ABSTRACT

IEVTUSHENKO, OLGA. Cost Modeling of Nonwoven Manufacturing Processes. (Under the direction of Dr. Behnam Pourdeyhimi and Dr. George Hodge.)

Nonwoven manufacturers operate in a highly competitive environment, where the reduction of production costs is of strategic imperative to stay in business. While the understanding and estimation of the production costs of nonwovens are very important, a literature review revealed a lack of published research in this field, available in the public domain. To fill the gap, this study is designed to lay the foundation for cost modeling and analysis of nonwoven products and process.

The first purpose of the research was to develop a detailed, bottom-up cost model for the spunbond process. This cost model was further used to investigate the influence of product and process related factors on the production cost of calendered spunbond nonwovens. This analysis revealed the cost behavior and cost breakdown structure, as well as insight into the most important cost drivers. In addition, the cost model was utilized to assess the effect of uncertainty in input parameters on the product cost.

The second purpose of the study was to develop a generic framework that can be applied to other nonwoven manufacturing technologies. The resulting framework describes the major steps required to define production parameters, resource requirements and then to relate these variables to the cost of the process itself and the resulting cost of the final product.

Cost Modeling of Nonwovens Manufacturing Processes

by
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DEDICATION

To my parents.

BIOGRAPHY

Olga Ievtushenko was born on December 24, 1983 in Ukraine. Her parents are Vasyliy and Valentyna Ievtushenko, and she has a younger brother, Olexiy Ievtushenko, and older sister, Natasha Fedorova. Olga is married to Iurii Sas. Olga grew up in Komsomolsk, Poltava Region and graduated from Advanced Physical and Mathematical High School in 2001. Upon her graduation, Olga enrolled at Kiev National Taras Shevchenko University where in 2007 she received a Master of Science in Quantitative Economics and Econometrics. After completion of her studies, Olga has been working for one year as an auditor at Deloitte in Kiev, Ukraine. In 2008, Olga began pursuing a doctoral degree in Textile Technology Management at North Carolina State University under the direction and supervision of Dr. Behnam Pourdeyhimi. She received a Graduate Certificate in Nonwovens Science and Technology, completed the requirement for her degree in the summer of 2012.

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1 INTRODUCTION

1.1 BACKGROUND AND RESEARCH MOTIVATION

Nonwovens are a distinct class of textile materials made directly from fibers, thus avoiding the intermediate step of yarn production. Nonwoven fabrics are produced in four steps: material preparation, web formation, web bonding, and fabric finishing. Fibers or filaments are first arranged into a web-like planar structure by one of several methods including carding, air-laying, wet-laying, spunlaying, or the like. Then, the web is bonded to impart mechanical strength by various means of mechanical, thermal, or chemical methods. Additional fabric functionality can be engineered by applying finishing treatments.

The ability to use assorted raw materials, and combine different web formation, bonding and finishing techniques, allows for the production of a wide variety of nonwoven fabrics with specific properties required by diverse final applications. Due to nonwovens' versatility and flexibility, they are used across a wide range of industrial, engineering, consumer, and healthcare products driving large, growing, and rapidly evolving nonwovens markets. According to the Association of the Nonwoven Fabrics Industry (INDA), global production of nonwoven roll goods was estimated at $26 billion in 2010. It is projected to rise at a 7.8 percent annual rate to $35 billion in 2015 (Holmes, 2011).

Although demand for nonwovens continues to rise, the world nonwovens industry is under stress due to the maturity and oversupply of developed markets, the emergence of new low-cost roll goods producers in developing countries, the competition from other types of materials including textiles, paper and plastics, and the elasticity of substitution (Singer, 2010). As a result, nonwoven manufacturers operate in a tough and highly competitive

environment that makes it difficult for producers to alter their prices. This pricing pressure adversely affects profit margins of nonwoven companies. In addition, the accelerating escalation of raw materials and energy prices further aggravates the situation by creating additional pressure on profits. Therefore, one of the main strategic imperatives of nonwoven companies is a continuous cost reduction for existing and new products to maximize profit. Cost models are the generally accepted tool that is used to estimate and optimize costs. While there is a broad body of literature on cost modeling for other industries, there is a lack of literature on cost modeling and estimation for nonwoven products.

A choice of specific raw materials, web formation, bonding, and finishing techniques not only defines the properties and performance characteristics of final products, but also has a significant influence on the product costs. It is difficult to develop one generic cost model that accounts for all possible combinations of production technologies. A review of the literature suggests that a process-based, "bottom-up" approach that allows the estimation of total production cost as a sum of costs of individual processes may be effectively used in such settings. The cost model for each process is a set of equations that relates product and equipment design parameters, processing variables and economic conditions to the cost elements of the process that, in turn, contribute to the total cost of the process. Such segmentation allows the development of models for each web formation, bonding or finishing technology individually, and then combining individual cost models for technologies defined by product specification to estimate the total manufacturing costs. In addition, this modularity offers the ability to study and analyze the economic performance of each process and control its operating conditions to minimize costs.

1.2 PURPOSE OF THE RESEARCH

The purpose of the research is two-fold: to model and conduct analysis of production costs of the spunbond technology, and to develop a cost modeling framework for nonwoven products and technologies. The first aim is to investigate the influence of product and process related factors on the production cost of calendered spunbond nonwovens. The research goal is to develop detailed cost models of the main steps involved in the process and combine them into the cost model for the spunbond line. The results of this study provide an insight into the cost behavior and cost breakdown structure, as well as, help to develop an understanding of the most important cost drivers that may be modified during the decision making to reduce production costs. The main questions that are answered during this part of analysis are:

- What are relationships between product/process design parameters and process cost elements?
- What are the step-wise and element-wise cost structures of the process?
- How do changes in input factors influence costs of the process and what are the cost drivers?

The second aim of the study is to summarize and generalize all steps involved in cost modeling and analysis of the spunbond process into a systematic guide that can be used to model costs of other nonwoven manufacturing technologies. These include the development of cost models for each production step considered, coupling of the production steps to yield the cost model of the line of the interest, and the application of the cost model for the most common types of cost analysis.

1.3 OBJECTIVES OF THE RESEARCH

The following are the objectives developed to achieve the purposes of the study:

RO1: Develop a detailed cost model for the calendered spunbond nonwovens production process.

a. Define the structure of the cost model in terms of processing steps considered and boundaries of each step.
b. Identify cost elements and product/process parameters that affect production cost of each processing step.
c. Build a chain of equations that relate cost elements for each step to product/process parameters identified.
d. Combine individual cost models of processing steps into the cost model of the spunbond line.

RO2: Perform cost modeling and analysis of the spunbond process using the model developed.

a. Establish base-case scenario for the input parameters.
b. Perform analysis to study the effects of input parameters and identify cost drivers.

RO3: Develop the framework for cost modeling and analysis that can be applied to other nonwoven processes by identifying steps involved in model building, data gathering, and analysis.

1.4 SIGNIFICANCE OF THE STUDY

While the understanding and accurate estimation of production costs of nonwovens are very important, the literature review reveals a lack of research in this field, in the public domain. To fill the gap, this study is designed to develop a detailed cost model for the most commonly used combination of web formation and bonding technologies, namely spunbond production process. The resulting model may be used by R&D teams and management to estimate costs of new spunbond products, compare design alternatives, support make-or-buy or capital investment decisions, and optimize production conditions. This study also establishes the research framework for cost modeling and analysis of other nonwoven production technologies that may be combined to estimate costs of different nonwoven products.

1.5 DISSERTATION OUTLINE

The main body of this dissertation is organized in four chapters. Chapter 2 is devoted to the literature review of the cost estimation techniques and overview of the spunbond production process. The detailed explanation of the cost model developed for the spunbond process, its implementation in MS Excel and the cost analysis conducted are given in Chapter 3. Chapter 4 introduces the cost modeling and analysis framework for nonwoven products. Finally, Chapter 5 summarizes the research findings, and provides the background for future research in the area of cost modeling and analysis of the nonwoven products and processes.

2 LITERATURE REVIEW

In this dissertation, the literature review consists of two parts. First, the main quantitative cost estimation techniques, their benefits and limitations, and their applicability to different stages of new product development stages are discussed in Section 2.1. This section has been published in the Research Journal of Textile and Apparel[1]. The literature review indicates a lack of studies in the cost estimation of nonwoven products. Then, in Section 2.2, a comprehensive overview of the spunbond technology is given including process stages, equipment, materials used and process variables. The information from both sections will be used for further development of the production cost model for the spunbond process.

2.1 REVIEW OF COST ESTIMATION TECHNIQUES

Today, the strategy of innovation is perhaps the most pervasive strategy for textile companies to achieve a competitive advantage while facing severe competition in the global textile market. To be successful a company must bring new products to the market, which can completely satisfy customers' expectations, as well as the company's desire to increase its profitability. Because product price is an important decisive factor that influences customers' purchase behavior, and it is generally established independently as a result of pure competition, the only way to get a higher profit margin is to reduce product costs. The product costs are committed as the product goes through new product development stages and it is therefore critical for the company to manage costs in every phase of this process.

[1]Ievtushenko, O., & Hodge, G. (2012). Review of cost estimation techniques and their strategic importance in new product development process of textile products. *Research Journal of Textile & Apparel*, 16(1), 103

The focus of this section is to review current cost techniques and methods, which can be successfully applied during the development of new textile products.

2.1.1 Introduction

The textile industry has been influenced by significant structural changes in the world production and trade patterns. The elimination of Multi-Fiber Arrangement quota system has led to trade liberalization and as a result to more intensive global competition. To compete effectively in the global market place US textile companies have changed their focus from a production orientation to a marketing orientation. Such an approach allows them to respond quickly and adequately to the changes in customers' wants and needs. The marketing orientation has led to increasing innovation's significance, and as a result, textile companies pay more attention to the new product development process (Powell & Cassill, 2006).

Although the development of new products is crucial for textile companies, it is risky because of high new product failure rate. The published literature reveals the most important reasons for new product failure, including misunderstanding of customers' needs, being late to market, and poor pricing (Cooper & Kleinschmidt, 2003; Tyagi, 2006; Urban & Hauser, 1993). Since the price of the product plays an important role in new product success in the market, it must be considered during the whole innovation process and must serve as one of the primary decision criteria. Today, prices of textile products are established by the market because of the strong global competitive environment. As the main objective of any manufacturer is to increase market share (Martinez, Fouletier, Park, & Favrel, 2001), a company usually uses price reduction as a tool to achieve growth in share, and prices are set

at lower levels. It is known that the price of a product is determined as a sum of product costs and the company targeted profit level, and that the latter should never be lower than what is required for long-term company's survival. The ability of a company to offer a product with lower costs without being detrimental to product quality and functionality leads to product success in the market (Predic & Stefanovic, 1999). Therefore, cost estimation, analysis, and optimization should be a part of the new product development strategy.

2.1.2 Strategic relevance of cost estimation in new product development process

New product development (NPD) is the process of creating new products for the market (Powell & Cassill, 2006). An NPD process consists of several steps, which are designed to move new products through the product development pipeline from idea to commercialization. Urban and Hauser's generic NPD process includes five phases: *opportunity identification*, *design*, *testing*, *introduction*, and *life cycle management* (Figure 2-1) (Urban & Hauser, 1993). The NPD process is costly and the funds invested in NPD are at risk in the final introduction phase (Anderson, 2004; Urban & Hauser, 1993). It is very important to eliminate failures early before they lead to a major loss in investment (Gagne & Discenza, 1995).

Product price is one of the most important factors for product success in the market (Saban, Lanasa, Lackman, & Peace, 2000). Thus, a product should be priced appropriately because overpricing will result in lost sales, while underpricing will lead to lost profits. Many companies just ignore the relationship between the product price and real costs of their product. Such an attitude often results in huge financial loss (Daly, 2002). Since costs make

up a substantial part of the price, it is of the greatest importance, during the process of new product development, to estimate product cost and use it as a benchmark for selecting successful products. In addition, the product life cycle has reduced significantly due to rapid technological change. Thus, there is no time for price adjustments once costing errors are detected. That is why cost management is critically important for the NPD process.

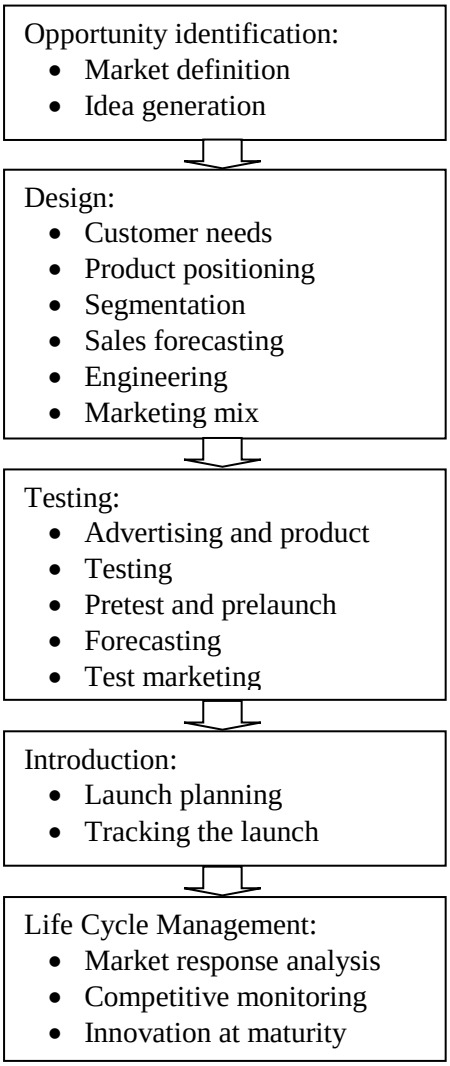


Figure 2-1: New product development process
(Urban & Hauser, 1993)

Many authors (Anderson, 2004; Dixon & Duffey, 1990) agree that by the time a new product is designed, about 80% of the product cost has been determined and when a product goes into production, 95% of its cost is committed (committed cost line, Figure 2-2). Once the cost is locked in, it is difficult for the manufacturer to reduce it. This can be explained by the fact that when the new product moves through the stages of the NPD process, the cost of product modification is growing exponentially and the possibility of cost reduction is decreasing (Figure 2-3) (Anderson, 2004; Rajkumar, 2003).

The opportunity identification phase alone determines about 60% of the product's future cost (committed cost line, see Figure 2-2). At this stage concept ideas are generated which define key product features and characteristics. Consequently, the opportunity identification step has the highest impact on cost reduction opportunities (Anderson, 2004; Ehrlenspiel, Kiewert, & Lindemann, 2007; Rajkumar, 2003).On the other hand, the beginning stages of the NPD process require low investment. By the time a product has been designed, only 8% of the total product budget has been spent. For subsequent NPD steps, a company has to invest a significantly larger amount of money to bring new products to the market (Anderson, 2004) (the incurred cost line, see Figure 2-2).

During the testing phase, a company does not have significant control over the committed cost of a product, but can examine, relatively inexpensively, the new products' market fit. In the case of a poor market fit, the company will consider either redesigning or discontinuing the product. The company has to avoid investing in a product that may fail.

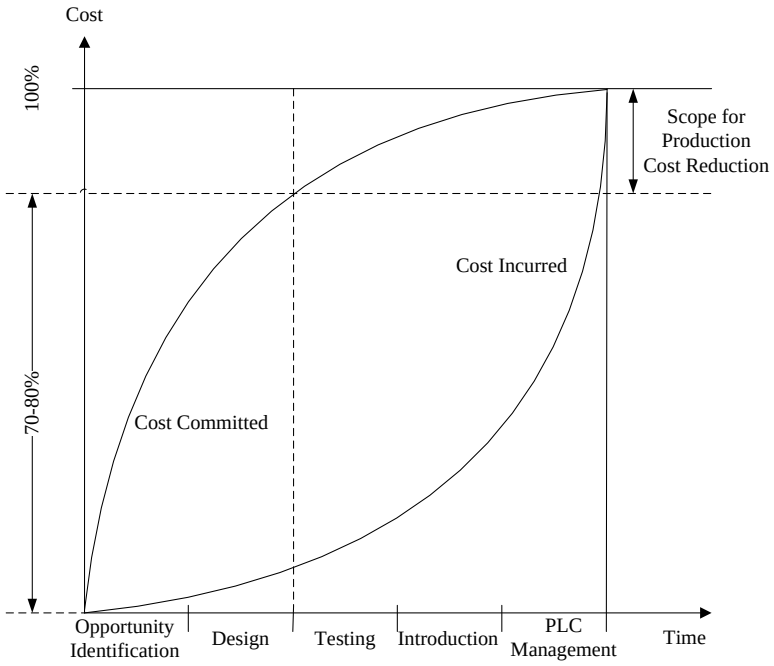


Figure 2-2: Costs dynamics in the new product development process
Adapted from (Rajkumar, 2003)

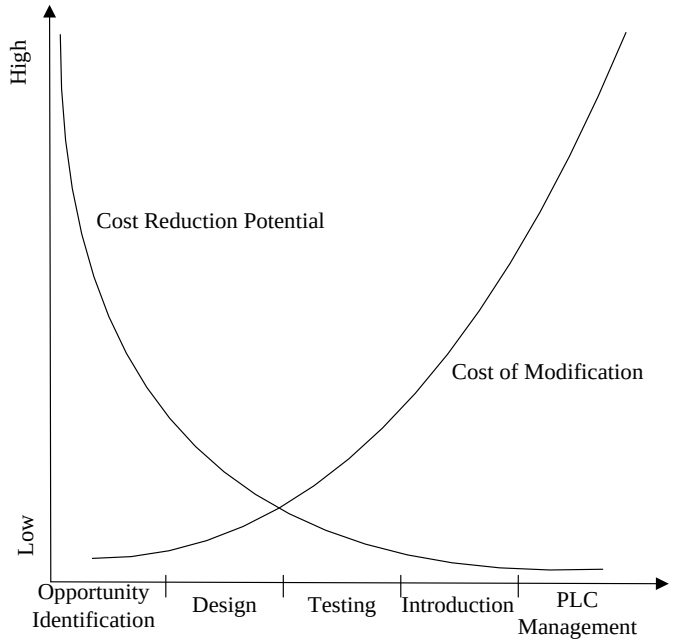


Figure 2-3: Cost reduction possibility
Adapted from (Duverlie & Castelain, 1999)

The introduction phase is the cornerstone of the NPD process. If the company launches a product that cannot meet customers' needs, there will be significant losses of the already invested funds and product redesigning will become extremely costly.

