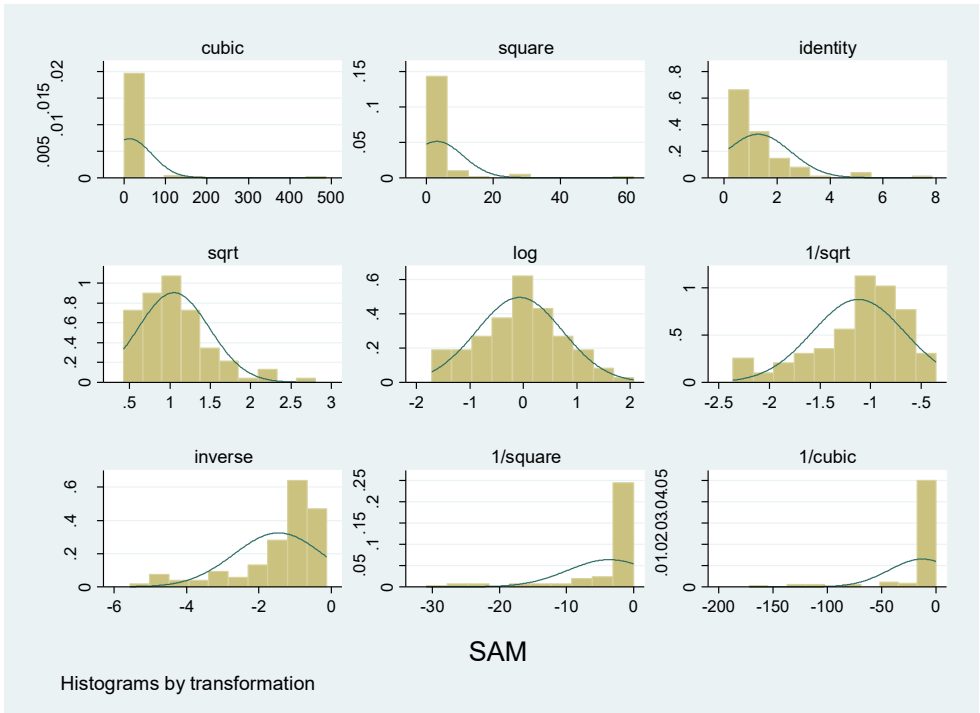


Figure 4.2 Histograms by power transformation for SAM

After employing power transformation for SAM (i.e., logSAM), a variance inflation factor (VIF) was performed to test independent variables' multicollinearity. If VIF coefficient is not greater than 4.0 for any of the independent variables used in the model and correlation coefficients (r) are not greater than 0.75, the regression analysis complies with no or little multicollinearity assumption (Berry & Feldman, 1985). The summary of VIF is given in Table 4.9 and the correlation coefficients are given in Table 4.13.

Table 4.9

*Summary of Variance Inflation Factor (VIF) Test for Independent Variables*

	VIF
Speed	1.99
Capacity	1.27
Seam length	2.14
SPI	1.10
logSAM	1.83
Knit (Fab 1)	1.99
Sportswear (Fab 2)	2.32

A further sub-regression analysis was performed to test the influence of the variables used in Table 4.7 over the dependent variable (energy consumption). Here, logarithm of energy consumption and logarithm of SAM were used in the model instead of actual energy consumption and SAM. The results of this sub-regression model are shown in Table 4.10.

Table 4.10

*Summary of Regression Analysis for Variables Predicting Energy Consumption*

	Coefficients	Standard Error	Beta	T	Sig.
Speed	-0.001	0.000	-0.350	-7.11	0.000
Capacity	-0.008	0.001	-0.429	-10.91	0.000
Seam length	0.004	0.002	0.104	2.04	0.044
SPI	0.080	0.020	0.146	4.00	0.000
LogSAM	0.771	0.067	0.544	11.54	0.000
Knit (Fab 1)	0.386	0.150	0.126	2.56	0.012
Sportswear (Fab 2)	0.260	0.121	0.114	2.14	0.035
Constant	9.283	0.452		20.54	0.000

A significant regression equation was found [ $F(7, 90) = 104.75, p = .000$ ], with an  $Ra^2$  of 0.882. Within the multiple regression, sewing machine motor speed ( $\beta = -0.35, t = -7.11$ ), motor capacity ( $\beta = -0.43, t = -10.91$ ), seam length ( $\beta = 0.104, t = 2.04$ ), SPI ( $\beta = 0.146, t = 4.00$ ), logSAM ( $\beta = 0.544, t = 11.54$ ), sportswear fabric type ( $\beta = 0.114, t = 2.14$ ), and knit fabric type ( $\beta = 0.126, t = 2.56$ ) had a significant influence on the energy consumption of apparel sewing operations.

A White's test was performed to determine the homoscedasticity nature, the fifth basic assumption of multiple regression analysis, of the model of Table 4.10. This test rejected the homoscedasticity nature of this model because the chi-square ( $\chi^2$ ) value for the heteroscedasticity nature of this model was significant [ $\chi^2(29) = 83.54, p < 0.05$ ]. The results of the White's test are shown in Table 4.11.

Table 4.11

*Summary of White's Test for Heteroscedasticity*

	Chi2 ( $\chi^2$ )	df	p
Heteroscedasticity	83.54	29	.000

White's corrected standard errors (also called "robust" standard errors) were computed and the t-test for each independent re-computed. A final sub-regression analysis with the "robust" standard errors was performed to test the influence of the independent variables used in Table 4.10 over the dependent variable (energy consumption). The results of the regression model are shown in Table 4.12.

Table 4.12

*Summary of Regression Analysis for Variables Predicting Energy Consumption*

	Coefficients	Robust Standard Error	Beta	T	Sig.
Speed	-0.001	0.000	-0.350	-5.18	0.000
Capacity	-0.008	0.001	-0.429	-8.91	0.000
Seam length	0.004	0.002	0.104	2.27	0.025
SPI	0.080	0.020	0.146	4.04	0.000
LogSAM	0.771	0.078	0.544	9.82	0.000
Knit (Fab 1)	0.386	0.122	0.126	3.15	0.002
Sportswear (Fab 2)	0.260	0.147	0.114	1.77	0.008
Constant	9.283	0.495	.	18.73	0.000

A significant regression equation was found [ $F(7, 90) = 91.45, p = .000$ ], with a coefficient of multiple determination ( $R^2$ ) of 0.891 (in the robust model, there was no adjusted coefficient of multiple determination). Within the multiple regression, sewing machine motor speed ( $\beta = -0.35, t = -5.18$ ), motor capacity ( $\beta = -0.429, t = -8.91$ ), seam length ( $\beta = 0.104, t = 2.27$ ), SPI ( $\beta = 0.146, t = 4.04$ ), logSAM ( $\beta = 0.544, t = 9.82$ ), sportswear fabric type ( $\beta = 0.114, t = 1.77$ ), and knit fabric type ( $\beta = 0.126, t = 3.15$ ) had a significant influence on the energy consumption of apparel sewing operation. Also, if the  $Ra^2$  (or  $R^2$  in robust analysis) of the sub-regression model increased substantially and complied with basic assumptions, it was considered over the original model. Therefore, in this study the most influential energy consumption factors were found as sewing machine motor speed, motor capacity, seam length, SAM, SPI, and type of fabric.

**Regression model.** It is found that the coefficient of multiple determination increased substantially [ $R^2$  (new) = 0.891,  $p = .000$ ;  $Ra^2$  (initial) = 0.653,  $p = .000$ ] while maintaining all basic assumptions of multiple regression analysis. Therefore, the final regression analysis of this study is depicted in Table 4.12 and the model is (according to *Equation 5* in Chapter 3):

$$\log(\text{EC}) = 9.283 + 0.771 * \log(\text{SAM}) + 0.386 * \text{knit fabric type} + 0.260 * \text{sportswear fabric type} + 0.080 * \text{SPI} - 0.008 * \text{capacity} + 0.004 * \text{seam length} - 0.001 * \text{speed} + 0.495$$

### **RQ3. Congruency between Qualitative and Quantitative Findings**

The qualitative findings of this study indicated number of sewing operations, standard allowed minute (SAM) or standard minute value (SMV), sewing machine motor capacity, sewing machine speed, operator production efficiency, and percent of sewing machine utilization as the most influential energy consumption factors. On the other hand, the quantitative findings indicated SAM, sewing machine motor capacity, sewing machine speed, seam length, stitches per inch, and type of fabric as the most influential energy consumption factors for apparel sewing operations.

**Number of sewing operations.** Eight out of nine participants revealed number of sewing operations as the most influential energy consumption factor. For mass production, any garment's sewing or assembling process consists of a number of sewing operations and this varies factory to factory. Each operation is mostly performed by one operator using one sewing machine. The total assembly time is the cumulative time of each sewing operation for a particular garment. Likewise, total consumed energy to assemble that garment is the summation of energy consumed by each sewing operation. Therefore, experts clearly named the number of sewing operations as the most influential energy consumption factor and they were clear about this in the interview. Analysis of the themes of the qualitative interviews found that experts explained this as the most influential energy consumption factor because of its impact on time. Past studies in the literature did not investigate number of operations' influence on energy consumption. However, by associating this factor with SAM, it can be argued that number of sewing operations dictate how long the product will be in the machine and hence, influence the energy consumption. In summary, a garment with a lower number of sewing operations will require less sewing time and will consume less electricity than a garment with a high number of

sewing operations. However, since this factor was not included in the quantitative analysis, the convergence within the mixed method (i.e., between qualitative and quantitative method) for number of sewing operations could not be determined.

**Standard allowed minute (SAM) or standard minute value (SMV).** SAM was defined as standard sewing time for a sewing operation performed by a trained operator (Babu, 2012). Since sewing time or assembling time for a particular operation varies from factory to factory, country to country, SAM is used for standardizing the assembly time for that operation. Both qualitative and quantitative findings indicated SAM as most influential energy consumption factor. Since SAM represents time for sewing (Babu, 2012; Solinger, 1988), it eventually represents how long the sewing machine will run and how long the machine will consume energy consumption. With increased sewing, the sewing machine will consume more energy. Consequently, participants pointed to SAM as the dictator of energy consumption in the sewing operation.

The quantitative findings indicated SAM as having the highest explanatory power among other energy consumption factors. Within the regression model,  $\log\text{SAM}$  ( $\beta = 0.544$ ,  $t = 9.82$ ) had a significant influence on the energy consumption of apparel sewing operation. This means that for every unit of standard deviation change in  $\log\text{SAM}$ , it predicts a 0.544 change in the standard deviation of the  $\log\text{EC}$ . Therefore, both qualitative and quantitative analysis represented similar findings in term of identifying SAM as the most influential energy consumption factor in apparel sewing operations.