Today, a set of managerial tools are available to assist product managers in their decision-making process regarding alternative product design solutions which, in turn, help to achieve reduced product costs committed during the NPD process (Ulrich & Eppinger, 1995). The two techniques mostly used are *design-to-cost* and *design for manufacturing*. According to Crow (2002), "the effective product cost management requires a design-to-cost philosophy as its basis" since 80% of product costs are locked in during the first two stages of the NPD process (Crow, 2002). Design-to-cost is a market-driven management strategy, which allows creating a new product with a market acceptable price by using the target cost as a goal that needs to be achieved by the NPD team. The target cost of the product is obtained by subtracting the target profit from the market price. The target profit is set by the management with respect to a company's long-term objectives margin. When the target cost is set up, and cost reduction strategies are defined, the development team is responsible for achieving target product costs through the rest of the product-development phase (Bird, Albano, & Townsend, 2004). This process heavily relies on product cost estimation models to evaluate product design alternatives and achieve a defined target cost (DRM Associates, 2006). Design for manufacturing is a strategic tool, which is used "to reduce manufacturing effort and cost related to fabrication and assembly processes" (DRM Associates, 2006).

Successfully developed and launched products are not enough to meet the main long-term objective of the company – profit. During the product life cycle, it is necessary to

consider profit maximization to cover not only operational expenses but also expenses that were incurred during the first three stages of the NPD process (see Figure 2-4). In addition, it is important to monitor and adequately respond to changes in the product environment including raw materials prices and availability, competitors' actions, and customer needs. Therefore, any organization requires an effective decision support system to maximize profit during the product life cycle (Urban & Hauser, 1993). One of such strategic frameworks is product life cycle cost management (PLCCM).

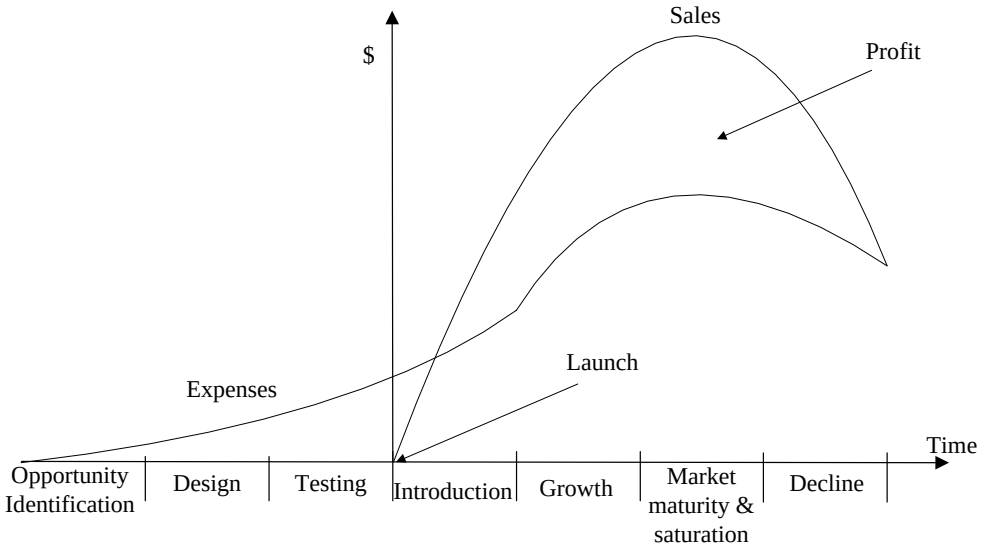


Figure 2-4: Sales and profits during the NPD and PLC
Adapted from (Urban & Hauser, 1993)

PLCCM is a tool used to help strategic decision making to improve a company's long-term competitive advantages. According to Pesonen (2001), effective product life cycle cost management consists of three elements: *life cycle costing*, *product life cycle management*, and *cost reduction methods*. Life cycle costing (LCC) follows a structured

approach to identify the cost elements of the product that are incurred through the stages of the life cycle. Each stage of the product life cycle includes at least one of the business functions, which increase total product costs. The result of an LCC is a cost breakdown structure that can be used to assist management in the decision-making process. LCC provides a basis for application of the cost reduction strategies, methods, and techniques (Asiedu & Gu, 1998).

Product life cycle management is the series of strategies used by management as a product goes through its product life cycle. The conditions in which a product is sold change over time and must be managed constantly to support product profitability. A company failing to manage its new products during the life cycle may lead to potential profit loss. Cost reduction is a method of costs analysis, which helps to optimize the company's expenses and improve profits. The most common methods used for cost reduction are process *value analysis* and process *re-engineering* (Bird et al., 2004).

Design-to-cost, design for manufacturing and PLCCM emphasize the strategic importance of the expected manufacturing cost of a new product. For this reason, much effort has been made within the field of cost engineering with respect to product cost estimation (Cavalieri, Maccarrone, & Pinto, 2004).

2.1.3 Cost estimation methods classification

Stewart (1991) enumerates four fundamental tools, which are necessary for successful cost estimating: *information*, *methods*, *schedule*, and *skills*. According to Stewart (1991), valid cost estimates can be built only if they are based on well-organized, complete, current,

and reliable information about product specifications, production schedules, and manufacturing plans. An important element in developing the cost estimate is a cost breakdown structure that decomposes costs within a company into cost centers, elements, types or units and serves as a framework for collecting and organizing data (Asiedu & Gu, 1998). In addition, there is a need for establishing a cost estimating schedule, especially for a detailed estimation when information is required from various departments. The quality of estimates is dependent on a number of skills, which should be closely integrated into the cost estimating process (see Figure 2-5). Finally, a cost engineer must decide on the estimating method or a composite of methods to be used by considering the time allowed for estimating, the accuracy and depth of estimates, and the availability of resources and information in a company (Stewart, 1991).

The literature on cost estimating reveals two main approaches for product cost estimation: *bottom-up* and *top-down* (Heemstra, 1992; ISPA, 2008; Lock, 2007; NASA, 1995). *The bottom-up (detailed, grass roots) approach* implies decomposition of products and the manufacturing process into individual parts and sub-processes, analysis and cost estimation of simple units, and integration of these costs into total product cost (ISPA, 2008). Cost estimation of simple units can be done by the application of different cost estimation techniques. Usually, this approach requires complete information about product specification and its manufacturing process. Therefore, it cannot be used at the early stages of the product life cycle. In addition, considering the great amount of information needed, this approach tends to be time and resource consuming (NASA, 1995). On the other hand, it gives more

accurate cost estimation and detailed cost structure, which can be effectively used for future cost reduction (Beischel, 1990).

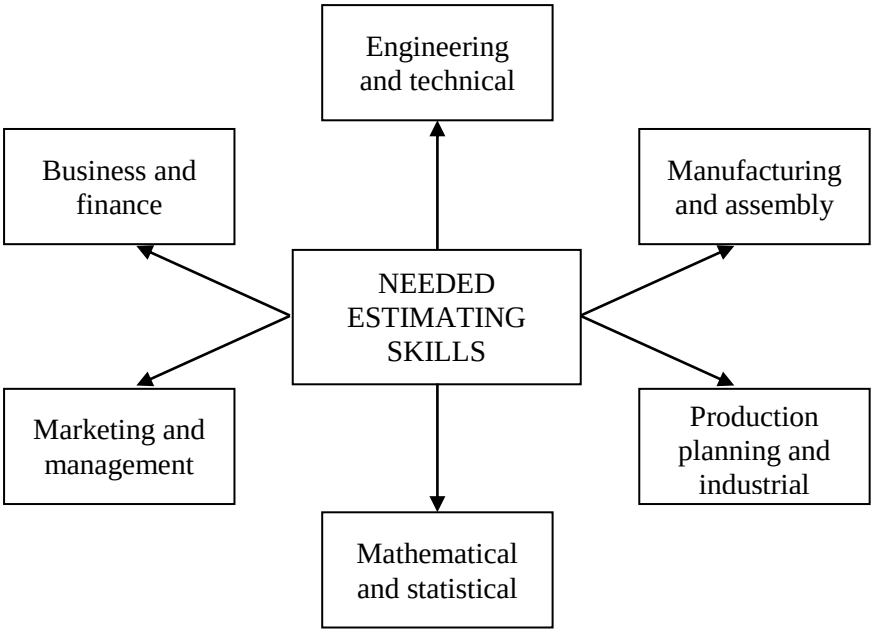


Figure 2-5: Skills needed for cost estimating
Adapted from (Stewart, 1991)

The top-down approach estimates product costs by looking at the product as a whole based on its global properties and characteristics (Heemstra, 1992; ISPA, 2008). This approach requires minimum product details, and is useful at the early stages of a product life cycle when complete product specification is unknown. In addition, it is less time and resource consuming and easier to implement. However, it gives less accurate product cost estimation and little information for cost analysis (NASA, 1995).

A great number of cost estimation methods were developed in cost engineering science during the last few decades based on the two approaches described above. To

organize cost estimation techniques in a more comprehensive and understandable system, many authors tried to classify them based on certain criteria. On the top level of this classification most authors distinguish *quantitative* and *qualitative* techniques (Cavalieri et al., 2004; Layer, Ten Brinke, Van Houten, Kals, & Haasis, 2002; Niazi, Dai, Balabani, & Seneviratne, 2006; Saravi, Newnes, Mileham, & Goh, 2008; Shi & Li, 2008).

Qualitative estimating techniques, also called intuitive (Shi & Li, 2008), rely on experience and knowledge of product cost estimators (Duverlie & Castelain, 1999). The main advantages of these techniques are that experts bring their experience to the new project and that they are relatively cheap and fast in implementation (ISPA, 2008). At the same time, qualitative methods have some disadvantages including subjectivity of cost estimation and an inability to establish a direct relationship between product characteristics and cost. Intuitive methods include such techniques as Delphi, subjective probability, personal judgment, expert conference, brainstorming methods and heuristic rules (Caputo & Pelagagge, 2008; Shi & Li, 2008). This review is aimed at a mathematical approach to cost estimation, and qualitative techniques will be disregarded in future discussion.

Quantitative estimating techniques define product cost with the help of mathematical algorithms and statistical tools and set the value of product cost with respect to product and manufacturing process specifications (Layer et al., 2002). Because the quantitative methods are more widespread and they are based on a variety of different theoretical backgrounds, such techniques are subject to further classification in literature.

Zhang et al. (1996) singled out traditional detailed-breakdown, simplified breakdown, group technology (GT)-based, regression-based, and activity-based cost estimations.

Weustink et al. (2000) and Scanlan et al. (2002) distinguished two groups: parametric (variant based) and generative. Park & Simpson (2005) categorized variant-based, generative-based, simulation-based, and hybrid-based cost estimation techniques. Verlinden et al. (2008) suggested variant-based, generative, hybrid categories. Duverlie & Castelain (1999), Bode (2000), Camargo et al. (2003), Cavalieri et al. (2004), Feldman & Shtub (2006), Castagne et al. (2008) classified quantitative cost estimation techniques into three broad groups: analogous (analogical, similarity-based), parametric (function-based) and analytical (detailed, expenditure-based, engineering). Asiedu, Besant & Gu (2000) and Layer et al. (2002) distinguished the same groups as mentioned above, but instead of using a parametric category, they used a statistical one which allowed them to include neural network cost estimation techniques in the statistical category. Based on a broad analysis of cost estimation techniques, which were done during the preparation of this work, the classification of techniques into *analogical*, *statistical*, and *analytical* groups is assumed to be the most descriptive and is therefore used for the purpose of this review (Figure 2-6).

Analogical cost estimation techniques define the cost of a new product or its components based on the similarity of the new product to existing ones and adapt this cost considering differences in existing and new products' characteristics (Camargo et al., 2003; Castagne et al., 2008; Cavalieri et al., 2004; Layer et al., 2002). These techniques can be applied only to technologically close products (Camargo et al., 2003) and rely upon the ability of a cost estimator to recognize similar and different properties and functions between new and sample products fully and correctly (Asiedu & Gu, 1998). The accuracy of these methods depends on the estimator's knowledge of specifications and manufacturing

processes of comparable products (Castagne et al., 2008). Analogous methods are useful because of their low cost and rapid implementation (Camargo et al., 2003).

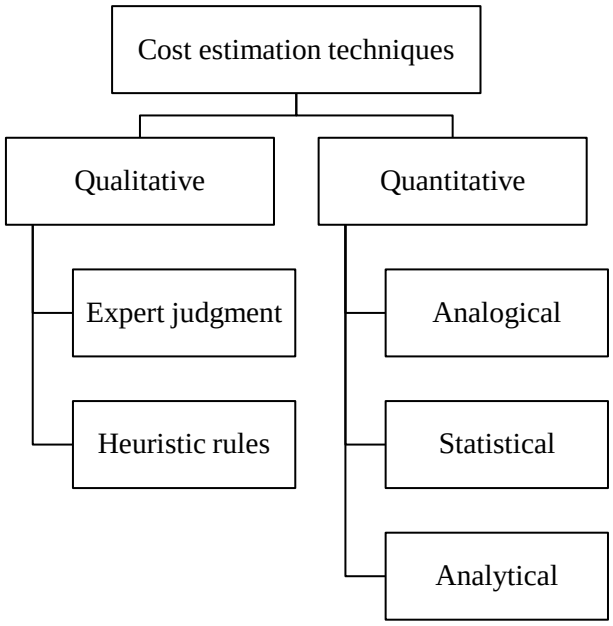


Figure 2-6: Classification of cost estimation methods
Adapted from (Caputo & Pelagagge, 2008)

Statistical cost estimation techniques identify mathematical relationships between cost and global product characteristics based on historical data with the help of statistical tools (Layer et al., 2002). Because detailed descriptions of a product and production process are not required, these methods are very helpful during the concept and design stages of the NPD process (Crow, 2002). In addition, these techniques are broadly used in practice because they give careful and sufficiently accurate estimates. However, the selection of independent variables, which explain product cost to the best advantage, is a complicated task (Wongvasu, Kamarthi, & Zeid, 2001). To achieve acceptable cost estimates statistical

techniques usually needs an appropriate historical database and therefore such methods cannot be used for cost estimation of completely new products. There are two main statistical techniques: *parametric* and *neural networks* methods. These two methods are able to provide comparatively accurate cost estimates, but each of them has its own advantages as well as disadvantages (Chen & Wang, 2007).

In contrast to analogical and statistical groups, analytical cost estimation techniques usually implement the bottom-up approach and estimate product cost based on detailed decomposition of the manufacturing process and products into simple tasks and parts (Asiedu & Gu, 1998; Camargo et al., 2003; Castagne et al., 2008; Cavalieri et al., 2004; Duverlie & Castelain, 1999; Layer et al., 2002). Therefore, this approach can only be used at the final stages of the new product development process when all product characteristics and manufacturing processes are clearly identified (Cavalieri et al., 2004). Although these methods yield the most precise product cost estimation, they consume significant amount of financial and human resources and are complicated in implementation (Castagne et al., 2008). On the other hand, due to the high level of detailed products and processes specifications these techniques allow to analyze and optimize product cost structure (Layer et al., 2002).

2.1.4 Cost estimation techniques

2.1.4.1 Case-based reasoning

Case-based reasoning is one of the most interesting approaches to the product cost estimation problem. It can be categorized as a form of artificial intelligence since it performs

functions that are usually associated with human intellect, such as self-learning and problem solving through the accumulated past experience (Avramenko & Kraslawski, 2006; Roy, 2003). In general, case-based reasoning is based on the postulate that "*similar problems have similar solutions*" and "*future problems are likely to be similar to current problems*" (Leake, 1996).

Aamodt & Plaza (1994) defined case-based reasoning as an iterative and integrated process of solving a new problem by reusing and if necessary adapting the solutions of earlier experienced analogous problems. In case-based reasoning terminology, a new problem, which has to be solved, is referred to as a new case. A prior experienced problem, which has been solved and learned in a way that the knowledge of that problem can be reused in solving of new problems, is called a previous case. The information pool, which contains information about previous cases, is named as a knowledge base (Aamodt & Plaza, 1994). A schematic representation of Aamodt & Plaza's traditional model of the problem solving cycle in case-based reasoning is depicted in Figure 2-7.

The cost estimation process, based on the case-based reasoning system, usually begins with the identification of a new product's design specifications. Then, by taking into consideration the new product specification, the system looks for a product similar to the new one and compares the new product to the similar product to identify the differences in the assemblies. Thereafter, the system tries to incorporate the differences in design by finding them in other similar products. This cyclical process continues until the new design conforms to the identified new product's design specification. The new product's design and cost information is later retained into the knowledge base for future reuse (Niazi et al., 2006).

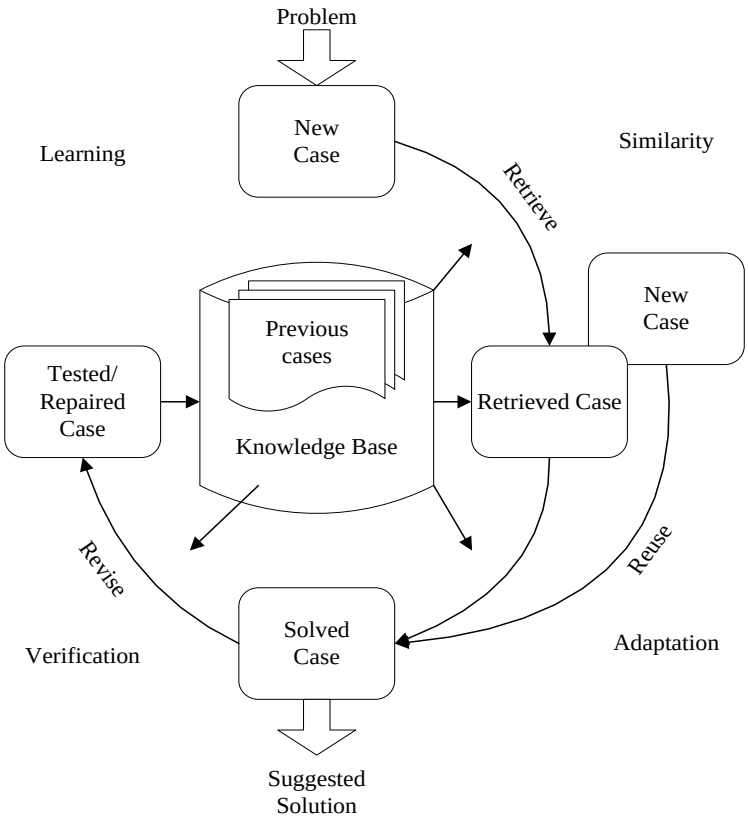


Figure 2-7: Case based reasoning process
(Aamodt & Plaza, 1994)

In the context of cost estimation, recent work has shown that case-based reasoning system has some advantages in comparison with other techniques such as neural networks or regression analysis (Kim, An, & Kang, 2004). First, case-based reasoning works in a transparent way; therefore, the origin of the estimates is known and the result can be easily revised (Duverlie & Castelain, 1999). In addition, this technique is applicable for long-term use since it can be updated easily and constantly through learning from experiences, and knowledge is stored in a consistent way (Kim et al., 2004). Nevertheless, utilization of this technique in a real company could be more complicated than in the case of parametric or

neural networks methods, since it requires a well-developed set of methods to select important information from experience, include a case into the knowledge base, and index the case for later matching with similar cases and adapting the past solution to a new case (Aamodt & Plaza, 1994; Duverlie & Castelain, 1999).

Since the case-based reasoning method uses past cases, it can generate new estimates very quickly (Duverlie & Castelain, 1999) and can be robust and helpful in making accurate estimates at the early stages of the NPD process (Niazi et al., 2006). However, this technique can only be used effectively when an adequate quantity of similar past cases is available to include important cost information during the new products cost estimation process (Niazi et al., 2006; Roy, 2003) and may not be applicable in highly innovative companies (Roy, 2003).

Case-based reasoning has a very important attribute: the ability to learn from experience (Roy, 2003). When new product cost estimate is generated, a case-based reasoning system organizes and retains new information in the knowledge base in order to use all available information for cost estimation of similar products in the future. It also stores information about unsuccessfully solved cases, which helps avoid mistakes committed earlier. Finally, case-based reasoning is able to provide cost estimates despite the lack of information concerning some product characteristics, and it allows the user to undertake several simulations with different meanings for unknown parameters (Duverlie & Castelain, 1999).

Although case based reasoning was successfully applied to cost estimating problems by many studies in many industries (Duverlie & Castelain, 1999; Layer, 2003; Marir &

Watson, 1995; Rehman & Guenov, 1998; Xu, Chen, & Xie, 2006), this technique has not been applied to textile products.

2.1.4.2 Neural networks based cost estimation

Recently, many researchers are investigating the use of neural networks to cost estimating problems. The creation of this technology was inspired by biological nervous systems concerning how the brain processes information (Cavalieri et al., 2004). In this way, it can be considered as an artificial intelligence system.

A typical neural network consists of a number of simple processing elements called neurons, units, or nodes (Figure 2-8). The main task of each unit is to receive an input from external sources or other units, transform the input into output signals, and propagate it to the other units. Neurons are grouped together into several layers (Figure 2-8): input layer, hidden layers, and output layer. Each processing element within the hidden layers is connected to all neurons in both the preceding and succeeding layers through unidirectional signal channels. However, it is not connected to neurons within the same layer. The input layer receives information about cost drivers and assigns weights to them by taking into account their relative importance as a cost-added driver. The information is then processed by the hidden layers in order to be converted into the required output. Finally, the output layer gives user output value that is a product cost (Bode, Ren, & Shi, 1995; Stockton & Wang, 2004).

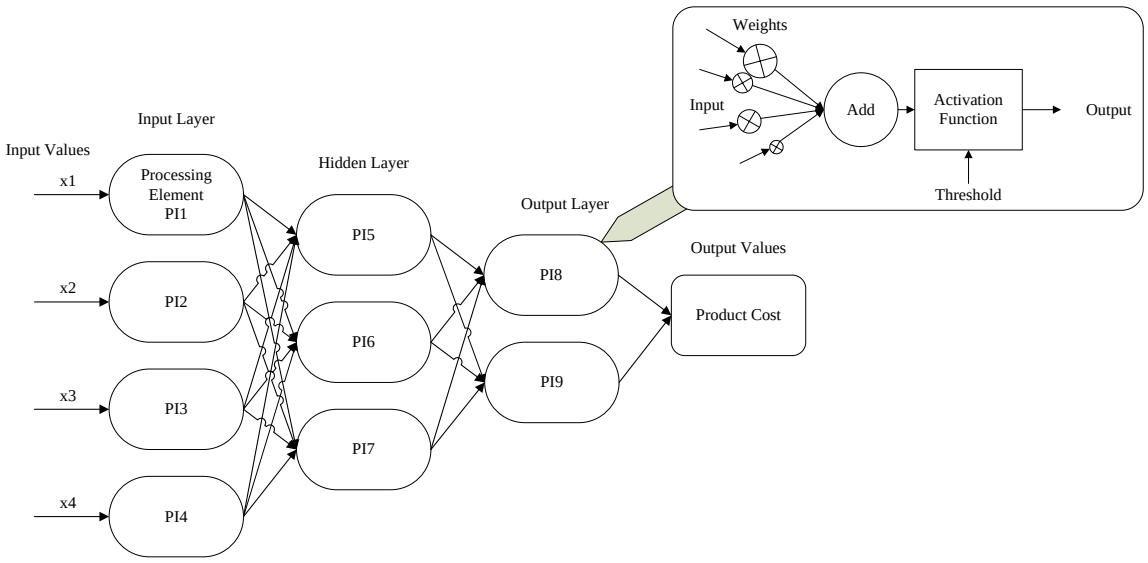


Figure 2-8: Artificial neural network structure
Adapted from (Gurney, 1997)

A schematic representation of the general cost estimation process by using neural networks is depicted in Figure 2-9. At the first step, an input, which consists of a limited number of cost drivers, is presented to the neural network and a corresponding target product cost is set up as an output. Then, the neural network system calculates an error as the difference between the actual target cost and the estimated product cost and compares it with a threshold value. In the case of an unsatisfactory result, the system feeds the error information back to the system in order to configure the neural network. This process is termed ‘learning’ or ‘training’ the network, which results in an adjustment of the weights of the connections between units according to some modification rules, so that the error is gradually minimized until neural network performance becomes acceptable. Finally, after the training phase, the NN parameters are fixed and the system can be deployed for cost estimating (Kamruzzaman, Begg, & Sarker, 2006).

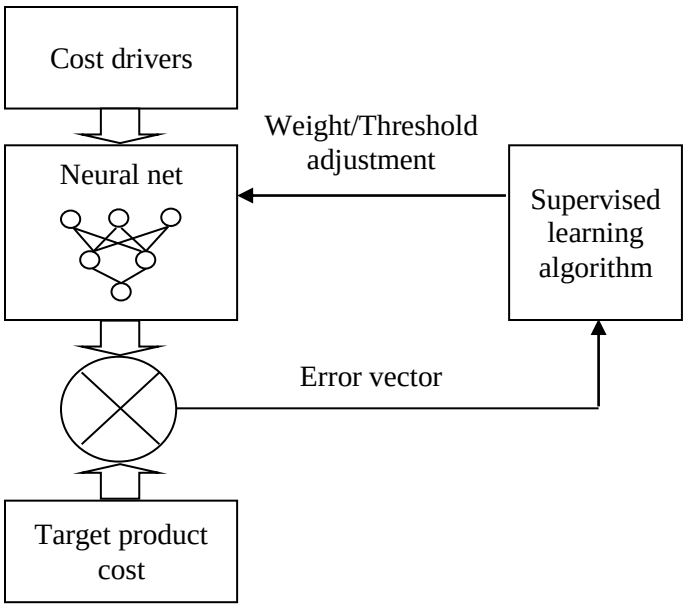


Figure 2-9: Neural networks process
Adapted from (Seo, Park, Jang, & Wallace, 2002)

In the literature, it was demonstrated that neural network technology produces more accurate cost estimations than other methods including regression method (Bode, 1998a; Bode, 1998b; Shtub & Versano, 1999; Smith & Mason, 1997). Generally, the cost engineer decides on network architecture, activation function, learning algorithm, and threshold value though there is a shortcoming that is autonomic adjustment of the parameters by the neural network system. Neural networks are usually perceived as a "black box' modeling technique, which makes it difficult to improve the quality of the estimates when the neural network system does not work appropriately.

There are some situations when cost engineers cannot specify a product to cost relationship. For this reason, the ability to identify a wide range of complex relationships between the input and output variables without defining the type of a cost function is a strong

advantage of neural networks over other cost estimation techniques. This ability makes the process of developing cost dependency easier and more efficient in terms of development time and recourses (Bode, 1998a; Bode, 1998b; Wang, 2007). However, due to the "black box" nature of the neural networks, the derived equation is not appropriate for the users who need to know the cost effect of product-related attributes in order to be able to find an optimal design solution (Curran, Raghunathan, & Price, 2004; Roy, 2003).

Another problem associated with using neural networks for cost estimating is that it requires a great number of cases for training, which are conformable to each other and to the new case (Bode, 1998a; Bode, 1998b). There is a direct correlation between the number of cases needed and the number of cost drivers. As the number of cost drivers increases, the number of cases required increases nonlinearly, so that a great number of cases are required even if there is small quantity of variables. Some industries that produce a limited range of product or new products cannot utilize this method because of the shortage of past cases (Curran et al., 2004; Roy, 2003). On the other hand, if there is plenty of accurate historical data for training, the neural networks can be used for cost modeling and estimating at all stages of a product life cycle.

A number of applications of neural networks for cost estimating have been reported in literature. For example, Zhang & Fuh (1998) applied the neural networks approach for cost estimating of packaging products based on cost-related packaged product features. Seo et al. (2002) showed that neural networks could be used for estimation of life cycle cost of a product in the conceptual design stage. Sonmez (2004) used regression and neural networks techniques for cost estimation of a building project at the conceptual stage. Cavalieri et al.

(2004) compared the application of parametric and artificial neural network techniques for the estimation of the unitary manufacturing costs of a new type of brake disks. Caputo et al. (2008) investigated the use of parametric and neural networks approaches in engineer-to-order companies with particular reference to the heavy carpentry sector and the manufacturing of large-sized pressure vessels.

Although many authors agreed that it is possible to achieve good product cost estimation by using neural networks, no attempt was made to apply this method for cost estimating of textile products.

2.1.4.3 Parametric cost estimation

Parametric cost estimation technique evaluates cost of a product by using an analytical function, which describes the relationship between product cost, and measurable high-level product attributes (Caputo & Pelagagge, 2008; ISPA, 2008; Qian & Ben-Arieh, 2008). In cost engineering science, this function is called Cost Estimation Relationship (CER) and product characteristics, which have an influence on product cost, are usually called Cost Drivers (Camargo et al., 2003; ISPA, 2008; Lamboglia, Gaudenzi, & Joumier, 2008).

The formation of an accurately predictive and statistically meaningful parametric equation is based on the collection and preparation of data and on applying appropriate mathematical and statistical techniques (ISPA, 2008). To develop CERs, most authors use a regression analysis as the most reliable and scientifically proven method (Asiedu & Gu, 1998; ISPA, 2008; Lamboglia et al., 2008; Pfleeger, Wu, & Lewis, 2005; Younossi, 2002). A

schematic representation of parametric cost model development and utilization processes is depicted in Figure 2-10.

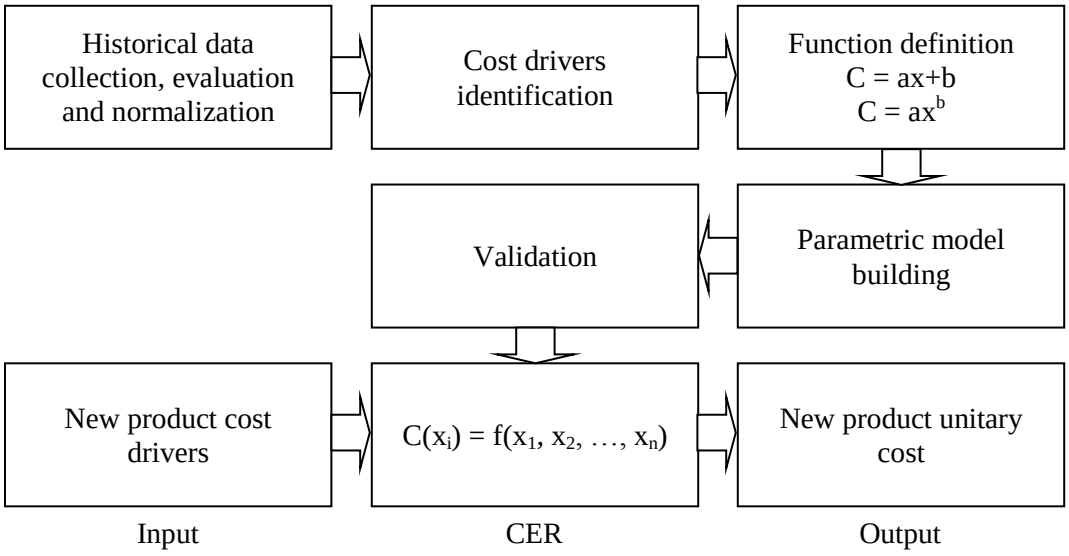


Figure 2-10: Scheme of the parametric cost model developing and utilization
Adapted from (Caputo & Pelagagge, 2008)

In the literature, many authors disclose the same advantages and disadvantages, which are peculiar to parametric cost estimating. Usage of this technique makes it possible to produce fast (Asiedu & Gu, 1998; Camargo et al., 2003; Castagne et al., 2008; Duverlie & Castelain, 1999; Lamboglia et al., 2008) and relatively accurate estimates (Roy, 2003) without requiring significant financial resources and detailed information about a product design and production specification (Camargo et al., 2003; Scanlan et al., 2002). Therefore, it can be easily used at the early stages of the NPD process (Watson & Kwak). In addition, because parametric cost estimation is based on the use of analytical function, it provides a deeper understanding of cost drivers and reveals their influence on product cost. Therefore,

this approach is useful during the development of product design, because it can make it feasible to improve design from an economical point of view (Duverlie & Castelain, 1999; Watson & Kwak). For example, if a company uses the target costing philosophy, CER can help it to achieve a target cost (Crow, 2002).

On the other hand, developing a good predictive and statistically meaningful parametric equation can be problematic (Younossi, 2002) because it heavily depends on historical data, which in reality often are not quality data (Curran et al., 2004). The method cannot be used for cost estimating of completely new products, or products with a major technical improvement (Younossi, 2002) or the ones that utilize new technologies (Asiedu & Gu, 1998; Castagne et al., 2008; Scanlan et al., 2002). In addition, long-term utilization of the model requires constant updating (Asiedu & Gu, 1998).

To make cost estimation, the user has to enter all parameters into the model, but during the design stage, the information about some needed cost drivers is not available. For these reasons, it is necessary to make estimates concerning some unknown parameters, and that, in turn, will lead to a lack of confidence in the final predictions (Duverlie & Castelain, 1999).

Parametric cost estimating technique found its application in many different industries including the aerospace, aircraft, telecommunication and automotive industries. Camargo et al. (2003) also applied this technique to cost estimation of wool fabric by using physical parameters and product complexity as independent variables. In her work, she supported the appropriateness of utilization of cost estimation techniques for cost estimation of textile products.

2.1.4.4 Activity-based costing

To meet the needs of changing markets and to survive and prosper in global competition, many companies are forced to diversify their products. Because of swift technological progress, the ratio between direct and indirect costs has changed considerably and now overheads compose the major portion of the total product cost (Baker, 1996; Roztocki, Valenzuela, Porter, & Monk, 1999).

A *traditional costing system* that relies on volume-based allocation of overheads (direct labor or machine hours) is often incapable of estimating the production costs accurately, especially in companies producing multiple products (Cooper & Kaplan, 1988; Johnson, 1991). It is mainly intended for accounting purposes, not for the needs of the decision makers who require accurate, relevant, and up-to-date cost information to make proper decisions concerning product pricing, process technology, and product design. Thus, a great number of businesses as well as researchers find this method impractical. To rectify drawbacks of the traditional cost system, Cooper and Kaplan developed another methodology called activity-based costing that assumes that costs are caused by activities, which are later absorbed by the products (Kaplan & Cooper, 1998).

The principal distinction between these two approaches consists in the procedure used for cost allocation. According to the traditional system, cost objects or final products consume resources; therefore, costs are directly assigned to the product. In turn, activity-based costing uses a two-stage cost allocation procedure where cost objects consume activities, which consequently consume resources. Thus, in the first stage, costs are assigned to each activity or cost pool in proportion to the amount of resources used, and then they are

allocated from the cost pool to cost objects in the proportion to the amount of activities used (Cooper, 1987a; Cooper, 1987b) (see Figure 2-11).

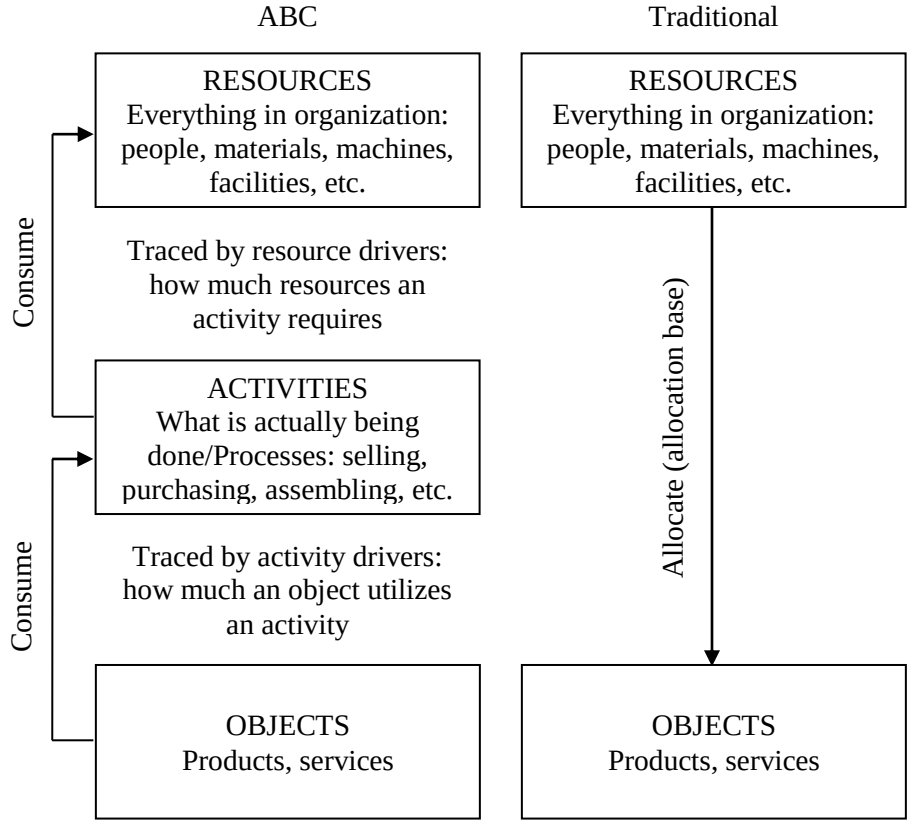


Figure 2-11: Activity-based costing versus traditional costing
Adapted from (Emblemsvag, 2003)

Noreen et al. (2008) describes the basic steps, which are necessary for the successful implementation of an activity-based costing system. According to him, it is necessary to first identify proper activities and activity cost pools, which a product must pass through during its production cycle. This is usually the most difficult and cumbersome part of the activity-

based costing implementation process since activities form the foundation of the system and the system's appropriateness depends on how correctly the activities are determined.

For the most part, this can be performed with the help of direct observation and interviewing of workers, supervisors, and managers involved in the product production process (Kaplan & Anderson, 2007). In addition, a production flowchart that is a visual image of the product routings during its movement through the plant can be a very useful tool to understand the manufacturing process and identify the primary manufacturing activities. This flowchart can also be used by each organization to define activities as "*value-added*" and "*non value-added*" for possible elimination of the latter (Beischel, 1990).

As a result of observation and interviewing, an activity-based costing team gets a lengthy list of activities performed by employees which must then be diminished by integrating similar activities. In addition, to get more accurate cost estimates, it is of greater importance to identify all costs that can be traced directly to the cost object (no activity pools required for them) and assign them directly to the product. This can be typically done for cost categories such as direct labor and material costs (Noreen et al., 2008).