**Sewing machine motor capacity and motor speed.** Both qualitative and quantitative findings indicated sewing machine motor capacity and speed as most influential energy consumption factors. According to the National Electrical Manufacturers Association (NEMA)



standardized practice, the motor nameplate should provide rated horsepower and rated full-load speed (or nominal speed). The rated horsepower denotes motor capacity, which represents the equipment's maximum output capacity. There are few specific motors used in the sewing machines with a few specific horsepower and RPM combinations (e.g., 0.5 hp with 3450 RPM, 0.6 hp with 5000 RPM, 0.75 hp with 3000 RPM). Theoretically, if two motors with different horsepower run for the same duration, the motor with the higher horsepower will consume more energy. This theory supports motor capacity as most influential energy consumption factor.

However, in explaining motor capacity as the most influential energy consumption factor, the participants connected this with motor speed. For example, they mentioned that sewing machine motor capacity determines how fast the machine can run. This supports the basic law of motor: motor capacity proportions with torque and RPM multiplication (i.e.,  $hp \propto \text{torque} * \text{RPM}$ ). Therefore, the reason motor capacity influences energy consumption is the same reason motor speed contributes to it. This supports participant 8's observation that "When I run my home machine on high, I can actually see the lights in the house dim."

According to the regression model, sewing machine motor speed ( $\beta = -0.35, t = -5.18$ ) and motor capacity ( $\beta = -0.429, t = -8.91$ ) had a significant influence on the energy consumption of apparel sewing operations. From the  $\beta$  value, it can be said that for every unit of standard deviation change in motor speed, it predicts a 0.35 change in the standard deviation of the logEC. Similarly, for every unit of standard deviation change in motor capacity, it predicts a 0.429 change in the standard deviation of the logEC. However, their inverse relations with energy consumption go against the basic theory, even though the inverse relation between motor speed and energy consumption supports the mathematical model (see *Equation 2* in Chapter 2) developed by Rogale et al. (2005). A conceivable rationale would be that the sewing time

decreases with increasing speed for a certain operation and consequently reduces energy consumption for that operation. Another possible reason would be both capacity and speed represented the maximum output capacity and full-load speed respectively, whereas operators were not utilizing the machine with full capacity and full-load speed. Sewing operators maintained their sewing speed and resultant capacity with the flow and complexity of the product. A further study with graph-based instruments could better answer this inverse relation.

**Operator production efficiency.** Sewing operators harmonized their sewing speed with the ease of their fabric manipulations. Their efficiency plays a significant role in speeding up production as well as maintaining quality. In the qualitative findings, six participants selected operator production efficiency as most influential energy consumption factor. Their rationales started with “operator efficiency is critical in every aspect of the sewing process” and ended with “the trained [efficient] operator... finishes the operation faster...will consume less energy.” Their logic is that an efficient operator shortens the sewing process, reduces SAM, utilizes the machine efficiently, and ensures quality, and everything leads to a reduction in energy consumption. In addition, it supports the collective finding of Juan (1988) and Babu (2012). Juan found productivity is a factor of energy consumption and Babu identified operator efficiency influences productivity. Hence, it can be inferred that operator efficiency influences energy consumption.

However, this same factor was not one of the most influential in the quantitative findings. From the initial regression analysis (see Table 4.5), it did not have significant explanatory power ( $\beta = -.012, p = .857$ ). This was because the influence of operator efficiency on energy consumption could be more explained through the influence of SAM (i.e., increasing operator efficiency reduces SAM) . Table 4.13 depicted they had a moderate level of association ( $r = -$

.307,  $p = .000$ ), and participants supported this interrelationship. Another reason would be a skilled operator could reduce the sewing process only to a certain extent. Time reduction of a sewing process is more likely when designers and industrial engineers reduce the number of operations.

Furthermore, while it is true that an efficient operator might reduce energy consumption for a single sewing operation, they can also finish more operations in a specific time period which might cancel out that energy conservation. If the product quantity is fixed, an efficient operator would conserve energy, but in reality, the product quantity is indefinite and companies tend to produce more to earn more profit.

**Percent of sewing machine utilization.** Similar to operator efficiency, machine utilization was found as another most influential factor in the qualitative findings but not in the quantitative findings. The sewing machine is employed when the operator engages the paddle while the machine is on. The consensus among the study participants was that efficient utilization of the machine reduces its down time, thus reducing sewing time and hence reducing energy consumption. Rogale et al. (2003) and Cooklin (2006) also found that higher machine utilization reduces the sewing time. The sewing time is the combination of machine time and fabric manipulation time. Machine utilization denotes how much the machine is actively involved with the sewing process instead of employed with fabric manipulation and thread changing.

However, in reality the machine consumes energy continuously if it is on, even when idle during fabric manipulation or thread changing. Therefore, sewing machines consume energy according to the total sewing time not according to when the machine is actually utilized. Hence, SAM explains energy consumption better than machine utilization because it represents the total

sewing time. Finally, additional functions (e.g., small spotlight, working aids) in the sewing machine enhances machine utilization, which also consumes additional energy. Therefore, no observations were taken from machines with these types of functions.

**Seam length, stitches per inch (SPI), and type of fabric.** Three factors – seam length ( $\beta = 0.104, t = 2.27$ ), SPI ( $\beta = 0.146, t = 4.04$ ), type of fabric (sportswear fabric type [ $\beta = 0.114, t = 1.77$ ], and knit fabric type [ $\beta = 0.126, t = 3.15$ ]) – were identified as most influential factors in the quantitative findings. However, they were not identified as most influential factors by the majority of the participants. The incongruence between these two findings could be explained their explanatory power, their  $\beta$  value. They have significant influence on the energy consumption but not as strong as machine speed, capacity, and SAM. Therefore, a few experts might select these three as most influential factors but not the majority of them.

### **Interrelationships among Energy Consumption Factors**

The second research objective includes determining interrelationships among energy consumption factors of the sewing process in the apparel industry. In order to attain this objective, three research questions were developed and both qualitative and quantitative research methods were used. The three research questions were:

RQ4: What interrelationships between energy consumption factors are identified by industry experts?

RQ5: What interrelationships between energy consumption factors are identified by the statistical analysis?

RQ6: Are interrelationships identified in RQ5 congruent with the expert findings in RQ4?

#### **RQ4. Interrelationships Identified by Industry Experts**

This research question focused on exploring interdependencies or interrelationships among energy consumption factors based on expert opinions. The researcher believed that knowing the interrelationships among factors might help explain energy consumption in apparel sewing operations more comprehensively as well as provide a realistic solution to reducing energy consumption. Some interrelationships (e.g., motor capacity with speed, motor capacity with fabric type, motor speed with fabric type, machine utilization with operator efficiency, machine utilization with SAM, and SAM with operator efficiency) were found from the participants' responses in RQ1. However, the interview design and survey did not reveal interdependencies as expected. Considering the limited interview time with experts, the researcher should ask interrelationship among most influential factors only. In addition, asking for explanation about factors' interdependency did not yield quality responses perhaps because participants felt that the question was redundant with earlier questions. Therefore, after the first interview, the researcher decided to move the interdependency question to the very end of the interview. Even changing the interview strategy, however, did not result responses with more descriptive. For example, participants 4, 6, and 9 mentioned, "Again it comes back to the situation we were discussing earlier," "You know [researcher name], it's same thing," and "Well again, it's the same thing," respectively. Face-to-face interviews resulted in similar responses.

In addition, discrepancy between responses to the online survey and to the interview for the same participant was found. Participant 5 selected number of sewing operations and type of fabric as interdependent. However, when he was being asked to explain this relationship, he mentioned, "I don't know that there is an interrelationship. I may have miss-spoken and then if that's the case in the survey. I think that there probably isn't."

In the survey and interview, almost all experts mentioned the energy consumption factors as interrelated in some ways. Participants did not specify any two factors' interrelationship over others. In addition, participants did not mention any direction and strength of the relationship; rather, they simply mentioned that they were interdependent or related. Mostly participants gave common responses while responding to the interdependency question and provided some examples. In response to the question "In your opinion, which factors are interdependent with the types of fabric?" participant 1 replied,

So, it would be number of sewing operations, SAM, types of stitch, number of threads, stitches per inch, layers of fabric, motor capacity, sewing speed, machine age, frequency of maintenance, operator's efficiency and machine utilization. I think those could all be interdependent with types of fabric.

All participants gave similar answers except they provided different examples while explaining the relationships. For instance, while explaining the relationship between stitch density (or stitches per inch) and type of fabric, participant 8 provided an example of sewing ribbed fabric, whereas participant 9 gave an example of sewing a waterproof garment. Consequently, the comparative analysis was unable to provide better explanation about the interrelationships among factors. The direct and quantitative observations used in the developed model yielded results about factor interrelationships and these are discussed in RQ5. Additionally, the good examples provided within the interviews helped the researcher interpret the combined findings, which are discussed in RQ6.

### **RQ5. Interrelationships Identified by Statistical Analysis**

The evaluations of all the basic assumptions of multiple regression analysis in the earlier analysis were eventually evaluated for the basic assumptions of correlation analysis (the

assumptions of normality, linearity, and homoscedasticity). In this study, Pearson's correlation coefficient ( $r$ ) was employed to explore the relationships among all independent variables. A significant, positive, and strong association has been found between woven fabric (Fab 3) and sewing machine motor speed ( $r = .630, p = .000$ ), and between fabric thickness and layers of fabric ( $r = .608, p = .000$ ). In addition, a significant, positive, and moderate association (or correlation) was found between the following factor pairs: SAM and seam length ( $r = .500, p = .000$ ); sewing machine utilization and motor capacity ( $r = .405, p = .000$ ); knit fabric (Fab 1) and number of threads ( $r = .491, p = .000$ ); knit fabric (Fab 1) and seam length ( $r = .347, p = .000$ ); and sportswear fabric (Fab 2) and fabric thickness ( $r = .413, p = .000$ ).