Once the main activities and all directly untraceable costs have been identified, then it is possible to estimate the total cost of each activity by assigning each incurred expense category to various activity cost pools based on correlated measures known as cost drivers ("first stage allocation") (Noreen et al., 2008). For instance, the expense category "salary" may be driven by the amount of time the employee spends on this activity and therefore it may be assigned to each activity by multiplying the total salary expenses by the percentage of time spent on each activity.

The next step consists of the determination of the activity rate for each activity (i.e., activity cost per unit driver occurrence). Each activity should have only one designated cost driver called the second stage cost driver. The total expense dollars associated with each activity should be divided by the total number of driver occurrences for that activity to arrive at an "activity rate". Then, by using "activity rates", it is possible to assign costs to cost objects or products ("second stage allocation"). The final step in the Noreen's methodology of activity-based costing implementation is to prepare management reports (Noreen et al., 2008).

The literature reveals two main advantages specific to activity-based costing. First, two-stage allocation of overhead costs allows calculating more accurately the consumption of indirect costs by products. Therefore, activity-based costing provides very precise product manufacturing cost estimates. Another big benefit of the activity-based costing method is that it helps managers to improve their understanding of cost causation and as a result to improve cost management and control. In other words, it can help them to identify and eliminate non value-added activities and concentrate their efforts to make value-added activities more efficiently and effectively (Ben-Arieh & Qian, 2003; Griful-Miquela, 2001).

Although activity-based costing models seem to be a great managerial tool for planning and controlling companies' scare recourses and enabling managers to obtain very accurate product cost information, many managers of large-scale corporations refuse to use the models in real business life because of several important issues.

First, the development and management of an activity-based costing system involves a great deal of data collection. As mentioned above, the successful realization of the method

requires proper identification of activities or cost pools involved in the production process. It means that the production processes should be mapped accurately and adequately throughout the organization. Then, resource expenses must be allocated to each activity based on the percentage of time people spent on these activities, which is usually determined through interviews, surveys, and direct observation. Processes such as creating a production flowchart and interviewing people can be very subjective and cumbersome, extremely expensive and time consuming because of organization complexity (Griful-Miquela, 2001; Kaplan & Anderson, 2007).

Another issue associated with the activity-based costing system is that it is very difficult and expensive to maintain system appropriateness even after the initial model has been built. As it is well known, organization is an active system; to stay competitive, its business processes have to change constantly. Thus, new activities must be added to the model to expand its complexity. Such an expansion usually results in new expenses including the costs of re-interviewing and re-surveying personnel and costs of updating software packages. Consequently, activity-based costing models are often not maintained and their cost estimates will soon become inaccurate (Griful-Miquela, 2001; Kaplan & Anderson, 2007).

To address the above-mentioned issues of activity-based costing, Kaplan and Anderson (2007) refined the model and proposed a method called *time-driven activity-based costing*. In the new approach for each activity time based cost rates are calculated and the costing of the products is based on the time required to perform a transactional activity, hereby possibly using time equations (Kaplan & Anderson, 2007). According to Kaplan and

Anderson (2007), a time-driven activity-based model is easy to implement and update to changes in the production environment. The model can be validated by comparing model's time estimates with data obtained by direct observation of activities. It can also be easily scaled and modified to account for variations in orders and customers' behavior.

2.1.4.5 Feature-based costing

Activity-based costing provides both precise product cost estimates and the opportunity to analyze a product cost structure. However, this approach is very complex and difficult to implement. Therefore, scholars in the field of cost engineering continue attempting to develop alternative methods, which present the benefits of activity-based costing, but at the same time simplify the operation and implementation of the approach.

One of the most well-known alternatives to activity-based costing is feature-based costing (Brimson, 1998), whose development was inspired by the growth of CAD/CAM programs in design. Nonetheless, this approach is not yet completely developed; attempts are still being made to examine the use of the feature-based modeling approach for the purpose of cost engineering (Roy, 2003).

In general, the feature-based costing methodology is based on the assumption that products can be defined as a set of product features. Each feature has its cost implication and, therefore, has an influence on the total product cost. It is also important to note that in the context of feature-based costing the term feature means not only geometrical characteristics of a product but also physical properties and attributes, processes and activities involved in production (Table 2-1) (Taylor, 1997).

Table 2-1: Examples of features

Feature type	Examples
Geometric	Length, Weight, Depth, Perimeter, Volume, Area
Attribute	Tolerance, Finish, Density, Mass, Material, Composition
Physical	Hole, Pocket, Skin, Core, Cable, Wing
Process	Drill, Lay, Weld, Machine, Form
Assembly	Interconnect, Insert, Align, Engage, Attach
Activity	Design Engineering, Structural Analysis, Quality Assurance

Source: (Roy, 2003)

Brimson (1998) describes the basic steps required to implement feature-based costing. At the beginning, it is necessary to determine all features that can be used for production of a company's products. These features may have a hierarchical structure, which means that some complex features can be subdivided into more simple ones. Then, the cost engineers have to identify activities that are needed to make features. Once all activities have been identified, the cost of each activity must be determined, and average activity cost must be calculated. The next step consists of determination of characteristics that specify the product (number of doors in the car, color of the car) and association of the needed features to the product (including activities). Finally, total product cost is calculated by adding the product's feature costs determined in previous steps (Brimson, 1998).

There are several important benefits peculiar to the feature-based costing method making the concept appealing for cost engineers. The main advantage of the feature-based costing method is that it allows designers to see a clear correlation between the built-in features and the total cost of the product. In turn, this makes it possible to optimize design of

the product in order to achieve the target cost. Moreover, feature-based costing requires less of an amount of information to collect as different features can be described once and then be used in different products. In addition, this technique can be applied to completely new cases because it computes costs of features and consequently product cost from the simplest parts and activities. Finally, unlike activity-based costing that can be used only for cost estimation at the final stages of the new product development process when no changes in product design can be made, feature-based costing is mostly used at the design phase of the new product development process (Roy, 2003).

On the other hand, there are some drawbacks, which limit the use of this method for the purpose of cost estimation. There are some difficulties with the allocation of overhead cost to the product features (Schreve, Schuster, & Basson, 1999), which can result in decrease of accuracy of cost estimates. In addition, this technique cannot be used for very complex and/or very small features (Niazi et al., 2006).

2.1.4.6 Technical cost modeling

Technical cost modeling (TCM) is a bottom-up cost estimation approach that defines the main stages required for building detailed predictive cost models that relate product and process design parameters to the manufacturing costs through a hierarchical set of equations (J. Busch, 1994). In contrast to other bottom-up approaches, TCM is designed to capture case specific casual interactions between key variables and costs that are defined by existing theories or business practices. To simplify the model development, the TCM approach breaks down the process being modeled into series of processing units, where each unit consumes

different resources during production and contributes to the total manufacturing cost. It turn, the total cost of each unit is a sum of its cost elements which can be estimated using simpler algorithms based on science, engineering, accounting or expert judgment (J. Busch, 1994). This methodology was developed by the Material System Laboratory research group at MIT and was initially described by Busch (1987) in his PhD dissertation for the case of plastic fabrication.

There are four main steps required for successful development of cost models using the TCM approach (Bhatkal & Busch, 1998; J. Busch, 1994; Kirchain & Field, 2001; Kirchain, 2001). First, the modeled process must be defined in terms of major sequential steps. This is important as it defines the structure of the model and shows which activities are included into the scope of the analysis. In the next phase, a model logic for each step is developed that illustrates how input factors, including product, process parameters and economic conditions, relate to intermediate variables and final cost elements, including materials, direct labor, energy, equipment, tooling and other elements. In addition to the logic, this phase helps to define all information required to collect. The data collection step is the most critical and time consuming because it defines the final quality of the model and requires direct interaction with experts and industry. The data collected are further used for verification of the theoretical equations and the development of predictive relationships, if required. Finally, the cost model developed must be validated comparing its output values with known or expected values.

Models developed using TCM describe the relationship between input parameters and process costs in details without black boxes. Each sub-process is modeled separately, which

allows the setting up of operating conditions for each of them and analysis costs and influences of parameters within and across manufacturing steps. It also adds flexibility in the type and order of sub-processes thereby allowing the substitution of some steps with alternatives and reusing sub-models in different models. Due to the hierarchical equations, the model is easily extensible in terms of details; lower level equations can be added to the model if information that is more accurate is needed. Extensive and time-consuming development, debugging, data gathering and validation can be mentioned as disadvantages of this approach. (Fuchs, Bruce, Ram, & Kirchain, 2006; Fuchs, Field, Roth, & Kirchain, 2008).

The TCM approach was mainly applied to develop a set of cost models for automotive, plastic, metal and optoelectronic industries. No work has been done in application to textiles.

2.1.5 Comparative analysis of different cost estimation techniques

Table 2-2 and Table 2-3 outline when each of these techniques is the best to use throughout the new product development process. Table 2-4 summarizes the main cost estimation techniques, their advantages, and limitations. There is no technique that can produce the best product cost estimation results at all stages of the new product development process. It is important to keep in mind that case-based reasoning, neural networks, and parametric cost estimation techniques require less information about product and process specifications; therefore, they can be used at the first stages of the new product development process. On the other hand, these techniques produce less accurate estimates and consequently, when there is detailed information available, it is better to use such techniques

as activity-based costing and time-driven activity-based costing. Feature-based costing can be used at all stages, but only if there is a complete informational database about all product features. In addition, this method is not completely developed and has some limitation, which leads to the necessity of using this method together with other techniques to ensure the accuracy of the results. Technical cost modeling should be mainly used at product development phase to compare cost implication of different product designs and equipment selection.

Table 2-2: Cost estimating techniques and new product development phases

NPD Phases	**CBR**	**NN**	**PCE**	**ABC/ TDABC**	**FBC**	**TCM**
Opportunity Identification	+	+	+	-	+	-
Design	+	+	+	-	+	+
Testing	+	+	+	-	+	+
Introduction	-	-	-	+	+	-
Life Cycle Management	-	-	-	+	+	-

Nevertheless, bottom-up methods are time and resource consuming to implement. Therefore, there are some situations when it is better to use statistical and analogical methods at the last stages of the new product development process in order to be more time and resources efficient. If transparency is important for the cost estimator in order to optimize product design, parametric and neural networks methods cannot be used because of their "black-box" nature.

Table 2-3: Application of cost estimating techniques during new product development

Use CBR When…	**Use NN When…**	**Use PCE When…**	**Use ABC When…**	**Use FBC When…**
… you have enough cases from the past	… you have quite a few similar cases from the past	… you have quite a few similar cases from the past	… you know the exact number of work hours and material quantities required	… you know all features which can be used for production
… you can match new product with previous cases	… you are quite certain which attributes have cost effects	… you know precisely which attributes have cost effects	… you know precisely which attributes have cost effect	… you can describe your product in terms of product features
	… cost drivers are few	… cost drivers are few	… there are many cost drivers	… you know the cost of each feature and process
	… you do not know how drivers influenced cost	… you are quite certain how drivers influence cost	… you know exactly how drivers influence cost	

Table 2-4: Comparison of cost estimation techniques

		Key Advantages	Key Disadvantages
Analogical	**CBR**	- works in a transparent way - is applicable for long- term use - generates new estimates very quickly - is able to estimate costs despite the lack of some information	- dependence on past cases - requires well-developed sets of methods to form the knowledge base and adapt past solutions to new cases - is not applicable in highly innovative companies
Statistical	**NN**	- has the ability to identify a wide range of complex relationships between the input and output variables without defining the type of a cost function - the process of developing cost estimation easier and more efficient in terms of time and recourses	- "black box" nature - requires a great number of cases for training - is not applicable in highly innovative companies
	PCE	- produces fast and relatively accurate estimates - does not require significant financial resources and detailed information about product design and production specification - provides deeper understanding of cost drivers than NN	- requires significant amount of historical data - cannot be used for new products - long-term utilization of the model requires constant updating - quality of estimates depends on the chosen functional form of CER and cost drivers
Analytical	**ABC**	- provides the most accurate cost estimates - provides detailed cost structure	- involves much effort in data collection - highly dependent on subjective data - expensive and time consuming - difficult to update and maintain - complexity of the system increases exponentially with adding new activities - requires detailed product specification
	FBC	- provides very accurate cost estimates - shows clear correlation between built-in features and the cost of the product - requires less amount of information than ABC - can be applied to new products	- has some unsolved problems with the overheads cost allocation to product features - cannot be used for a very complex and small features
	TCM	- models for each sub-process - analysis costs and influences of parameters within and across manufacturing steps - flexibility - extensible in terms of details	- extensive and time-consuming development, debugging, data gathering and validation

2.1.6 Conclusions

This section describes and emphasizes the vital importance of cost estimation during the new product development process. The price of a product is one of the most important criteria of a products' success in the market; and cost is the main factor that determines price. Thus, companies have to continuously monitor product costs during the new product development process and compare them with the target market cost.

In addition, main quantitative cost estimation techniques and approaches, their benefits and limitations as well as their applicability to different stages of new product development stages were discussed. All identified techniques were summarized and compared in a way that allows cost engineers to select the most appropriate technique quickly and easy.

The literature review indicates a lack of studies in the cost estimation area concerned with the development of new textile and nonwoven products. This topic is of great importance to firms who operate in the highly competitive environment of the textile industry. Due to an abundance of competitors, constant innovation is needed for textile companies to survive but successful product development, launch, and support are nearly impossible without cost modeling, estimating, and control. Therefore, textile companies should implement the techniques and strategies described in this section. This review provides a basis for future research in the field of cost engineering for textile products, and as a theoretical background for textile companies in their attempts to build more effective cost management processes.

2.2 OVERVIEW OF THE SPUNBOND TECHNOLOGY

A nonwoven fabric is a textile structure manufactured from natural or man-made fibers or filaments, constructed by putting them together in the form of a sheet or web, and then bonding them either mechanically, thermally or chemically. This process is in the absence of weaving or knitting, and does not demand the spinning of fibers into yarn (INDA, 2012). A typical nonwoven manufacturing process consists of the following generic steps: raw material preparation, web formation, bonding, and finishing (Batra & Pourdeyhimi, 2012). Based on web formation techniques, nonwovens can be classified into three categories as dry-laid, wet-laid and polymer-laid (Wilson, 2007). Polymer-laid nonwovens are made directly from the polymeric melt or solution that is extruded through a spinneret into fine filaments. These filaments are subsequently laid on a moving collecting belt, and form a continuous web that is bonded to produce a fabric (INDA, 2012). The spunmelt web forming processes include spunbond, meltblown and flash spinning. This section will focus on spunbond technology.

In the spunbond process, a thermoplastic polymer is melted, extruded through the spinneret, quenched, drawn and laid down on the moving belt in a form of web composed of randomly dispersed continuous filaments. The web is subsequently bonded to provide fabric integrity using one or more bonding techniques including thermal, mechanical and chemical. Calendering is the most widely used bonding techniques for spunbond nonwovens in the market today (Zamfir, McCulloch, & Pourdeyhimi, 2003).

The machinery for spunbond nonwovens production is constantly improving and the world's spunbond capacity continues to grow steadily. Several companies offer production

lines for spunlaid nonwovens, including Reifenhäuser, Rieter, Neumag and Hills. With its closed spunbond system, called Reicofil, Reifenhäuser holds about 70% of the spunbond equipment market (Russell & Textile Institute (Manchester, 2007). Other equipment manufacturers supply open systems (Wilkie & Shuler, 2007).

The main characteristics of spunbond nonwovens are near random structure, high opacity, high strength-to-weight ratio, high liquid retention capacity, air permeability, wear properties, softness and comfort (Rupp, 2008; Russell & Textile Institute (Manchester, 2007). The basis weight of spunbonded products can vary from 5 to 1000 grams per square meter (Zamfir et al., 2003) and width ranges from 2.1 to 7 meters (Textile World, 2007). The biggest markets for spunbond nonwovens are automotive, civil engineering, hygiene, medical and packaging (Russell & Textile Institute (Manchester, 2007).

2.2.1 Spunbond process description

In general, spunbond technology combines the filament extrusion and drawing operation with web formation and bonding operations in a single step process (Malkan, 1995). Figure 2-12 shows the main process stages with the corresponding equipment required to manufacture the spunbond nonwovens. The process starts with conveying the polymer feedstock, in a granular or pellet form, out of storage silos to the dosing station on top of the extruder where it is mixed with pigments, resin modifiers or other additives. This blend of raw materials is melted and homogenized inside the extruder and then pumped through a resin filter system and a metering pump to provide a stable flow of pure melt for the feed distribution section and spinneret (Cheng, 1994).

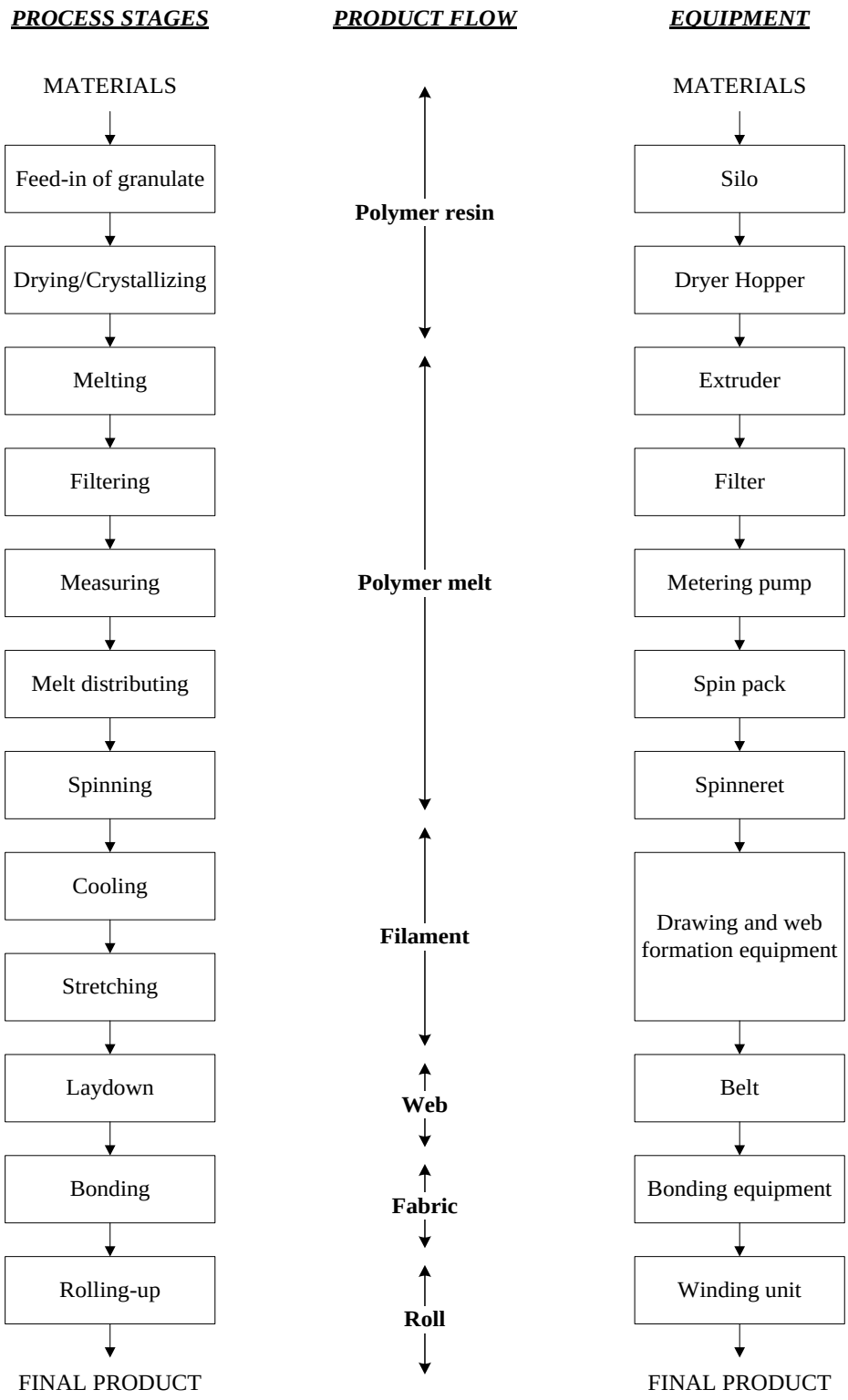


Figure 2-12: Spunbond process stages and the equipment required

The polymer melt is forced through small orifices in the spinneret plate to form a curtain of continuous filaments. The filaments then travel downward into a quench chamber, where they are cooled and solidified by means of a stream of cool air to withstand the subsequent attenuation force. A second stream of high velocity air causes acceleration and stretching of the fibers. Stretching is a critical process step as it leads to both increase in molecular orientation thereby strengthening the filaments and reduction of the fibers diameter. Filaments are then deposited on a moving perforated belt as a random nonwoven web (Geus & Sommer, 2007; Malkan, 1995).

An air suction device beneath the belt assists in fiber filament drawing, web formation and removes the air used for filament cooling and stretching. The belt conveys the web to the bonding station to impart strength and integrity to the web. Then, the bonded fabric is trimmed to eliminate non-uniform, rough edges. It may also be split into smaller widths to provide finished rolls of specific dimensions. The fabric is then wound, wrapped and shipped to the customer.

2.2.2 Major components of a spunbond nonwoven production line

Figure 2-13 shows the layout of the spunbond equipment. Typically, a spunbond line consists of the following subsystems: a material handling system, extrusion system, spinning beam assembly, filament cooling, drawing and dispensing system, web forming table, web bonding system, winding and slitting system. The top section consists of the extrusion system and spin beam assembly. The fiber cooling and drawing system is located in the middle

section. The bottom section consists of the web formation, bonding, winding and slitting systems.

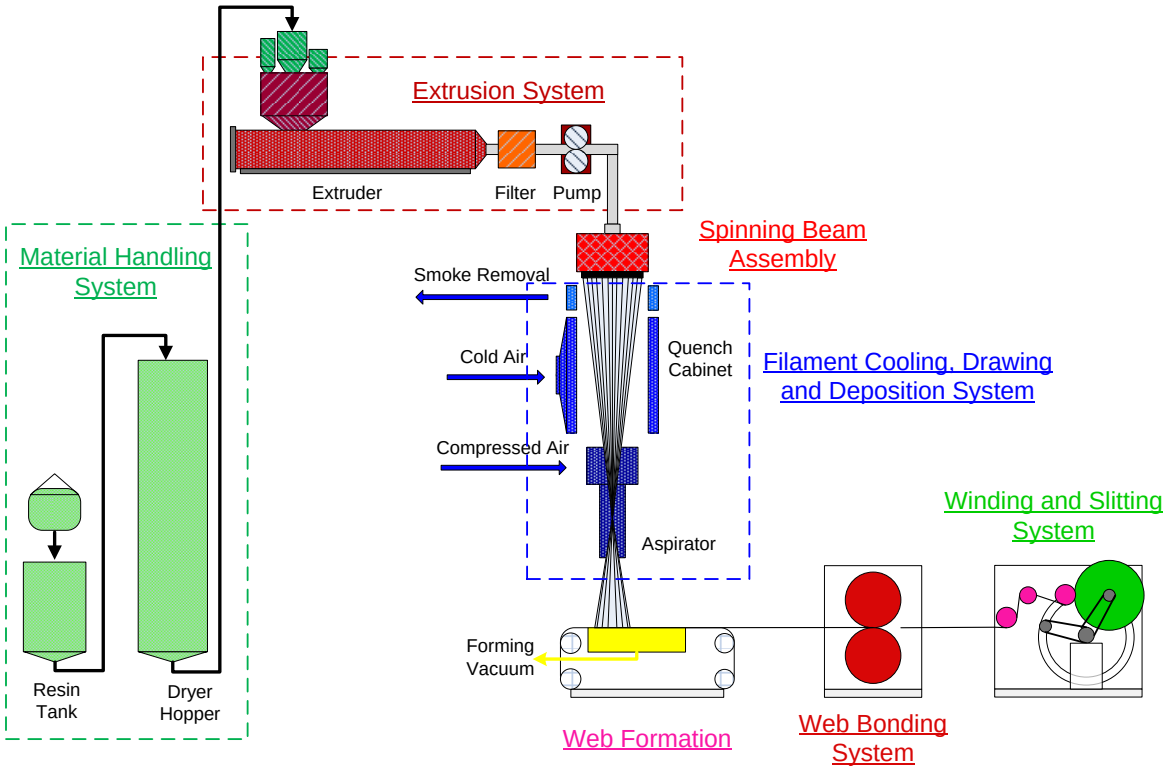


Figure 2-13: Spunbond process flow sheet and components

Material handling system

A fully automated material handling system is an essential component of any spunbond production line. It is mainly used to provide the extrusion system with dry polymer pellets and must have the ability to add color pigments and additives, as well as mix the materials in proper amounts (Harmon, 1992). The raw material handling system typically includes storage silos, a material transfer system, a polymer dryer and dosing station. In

spunbond processes, the pump and equipment size of the material handling system depend on the maximum throughput capabilities of the fiber forming section of the spunbond line.

The material transfer system must provide a continuous, highly coordinated material flow between successive stages in a manufacturing process. It is responsible for the transport of bulk polymer materials, in pellet or granular, from trucks or railcars to large storage silos usually located outside the plant, and finally to the processing equipment, i.e., dryer/blender/extruder hoppers. The handling, movement or conveying of plastic resin is typically performed mechanically or pneumatically, and is automatically controlled by an industrial computer to minimize transfer delays, waiting and intermediate storage.

In some cases, drying equipment should be installed to handle hydroscopic/condensation polymers such as polyester (PET), Nylon (PA), Poly Lactic Acid (PLA), etc. Resin drying assures the lowest moisture levels in the material, thereby improving quality and reducing process problems and instability. Moreover, crystallizing equipment is required for systems that process polyester (PET) resins.

A dosing station, mounted on the top of the hopper of the extruder, is responsible for metering, mixing and delivering of raw materials such as polymer granules or pellets, masterbatch, pigments and/or additives to the extruder feed hopper. It must assure that the correct materials and proportions make it into the final product.

Extrusion system

In the spunbond process, the polymer extrusion system, comprised of extruders, filters and metering pumps is responsible for polymer melting, filtering, homogenizing and

pressurizing (Cheng, 1994). The quality of the polymer melt is of great importance. Inadequate quality of the polymer melt affects the subsequent fiber spinning operation and results in a considerable reduction of the machine efficiency, increase of machine downtime that in turn leads to decrease the production throughput, and poor quality of the final product. Therefore, all components of the extrusion system must be designed, built and combined such that the molten polymer is delivered to the spinning beam assembly with minimum degradation, while maintaining maximum purity and homogeneity.

The main purpose of the extruder is to convert materials from pellet or granular form into a liquid like material that is consequently used for fiber formation. Figure 2-14 shows the single screw extruder typically used in a spunbond process. From the dosing station, the polymer/additive mix is delivered to a feed screw that is rotating in a heated barrel. The material is conveyed along the barrel through the turning of the screw. As the material moves along the barrel, it melts due to the heat and friction between the melt/granulate and the screw/barrel (Turbak, 1993).

The size and screw speed determine the output rate capabilities of the extruder. In most cases, dimensioning the extruder size for the spunbond process depends on the fiber formation capabilities and the working width of the spunbonding machine. A high length to diameter (L/D) extruder is recommended, since it increases the polymer residence time for melting and mixing, allowing the melt temperature to achieve its equilibrium (Cheng, 1994).

The single screw extruder is the most common type used in the spunbond process. However, twin-screw extruder can also be utilized increasing the versatility of the spunbond machine and providing ability to process different polymers. In this case, the polymers would

not have to be dried and/or crystallized. Usually, twin-screw extruders are more complex in design and more expensive to acquire than single-screw extruders. Their operating and maintenance costs are also higher. Therefore, twin-screw extruders are less typical for spunbond process.

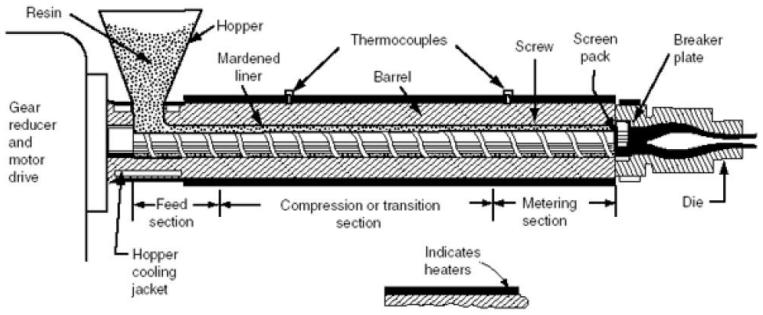


Figure 2-14: Single screw extruder

Source: (Turbak, 1993)

The throughput and quality of the polymer melt is highly influenced by the design and geometry characteristics of the screw/barrel unit. Usually, the barrel is divided into several cooling and heating zones, therefore all extruder are equipped with barrel heating and cooling systems. Electric heater bands or thermocouples are used for heating. Air or water can be used for cooling, although water cooling system provides superior temperature control and rapid cooling during the line shutdown.

The extruder screw is also spit up into several sections. The basic screw design includes feed, transition and metering sections. More advanced screws may also include barrier zones and/or special mixers. The screw channel depth, from the feed to metering sections, gets progressively shallower to squeeze and pressurize the melt. The purpose of the

feed section is to feed the polymer mix into the extruder, preheat and premelt a portion of the polymer, so that it can be melted, compressed and homogenized at the transition section. The metering section is responsible for generating pressure and the complete melting of the polymer before it reaches the end of the screw. Special mixing sections may be included to aid in mixing and homogenizing the additives, pigments, and recycled materials with pure polymer. Barrier zones serve to separate the polymer melt from unmelted pellets, as these can cause problems with subsequent fiber formation process and with the quality of final product.

Plastic pellets or granules undergo a series of handling steps before being introduced into a polymer extrusion system. These include unloading and silo storage, pneumatic conveying, drying and/or crystallization, blending and feeding. As a result of this handling, the granules often become contaminated with various unwanted particles and debris including dust, sand, dirt, rust, metal chips, bolts, nails, other types of polymer chips, etc. Moreover, the polymer melt can also become contaminated with undispersed pigments or additives, gels, unmelted pellets and carbonized material from the screw and barrel, while in the extrusion system.

The presence of these contaminants in the polymer melt can lead to equipment damage, frequent spinneret blockage, fiber breakage, defects in the web and final product such as thin spots, irregularities in web structure and much more. To overcome these problems and deliver the purest polymer melt to the spinning beam assembly, nonwovens producers utilize two filtration devises in the extrusion system. The first one, the metal trapping device, is mounted between the hopper and extruder throat. In the simplest form, it

represents a set of magnets that trap and remove pieces of metal from the incoming resin and which could damage the extrusion system.

The second filtration device is located at the end of the extruder, before the metering pump. The main purpose of this device is to remove undesired contaminates and impurities from the polymer melt. The most common way to filter the polymer melt is through a screen-changing filtering system (screen pack). Usually, a screen pack is made from a set of wire screens, having a cascade configuration and increasing in mesh, and a breaker plate that supports the screens. The screen pack can be changed continuously or discontinuously. Continuously working screen exchangers do not interrupt the polymer flow, while discontinuous screen exchanges require complete stopping the polymer flow. Screen packs that can be easily removed and replaced with minimal polymer flow interruption and costs are best.

After being filtered, the molten polymer continues into a metering pump, also known as a gear or spin pump. The main purpose of the pump is to maintain consistent pressure, and to ensure a continuous and uniform polymer flow to the spinning block under variations in viscosity, temperature and pressure. A constant polymer flow rate is critically important to maintain a uniform basis weight of the final product. The number of pumps in the spunbond system depends on type and width of the spunbond machine.

Generally, the metering pump consists of two intermeshing toothed wheels that are rotating in opposite directions (see Figure 2-15). The polymer melt enters the pump and fills the spaces between the teeth and then rotating gears empty the polymer at the discharge side. A feedback control loop is often used to regulate the inlet pleasure to the melt pump. It

directs the speed of the extruder screw to maintain a specific pressure. The pump outlet pressure must always be lower than the maximum rated pressure of the spinneret.

Spinning beam assembly

The spinning beam assembly, also known as the spinning block, is one of the most important components of the spunbond process. It is connected to the discharge side of the metering pump and extends across the machine defining the width of the fabric to be made. The spin block body and spin pack are the major components of the spinning beam assembly (James, April 2000).

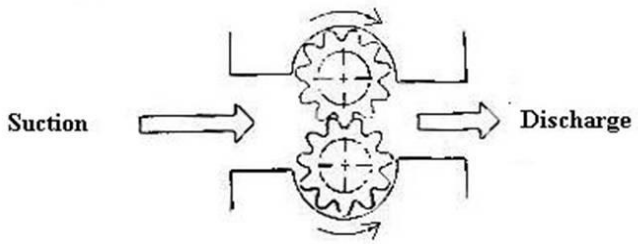


Figure 2-15: Schematic of a metering pump
Source: (Turbak, 1993)

The main function of the spinning block body is to hold and heat the spin pack. It must support the spinpack, providing easy access for operators to perform spinpack changes. Since temperature differences produce variations in the viscosity of the melt (Sievering & Waltermann, April 1997), the spin block usually has a cavity filled with a circulated fluid to provide uniform heating to the spinpack. The fluid can be heated using internal electric immersion heaters or by external heaters (James, April 2000).

The spinning pack is designed to receive the polymer melt from a pump, filter it, and distribute it at controlled pressure to the spinneret. A typical spin pack consists of the following components (James, 1997; Sharp, 2011): a pack top plate, a distribution plate, a screen pack, a spinneret plate.

A pack top plate has an inlet port that receives the flow of molten polymer form the pump block. A distribution plate, often referred to as a breaker plate or screen support plate, is located beneath the top plate. It has two main functions: the first is to accept flowing polymer and distribute it uniformly along the width of the pack; the second is to hold the screen pack. A screen pack is used to filter hot polymer in order to prevent the obstruction of the holes in the spinneret. A typical screen pack is assembled from a series of screens, one laying on top of another and decreasing in mesh. A spinneret plate is a single block of metal having several thousands of capillaries for spinning polymer into filaments. A typical capillary has a diameter of a hole ranging from 0.25 to 0.65 mm and a length to diameter ratio from 1:2 to 1:4 (L/D). The cross-sections of the capillaries are commonly circular, however trilobal, hollow, dogbone and others sometimes also used. The capillary density and layout vary with the process. Seals and gaskets are placed between the spin pack components in order to prevent bypassing and leaking in the pack.

Web bonding

Spun webs can be bonded by thermal, chemical, and mechanical means. The final fabric application, the web basis weight, and limitations of the processes dictate the choice of bonding methods. Thermal and chemical techniques rely on fiber-to-fiber attachment to bond

the web. Mechanical bonding includes needlepunching and hydroentangling techniques both of which utilize fiber entanglement and fiber-to-fiber friction to impart strength to the web. Sometimes, the spunbond web may be bonded using a combination of several bonding techniques.

Chemical bonding is the least frequently used method for the construction of spunlaid webs. During this process, the web is sprayed or saturated with a latex or polymer solution and then thermally cured. Such fabrics are used as roofing materials (Smorada, 2002). Spunbond polyamide webs are chemically bonded by gaseous hydrogen chloride that initiates formation of hydrogen bonds on fiber-fiber crossovers. This process is solely used by Cerex Advanced Fabrics, Inc. to produce fabrics for apparel and bedding backings, carpet underpad reinforcements and automotive applications (Cerex Advanced Fabrics, 2008).

In the needle-punching process, the spunlaid web is entangled by barbed needles that rapidly penetrate the moving web. In comparison to the aforementioned techniques, this method is the simplest and the least expensive, but operates at low speed. Since no chemicals are involved, it is an environmentally friendly bonding technology. This is the only method that can be used for processing heavyweight nonwovens (800 gsm and more), but is unsuitable for webs with a basis weight of 100 gsm or lower (G. S. Bhat & Malkan, 2002). Needle design, punch density, and depth of punch are the variables that influence the fabric properties. Mechanically needled spunbonds are bulky and can be easily deformed, thus they are often used for geotextile, roofing and coating substrates applications (Watzl, 2005).

In the hydroentangling process, the web is entangled by means of fine, high-pressure water jets. In the past, it was not economically feasible to combine spunbonding and

spunlacing technologies, due to differences in production speed. Now, after major advancements in the hydroentangling process, this combination is becoming more popular. It may even be considered the future of spunbond nonwovens, as it allows the manufacturing of fabrics with higher strength, better hand, softness, and drape, in comparison to other bonding techniques (Watzl, 2005). Hydroentangling allows entangling webs with basis weights ranging from 10 to 600 gsm. The number of hydro entanglement beams, water pressure, forming wire texture, and hole density are the main operating variables of the process. Splitting of the spunlaid bicomponent fibers with hydroentangling allows the creation of strong, durable micro-denier fabrics. An example of such commercially available fabrics is Evolon® (by Freudenberg), which is produced with 16 segmented pie filaments, composed of polyester and nylon. The potential markets for hydroentangled spunbonds are high-tech wiping, technical packaging, clothing, bedding, printing media, etc.

During the thermal bonding, fibers in a web are partially melted and fused together on fiber-fiber crossovers, and form bonds after cooling. This can be accomplished using hot air, infrared light, ultra sound, or hot rolls. The latter is the most commonly used approach for spunbond nonwovens. Flat or embossed rolls can be used during calendering, which creates area or point bonded fabrics, respectively. If the web is highly bonded, as in the case of area bonding, the resulting fabric has a stiff, paper-like structure with higher tensile strength and modulus, but lower tear resistance compared to point bonded webs. While passing between rolls, the web proceeds through three stages: compressing and heating the web, bonding the web and cooling the bonded web (Michielsen, Pourdeyhimi, & Desai, 2006). This technique is mostly used to bond light to medium-weight webs (preferable up to 80 gsm). Today,

calendered spunbond nonwovens mostly dominate the hygiene and healthcare markets; however, there is a great variety of other applications found on the market.