On the other hand, a significant, negative, and strong association was found between sewing machine motor speed and number of threads ( $r = -.693, p = .000$ ). In addition, a significant, negative, and moderate association was found between the following factor pairs: motor capacity and number of threads ( $r = -.339, p = .000$ ); knit fabric (Fab 1) and sewing machine motor speed ( $r = -.368, p = .000$ ); sportswear fabric (Fab 2) and sewing machine motor speed ( $r = -.351, p = .000$ ); sportswear fabric (Fab 2) and seam length ( $r = -.415, p = .000$ ); woven fabric (Fab 3) and number of threads ( $r = -.352, p = .000$ ); SAM and operator efficiency ( $r = -.307, p = .000$ ); and woven fabric (Fab 3) and fabric thickness ( $r = -.498, p = .000$ ). Despite being significant, all other correlations were found as weak associations. The interrelationship among different type of fabric was ignored because they were dummy variables. The results of the Pearson correlation are shown in Table 4.13.

Table 4.13

*Correlations Among all Independent Variables*

	Speed	Capacity	Seam Length	SPI	Threads	SAM	Efficiency	Utilization	Layers	Thickness	Knit
Speed	1.000										
Capacity	0.197	1.000									
Seam length	-0.055	-0.191	1.000								
SPI	-0.108	0.069	-0.090	1.000							
Thread	<b>-0.693</b>	<b>-0.339</b>	0.113	0.133	1.000						
SAM	0.253	-0.070	<b>0.500</b>	-0.003	-0.275	1.000					
Efficiency	0.014	0.259	-0.280	-0.021	0.033	<b>-0.307</b>	1.000				
Utilization	0.016	<b>0.405</b>	0.088	0.028	-0.038	-0.197	0.208	1.000			
Layers	0.071	0.086	-0.219	0.079	-0.193	0.090	0.034	0.050	1.000		
Thickness	-0.166	0.234	-0.154	0.107	-0.016	-0.091	0.128	0.112	<b>0.608</b>	1.000	
Knit (Fab 1)	<b>-0.368</b>	-0.157	<b>0.347</b>	-0.116	<b>0.491</b>	-0.128	0.034	0.091	-0.184	0.109	1.000
Sportswear (Fab 2)	<b>-0.351</b>	0.257	<b>-0.415</b>	0.279	-0.017	-0.170	0.023	0.016	0.189	0.413	-0.382
Woven (Fab 3)	<b>0.630</b>	-0.141	0.157	-0.194	<b>-0.352</b>	0.268	-0.049	-0.084	-0.052	-0.498	-0.367
	Sportswear (Fab 2)	Woven (Fab 3)									
Sportswear (Fab 2)	1.000										
Woven (Fab 3)	-0.719	1.000									



## **RQ6. Congruency between Qualitative and Quantitative Findings**

Since the interview question to identify factors' interrelationships did not yield overall trustworthy findings, the congruency between qualitative and quantitative findings could not be determined. However, participants gave some examples while explaining a couple of interrelationships. All the energy consumption factors were used in the regression model. Therefore, no correlation will be found higher than 0.75 (i.e.,  $r < |0.75|$ ); otherwise it would violate the assumptions of the regression model.

From the quantitative analysis, it was found that sewing machine motor speed is correlated with fabric type and number of sewing threads. From direct observation, the researcher found that high RPM (revolution per minute) based sewing machines are used in the woven garment assembling process. On the other hand, low RPM based sewing machines are used in the knit and sportswear assembling process. Therefore, a positive relation was found for woven fabric type and negative relations were found for knit and sportswear fabric types. Also, the relationship between fabric type and speed can be explained from participant 1's response. She stated, "If you're sewing a very heavy fabric, it's going to take more effort by the machine. Your sewing speed would generally be slower for heavier fabric." Both thickness and number of fabric layers represent the fabric's bulkiness and they have a strong association ( $r = .608, p = .000$ ). Based on participant 1's explanation, fabric type correlated with speed and can be explained in terms of fabric thickness. From the correlation table, it can be said that woven fabric type has a negative correlation with fabric thickness ( $r = -.498, p = .000$ ), which means woven fabric has less thickness therefore allowing the machine to run at a higher speed. The same explanation can be provided for the relationships among knit and sportswear fabric type, speed, and thickness.

Another strong association was found between sewing machine motor speed and number of sewing threads. Different stitch types used different numbers of threads. The researcher observed that the industry's multi-thread machines are slower and lower capacity. Therefore, both speed ( $r = -.693, p = .000$ ) and capacity ( $r = -.339, p = .000$ ) has a negative correlation with number of threads. However, these relationships can be explained in terms of fabric type. While explaining the interrelation between type of fabric and number of threads, participant 1 revealed that number of threads is affected by fabric type, and participant 3 mentioned,

Different types of fabric are going to require different numbers of threads. So, the simplest form you could use is 301 single needle lock stitch to make a seam and the most complex you would use a 600 class, six thread flat seam to do a butt seam on a sportswear or on woven. You would use 516 five thread to safety stitch. So, depending on what your fabric is, different fabrics require different numbers of thread to sew the proper seam.

Generally, the industry uses stitch type 301 (i.e., single needle lock stitch) with two threads for woven fabric and stitch type 516 and 600 with 3-6 threads for knitwear and sportswear. Participant 8 elaborated on this:

[Since] knit stretches, they need types of stitches that stretch, and there are machines made specifically for wovens and machines made specifically for knits. And the only machine that tends to work for both are be used is single needle machine which is standard types of stitch [stitch type 301] that you get on a home sewing machine. But single needle [lock stitch] does not stretch, so single needle for knit has to be very carefully use. So, types of stitches also directly related to the type of fabric.

This explains the relationship between knit fabric (Fab 1) and number of threads ( $r = .491, p = .000$ ) and between woven fabric (Fab 3) and number of threads ( $r = -.352, p = .000$ ). Therefore, the interrelation between sewing machine motor speed and number of threads can be explained from the earlier interrelation between sewing machine motor speed and fabric types.

The interrelation between SAM and seam length ( $r = .500, p = .000$ ) and between SAM and operator efficiency ( $r = -.307, p = .000$ ) can be explained by SAM. A longer seam will take longer time to accomplish and hence depicts a higher SAM. Since other issues such as operator

performance rating and allowances (see *Equation 3* in Chapter 2) determine SAM, the value of  $r$  is less than 1. The interrelation between SAM and operator efficiency is illustrated by participant 5: “it [operator production efficiency] speaks to the amount of time the product is going to be in the sewing machine.” In addition, participant 3 mentioned, “an efficient operator is going to be operating at higher rpms and it’s gonna have much less downtime than an inefficient operator.” Therefore, an operator with high efficiency will take less time to stitch, which results in a lower SAM and vice-versa.

The relationships between sportswear fabric (Fab 2) and seam length ( $r = -.415, p = .000$ ), between knit fabric (Fab 1) and seam length ( $r = .347, p = .000$ ), and between sewing machine utilization and motor capacity ( $r = .405, p = .000$ ) cannot be explained by the participants’ responses. In this study, the observed data from the sportswear factory and knitwear factory included small seam lengths and longer seam lengths, respectively, because at the time of data collection, that was the nature of product being produced. It might not be the same for the whole year of their production. Therefore, sportswear fabric (Fab 2) and seam length might be depicted as having a negative correlation and knit fabric (Fab 1) and seam length might be represented as having a positive correlation. In general, seam length is contingent upon type of garment rather than type of fabric. For example, a pair of pants has a longer seam length than a dress shirt or a t-shirt, regardless of fabric type.

Similarly, the relationships between sewing machine utilization and motor capacity ( $r = .405, p = .000$ ) cannot be explained by the participants’ responses. Machine utilization represents the time a sewing machine is actively involved in a sewing operation in comparison to the total operation time (i.e., combination of both machine time and fabric manipulation time). Participant 9 defined it as, “it [machine utilization] gets back to idle time and how much of that machine is

being used.” No matter what capacity the motor has, machine utilization is dependent on the simplicity of the operation and the sewing machine. From the response of participant 6, it can be inferred that machine utilization will be higher for sewing a straight seam or sometimes a curve seam than a complex seam.

### **Steps to Reduce Energy Consumption**

The third research objective included identifying steps to reduce energy consumption within sewing processes in the apparel industry. In order to attain this objective, only the qualitative method of research was employed and the following research question was developed:

RQ7: What potential solutions for reducing energy consumption in apparel industry are identified by industry experts?

#### **RQ7. Potential Solutions Identified by Industry Experts**

The participants suggested solutions related to the themes of greener energy, production, management, and government. In terms of greener energy, participants emphasized using alternative sources of energy (e.g., solar power, wind power, hydroelectric plant). Participant 8 suggested, “find alternative ways to provide that energy so that it is sustainable.” Experts’ mentioned alternative sources of energy were also renewable in nature and their recommendation of using alternative energy supported the findings of a report by Working Group III of the Intergovernmental Panel on Climate Change (IPCC, 2012). The report showed that for every kWh of electrical energy generated, concentrating solar power plants emit 89 grams of carbon dioxide equivalent (g CO<sub>2e</sub>), compared to 43 g CO<sub>2e</sub> hydroelectric plants, 81 g CO<sub>2e</sub> for wind energy plants, 217 g CO<sub>2e</sub> for solar photovoltaic plant, 220 g CO<sub>2e</sub> for nuclear energy plant, and

1,689 g CO<sub>2</sub>e for coal-fired power plants (all at maximum level). Therefore, using alternative source of energy emits less CO<sub>2</sub> and is beneficial for the environment. In addition to using solar panels as a sustainable means of alternative energy, participant 4 suggested using natural light in the factory to reduce dependency on overhead electric lights.

In terms of production-related solutions, participants advocated the use of energy efficient equipment, upgrading equipment or equipment modernization, restyling garments, and implementing standard operating procedures in the sewing room. The argument for using upgraded equipment or newer equipment was they would be more energy efficient, would engage automation, and would speed up the sewing operations by reducing labor-intensive work. In this regard, participant 6 stated, “as you gain more and more automation, there is less manual work” and participant 2 mentioned, “just the amount of humans touching the process, if you lower it, you’re saving on energy, no doubt about that.” Here, they inferred that human touches for fabric manipulation in the sewing operator kept the machine running longer and hence consuming more energy. Similarly, participant 6 said that automation helps to eliminate complex handling needed in positioning the product in preparation for assembling. On the other hand, participant 1 recommended using efficient machines that have more functions. She pointed out, “use more efficient machines that do more or add more functions on them [sewing operations] and are more reliable.” However, the participants did not address another point of view; automation could be a cause for more energy consumption because automation requires electricity. It seems experts were unable to provide a balanced solution in this regard.

Another production-based solution to reduce energy consumption dealt with reengineering product construction, finding simpler ways to do the sewing that involves less stitching, and adopting consequential standard operating procedures pertaining to restyled

garments. Participants 5, 7 and 8 suggested hiring industrial engineers or garment construction engineers for garment reengineering and for fine-tuning sewing processes. Using templates to fine-tune sewing processes was recommended by participant 2. It supported the recommendation of Cooklin (2006) to reduce the sewing time; using templates, a common work-aid in the sewing process, ensure smooth and faster fabric handling while stitching. The restyling solution was based on the notion that “the amount of energy is dictated by the design house that provided production work to the factory,” as said by participant 8. She gave an example from Levi’s by stating, “sewing factory has very little control over the design of the garment...Levi’s controls that.” However, participant 5 recommended that the restyling would be a viable solution when it is implemented without sacrificing the style integrity and the marketability of a garment. Adhering to the standard operating procedures suggested by participant 9 supported the earlier finding of maintaining improved work method and practices to conserve energy by Sivaramakrishnan et al., (2009).

Another production-based solution that emerged from the conversations is designers should design a garment from the very beginning in such a way that requires less energy to assemble. However, participant 8 addressed this issue and found it unrealistic:

[T]he perspective of designing a garment that uses less energy...puts a constraint on the industry. This is unrealistic because folks want to make what consumers want to buy and consumers don’t care that much about how much energy went into making their clothes.

Production-based solutions related to operators included more training to hone their sewing skills and to change their attitudes. Sewing skills consist of speeding up the process, reducing idle time, gaining efficiency, and enhancing quality while reducing waste. In summary, speeding up the process reduces sewing time for a particular operation, specifically operations related to a complex design or delicate fabric, and consequently reduces energy consumption.

Participant 7 emphasized “efficiency training” because he mentioned “operator efficiency skill” as the biggest way to reduce energy consumption of sewing operations. All these skills were summarized as “shortening the process” by participant 2. When asked about his suggestions to reduce energy consumption, he specified, “[T]o me, it’s always shortening the process of every aspect of garment production.”

Operator skill influences garment quality in terms of having to rework or re-stitch garments and wasting garments (producing garments that cannot be sold because of inferior quality). Both reworking and wasting garments have consequences on time, money, and energy consumption. Especially, reworking garments consumes additional energy and time (Palamutcu, 2010) and hence, employing right-first-time (RFT) approach in the sewing process reduces energy consumption in the apparel industry. Participant 2 coupled operator efficiency and quality output in this regard and mentioned, “the more efficient your worker is, the higher the [quality] output and the higher percentage of the output that doesn’t go back into the line.” According to Participant 9, improving the training and skill of the operator should “get everything out as error free as possible, as fast as possible” and this error free and speedy output would reduce time, cost, and energy consumption. Participant 7 linked operator efficiency with garment reworking by stating

You're not talking about a tiny marginal increase in efficiency, you're talking about reducing your energy consumption directly by a factor of how much reworked and scrapped out garments you need to redo.

Mostly, turning off sewing machines during breaks and at the end of the shift was related to operator attitude. It is very logical that keeping a machine on unnecessarily will consume energy without contributing to production. The importance of turning off machines was equally articulated by participants 3 and 4. The recommendation of Participant 3 was,

[W]hen operators go on break or lunch they should shut down their machines, they should turn them off. And then, obviously at the end of the shift it's important that all the machines get turned off ...if you move to another machine to do another operation and you're not going to be using the machine for a while it should be turned off.

A number of participants highlighted solutions related to management and a company's investment in reducing its environmental footprint. From the interviews, it was found that management support is one side of the solution and production and operator support are another side of the solution. Some participants mentioned that management should take the lead to reduce energy consumption and implement it with the help of operators. In addition, participants urged consideration of cost factors such as profit and return on investment when making decisions related to energy consumption reduction. In this regard, participant 9 stated, "I think that [reducing energy consumption] is part of education on the management side by thinking about how you can save money...it [reducing energy consumption] is about making the return on investment argument for it too."

A similar response was given by participant 7. He thought that considering the cost is the starting point. He stated, "I think that the starting point is that costs need to be studied, quantified, and recognized so that you can make informed decisions." In addition, participant 4 defined this management related solution as a "top-down approach" and he stressed dealing with cost factors as the best way to reduce energy consumption:

I think it [reducing energy consumption] should be a top-down approach also. I think the management has to understand in two ways. One way is if you can reduce energy usage, it will be more sustainable in terms of the resources. The other side of it is, the less the energy consumption, you can make more profit. So, I think you can tackle it in both ways, but the cost factor would be the best way to tackle it.

In addition to the above-mentioned energy reduction solutions, participants articulated government support related to law enforcement, regulations, and work ethic. Both participants 4



and 8 discussed these ideas. While discussing sustainable energy sources, participant 8 mentioned, “I believe that local and federal government should assist with sewing factories seeking out and setting up alternate means of energy.” However, participants did not mention any specific ideas for laws, regulations, and work ethic that would reduce energy consumption.

In summary, all participants gave realistic solutions – using greener energy, training people, improving production, and engaging management and government – to reduce energy consumption of apparel sewing operations. In order to address solutions related to global climate change, incorporating management and government along with other stakeholders (e.g., suppliers, designers, manufacturers, consumers, etc.) also recommended by the Department for Environment, Food, and Rural Affairs (DEFRA, 2011). This study addressed global climate change issue through exploring energy consumption and associated GHG emissions in the apparel manufacturing process. However, the industry may undervalue these recommendations as factories seek immediate results. In addition, factories may find difficulties in relating energy reduction to profit, and according to participant 9, “money is the language everybody speaks.” Regardless, participants urged these solutions even if only a small fraction of time and associated energy consumption can be reduced. The summation of small fractions could result in a huge time and energy savings and eventually, substantial cost savings. In this regard, participant 2 mentioned, “if you cut seconds, seconds become minutes, minutes become hours,” and participant 8 said:

I will give you an example – Levi's. If you wear a pair of Levi's [jeans] you can look at the back yoke. That back yoke used to be lapped up. It is now easily lapped down and that was a direct result of an engineer watching a sewing operator work and flipping the direction for efficiency sake. It probably only saved less than 10 seconds per garment but that 10 seconds adds up over millions and millions of garments. But even that saved Levi's some money and other companies have since followed and begun to adopt the same construction method.

## **Exploring Experts' Level of Concern**

The final research objective includes exploring the level of concern regarding energy consumption, the contribution to greenhouse gas emissions, and climate change in the apparel manufacturing. Other research objectives focused on energy consumption from the apparel sewing process. However, this objective covers the whole apparel manufacturing in terms of achieving sustainability and related issues. In order to attain this objective, five research questions were developed and they were posed to industry experts:

RQ8: What level of concern is expressed by industry experts regarding energy consumption in the apparel manufacturing?

RQ9: What (if any) energy reduction initiatives have been initiated by the industry experts' company in order to reduce consumption?

RQ10: What type of energy consumption and climate change conversations are industry experts having with other apparel industry professionals?

RQ11. How might an energy consumption model be used by apparel industry professionals?

RQ12. What level of importance might industry experts give to energy consumption as a decision-making component within apparel production in the future?

### **RQ8. Experts' Level of Concern about Energy Consumption**

Seven out of nine participants revealed that they were concerned about the apparel manufacturing's energy consumption. They discussed cost related to energy consumption and sustainability in terms of garment waste and fossil fuels. The interview responses suggest that participants' concern about energy consumption is mostly based on product cost. This sentiment is illustrated by participant 6's generalized answer to explain his level of concern: "I think

everyone has to be to some degree because there is a cost factor.” His further argument was energy becomes more expensive and it becomes scarce as the population grows around the world. Consequently, there are power failures, requiring factories to use generators to keep their production running, which is much more expensive and less efficient. Participants 8 and 9 stated, “one of their largest expenses is electricity” and “[garment] costs rise because electricity bills go up,” respectively. Similarly, participant 3 stated, “[energy consumption] is a fixed expense that has to be factored in when you set the cost of the garment.” Her argument was energy consumption need to be reduced to earn higher profit margin.

Another concern about energy consumption related to waste. “Our industry is really an unsustainable industry, not from an energy point of view only, also wastage point view.” His wastage argument was based on the industry making excess garments. When they cannot sell the garment, they dump it, which is a waste of resources (e.g., raw material, energy, labor). A similar statement was given by participant 7. He blamed the rise of fast fashion, international brands like H&M and Zara, and consumers for facilitating unsustainable apparel consumption. He quoted a national newspaper that mentioned waste:

The New York Times is accusing essentially the apparel industry for producing these disposable garments that people buy over and over again and one of the big problems with that is the effect on the environment. So, I think both consumers and producers need to be increasingly aware about the energy consumption of the apparel industry.

Two participants mentioned they were not concerned about the level of energy consumption before this interview. Their argument was water consumption is a more serious issue than energy consumption, specifically in California. In the opening question, it was evident that a number of experts expressed their surprise when asked about energy consumption of the apparel industry, particularly the sewing process. They were well aware of the high level of energy consumption by textile production (participant 4), by dye houses (participant 7), by

sublimation print (participant 5), water consumption in the denim industry (participant 2), global ecosystem (participant 9), global warming (participant 2), and so on. By contrast, most of the participants were unaware of energy consumption issues in the apparel sewing process, with the exception of participants 4 and 8. Participant 8 mentioned, “It is the largest cost the [apparel] factory faces in their electrical bill,” and participant 4 said that the “apparel industry consumes a lot of energy... pretty much every sewing operator needs a machine.” However, this interview prompted them to ponder this issue and they both agreed that cost saving was a benefit of reducing energy consumption.

Some participants also thought of garment waste and fossil fuel usage as environmental issues. In addition to the cost issue, participant 9 stated, “it [energy consumption] is about the environment, being a good stewardship of the environment too.” Though he did not clarify how energy consumption affects environment, participant 1 discussed our reliance on fossil fuels to generate electricity. She mentioned, “We are consuming a lot of energy [electricity] in the factories using fossil fuels, it’s a global issue.” It is indeed a global issue because GHG emissions occur with burning fossil fuels and fossil fuel is still the most-used source of generating electricity around the globe. A few participants tied sustainability into their responses. Participant 2 associated energy consumption with global warming and mentioned, “We are looking at global warming, we are looking at all these [energy consumption and global warming] things much closer than we ever looked at before.” While responding to this question, participant 9 also linked energy consumption with the cost savings and sustainability by stating,

In general, I think the first thing is cost savings, I think sustainability, being good stewards of the land those things and then it is about... I think they are interconnected to the whole process; I think it is part of the larger ecosystem of how we get something from the raw material to consumers.