The main calender bonding processing parameters are roller temperature and diameter, nip pressure, and the production speed which determines the web residence time (contact time) in the nip of the calender (Pourmohammadi, 2007). These parameters are interrelated and must be carefully defined such that right amount of heat is transferred to the web, thus avoiding under or over bonding. Strong thermally bonded fabric is formed when the temperature in the middle of the web reaches the appropriate bonding temperature. Increasing production speed leads to a decrease in the time that the web spends in the nip, thus resulting in a lower temperature mid-plane. This can be counteracted by increasing the roll temperature. However, the roll temperature cannot be higher than the melting point of the polymer used, and therefore limits the speed at which the fabric can be bonded (Michielsen et al., 2006).

Winding and slitting

Following web bonding, winding and slitting is the final phase of the spunbond process. Here, the fabric is trimmed from both sides to eliminate rough, non-uniform edges, and prevent interweaving. It is then slit and wound into rolls of width and diameter required by customers (Nordson Fiber Systems). Edge trimming generates some amount of scrap, and reduces the actual yield of the spunbond process.

These operations can be performed in one-step or two-step processing. Accordingly, there are two types of winding-slitting equipment: on-line slitter-winders and on-line

winders/off-line slitter-rewinders. The system with on-line slitting was widely used in the past, but off-line slitting is now preferred (Celli, 1996), due to: better control over final reels quality; higher flexibility and lower downtime (no need to the stop spunbond line to change the dimensions of final rolls or when the slitting equipment breaks); better chance to eliminate defects coming from production line, which results in a lower volume of waste. After this final step, the formed rolls are packaged and shipped to customers.

2.2.3 Key process variables

At the first glance, it seems that the spunbond process is quite simple; however the large number of operating variables involved, and interactions between them, make the process very complex. There are two categories of process variables associated with spunbond process: operational, or machine variables (see Table 2-5), and material variables (see Table 2-6) (G. Bhat & Malkan, 2007).

Table 2-5: Key operational variables for spunbond process

On-line variables	**Off-line variables**
Polymer throughput rate	
Polymer melt temperature	
Quench air rate	Spinneret hole size/shape
Quench air temperature	Spinneret-to-collector distance
Filament draw speed	Bonding system
Collection speed	
Bonding conditions	

Source: (G. Bhat & Malkan, 2007)

Table 2-6: Material variables for spunbond process

Materials variables	
Polymer type	Melt viscosity
Molecular weight	Polymer additives
Molecular-weight distribution	Polymer degradation
Melt flow rate and index	Polymer form

Source: (G. Bhat & Malkan, 2007)

By manipulating these variables, a wide range of spunbonded products can be designed. The quality and cost of these products relies heavily on the appropriate selection of these parameters.

2.2.4 Materials

The intrinsic properties of the spunbonded fabric, for instance, fiber density, temperature resistance, chemical and light stability, surface energies and ease of coloration, are determined by the polymer and additives used (G. S. Bhat & Malkan, 2002). Therefore, the choice of material is closely connected with the desired end-use properties to be met by the final product.

Most commercial spunbonded structures are produced using isotactic polypropylene (~79% of the total world output) and polyester (15 % of the total world output) (INDA, 2008). Small quantities are made from nylon, and increasing amounts from high-density polyethylene. Representative characteristics of these polymers are presented in Table 2-7.

Table 2-7: Common polymers used in spunbond process

Polymer	**Some important characteristics**
Polypropylene (PP)	- Relatively good strength, hand - Easy processing, the highest yield and covering power - Lower melting point (~160°C) - Cost effective - Scrap may be repelletized - Difficult to dye after processing - Used in most disposable applications and several durable products
Polyester (PET)	- Good physical properties (tensile, modulus, heat stability), UV resistant - Moderate ease of processing - Higher melting point (~255°C) - Requires surface crystallization and pellet drying prior to melt spinning - Scrap is not readily recycled - Easily dyed and printed - Used in long-life durable products and high temperature applications
Polyethylene (PE)	- Very soft hand - Poor physical properties when used alone in meltspun filaments - Low melt temperature (115°C) - High cost - Mainly used in bicomponent fibers
Nylon 6 & 6,6 (PA)	- Excellent physical properties, wear resistance, strength and dyeability, good thermal resistance, absorb water - Not easy to work with - High melt temperature (260°C) - Requires crystallization or drying prior to melt spinning - Highly energy-intensive, high resin cost - Limited use

Today, the nonwovens industry is demanding unique polymers that may bring new properties to spunbond nonwovens. New polymers, including renewable polymers, removable polymers for bico-separation, elastic polymers are being introduced. The processing of these polymers is still at the development stage. Examples of emerging new polymers for special end-uses are given in Table 2-8.

Table 2-8: New polymers used in spunbond process

Polymer	**Some important characteristics**
Poly Lactic Acid (PLA)	- Biodegradable - Difficulties to process and cost are currently limiting growth - Melt temperature 130-175°C - Spun at high velocities (>3500 m/min) - Requires drying - Very limited use but growing / PET like products
Poly (trimethlene terephthalate) (PTT)	- High stretch, elastic recovery, soft hand, and bulk - Extrusion is relatively simple - Melt temperature 228 °C - Requires drying - Easily dyed and printed - Offer many of the best qualities of nylon and polyester in many carpet and textile fiber applications
Poly (butylene terephthalate) (PBT)	- Similar in both composition and properties to PET - It has lower strength and stiffness than PET but is a little softer - Melt-spinning conditions similar to those of polypropylene - Requires drying - Lower melting point (227°C) than in PET - Potential applications include specialty hygienic products, medical and industrial nonwoven fabrics
Polyurethane (TPU)	- Good stretch, recovery and fit - Requires drying - Apparel and other products that need stretch

In some cases, resin additives may be added to spunbond prior to extrusion to impart specialized characteristics, or to overcome shortcomings of a particular resin. Additives allow for the production of spunbonded fabrics with specific characteristics including hydrophilic, UV resistant, flame retardant, antistatic, antibacterial, and other properties. Colorants may also be added prior to the extrusion process, so they are permanently locked in the filaments, giving the color exceptional stability.

2.2.5 Bicomponent spunbond technology

By definition, a bicomponent fiber consists of two polymers, with different chemical or physical properties, extruded from the same spinneret hole. This imparts the properties of both polymers upon the fiber, and increases the number of possible fiber performance characteristics. Utilizing a bicomponent fiber technology to produce spunbond nonwovens offers the ability to engineer fabrics with improved properties and functionalities.

The bicomponent spunbond equipment is technologically similar to the homocomponent equipment. The main difference is that the bicomponent spunbond machine includes two extrusion systems (see Figure 2-16). Each one is responsible for melting, filtering, homogenizing, and pressurizing one of two polymers. The spinning beam assembly is connected to the discharge end of each extrusion system.

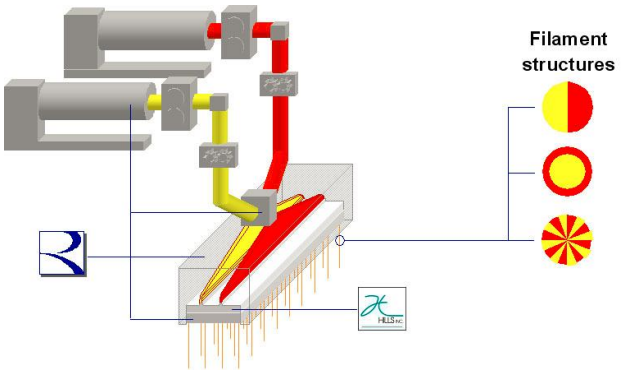


Figure 2-16: Reicofil-Hills bicomponents system
(REICOFIL, 2011)

To form the required fiber cross-section, the spin pack is also modified by adding distribution plates to convey flows of two polymers appropriately. By replacing spin packs, it

is possible to produce spunbond nonwovens of various bicomponent fiber configurations using the same spunbond equipment. Hills, Inc. is the world leader in bicomponent spunbond technology and offers its own complete bicomponent spunbond systems, cooperates with other spunbond equipment manufacturers (Reicofil) and designs bicomponent spin packs by request (Shuler & Hagewood, 2009).

Currently, the total output of bicomponent spunbond nonwovens is relatively low. US, Europe and Japan are the major production areas. As reported by IntertechPira, a demand growth rate of 17.7% is expected for 2010-2015, with usage estimated at 186,000 tons by 2015 (IntertechPira, 2010). The exponentially growing demand for bicomponent spunbond nonwovens will make this technology one of the world's most prominent technologies in the near future.

3 PRODUCTION COST MODEL FOR THE SPUNBONDING PROCESS

This chapter presents a production cost model for the spunbonding process. The model considers material preparation, spunlaying, thermal calendering, and winding production steps with the greater emphasis on the spunlaying itself as the most expensive and complicated step. In the first part of the chapter the detailed discussion of the scope of modeling assumptions, parameters definitions, and comprehensive analytical formulation of the model is given. In the next section, the cost calculation tool developed in MS Excel is discussed. In the third section, several analytical studies are conducted to illustrate some of the possible model applications as well as to explain the relationships between model parameters and output results. Finally, the summary of the work accomplished, model limitations, and further steps for model improvement are given in the last section of the chapter. The work conducted in this chapter is a basis for a generic framework for cost modeling, estimation, and analysis of nonwoven products that is presented in the Chapter 4 of this dissertation.

3.1 BASIC PRINCIPLE AND STRUCTURE OF THE COST MODEL

This section is devoted to theoretical development of the cost model. This includes the cost model scope and assumptions made, and detailed discussion of relationships between input parameters and outcomes of the model. Model equations were developed based on published literature and discussions with industry experts, and were validated by comparing cost modeling results with cost estimates obtained from industry.

3.1.1 Cost model scope and assumptions

The model discussed in this chapter is focused on the cost estimation of spunbond nonwovens. In general, the total product cost is composed of expenses incurred at a company, plant, line, and machine levels. These cost components can be related to manufacturing and non-manufacturing activities. Non-manufacturing costs is general expenses required to carry out business functions (Turton, Bailie, Whiting, & Shaeiwitz, 2008). This includes costs associated with administration, marketing, financing, research, and development. Manufacturing costs include production costs as well as distribution costs (Humphreys, 2005). The cost model in this dissertation is designed to relate product and equipment design parameters with production costs. Therefore, the level of cost model and analysis is limited to the production line related costs, as well as to the cost contribution of major production steps involved in the spunbonding process. The model does not account for any plant and company specific overheads or distribution costs that add to the total product cost but do not depend on product specification. As a result, production costs obtained from the model is lower compared to the actual cost, but they are representative enough to support decision making regarding selection of product design parameters, equipment specification, capital investment etc.

More specifically, only core production steps, namely spunlaid web formation, thermal calendering and winding, were selected for analysis. In addition to the core steps, the model includes the drying equipment that may be needed before spunlaying in some cases (i.e., for hydroscopic/condensation polymers such as PET and PA) to improve quality and reduce process problems and instability. The final product assumed in the model is a master

roll of nonwoven fabric with trimmed edges. Therefore, further processing steps, like fabric finishing, slitting, and packaging, are not considered.

Modern spunbond production lines are quite flexible and capable of running most polymers. By installing different spin packs, it is possible to produce a variety of webs made of fibers of different shapes and composition. However, the high cost of downtime and material waste encourage producers to focus on a chosen polymer and product. As a result, an assumption was made that the production line for spunbond nonwovens is dedicated to the one specific product.

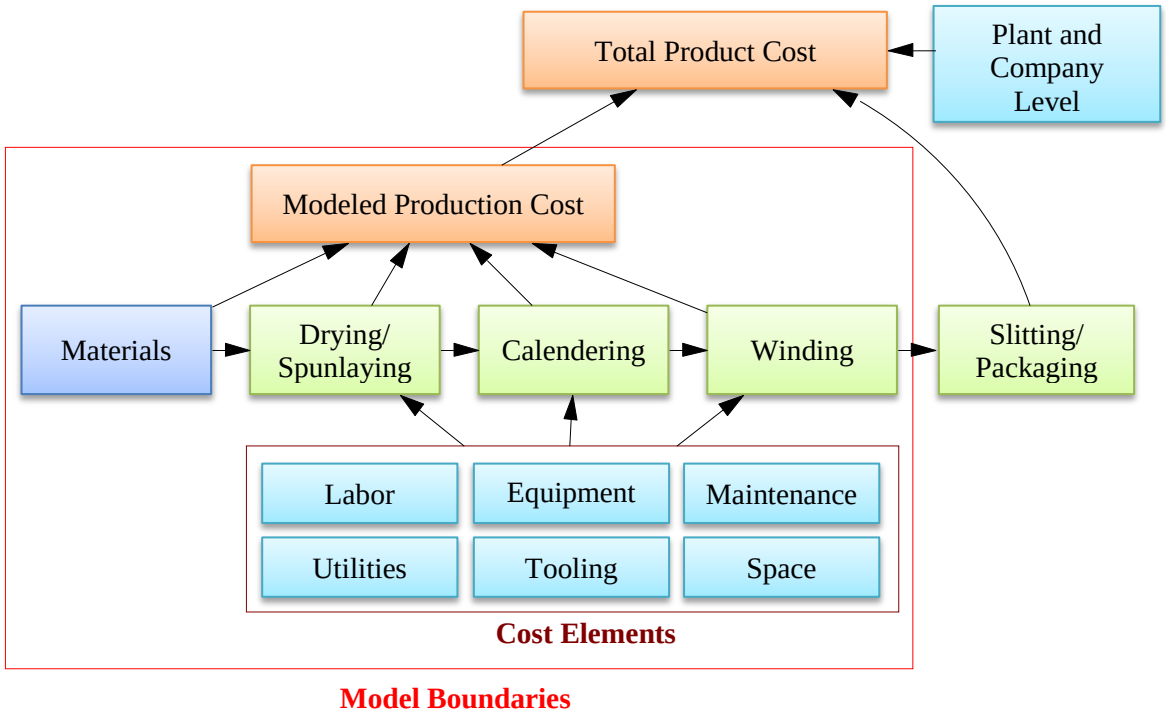


Figure 3-1: Schematics of the cost model scope

In addition to the raw materials cost, six main cost elements were identified. This includes equipment, tooling, space, labor, utilities, and maintenance. The annual net output of the spunbond line is a weight of fabric produced after edge trimming. Cost normalized by the weight of the fabric produced will be used as an output of the cost model developed in this dissertation. The graphical representation of model scope can be seen on Figure 3-1.

3.1.2 Cost model formulation

The following is a definition and detailed theoretical formulation of all components of the cost model and relationships between them. The discussion starts with the formulation of top-level equations and then each term of these equations will be discussed in details.

3.1.2.1 Top-level model equations

Following the model scope defined, Equations (1)-(3) show the top-level relationships between final product cost, cost of raw materials and spunbond processing steps, as well as contribution of each cost element:

$$C_F = C_{RM} + \sum_p C_p \,, \forall p \in P \tag{1}$$

$$C_p = \sum_e C_{e,p} \,, \forall p \in P \; and \; \forall e \in E \tag{2}$$

$$C_{e,p} = \frac{AC_{e,p}}{AQ_{Line}^{Net}} \,, \forall p \in P \; and \; \forall e \in E \tag{3}$$

where p denotes the process step index, $p \in P$ = {Drying (DR), Spunlaying (SL), Thermal Calendering (TC), and Winding (W)}, e denotes cost element, $e \in E$ = {Labor (L), Utilities

(U), Maintenance (M), Equipment (E), Tooling (T), Space (S)}, C_F represents the cost of calendered spunlaid fabric in dollars per kilogram, C_{RM} is the cost of raw materials per kilogram of spunbond fabric, C_p is the total unit cost of the processing step p in in dollars per kilogram, $C_{e,p}$ is the unit cost of resource e for process step p in dollars per kilogram, $AC_{e,p}$ is the annual cost of resource e for process step p in dollars per year, AQ_{Line}^{Net} is the annual net output of the spunbonding line in kilograms per year.

3.1.2.2 Production parameters

As can be seen from top-level Equation (3), annual cost for each cost element of each processing step is normalized by the net annual production of the line to obtain costs in per unit basis. Annual net production is limited by the line capacity, which depends on plant operating conditions, equipment specifications, and product parameters. In addition, annual production, product material composition, line yield, and material losses determine annual usage of raw materials and as a result cost of raw materials per unit of product. The relationships between input parameters and resulting annual production and material usage are discussed below.

3.1.2.2.1 Production rates

In the spunbonding process, all core operational modules (i.e., polymer drying, spunlaying, calendering, and winding) are coupled into a continuous process. As a result, production rates and linear production speeds of all modules involved are synchronized. The

spunlaid module is the rate-setting step[2] and its rate strictly depends on the desired properties of a final product. Figure 3-2 shows the interaction between the main processing steps of the spunbonding process.

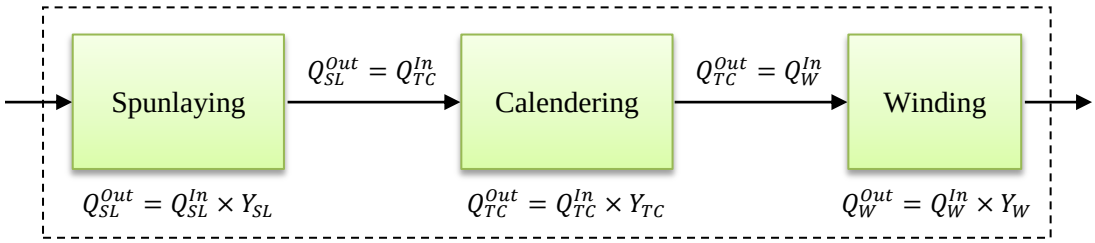


Figure 3-2: Coupling of the spunlaying, calendering and winding processes

The output rate of a spunlaid machine (Q_{SL}^{Out} in [kg/h]) is a function of the machine's specific throughput ($\dot{Q}_{SL}$ in [kg/h/m/beam]), the number of spinning beams (N_B) and the working width (W in [m]) and is calculated as:

$$Q_{SL}^{Out} = \dot{Q}_{SL} \times N_B \times W \tag{4}$$

From Equation (4) it is evident that a machine's specific throughput, working width and the number of spinning beams can be selected to achieve the desired production rate. However, the number of spinning beams influences the product properties and it is usually predefined during the product development. As a rule of thumb, multiple spinning beams are preferred for lightweight webs (basis weight < 60 g/m^2) to improve uniformity, and heavier webs are usually produced with a single beam (Pourdeyhimi, 2012). The specific throughput ($\dot{Q}_{SL}$ in

[2] "*The output rate of the spunlaid process is determined by the fiber formation capability of the system, such as cooling, line speed and fiber drawing capabilities*" (Cheng, 1994)

[kg/h/m/beam]) is also limited by the product and machine design parameters and is calculated as (Kittelmann & Blechschmidt, 2003):

$$\dot{Q}_{SL} = \dot{q} \times N_H \times 0.06 \tag{5}$$

where $\dot{q}$ is the polymer mass flow rate in g/hole/min, N_H is the number of holes per meter of spinning width of a beam, and 0.06 is a conversion coefficient from g/min to kg/h. The polymer flow rate depends on the polymer type and the required filaments linear density that are usually defined by the product specification. The flow rate ($\dot{q}$ in [g/hole/min]) and linear density (d_F in [denier]) are related through the filament take-up velocity (V_F in [m/min]) as shown in Equation (6) (Lu & Moller, 1997).

$$\dot{q} = \frac{V_F \times d_F}{9000} \tag{6}$$

Therefore, only the working width, which is also the gross width of the fabric produced, may be changed to increase the capacity of a spunlaid machine without any changes to the product properties.