## **RQ9. Initiatives Implemented to Reduce Energy Consumption**

The participants mentioned having implemented both direct and indirect initiatives to reduce energy consumption in their respective organizations. The direct initiatives were meant to reduce energy consumption and the indirect initiatives were meant to gain something else but energy consumption reduction was resultant effect. The direct initiatives were installing energy efficient lights (participant 7), gaining efficiency in the heat transfer press of the dye sublimation process (participant 5), establishing a scheme to turn off the HVAC system during national holidays (participant 3), and purchasing energy efficient machines (participant 4). The indirect initiatives were measuring compressed air leaks (participant 7), using templates to shorten the sewing process to achieve production efficiency (participant 2), finding ways to reduce SAM and number of operations to save cost (participant 8), and cooling the factory through having plants and trees on the roof (participant 4).

Both participants 4 and 9 undertook initiatives to reduce energy consumption in order to establish their organizations as social responsible companies rather than directly as environmentally friendly companies. Their organizations were members of the Fair Labor Association (FLA). They said their association with the FLA bound them to reducing their environmental footprint; hence, indirectly they tried to reduce energy consumption. According to participant 9:

Fair Labor Association looks at the entire supply chain and they do ask questions such as are you partnering with socially responsible people, are you partnering with people who care about issues like the environment, and how to minimize the footprint in the manufacturing process.

On the other hand, some participants said they had not implemented any initiatives to reduce energy consumption. Even though participant 7 undertook some initiative to reduce

energy consumption, he indicated lack of knowledge as a reason for not focusing on this issue. It is true that energy consumption has not yet been a big focus, but it also means a big area of opportunity to save energy and eventually save cost. In addition, both participants 1 and 6 mentioned labor cost and prioritized it over energy cost. Their argument was factories are closing their domestic production units and outsourcing because of higher labor costs and therefore there is no point of discussing how to reduce energy consumption in their facilities. Participant 6 explained this situation by stating:

I think we are still in a situation where people are able to move product around the world from more expensive to less expensive locations basically because of labor rates rather than the energy rates. I think we are almost reaching the point of saturation where simple movement of product from one region to another is not going to really start making significant cost differences. So, I think once that happens then they are gonna look for other areas of efficiency and energy certainly could be a consideration.

#### **RQ10. Discussions with Other Professionals to Address Climate Change**

Four participants discussed the importance of reducing GHG emissions while the other five were not concerned about this. Participants said this issue was discussed with professionals like apparel manufacturers, stakeholders, supply chain personnel, and various accreditation authorities (e.g., FLA, Worldwide Responsible Apparel Production) in trade organizations, seminars, conferences, overseas factories, and other sponsored events. They discussed diverse issues including supporting alternative means of supplying energy (participant 5), finding solutions to reduce carbon footprints and attaining sustainability (participant 3), knowing environmental impacts on logistics to get raw materials from one place to another (participant 9), and balancing costs and environmental components within apparel products (participant 7). Interacting with environmentally-friendly accreditation authorities was one of the motives for discussing such issues, and another motive was the fact that sustainability is a buzzword in the

apparel industry and consumers are increasingly aware of it, and trying to be green is one of the best ways to sell garments to a brand.

Participants who had not discussed GHG emissions and global climate change with professionals said they had general conversations about water conservation (participant 2), changing of weather patterns (participant 4), global warming (participant 5) and reducing waste (participant 1). In addition, their general conversations were not tied to the apparel production industry. Nonetheless, participant 6 discussed sustainable apparel production through facilitating the reuse of materials. His argument was reusing raw materials could help conserve energy because “a lot of energy and resources are used in the actual manufacturing of the raw fiber and so forth.”

Based on the responses of participants 5 and 6, it was evident that they had a clear understanding of GHG emissions and global climate change issues. Participant 5 mentioned “global warming is a reality...burning coal and flowing it into the environment” and participant 6 stated “there is a move on for sustainable production and that is a catch word that’s gaining more and more momentum in the industry.” Therefore, lack of knowledge was not an issue for not having this discussion. However, participant 5 explained the reason for not having this kind of discussion with other professionals as,

I think it's endemic of business in general. We're trying to get more done with less personnel so the question is do we have enough time to get the business side of it done as well as the social responsibility.... It's just not expedient and it doesn't have a direct impact today, we tend as humans to procrastinate about the future. I'm not saying it's a good thing. I'm not saying I'm proud of it.

#### **RQ11. Modifying Assembling Processes with the Help of an Energy Consumption Model**

This study developed a regression based energy consumption model for apparel sewing operations. Before developing this model, participants were asked about the usability of such a

model. All participants agreed to use this model in their respective factories with the intention to reduce energy consumption. However, they wanted to see certain features, specifically cost-related features, to ensure the model's functionality. The cost related features identified by the participants were ability to show cost savings (participant 3), quantifiable results in terms of cost savings (participant 7), quick return on investment (participant 5), ability to determine both energy and cost savings (participant 2), and tied up with dollar value (participant 4). It was evident that they were interested in the model primarily for cost savings. Other expected features were flexibility according to product and quantity changes (participant 8), ease of comprehension and implementation (participant 3), and being visual based and interactive (participant 4). The researcher believed that flexibility according to product and quantity changes would be difficult to achieve. However, a solution for this was provided by participant 8 when she mentioned, "If you were broken down to a specific part of the garment that was generic, it [the energy consumption model] could be applied." The researcher found the sewing operation is generic in the apparel assembling process, and therefore, he developed the energy consumption model for apparel sewing operations.

It is imperative that energy consumption first be quantified to determine energy savings. The researcher found that the apparel industry does not use any instrument or mathematical model to determine energy consumption of their sewing process. Therefore, energy conservation and subsequent environmental footprint reduction could not be addressed by the industry. The energy consumption model developed in this study was able to determine energy consumption level and it might be a small step towards achieving environmental sustainability in the apparel sewing process.



## **RQ12. Production Rate vs. Energy Consumption in the Decision Making Process**

In apparel production decisions, production rate is at the heart of the decision process. The production schedule, machine allocation, sequence of the operations, and product flows are all decided based on production rate. Even though production rate is the primary consideration, this research question asked industry experts to consider whether energy consumption might become another important consideration. All participants unequivocally denied energy consumption as another important consideration in the context of current apparel production practices, at least presently. In this regard, participant 4 stated, “it [energy consumption as an important consideration] is not going to happen very soon, it will happen one day” and participant 6 mentioned, “I think it will in the future. I don’t think it’s there on the radar so to speak yet.” In addition, they explained why energy consumption could not be considered in the current apparel manufacturing decision making process. The reasons as stated by participants 3 and 6, respectively, were “I think we are still looking at cost, efficiency is a big part of cost” and “probably production rate would trump the energy consumption because of profit issues.” These same reasons also confirmed that the triple bottom line has not been adopted in apparel manufacturing sector.

If any product has a low production rate, all the efforts from the production personnel will be related to increasing this production rate. Sometimes, using additional equipment is a means to increase productivity even though this equipment might consume more energy. In every aspect, the production rate trumps energy consumption and cost is the biggest reason behind this. Labor cost is much higher than energy cost around the globe. In addition, higher production rate ensures faster product availability in the market and subsequent profit. However,

participant 4 suggested that inserting energy consumption into the cost sheet might be a solution for considering it (energy consumption) as an important decision making tool.

From the convergence of qualitative and quantitative method of analysis, SAM, motor capacity, and motor speed were evident as most influential energy consumption factors. The qualitative portion of this study revealed potential solutions to reduce energy consumption. One such finding, from the experts' perspective, included speeding up or gaining efficiency in the production process to reduce energy consumption, yet energy consumption was more of a secondary focus behind earning profit. Overall, experts divulged deeper understanding of energy consumption phenomenon in the sewing process. However, in terms of pragmatism in net energy conservation, they explicitly and implicitly introduced a debate of production rate versus energy consumption. One participant (participant 6) mentioned, “[P]roduction rate would trump the energy consumption because of profit issues.” This debate encompasses the notion that gaining efficiency results in higher production rate by reducing sewing time for a particular garment and hence, saves energy. On the other hand, some may argue that a higher production rate translates into increased apparel production (and profit), as well as greater net energy consumed. Apart from this debate, reusing raw materials and ensuring sewing quality from the beginning to avoid reworking and waste were additional solutions to reduce energy consumption in the apparel industry.

From a more holistic perspective, an important outcome of this study was the disclosure regarding the lack of environmental awareness by these industry experts. Subsequently, the triple bottom line characteristic of sustainability has not been fully practiced in the apparel industry. Apart from experts' profit concern, lack of tools to determine energy consumption levels and associated GHG emissions might make it difficult to comprehend the importance of triple bottom

line. Among various approaches for increasing awareness of environmental impact discussed in the literature, measuring a company's carbon footprint (GHG emission levels) is imperative. Robertson (2014) suggested a four-step program to reduce climate impact from any process: make a plan, measure, reduce emissions, and offset the emissions that remain. The measuring step included preparing a GHG inventory along with knowing all process-based carbon footprints. In another study, Thiede, Posselt, and Hermann (2013) developed a seven-step approach to reduce environmental footprints from any textile and apparel processes. Four steps in this approach included identification of potential energy consumption sources, calculation of consumed energy, and assessment of improvement measures to reduce energy consumption (or, energy conservation) and resulted GHG emissions. The current study facilitated assessment of GHG emission levels by developing an energy consumption model and assists the apparel industry to advance toward greater environmental sustainability in the apparel sewing process.

## **Chapter 5 - Integrated Discussion, Implications, Limitations, and Recommendations for Future Research**

This concluding chapter summarizes the study's sample, design, and analysis. Though most of the discussions were covered in the earlier chapter, this chapter provides an integrated discussion, implications and recommendations for textile and apparel (TA) practitioners, particularly apparel manufacturers, as well as for educators. The chapter concludes with identification of the study's limitations and recommendations for future research.

### **Summary of Research Method**

The research questions of this study addressed energy consumption in apparel sewing processes. The TA supply chain starts with fiber cultivation and ends with final product consumption. Every step within the supply chain causes a great deal of environmental damage. Some damages are direct in nature and some are indirect by way of energy consumption and resultant greenhouse gas (GHG) emissions. Since burning fossil fuels is still the single most reliable source for generating electric energy, reducing energy consumption is key to minimize environmental footprints of apparel sewing process. Therefore, this study investigated means for reducing energy consumption of apparel sewing operation through identifying energy consumption factors and their interrelationships. The following research questions guided this study:

RQ1: Which apparel sewing operation factors do industry experts identify as being most influential on energy consumption and why?

RQ2: Which apparel sewing operation factors are identified as most influential on energy consumption through statistical analysis?

RQ3: Are the factors identified in RQ2 congruent with the expert findings in RQ1?

RQ4: What interrelationships between energy consumption factors are identified by industry experts?

RQ5: What interrelationships between energy consumption factors are identified by the statistical analysis?

RQ6: Are interrelationships identified in RQ5 congruent with the expert findings in RQ4?

RQ7: What potential solutions for reducing energy consumption in apparel industry are identified by industry experts?

RQ8: What level of concern is expressed by industry experts regarding energy consumption in the apparel manufacturing?

RQ9: What (if any) energy reduction initiatives have been initiated by the industry experts' company in order to reduce consumption?

RQ10: What type of energy consumption and climate change conversations are industry experts having with other apparel industry professionals?

RQ11. How might an energy consumption model be used by apparel industry professionals?

RQ12. What level of importance might industry experts give to energy consumption as a decision-making component within apparel production in the future?

### **Summary of the Data Collection**

A mixed method approach was utilized and the data was collected through qualitative and quantitative techniques. For the qualitative data, an online survey was distributed using the Qualtrics survey distribution platform followed by participant interviews. The interviews were conducted by utilizing the Zoom software for distant participants and by using voice recorder for

local participants. The interview was semi-structured in nature and all interviews were subjected to audio recording. The recorded interviews were then transcribed by the researcher.

The quantitative portion of the study utilized direct observation to collect and quantify energy consumption and its factors from the apparel sewing operations of three factories. An energy consumption meter and two high-resolution video recorders were used for this direct observation and data collection. Then, Sony Vegas Pro software was used for extracting data from the direct observation.

### **Summary of the Sample**

The population of interest in this study was US apparel industry experts. Through employing both purposeful intensity and snowball sampling, a total of nine US apparel industry experts participated in this study. All experts had remarkable experience in the apparel industry and were able to provide current information from the industry. The mean age of the experts was 53 years old, the average number of years of experience in the apparel production process was 27, and the number of years they had been involved in managerial and/or production decisions averaged 23. Three participants were female and six were male.

The quantitative data were collected from the apparel sewing operations. A total of 98 sewing operations were observed to gather data directly from three apparel production factories (a knitwear, a sportswear, and a woven-wear). Among 98 observations, 16% were collected from knitwear sewing operations, 41% from woven-wear sewing operations, and the remaining 43% from sportswear sewing operations. These 98 observations consisted of 62 sewing operations, performed by 39 sewing operators using 47 sewing machines.

## **Summary of Data Analysis**

A realist approach was employed to reveal the participants' lived experience with energy consumption in the apparel industry. The analysis of the interviews is composed of qualitative content analysis and comparative analysis. In addition, incident-to-incident approach of coding was applied in this study and word-based techniques (e.g., word repetitions and key-words-in-context) were applied to identify themes.

The quantitative data analysis focused on determining the most influential energy consumption factors and developing an energy consumption model using multiple regression analysis. In order to measure factors' interrelationships, Pearson correlation analysis was conducted. Both qualitative and quantitative findings were reviewed, compared, and then integrated to understand the energy consumption of apparel sewing process comprehensively.

## **Integrated Discussion and Implications**

The overarching purpose of this study was to determine a way for the apparel industry to quantify effortlessly their energy consumption of sewing process. Currently, apparel firms might determine their overall energy consumption from the electric bill, but they do not know their energy consumption based on specific sewing operation or specific garment assembly processes. Rogale et al., (2005) and Sivaramakrishnan et al., (2009) identified several factors influencing energy consumption: motor speed, seam length, stitch density, number of fabric layers, and type of fabric; however, they did not test these factors in a mass production setting (except type of fabric) and did not directly measure energy consumed by apparel sewing processes. In a more comprehensive approach, this study investigated these factors as well as additional factors related to productivity that have not been tested in relation to energy consumption. Rogale et al. (2003) found that higher productivity has a direct beneficial impact on energy consumption in

the apparel industry. Hence, the inclusion of these additional factors as well as seeking input from industry practitioners was deemed important to ensure that all influential factors were tested and explained.

From experience gained while the researcher was employed in the apparel industry, it became evident that there was no easy way to determine the level of energy consumed during the sewing process. The developed model in this study could be used to determine energy consumption for each sewing operation. The independent variables or factors – SAM, fabric type, motor speed and capacity, seam length, and SPI – used in the model were readily available in the industry to determine individual sewing operations' energy consumption. The prediction capability of the model (i.e., coefficient of multiple determination [ $R^2 = 0.891, p = .000$ ]) was very reliable. It enabled the practitioner to measure energy consumption level with 90% accuracy. It also meant that by manipulating these factors, energy consumption by apparel sewing processes could be reduced. Apparel firms need to reduce the energy consumption of each sewing operation to achieve a substantial reduction in their carbon footprints. However, it is imperative for these firms to be able to determine easily the current energy consumption levels so that they can seek effective ways to reduce them.

A garment sewing process consists of series of sewing operations. The model developed in this study can determine energy consumption for each sewing operation. A sewing operation is the smallest generic part in the apparel sewing process. Therefore, developing a model that can determine energy consumption for a sewing operation is logical considering its practical application. The same rationale was found from the response of participant 8. She stated, “If you were broken down to a specific part of the garment that was generic, it [the energy consumption model] could be applied.” However, determining all sewing operations' energy consumption and



associated GHG emissions (by using GHG calculator) levels would reveal the magnitude of energy consumption and GHG emissions of a whole garment.

### **Implications for Practitioners**

The findings of this study have far-reaching implications for apparel practitioners. These implications include:

- Energy consumption reduction strategies.
- Associating energy consumption with global climate change in terms of GHG emissions.
- Argument or persuasive appeal to practitioners regarding energy consumption reduction.
- Challenge to implement energy consumption reduction strategies in the light of Jevons' Paradox or Rebound Effect

Among the most influential factors, seam length, SPI, and fabric type are contingent upon the product category. For instance, children's apparel has a smaller seam length than that of menswear. The apparel production unit has no control over this. Other factors, except SAM, do not influence energy consumption remarkably for the sewing process. Therefore, developing solutions aimed at reducing SAM will be the biggest and most practical energy consumption reduction initiative.

Almost every expert interviewed supported speeding up production, gaining efficiency, and shortening the sewing process. Both designers and industrial engineers need to play a part in these efforts, because sewing operators have little control over these issues. Designers and industrial engineers need to work together to restyle the apparel product through reengineering product construction, finding simpler ways of sewing, and adopting consequential standard

operating procedures. Even shortening each operation by 10-20 seconds would be a significant time saving as well as cost saving in terms of bulk quantity. At one point, participant 8 mentioned that both designers and industrial engineers were able to save 10 seconds from the back yoke joint operation in a pair of Levi's jeans and that 10 seconds added up over millions and millions of garments.

In order to see how much a change in SAM explains a change in energy consumption, an additional analysis was computed. An ad hoc based bivariate analysis ( $\beta = 0.903, p = .000$ ) between logEC (log-transformed energy consumption) and logSAM depicts that a 1% decrease in the average SAM would yield a 0.90% decrease in the average energy consumption. In this study, the average SAM was 1.29 minutes (77.4 seconds) and average energy consumption was 180.4 watt-minutes (Wmins). Therefore, by eliminating 10 seconds (13% of average SAM) from a sewing operation, it is possible to save 21 Wmins energy consumption.

A typical apparel industry performs hundreds of sewing operations each day. Conserving 20 Wmins from each operation will reduce greenhouse emissions significantly over the course of a year. For example, the average weekly apparel production for one small factory (used in this study) was 800 pieces and they had an average 15 sewing operations per garment. The average energy consumption per operation in this study was 180.4 Wmins. With reducing 20 Wmins energy consumption per operation, according to the Environmental Protection Agency's (EPA, 2013) GHG emissions calculator, it is possible to reduce 0.146 metric tons equivalent CO<sub>2</sub> (MTCO<sub>2</sub>e) in a year. This amount from one small factory (with annual production around 42,000 pieces) is not a dramatic savings and perhaps that is why the energy consumption from the apparel sewing process had not received much attention. However, against total apparel produced for over seven billion people on the planet, the environmental gain would be

remarkable. Since more than 150 billion garments are produced annually in 2010 (Kirchain, Olivetti, Miller, & Greene, 2015), it is possible to save over 527,082 MTCO<sub>2</sub>e emissions globally from the sewing process (considering the same production scenario of a conservative 15 sewing operations for each garment). The same emission occurs from burning over 562 million pounds of coal.

In this study, the average machine utilization was 21%, meaning the sewing machine was actively involved in stitching only 21% of the sewing time. The remaining 79% of the sewing time was taken up with arranging, handling and disposing of work, changing bobbins, re-threading, and attending personal needs. This supports the earlier findings of Rogale et al. (2003) and Cooklin (2006), who found that operators in the apparel industry use sewing machines only for 20-25% of their total working time in a typical day. About 80% of energy consumed by the sewing machine when it is not actively stitching. This finding revealed that there is an opportunity to conserve energy from 80% of sewing time for each sewing operation. From the recommendations of Cooklin (2006), using work-aids (e.g., fabric guides, templates, auto thread trimmer) could reduce the fabric manipulation time.

With globalization, new exporters enter the market, increasing competition among existing players. New competitors mean new lines of textile and apparel, resulting in a broader spectrum of clothing options to consumers. In order to compete in this dynamic market, the TA industry needs to meet diversifying consumer tastes through launching new products prior to their competitors. To cope with and stay in this fierce competition, apparel brands split their orders into a number of factories (mostly outsourcing). Splitting orders reduces lead-time (time between the placement of an order and delivery), and subsequently it leads to a shorter product life cycle (PLC) – the lifespan of a product. The whole process is cyclical: more competitors

(because of globalization) lead to frequent introduction of new products, which in turn leads to shorter PLC and adoption of fast fashion. Consequently, factories and brands have to embrace niche production (specialized production) instead of mass production (volume production) (Yuasa, 2001). Even though the majority of this study's participants selected operator efficiency as the most influential factor on energy consumption, this efficiency cannot play a big role in niche production. Beard (2008) claimed that the marketing strategy for sustainable apparel in general is still based on niche production rather than mass-market reality. In addition, an operator gains efficiency through repetition and long-term repetition does not happen with niche production. Therefore, producing a higher quantity of fewer styles (i.e., different designs) in the apparel sewing process would be beneficial for the environment in relation to energy consumption.