The output production rate (Q_{TC}^{Out} in [kg/h]) of a thermal calendering machine is equal to the input rate (Q_{TC}^{In} in [kg/h]) adjusted for a calendering process yield (Y_{TC} in [%]) as shown in Equation (7). In turn, the input rate of a thermal calendering machine (Q_{TC}^{In} in [kg/h]), as a separate production unit, is a function of its linear production speed (V_{TC} in [m/min]), width (W in [m]) and basis weight (b_w in [g/m^2]) of a fabric to be bonded and is calculated using Equation (8).

$$Q_{TC}^{Out} = Q_{TC}^{In} \times Y_{TC} \tag{7}$$

$$Q_{TC}^{In} = V_{TC} \times W \times b_w \times 0.06 \tag{8}$$

When a calender is coupled with a spunlaid machine, their linear production speeds are equal:

$$V_{TC} = V_{SL} = \frac{Q_{SL}^{Out}}{W \times b_w \times 0.06} \tag{9}$$

$$Q_{TC}^{In} = \frac{Q_{SL}^{Out}}{W \times b_w \times 0.06} \times W \times b_w \times 0.06 = Q_{SL}^{Out} \tag{10}$$

However, the quality of calendering depends on the time that the web spends in the nip and the temperature of a bonding roll (Michielsen et al., 2006). An increase in the linear speed reduces time that the web spends in the nip and requires an increase in the roll temperature. Since the roll temperature cannot be higher than the melting temperature of polymers in fibers, the linear speed of the web that passes through the calender is limited. Therefore, this limitation should be checked for each specific case when spunlaying machine is coupled with thermal calender based on the equations described in the reference cited above.

The output rate (Q_W^{Out} in [kg/h]) of a winder, which is also the net production rate of the spunbonding line (Q_{Line}^{Net} in [kg/h]) under consideration, is equal to the input rate (Q_W^{In} in [kg/h]) adjusted for a winding process yield (Y_W in [%]):

$$Q_W^{Out} = Q_W^{In} \times Y_W = Q_{Line}^{Net} \tag{11}$$

When coupled with a calender, the linear production speed (V_W) of the winding unit is defined by calendering machine and is equal to the linear production speed (V_{Line}) of the spunbonding line:

$$V_W = V_{TC} = V_{Line} \tag{12}$$

$$Q_W^{In} = Q_{TC}^{Out} \tag{13}$$

Since modern winders can be run at a speed significantly higher than the speed of spunlaid process, this step does not set any limitation on the production rate.

Based on the above discussion, the net production rate of the spunbonding line (Q_{Line}^{Net}) is equal to the output rate of a spunlaid machine multiplied by yields of the calendering and winding units as shown in Equations (14) and (15).

$$Q_{Line}^{Net} = Q_{SL}^{Out} \times Y_{TC} \times Y_W \tag{14}$$

$$Q_{Line}^{Net} = ([\dot{q} \times N_H \times 0.06] \times N_B \times W) \times Y_{TC} \times Y_W \tag{15}$$

If a spunbonding line requires a polymer drying system, it should be designed to deliver a dry polymer at the rate required by the spunlaid machine. Figure 3-3 shows the interaction between drying and spunlaying steps.

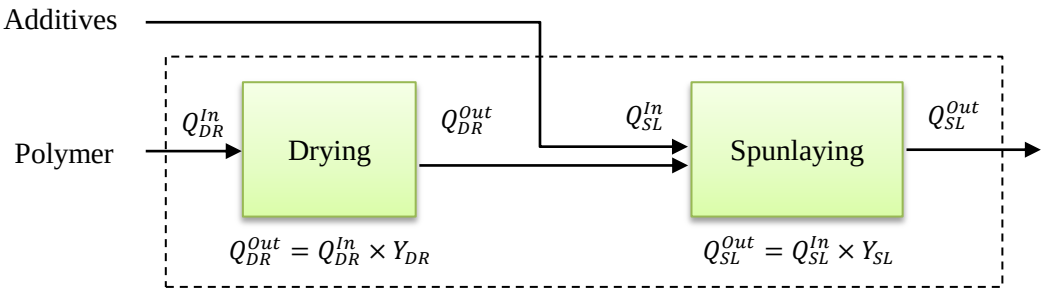


Figure 3-3: Coupling of the polymer drying and spunlaying processes

The output production rate (Q_{DR}^{Out} in [kg/h]) of a dryer equals the input rate (Q_{DR}^{In} in [kg/h]) adjusted for a drying process yield (Y_{DR} in [%]), as shown below:

$$Q_{DR}^{Out} = Q_{DR}^{In} \times Y_{DR} \tag{16}$$

In turn, the production rate of a dryer (Q_{DR}^{In} in [kg/h]) depends on a polymer drying time (t_{DR} in [h]), dryer volume (ϑ_{DR} in [m^3]) and the bulk density of the polymer chips (ρ in [kg/m^3]) that have to be dried as shown in Equation (17):

$$Q_{DR}^{In} = \frac{\vartheta_{DR} \times \rho}{t_{DR}} \tag{17}$$

$$Q_{DR}^{Out} = \frac{\vartheta_{DR} \times \rho}{t_{DR}} \times Y_{DR} \tag{18}$$

Here, drying time depends on the type and grade of the polymer being processed and the drying temperature (T_{DR}) used.

The inflow rate of a spunlaid machine (Q_{SL}^{In} in [kg/h]) is calculated as the output rate (Q_{SL}^{Out} in [kg/h]) divided by a process yield (Y_{SL} in [%]) as shown in Equation (19). The yield of the spunlaid machine may be lower than 100% due to possible material losses during polymer melt preparation (i.e., in the extrusion system) that need to be accounted for in the model.

$$Q_{SL}^{In} = \frac{Q_{SL}^{Out}}{Y_{SL}} \tag{19}$$

In case of composite fibers (e.g., bicomponent fibers and/or fibers with additives), the inflow rate of material i ($Q_{SL_i}^{In}$ in [kg/h]) to the extruder feed hopper is calculated as total inflow rate (Q_{SL}^{In} in [kg/h]) multiplied by a weight percent of material i in the fiber (ω_{RM_i} in [%]) as shown below:

$$Q_{SL_i}^{In} = Q_{SL}^{In} \times \omega_{RM_i} \tag{20}$$

$$Q_{SL_i}^{In} = \frac{Q_{SL}^{Out}}{Y_{SL}} \times \omega_{RM_i} \tag{21}$$

If some fiber component i has to be dried before further processing, the output rate of the drier should be synchronized with the required input rate of the spunlaid machine:

$$Q_{DR_i}^{Out} = Q_{SL_i}^{In} \tag{22}$$

Substituting Equation (18) and Equation (21) into the left and right hand side of Equation (22) respectively, the minimum required volume of the dryer component i can be determined as:

$$\vartheta_{DR_i} = \frac{\frac{Q_{SL}^{Out}}{Y_{DR_i} \times Y_{SL}} \times \omega_{RM_i} \times t_{DR_i}}{\rho_{RM_i}} \tag{23}$$

3.1.2.2.2 Material usage rates

As was discussed above, each spunbond production step may have its own yield. Therefore, the quantity of raw materials used is higher than the net output of the line. Since the spunlaid machine is a rate setting step, the steady-state input rates of each material may be calculated based on Equation (24)

$$Q_{RM_i}^{In} = \begin{cases} Q_{SL}^{Out} \times \frac{1}{Y_{DR_i} \times Y_{SL}} \times \omega_{RM_i}, \varphi = 1 \\ Q_{SL}^{Out} \times \frac{1}{Y_{SL}} \times \omega_{RM_i}, \varphi = 0 \end{cases} \tag{24}$$

where $Q_{RM_i}^{In}$ is the input rate of material i in kg/h, and φ identifies if material i requires drying ($\varphi = 1$ denotes that dyer is required). In turn, the usage rate of material i per kilogram of fabric ($UQ_{RM_i}^{In}$ in [kg/kg]) in steady state can be calculated as:

$$UQ_{RM_i}^{In} = \frac{Q_{RM_i}^{In}}{Q_{Line}^{Net}} \tag{25}$$

3.1.2.2.3 Yield

The yield of a production process is an important criterion used in the manufacturing industry for measuring process efficiency. It represents the output that can be produced given a fixed level of input. In every production process, the goal is to reach a yield value of 100%, which means minimizing material losses and machine time wasted on production of scrap. In real-life production, this is practically impossible to reach.

In a multi-step production process, each step may have its own yield and contribute to the overall yield of the line. From costing standpoint, it is important to consider the yield of each individual production step because some cost elements for a step depends on the volume of materials processed at this step. The yield of each production step may consist of two distinct variables: chemical (due to chemical reaction) and mechanical yields. Usually, estimation of the processing step yield is based on process test trials performed during NPD process, material balance estimations, or analytical calculations and is expressed as:

$$Y_p = \frac{Q_p^{Out}}{Q_p^{In}} \tag{26}$$

where $0 < Y_p \leq 1$ is a yield of process p, Q_p^{In} is an weight of materials going into process p and Q_p^{Out} is a weight of products after processing at step p. Knowing yield of each step, the overall yield factor of the manufacturing line can be calculated as a product of individual yields of all steps involved in the production process:

$$Y_{Line} = \prod_p Y_p \tag{27}$$

When the spunbond process is in a steady state, the most significant material losses occur during winding, where fabric are trimmed from both sides to eliminate the non-uniform, rough edges. Knowing the width of trimmed edge from each side (W_{ET} in [m]) and the gross width of the fabric produced (W in [m]), the yield of the winding stage can be calculated as:

$$Y_W = \frac{W - 2 \times W_{ET}}{W} \tag{28}$$

Here it is assumed that trimming width is constant and does not depend on the width of the web formation equipment. Therefore, as width of the web formation section increases the yield increases. Some losses may also occur during the polymer drying, spinning or web bonding (e.g., weight reduction due to water evaporation during drying). Usually, losses due to these steps are insignificant. However, the model includes the corresponding yield for generality. In the model, the overall yield of the spunbonding line (Y_{Line} in [%]) is calculated as:

$$Y_{Line} = \frac{Q_{Line}^{Net}}{\sum_i Q_{RM_i}^{In}} \tag{29}$$

where Q_{Line}^{Net} is the net production rate of the spunbonding line in kg/h, and $\sum_i Q_{RM_i}^{In}$ is the total materials input rate in kg/h.

3.1.2.2.4 Maximum available production time

The maximum available production time is the number of hours per year that the spunbond line is available for production. Its duration depends on a company's internal policy and may range from 0 to 8760 hours, where the later number representing the

maximum possible time the process is available for production (i.e., 24 hours per day, 365 days per year). Equation (30) is used for the calculation of annual operating hours:

$$MPT = HPS \times SPD \times DPW \times (WPY - CMT) \quad (30)$$

where MPT is the maximum available production time in hours per year, HPS is the number of operating hours per shift, SPD is the number of working shifts per day, DPW is the number of plant operating days per week, WPY is the number of operating weeks per year, and CMT is the duration of annual capital maintenance in weeks per year. Usually, spunbond plants operate 24 hours a day, 7 days a week and run on three shifts per day, for a total of 48-50 working weeks per year (the plant is closed 2 weeks per year for general maintenance).

3.1.2.2.5 Actual available production time

The actual available production time is the number of hours per year that the line can be used in full production of a particular product. It is usually less than the maximum available production time due to regular line shut downs required to perform maintenance. Regular spin pack cleaning and maintenance is necessary as it directly influences the overall quality of the web structure. It is assumed that the maintenance of other equipment is performed at the same time and does not contribute to the annual downtime of the line. Therefore, the line downtime (DT in [h/yr]) equals the number of required cleanings (line stops) per year (N_M) multiplied by the duration of line maintenance (t_M) in hours, as shown in Equation (31):

$$DT = N_M \times t_M \quad (31)$$

In turn, the time to perform regular maintenance (t_M in [h]) includes line shutdown and startup time (t_{Setup} in [h]), spunlaid machine purge time (t_{Purge} in [h]) and spin pack change time:

$$t_M = t_{Setup} + t_{Purge} + N_B \times t_{PackChange} \tag{32}$$

where N_B is the number of spinning beams, and $t_{PackChange}$ represents time needed to perform pack change in hours per pack.

The number of pack cleanings per year depends on polymer type, grade and quality, and is usually determined based on experience. The time required to change and clean a spinpack depends on whether there are spare packs available. In this case the cleaning time includes the time to remove the spin pack from the line, perform routine maintenance of the line and install a clean spin pack. If there are no spare packs available, this time must also include the actual time required to clean a spinpack, which may be significantly long.

Thus, the actual available production time (APT in [h/yr]) is the maximum available production time (MPT in [h/yr]) reduced by the line downtime (DT in [h/yr]):

$$APT = MPT - DT \tag{33}$$

Alternatively, the actual available production can be estimated using an "uptime factor" (U_f), which represents the fraction of time that the line can be utilized in full production:

$$APT = MPT \times U_f \tag{34}$$

This equation is employed when it is difficult to estimate the number of maintenance periods per year, and the time to perform them.

3.1.2.2.6 Annual production output and material usage

The maximum annual production output (i.e., net annual line capacity) (MAQ_{Line}^{Net} in [kg/yr]) of the spunbonding line can be calculated based on line hourly net production rate (Q_{Line}^{Net} in [kg/h]) and the actual available production time (APT in [h/yr]):

$$MAQ_{Line}^{Net} = Q_{Line}^{Net} \times APT \tag{35}$$

Since the desired annual production output (DAQ_{Line}^{Net} in [kg/yr]) may differ from the line annual capacity (MAQ_{Line}^{Net} in [kg/yr]), the minimum of these two values will be used for cost estimation per unit of product:

$$AQ_{Line}^{Net} = min\{MAQ_{Line}^{Net}, DAQ_{Line}^{Net}\} \tag{36}$$

The ratio of the annual output (AQ_{Line}^{Net} in [kg/y]) to maximum annual output (MAQ_{Line}^{Net} in [kg/yr]) defines the utilization of the line (U_{Line}):

$$U_{Line} = \frac{AQ_{Line}^{Net}}{MAQ_{Line}^{Net}} \tag{37}$$

Total annual quantity of material i (AQ_{RM_i} in [kg/y]) required for production is calculated as follows:

$$AQ_{RM_i} = UQ_{RM_i}^{In} \times AQ_{Line}^{Net} + Q_{RM_i}^{In} \times N_M \times t_{Setup} \tag{38}$$

where $UQ_{RM_i}^{In}$ is the usage rate of material i per kilogram of fabric, $Q_{RM_i}^{In}$ is the input rate of material i in kg/h, N_M is the number of line stops per year, t_{Setup} is the line shutdown and startup time in hours. The first term in Equation (38) quantifies the annual quantity of raw materials required by the line to achieve the desired output. The second term accounts for material waste that occurs during the start/stop of the production line. In this case, the

first/last square meters of the web must be discarded as the machine takes some time to adjust to the optimal process conditions.

3.1.2.3 Modeling of cost components

In this section, the influence of production parameters defined above on annual and unit cost of each cost element is discussed. First, resource requirements of the spunbond line are identified. Then, for each cost element, definition, cost calculation algorithm, and data requirements and availability is discussed.

3.1.2.3.1 Materials

Materials cost includes all items (direct materials) that become a part of a finished product. It is considered to be a variable cost, as the usage of direct materials increases with greater production volume. Cost of materials is an important component of the production cost model for the spunbonding process, usually constituting the largest portion of the total manufacturing costs (about 65%) (Laukien, 2009).

Generally, the final product of a spunbond plant is a nonwoven fabric in a roll good form. Figure 3-4 graphically represents a spunbond product structure in its simplest form. This structure varies from company to company depending on product characteristics required, manufacturing process utilized and may include additional types of materials (e.g., finishing materials). In Figure 3-4, Level 0 is a finished roll good. Level 1 shows the materials required at the packaging stage. Level 2 shows the raw materials required at the

manufacturing stage. Since the cost model described in this dissertation is focused on the spunbond manufacturing stage, only materials from Level 2 are considered.

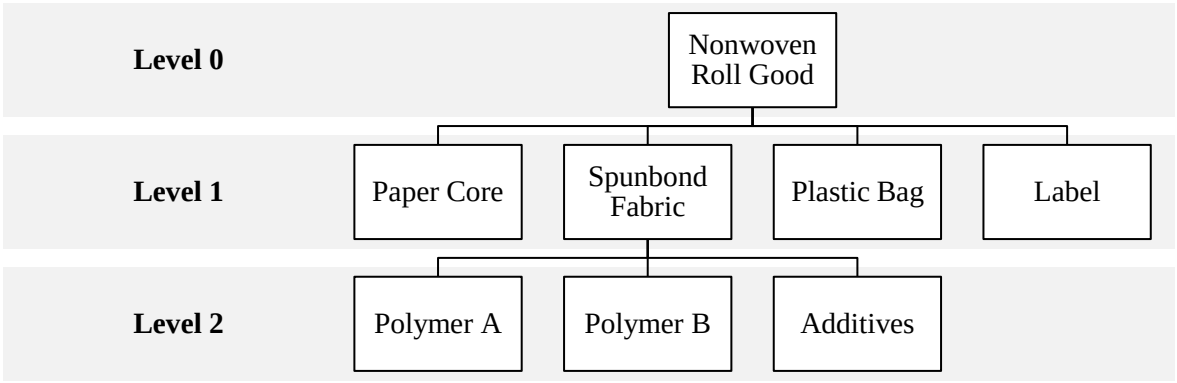


Figure 3-4: Spunbond product hierarchy

Thermoplastic polymers are basic ingredients used in manufacturing of spunbond nonwoven fabrics. Commonly used polymers were discussed in Section 2.2.4. In some cases, polymers are mixed with additives prior to extrusion to enhance existing properties, or to impart new unique ones to the final product.