### **Jevons' Paradox or Rebound Effect**

The sewing efficiency suggestions provided by the participants inferred that speeding up the production process through gaining efficiency is the best solution to reduce energy consumption. However, "increased efficiency does not by itself lower consumption" (Heinberg, 2011, p. 171); rather, it leads to increased energy consumption because more apparel products could be produced through gaining efficiency as well as higher production rate. Higher production rates might lead to overproduction, which in turn might lead to lower product prices and ultimately over consumption. Globally 150 billion garments production represented more than 20 new articles per person in 2010 (Kirchain et al., 2015). The consequence of this overconsumption is that people discard 7.5 billion clothing items every year globally (ABAC Women's Forum, 2012). It seems the solution to energy consumption reduction, as conceived by

these industry experts, is also the direction to higher energy consumption. This paradoxical situation is known as the rebound effect or Jevons' Paradox (Robertson, 2014).

It is a vicious cycle and either way the environment is the unintended victim. There is no simple and straightforward solution for breaking this cycle: neither governments, non-governmental organizations (NGOs), industries, nor consumers can address these issues on their own. Therefore, perhaps the most important implication of this study is the need to work closely with TA industry experts and stakeholders (e.g., suppliers, designers, manufacturers, consumer, retailers, and waste managers) to understand this paradoxical situation holistically, and to develop a coordinated action, including action by government and NGOs. A similar suggestion was found in the sustainable clothing roadmap, initiated by the Department for Environment, Food, and Rural Affairs (DEFRA, 2011), UK. They undertook four steps approach (review impacts, engaging stakeholders, action plan, and implementation and evaluation) in the TA sector to deal with climate change.

All stakeholders need to work together to better manage this unsustainable demand either by slowing the rate of stylistic changes or by increasing price. Brands need to step away from a business-as-usual mindset and consumers need to avoid their hedonic mentality that lead to overconsumption. Hutchins (2016) recommended applying future-fit logic (e.g., for-purpose, multi-stakeholder perspective, enhances current and future well-being, guided by moral compass) in business instead of yesterday's logic (e.g., for-profit, shareholder focus, undermines the future for today, guided by money). Chapman (2015) asserted, "[A]sk a developed world human to stop consuming and you might as well ask a vampire not to suck blood" (p. 29), however, hedonic motivated consumers must understand that their unsustainable consumption causes significant environmental damage. In comparison to garments worn 50 times and kept for

a whole year, fast fashion garments (i.e., wear less than five times and keep for 35 days) produce over 400% more CO<sub>2</sub> emissions per item per year (Conca, 2015). Since the average energy consumption was 180.4 Wmins in this study, removing only one million garments from production, as a result of changing consumers' hedonic attitude, would save 31.7 MTCO<sub>2</sub>e globally from the sewing process alone. The same emission occurs from burning 33,822 pounds of coal.

### **Implications for Academia**

University-industry collaboration is needed to address problem-based research like this. Such collaboration needs to include two-way education between both parties – academics and practitioners. In this study, practitioners' interest in conserving energy was motivated by cost savings, and their suggestions focused on increasing productivity within the apparel industry. They then tried to connect energy conservation and faster production with the environmental benefits, but not as their primary focus. Academic researchers can educate practitioners in the form of university-industry collaboration in order to transform their current mindset into future-fit logic.

Academic researchers could use the findings from this study in the classroom to illustrate how factors are influencing energy consumption, thus educating the next generation of apparel industry professionals, especially designers and product developers. Nielsen (2010) made a link between designer with sustainable design by stating that “The designer creates products and thereby consumption. This is why the role of the designer in relation to sustainable design is so important to investigate.” (p. 88). The learning process will facilitate future professionals'

understanding of how they could contribute to producing environmental friendly apparel through the designing and developing process.

### **Limitations**

This study's findings are limited by a number of issues. The sewing operations observed for this study are not representative of sewing processes of all apparel industries in the US and not a truly random sample. In addition, due to limited access to the industry and lack of specific knowledge about distinctive US apparel production process, the researcher's data collection process had a few weaknesses. Some energy consumption factors could not be used identically in both the qualitative and quantitative methods. The researcher was unable to predict a few data collection related hurdles while quantifying factors such number of sewing operations, types of stitch, and fabric thickness from the industry. Also, factories were unable to provide reliable information regarding sewing machine age and maintenance. The method used to determine SAM in this study included the subjective prediction of operators' ratings, which varies according to observer's skills. The method of determining SAM based on general sewing data (GSD) could overcome this limitation, because it eliminates subjective rating. However, lacking the ability to purchase expensive GSD software prevented its use.

The interview question designed for exploring interrelationships between factors did not elicit information as expected. After the first interview, the interrelationship question was moved to the end of interview period as it changed the tone and mood of the session, however, it still did not yield information as hoped. Additionally, the quantitative analysis (e.g., regression analysis) is bound by hard-and-fast rules; it oftentimes restricted the ability for explorations and new findings and instead simply identifies a factor as significant or not. Even though some of the interrelationships were significant (e.g., thickness with fabric types; seam length with fabric

types) in the quantitative analysis, these interrelationships may not hold true for other apparel production cases. For instance, both corduroy and terry fabrics hold greater thickness but are different types of fabric. Also, children-wear has smaller seam lengths than that of menswear regardless of the fabric type. Their interrelationships were right for the three factories studied in this project, but they might not apply to the whole apparel sector.

Another limitation of the study was that the analyses of the interview responses might not represent experts' intended meanings due to the researcher being a non-native English speaker. However, the researcher asked help from his academic supervisor on multiple occasions to overcome this problem. Also, the knowledge level of experts and their personal characteristics might affect the comprehensiveness of interview responses. In addition, the participants' busy schedule, their inability to provide sufficient time, their job-related interference during interviews, and the power differential between experts and researcher may have had an impact on interview quality. Finally, since this is an exploratory research study, there was a lack of relevant literature related to energy consumption in the apparel sewing process; therefore, some of the findings could not be supported by previous research.

### **Recommendations for Future Research**

Future research recommendations are provided; several address limitations of this study. The study participants were clearly more concerned about reducing cost than achieving environmental sustainability. They considered reducing energy consumption from their apparel production process mostly for the consequential cost reduction. Therefore, there is lack of incorporating triple bottom line (TBL) aspect of sustainability in their apparel production and sourcing decisions. Since SAM in the apparel sewing process has a clear connection to overall production cost, it is an important element in the cost sheet of garments. Researchers interested



in apparel production environmental sustainability should focus on economic sustainability in term of SAM at the outset of their research instead of starting with an environmental sustainability angle. Subsequently, they could explore a way of integrating energy consumption or carbon footprint information into the cost sheet of garments. This combined study will help tracking carbon footprints from apparel production process along with educating both apparel producers and brands, and will facilitate their environmental friendly decisions related to apparel production and sourcing.

Another recommendation for future research is to use GSD based SAM on energy consumption and compare the results with the current findings. It is believed that a study with GSD based SAM would provide more accurate explanatory power on energy consumption, because GSD does not include subjective evaluation. Also, a future study on different volts could be pursued to determine any voltage-based difference in energy consumption because during data collection, the researcher found some manufacturers use sewing machines with 220-volt electricity, but the energy consumption meter used in this study was not compatible with 220-volt. In addition, since this study fails to explain the negative relation of motor capacity with energy consumption, future research using an instrument with more graphic display is recommended. Such a study might provide additional findings related to energy conservation through controlling motor capacity of sewing machines.

A similar study could also be replicated in different countries. Since the US is not involved with apparel production extensively, both incorporating expert input and data from different countries could provide more insights and further practical-based solutions. Finally, an important future study focused upon developing a motor for industrial sewing machines that will

not consume any electricity without paddle engagement is highly recommended. This would be a revolutionary energy savings project for the apparel sewing process.

## **Conclusion**

This study set out to identify the most influential energy consumption factors of apparel sewing processes in order to increase environmental sustainability in the apparel industry. This study integrated a mixed method of research: qualitative and quantitative analysis of a list of energy consumption factors. The list was developed from a review of academic literature and researcher experience in the apparel industry. A realist approach with expert interview was employed in the qualitative part. The quantitative part consisted of multiple regression analysis where energy consumption was the response variable and factors were predictor variables. Despite discrepancy between the qualitative and quantitative analyses findings, overall the idea of incorporating mixed-method research holds merit in terms of attaining comprehensive insights regarding energy consumption and to comprehend the implications holistically of this study.

This study also investigated the interrelationships among energy consumption factors and identified solutions to reduce energy consumption. It further explored industry experts' level of concern regarding energy consumption, the contribution to greenhouse gas emissions, and climate change in the apparel manufacturing. Knowing interrelationships among factors from statistical analysis and expert opinions helped identify potential solutions to reduce energy consumption in the sewing process. Experts provided factual solutions (with examples) to produce energy efficient apparel and battled between environmental gains versus incurred cost. However, a summary of their concerns can be expressed as follows: "I don't think people are going to be willing to pay more for energy efficient products."

Today and even more so in the future, the pressure to reduce energy consumption will come from the twin drivers of improving cost competitiveness and the growing demand for garments with low environmental footprints. Performing energy conservation through studying energy consumption can considerably reduce the energy cost. With maintaining a sustainable production quantity, minimizing the waste of energy will be a win-win effort on both sides: reducing energy cost and reducing environmental damage. Addressing the most influential energy consumption factors and conservation opportunities will enhance the global competitiveness of the apparel industry and its related sectors (e.g., spinning mill, fabric mill, and wet processing mill) while reducing their environmental impact. This study identifies potential energy consumption factors, develops an energy consumption model, and assesses conservation improvement measures. With boundless apparel consumption and day-by-day increasing consumed energy, it is now time to put our utmost focus on efficient use of energy within the TA supply chain, especially in the short-focused apparel industry. The crisis related to global climate change is cumulative, but the solutions are cumulative too. A small solution carried out from the findings of this study along with other potential solutions might have a bigger impact if we apply them together. According to Robertson (2014), we need to be concentrated instead of diluted, focused instead of aimless, and integrated instead of disconnected.

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# Appendix A - Interview Design

## Interview Design

*Introduction:* The following is a semi-structured interview guide focusing on understanding the lived experiences of apparel industry experts. The questions and topics will focus on how the energy consumption phenomena are prevailing for various sewing operations in the apparel industry, which factors are influencing these energy consumption phenomena, how they relate to each other, and what steps need to be taken to reduce the energy consumption for different sewing operations in the apparel industry. Some questions are written in **BOLD** which indicates they should be read as they are written. Other questions/topics are bulleted (●) which indicates a necessary probe if not spontaneously discussed by participants. Some information is written in *italics*. This information is only for the researcher and is not to be shared with participants.

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\*\*\*Start Audio/video Recording

**Hello, my name is Imran. It's really nice to meet you. First of all, I want to thank you for agreeing to participate in this study. Also, I would like to thank you for your time spent taking my Qualtrics survey. As a result of this discussion, I hope to understand more about your experience as an apparel production expert. Questions will cover topics such as your experiences in apparel production, identifying and explaining the factors you believe are the influential determinants contributing to energy consumption, your perception about the interdependence of these factors, and finally your suggestions to reduce energy consumption for different sewing operations in the apparel industry. The discussion is being audio/video recorded according to your signed consent. I may stop and ask for clarification on something. Also, please stop me at any time if you need a question clarified. Just as a reminder, your name will not be used in the data analysis or reporting processes. Any identifying information, such as what department/program you are in, names of other employees'/operators' names/machine brands/company name you mention, will not be included in the final transcription. What questions do you have? .... Okay, let's get started.**

*Objective 1: From expert perspective, what sewing operation factors significantly contribute to energy consumption in the apparel industry?*

**First, I'm going to ask you some questions pertaining to your experiences from the apparel industry in this interview. I know you have been involved with this industry for --- years.**

- I would like to know what comes to your mind when I ask you to talk about the energy consumption in the apparel industry.

**Next are a series of questions based upon your response in the Qualtrics Survey:**

**Please consider the list of energy consumption factors provided. The factors were-**

- |                        |   |                                      |
|------------------------|---|--------------------------------------|
| ✓ Types of fabric      | ✓ SPI                                   | ✓ Operator's efficiency              |
| ✓ Number of operations | ✓ Layers of fabric and fabric thickness | ✓ Sewing machine utilization percent |
| ✓ SAM/SMV              | ✓ Motor capacity                        | ✓ Sewing machine age                 |
| ✓ Types of stitch      | ✓ Machine speed                         |                                      |
| ✓ Number of threads    | ✓ Frequency of maintenance              |                                      |
| ✓ Length of seam       |   |                                      |

- A. From your perspective, are there any other factors from the assembling process that significantly contribute to energy consumption?**
- If yes, please describe and explain how it contributes.

**Ok. In the Qualtrics Survey, ----- these are the factors (one by one) you have already identified as most influential energy consumption factors for different sewing operations in the apparel industry. They may or may not have equal influence on this energy consumption phenomenon.**

- B. Please explain why you identified these factors as highly contributing factors.**
- C. In your opinion, will these most influential energy consumption factors remain the same regardless of the type of industry: woven apparel, or knit apparel, or sportswear?**

*Objective 2: From expert perspective, which energy consumption factors are interdependent with others and why?*

**Now, I would like you to think about relationship/interdependency among the factors. You did mention some inter-dependency among some factors in the Qualtrics Survey.**

- A. Considering ----- factors identified as inter-dependent to each other in the survey, how and to what extent are they related to each other? Please explain the relationship.**

*Objective 3: What steps could be taken to reduce the energy consumption for different sewing operations in the apparel industry?*

**You have already given information regarding a number of energy consumption factors for different sewing operations in the apparel industry along with their inter-dependent nature. Now I would like to know what steps you believe could be taken to reduce this energy consumption phenomenon.**

- A. What suggestions would you give to reduce the energy consumed?**

*Objective 4: Are apparel production experts concerned about energy consumption in the apparel manufacturing and the contribution to GHG emissions and climate change.*

- A. As a professional in the apparel industry, are you concerned about the level of energy consumption in the apparel manufacturing?**
- Why?
- B. Has your organization implemented any energy reduction initiatives in order to reduce consumption?**
- If yes, what initiatives? If no, why?
- C. Have you had discussions with other professionals regarding the importance of reducing GHG emissions in an effort to address climate change concerns?**
- If yes, would you please describe the type of conversation and the context?
  - If no, is there any reason why you had not these type of conversation with professionals. Do you believe this type of conversation is important in the future? Why?
- D. If a model was developed to determine the most influential energy consumptions factors within the assembling process, would you consider modifying your assembling processes in order to reduce energy consumption?**

- If yes, are there certain features or characteristics you would like to see in this model?
  - If no, what barriers are in place that will keep you from using such a model?
- E. In the decision making process, production rate is an important consideration. Do you believe energy consumption may become another important consideration in your decision making?**
- If yes, could you please explain?
  - If no, why?

**We have come to the end of the interview. Is there anything that you would like to add that was not asked or covered?**

**Again, thank you for your participation in this interview. All the information and unique experiences you offered will be helpful in understanding more about how energy consumption can be reduced in the apparel industry. On the informed consent, there was a place for you to initial if you consent to being contacted in the future regarding this research topic. If you initialed that area, I may be getting in touch with you in the coming weeks to make sure that I captured what you said correctly. If at any time you wish to withdraw your interview data from the study, you may do so.**

**\*\*End Audio/Video Recording**

## Appendix B - Themes within the Qualitative Interview Responses

Objectives	Interview questions	Themes
To identify most influential energy consumption factors of the sewing process in apparel manufacturing industry	Significantly contributing energy consumption factors	<ul style="list-style-type: none"> <li>• Time</li> <li>• Cost</li> <li>• Waste</li> </ul>
	Additional Factors	<ul style="list-style-type: none"> <li>• Direct production elements</li> <li>• Production supportive elements</li> <li>• Waste factor</li> </ul>
	Factor's influence on product differentiation	<ul style="list-style-type: none"> <li>• Same</li> <li>• Not same</li> </ul>
To determine the interrelationships among energy consumption factors	Factor to factor interrelationship	<ul style="list-style-type: none"> <li>• General correlations</li> <li>• Examples</li> </ul>
To identify steps to reduce energy consumption within sewing process in apparel manufacturing industry	What suggestions would you give to reduce the energy consumption?	<ul style="list-style-type: none"> <li>• Greener energy</li> <li>• Production</li> <li>• Operator</li> <li>• Management</li> <li>• Government</li> </ul>
To explore the apparel industry experts' level of concern regarding energy consumption, the contribution to greenhouse gas emissions and climate change in the apparel manufacturing industry.	As a professional in the apparel industry, are you concerned about the level of energy consumption in the apparel manufacturing?	<ul style="list-style-type: none"> <li>• Energy consumption cost</li> <li>• Sustainability in terms of garment waste and fossil fuels.</li> </ul>
	Has your organization implemented any energy reduction initiatives in order to reduce consumption?	<ul style="list-style-type: none"> <li>• Direct initiatives</li> <li>• Indirect initiatives</li> <li>• No initiatives</li> </ul>

---

Have you had discussions with other professionals regarding the importance of reducing GHG emissions in an effort to address climate change concerns?

- General conversations
- Conversations related to GHG emissions

---

If a model were developed to determine the most influential energy consumption factors within the assembling process, would you consider modifying your assembling processes in order to reduce energy consumption?

- Model's cost related features
- Model's non-cost related features

---

In the decision making process, production rate is an important consideration. Do you believe energy consumption may become another important consideration in your decision making?

- Current consideration
  - Future consideration
-

## Appendix C - Example of Quantitative Data Set

Name of operation	Operator's Name	Sewing machine Company	Machine Model	Stitch name	Y	X1	X2	X3	X4	X5	X6	X7	X8	X9	X10	X11
					Energy consumption per pc	Motor Speed	Motor Capacity	Length of seam per pc	Stitches per inch	Number of Threads	SAM or, SMV	Operator's Efficiency	Machine Utilization	Layers of fabric	Total Fabric Thickness	Types of Fabric
					Watts/min	RPM	Watts	inch	SPI	minute	%	%		mm		
					EC	Speed	Capacity	Length	SPI	Threads	SAM	Efficiency	Utilization	Layers	Thickness	Fab types
Shoulder joint	Mui Cool	Juki	MO-3743	4TOL	120.0	3450	400	12	12	4	0.44	0.75	0.16	2	1.08	Knit
Sleeve joint	Voan	Juki	MO-3743	4TOL	228.0	3450	400	53	9	4	0.82	0.77	0.15	2	1.8	Knit
Side Seam	Voan	Juki	MO-3743	4TOL	312.0	3450	400	82	9	4	1.03	0.82	0.18	2	1.8	Knit
Side Seam	Ming	Juki	MO-3743	4TOL	192.0	3450	400	85	8	4	0.74	0.94	0.35	2	1.8	Knit
Bottom hemming	Xiu	Pegasus	W-600	5TFL	67.5	3000	550	47	10	5	0.49	0.89	0.49	2	1.08	Knit
Neck hemming	Kim Lee	Pegasus	W-600	5TFL	72.0	3000	550	32	11	5	0.33	0.80	0.41	3	1.62	Knit
Side Seam	Felips	Juki	MO-6716S	5TOL	96.0	3450	400	25.25	14	5	0.33	0.98	0.21	2	0.58	Woven
Yoke joint	Alex	Juki	DDL-8700-7	SNLS	60.0	5000	450	31	11	2	1.42	0.95	0.25	3	1.26	Woven
Neck preparation	Diego	Juki	DDL-8700-7	SNLS	72.0	5000	450	48	8	2	1.14	0.75	0.22	2	1.01	Woven
Yoke top stitch	Margarita	Juki	DDL-8700-7	SNLS	12.0	5000	450	14.25	9	2	0.39	0.67	0.24	4	1.68	Woven
Base hemming	Myrna	Yamato	VE2711-156S-2/UT-A32	3TFL	73.3	3000	550	28	11	3	0.86	0.95	0.29	4	2.84	Sportswear
Collarband joint	Debb	Juki	MO-6716S	3TOL	8.6	3300	550	2.5	11	3	0.24	0.96	0.20	2	0.72	Sportswear
Neck tape joint	Samm	Juki	DDL-8300N	SNLS	231.4	3450	400	10.5	11	2	1.24	0.79	0.13	3	1.08	Sportswear
Sleeve hemming	Samm	Kansai Special	W-8103D	3TFL	600.0	3450	400	10	10	3	1.73	0.74	0.17	2	0.72	Sportswear
Label attaching	Michelle	Siruba	DL918-M1-13	SNLS	6.0	5000	550	2	12	2	0.21	0.98	0.23	3	1.48	Sportswear