The total cost of raw materials is calculated as the sum of costs of individual materials (i.e., polymers, additives) used in the production of a spunbond fabric. As was discussed in Section 3.1.2.2 the material input in production is higher compared to the weight of the final fabric due to production losses, machine shutdowns, and start-ups. When a production line is in a steady state, the cost of raw materials per kilogram of spunbond fabric (C'_{RM} in [$/kg]) should be adjusted by the overall yield of the spunbonding line (Y_{Line}). The term ($1/Y_{Line}$) represents a true material input (i.e., the quantity of raw materials required to

produce one kilogram of fabric). To calculate the cost of each material, the unit price of a material i (P_{RM_i} in [$/kg]) is multiplied by its weight percent (ω_{RM_i} in [%]) in the fabric under consideration. Equations (39) and (40) show formulas used to calculate cost of materials per kilogram of fabric in a steady state, where i represents a material type.

$$C'_{RM} = \frac{1}{Y_{Line}} \times \sum_i \left(\omega_{RM_i} \times P_{RM_i}\right) \tag{39}$$

$$\sum_i \omega_{RM_i} = 1 \tag{40}$$

Equation (39) is valid only for a steady state production with no loses due to machine shutdowns and startups. To account for such losses, it is preferable first to estimate the annual quantity of each raw material (AQ_{RM_i}in [kg/y]) required for fabric production using Equation (38), then to calculate the total annual materials cost (AC_{RM} in [$/y]) as shown below in Equation (41) and then to divide this amount by net annual output of the line (AQ_{Line}^{Net} in [kg/y]) as shown in Equation (42):

$$AC_{RM} = \sum_i AQ_{RM_i} \times P_{RM_i} \tag{41}$$

$$C''_{RM} = \frac{AC_{RM}}{AQ_{Line}^{Net}} \tag{42}$$

where C''_{RM} is the cost of raw materials per kilogram of fabric, accounting for processing yield and line start/stop losses.

To complete the estimation of raw materials cost, Equation (42) should be further modified to account for additional costs (benefits) of scrap material treatment. It is assumed that scrap is generated during fabric edge trimming at winding stage and production line

stops/starts. The annual weight of such scrap fabric (AQ_{Scrap} in [kg/y]) can be estimated based on the Equation (43):

$$AQ_{Scrap} = \left(\frac{AQ_{Line}^{Net}}{Y_W} - AQ_{Line}^{Net}\right) + N_M \times Q_{SL}^{Out} \times t_{Setup} \tag{43}$$

where Y_W is the yield of the winding machine, N_M is the number of line stops per year, Q_{SL}^{Out} is the output rate of a spunlaid machine in kilogram per hour, t_{Setup} is the line shutdown and startup time in hours. In this equation, the first term represents the total scrap generated during edge trimming and the second term is the total scrap generated during production line starts/stops for scheduled maintenance.

There are several ways to deal with scrap material embedded into the cost model. In some cases, scrap fabric can be recycled back into the manufacturing process (used instead of virgin raw materials). Some spunbond production lines are equipped with a recycling extruder, and scrap is directly fed into this extruder. Some spunbond facilities may have a re-pelletizing extrusion line. However, scrap fabric made of certain polymer blends cannot be recycled or recycled resin is prohibited to be used in certain products (e.g., in fabrics used for medical and food related applications). In this case, scrap can either be sold at a minimal value or disposed of at some cost. The cost of raw materials (C_{RM} in [$/kg]) per kilogram of fabric adjusted by cost (benefit) of scrap treatment is shown in Equation (44):

$$C_{RM} = C''_{RM} + \frac{AQ_{Scrap} \times \left(f_D \times C_D - f_S \times P_S - f_R \times (P_R - C_R)\right)}{AQ_{Line}^{Net}} \tag{44}$$

$$f_D + f_S + f_R = 1 \tag{45}$$

where C''_{RM} is a cost of raw materials per kilogram of fabric without scrap treatment cost adjustment; f_D, f_S, and f_R are shares of scrap to dispose, sell and recycle, respectively; C_D is a disposal cost per kilogram, P_S is a selling price of scrap per kilogram, and $(P_R - C_R)$ is benefits from recycling a kilogram of scrap, P_R is a value of kilogram of recycled materials and C_R is a recycling cost in dollar per kilogram. Equation (44) implies that the total raw materials cost also depends on the scrap treatment option chosen: scrap disposal increases a raw materials cost while selling and recycling scrap decreases it.

As follows from the discussion, the cost of raw materials depends on product design parameters, processing conditions, production efficiency and prices of materials themselves. Prices of raw materials have a significant influence on the accuracy of cost estimation. Generally, raw materials prices vary significantly depending on manufacturer, location, quantity, grade, delivery mode, time of year, and other variables. Therefore, the prices of raw materials used for cost estimating should be selected as close as possible to the specific case analyzed.

During the preliminary cost modeling and estimating, when the exact plant location and raw materials suppliers are not defined, market prices can be used. However, due to the high volatility of market prices, it is preferable to use average prices over a period of several months instead of the most recent values. Such information can be obtained from market reports or pricing databases (e.g., Independent Chemical Information Service (ICIS pricing, www.icis.com), Information Handling Services (HIS Inc., www.ihs.com), RISI Nonwovens Markets (www.nonwovens.com), Plastics Technology (www.ptonline.com), and Plastics News (www.plasticsnews.com)) or other available published literature. For example, Table

3-1 summarizes the US average market prices of the most commonly used polymers on Jun 25, 2012 obtained from Plastics News. At the later stages of product development more specific prices, provided by potential suppliers, can be used to get better estimates. The obtained vendor's invoice prices should be adjusted for purchase discounts and freight-in costs.

Table 3-1: Market prices of typical polymers for spunbond, $/lb.

Polymer		High Volume	Low volume
Polypropylene[1]	PP	1.05 - 1.07	1.08 - 1.10
Polyethylene (HDPE)[1]	PE	0.97 - 0.99	1.01 - 1.04
Poly(ethylene terephthalate)[1]	PET	1.0.7 – 1.09	1.10 – 1.12
Nylon 6[2]	PA 6	2.06 – 2.16	2.19 – 2.23
Nylon 66[2]	PA 66	1.92 – 2.00	2.04 – 2.15

Source: Plastics News (www.plasticsnews.com)
[1] Low volume: between 2 and 5 M lbs. annually; high volume: more than 20 M lbs.
[2] Low volume: between 0.3 and 0.5 M lbs.; high volume: more than 1 M lbs.

3.1.2.3.2 Labor

Labor cost is generally defined as expenditure incurred by a company for the purpose of employing staff required for carrying out its core activities. Labor is typically broken into two main groups: direct and indirect labor. Direct labor includes all employees who operate machinery of the spunbond production line (i.e., operators of the spunlaying, calendering and winding machines). Indirect labor includes all other employees who do not operate machines themselves but are essential to the manufacturing process (i.e., maintenance mechanics, material handlers, technicians, etc.). In highly automated plants, including nonwovens

production lines, labor cost is considered as a fixed cost since the number of people operating such plants are not easily adjusted as demand fluctuates.

According to the modeling approach the cost of labor for each individual production step in the spunbonding process are allocated to the unit of product separately. Cost of labor ($C_{L,p}$ in [$/kg]) per unit of manufacturing output for process step p is obtained by dividing total annual labor compensation ($AC_{L,p}$ in [$/y]) by net output of the line (AQ_{Line}^{Net} in [kg/y]) as shown in Equation (46):

$$C_{L,p} = \frac{AC_{L,p}}{AQ_{Line}^{Net}} \tag{46}$$

It is assumed that each production step may require several types of labor that differ by wage rate and working time dedicated to the processing step. Therefore, the annual cost of labor ($AC_{L,p}$ in [$/y]) for process p is a function of the annual paid time ($APT_{l,p}$ in [h/y]), wage rate (LR_l in [$/h]), and labor burden rate (LBR_l in [%]) for each labor type l required at the step as shown in Equations (47):

$$AC_{L,p} = \sum_{l} \left(APT_{l,p} \times LR_l \times LBR_l \right) \tag{47}$$

where p denotes the process step index ($p \in \{PD, SL, TC, W\}$), l denotes the labor type (e.g., technicians, skilled such as maintenance mechanics, semiskilled such as machine operators, unskilled such machine helpers and material handlers).

In turn, the annual paid time ($APT_{l,p}$ in [h/y]) of labor type l directly associated with the process p is a product of the number of laborers per shift ($L_{l,p}$ in [persons/shift]), the number of working shifts per day ($SPD_{l.p}$), the number of operating hours per shift (HPS),

and the number of plant operating days per year (DPY), as shown in Equation (48). The number of laborers may be fractional meaning that the same employee could be associated with several processes (e.g., supervision of the entire line).

$$APT_{l,p} = L_{l,p} \times SPD_{l,p} \times HPS \times DPY \tag{48}$$

The main inputs to the labor cost estimation are the number of laborers required for each process, wage rate and burden rate. If the equipment that will be used for production are known the best estimates of the number of employees could be obtained from the equipment specification that usually indicates operating, maintenance and overhead personnel required for each process step. Otherwise, estimates may be developed based on experts' opinion, comparison with similar production processes, or using detailed estimating techniques.

There are several commonly used methods in the literature that can be utilized to estimate labor requirements including the Wessel ratio, the Ulrich method and parametric models (Brown, 2000; Turton et al., 2008; Vatavuk, 2005). All these methods are based on actual information about staffing of similar equipment. The Wessel ratio correlates labor requirement and equipment capacity as shown in Equation (49). The exponent a is estimated using equipment capacity and corresponding labor requirement for known cases. Then using this value, labor requirements for new equipment can be found by comparing its capacity with known capacity of the similar equipment.

$$\frac{L_2}{L_1} = \left(\frac{V_1}{V_2}\right)^a \tag{49}$$

where L_1 and L_2 are labor requirement and V_1 and V_2 are capacities of a machine 1 and 2 correspondingly. Parametric methods are similar to the Wessel method and allow correlating

labor requirements to different equipment parameters using statistical methods. The Ulrich approach utilizes a table of the most common types of equipment with assigned number of operators per shift to each type of equipment developed based on past experience. Crew size can be tabulated based on number of operators needed for each piece of equipment to be used in the process. While these methods are commonly used in chemical industry, they require a significant portion of information about staffing of different equipment that is not publicly available for nonwovens plants.

The second input to labor cost estimating model is gross hourly wage rates (i.e., net hourly rate plus employee payroll taxes) adjusted by burden rates (e.g., employer payroll taxes plus fringe benefits). These rates are company specific, depend on type of the labor and location of the plant (e.g., operator costs 17 $/h in the US, and costs 2 $/h in China). For quick estimates, average wage rates in the US can be obtained from the US Bureau of Labor Statistics (http://www.bls.gov). For example, Table 3-2 shows the average wage rates for textile mill for different types of labor that can be used for cost estimation.

Table 3-2: Average wage rates for different types of labor as of May 2011

Labor Type	Occupation Code	Average Wage Rate in $/h
Extruding machine operators	51-6091	16.96
Maintenance and repair workers	49-9071	17.93
Line supervisors	51-1011	23.45

Source: US Bureau of Labor Statistics (http://www.bls.gov)

Labor burden represent a significant part of labor cost and usually it accounts for 35-50%, which can be used for quick estimation. The most common components of the burden rate are federal and state employer payroll taxes, worker's compensation costs, long-term and short-term disability insurance, health/life insurance, retirement contribution, paid time off (vacation, holidays, sick and personal days). The detailed estimation of hourly labor rates can be done by adjusting gross wage rates for all legally required payments and fringe benefits as shown in Table 7-1 in Appendix C.

3.1.2.3.3 Utilities

Each process requires one or more types of utilities (e.g., electricity, water, compressed air). In manufacturing, utilities generally represent a significant portion of total production cost. At the plant level, utilities are consumed by production equipment, supporting machinery (e.g., maintenance) and for non-production purposes (i.e., lighting, plant heating and air conditioning). In the cost model, only production-related utilities are considered as a separate cost element. Cost of nonproduction utilities (e.g., electricity for lightening and HVAC) is assumed to be included in plant floor space cost. To calculate the cost contribution of the process p utilities to the cost of a unit of product ($C_{U,p}$ in [$/kg]), the total annual cost of utilities ($AC_{U,p}$ in [$/y]) for this process is divided by the annual net output (AQ_{Line}^{Net} in [kg/y]) of the line as shown in Equation (50):

$$C_{U,p} = \frac{AC_{U,p}}{AQ_{Line}^{Net}} \tag{50}$$

The total annual cost of utilities consumed by process p ($AC_{U,p}$ in [$/y]) is a sum of cost of each type of utility used by the process, which is calculated as the annual consumption of utility type u ($AU_{u,p}$ in [units/y]) times the price of corresponding utility (UP_u in [$/unit]):

$$AC_{U,p} = \sum_{u} \left(AU_{u,p} \times UP_u \right) \tag{51}$$

In turn, the annual consumption of utility of type u by process p ($AU_{u,p}$ in [units/y]) can be estimated by multiplying hourly consumption rates ($UR_{u,p}$ in [units/h]) by the actual available production time (APT in [h/y]) adjusted for the line utilization (U_{Line} in [%]):

$$AU_{u,p} = UR_{u,p} \times APT \times U_{Line} \tag{52}$$

There are two main types of utilities used in the spunbond process, namely electricity and water. The spunbonding process is energy intensive. Electricity is used by all processing steps for polymer drying, melting, extrusions, filament drawing, fabric conveying, calendering and winding. Water may be used in the spunlaid machine and the thermal calender for extruder and fabric cooling, correspondingly. Since water contributes insignificantly to total production costs it is assumed that water consumption rate do not change significantly with processing variables. Equations (50)-(52) may be used for estimation of utilities costs when consumptions rates are known and constant (i.e., assuming that they do not depend on product and process parameters).

However, energy consumption of the spunbond equipment is influenced by product characteristics, processing parameters, and equipment design parameters. Therefore, for more accurate estimation, it is preferable to use models that relate energy consumption to

processing parameters. These models allow predicting energy consumption as well as studying the effects of processing parameters. Such relationship can be developed based on theoretical consideration about dynamics and mechanics of a process. However, such development is complicated, time consuming and impractical to be applied in industrial settings. Alternatively, energy consumption relationships may be estimated using statistical analysis (e.g., regression analysis, neural networks) of the observed data. Unfortunately, there is no published studies that estimate energy consumption for spunbond technology.

If the detailed energy consumption model is used, Equation (52) that calculates annual energy consumption for process p, can be modified as follows:

$$AU_{Electricity,p} = AQ_p^{In} \times SEC_p \times EAF_{r,p} \quad (53)$$

where AQ_p^{In} is an annual quantity of materials that should be processed by step p in kilogram per year, SEC_p is the specific energy consumption of step p for base type of raw materials in kilowatt-hours per kilogram, $EAF_{r,p}$ is the energy adjustment factor to account for changes in energy consumption due to usage of material r instead of the base material.

Specific energy consumption of process p is a function of processing parameters as shown in Equation (54).

$$SEC_p = f(Product\ and\ Process\ Parameters) \quad (54)$$

To estimate the functional relationship, different combination of processing parameters and corresponding specific energy consumption of the process should be collected. To reduce the number of observations required, the function should be developed for one base polymer (e.g., polymer that is the most commonly used at the machine) assuming that trends for other

polymers are proportional to the trend of the base polymer. The list of processing variables that may have significant influence on specific energy consumption for each processing step of the spunbonding line is shown in Table 3-3.

Table 3-3: List of parameters affecting SEC of each machine

Machinery	**Processing Variables**
Resin dryer	Drying time, drying temperature
Spunlaid web formation machine	Polymer throughput rate, filament size, width, number of beams
Thermal calendering machine	Linea production speed, roll temperature, width
Winding	Linea production speed, fabric basis weight

To find the coefficients of proportionality for different polymers, it is enough to have one point estimate of specific energy consumption for each polymer with known corresponding processing parameters. The adjustment factor ($EAF_{r,p}$) is estimated as a ratio of specific energy consumption for polymer r ($SEC_{r,p}$) to the specific energy consumption for the base polymer (SEC_p) with the same level of processing parameters:

$$EAF_{r,p} = \frac{SEC_{r,p}}{SEC_p} \tag{55}$$

Similar to labor cost and material prices cost of utilities may vary significant between countries and even within a country. Therefore, for preliminary estimates average country value should be used. If the location of a plant is know, this value should be obtained from local utilities suppliers. For the US, electricity prices could be obtained from the website of the U.S. Energy Information Administration (http://www.eia.gov) as shown in Table 3-4.

Table 3-4: US average price of electricity for industrial customers by region

Region	Price in cents/kWh*
New England	12.09
Middle Atlantic	7.48
East North Central	6.48
West North Central	6.06
South Atlantic	6.40
East South Central	5.75
West South Central	5.40
Mountain	5.76
Pacific Contiguous	7.35
US Average	6.52

* As of March 2012
Source: U.S. Energy Information Administration (http://www.eia.gov)

There are many local organizations that study water rates for some specific states, regions or cities. For example, UNC Environmental Finance Center (http://www.efc.unc.edu/) publishes annual report on water and waste water rates for North Carolina. However, to the best of the author knowledge, there is no organization that publishes consolidated reports on the cost of water for industrial users in the US.

3.1.2.3.4 Equipment

The equipment cost category includes all costs associated with purchasing and owning process-related equipment. Generally, equipment-related costs can be divided into two distinct groups, namely initial capital expenditures for purchasing process equipment,

which represent a single payment occurring in the initial year of the project, and annual expenses, which represent recurring payments like interest on borrowed capital, property taxes and insurance charged annually on constant rates.

To allocate cost of equipment related to process p to each unit of final product ($C_{E,p}$ in [$/kg]), the annual cost of owning process equipment ($AC_{E,p}$ in [$/y]) must be divided by an annual net output (AQ_{Line}^{Net} in [kg/y]) of the line under consideration as shown in Equation (56):

$$C_{E,p} = \frac{AC_{E,p}}{AQ_{Line}^{Net}} \tag{56}$$

where p denotes the process step index, $p \in \{PD, SL, TC, W\}$.

The annual cost of owning the process p equipment is a sum of annualized capital cost of equipment and annual recurring payments related to equipment ownership. Annual recurring payment may include such costs as property taxes and insurance and it can be calculated as a constant percentage of the total equipment cost. To derive annualized capital cost of equipment, straight-line depreciation and capital recovery factor are the two most common methods found in the literature. Both methods assume that the production levels are constant over the duration of production. Therefore, costs are distributed evenly over the economic life for the equipment and then over each unit of production. The decision about which method to use depends on the internal policies of a company, and it varies from one company to the other.

For study estimates, the straight-line depreciation method is used because of its simplicity and easy in application. According to this method the annual cost of owning the process p equipment ($AC_{E,p}$ in [$/y]) is found as follows:

$$AC_{E,p} = \frac{CI_{E,p} - SV_{E,p}}{n_{E,p}} + CI_{E,p} \times (i + k) \tag{57}$$

where $CI_{E,p}$ represents the initial capital expenditures for purchasing equipment for process p in dollars, $SV_{E,p}$ is the estimated salvage value of the equipment in dollars, n_E represents the number of periods in years over which investment is distributed, i represents interests on borrowed capital, and k is the capital related fixed charges including (e.g., property taxes, insurance). In Equation (57), the first term represents annualized capital cost of process p - related equipment. The second term represents annual recurring payments related to equipment ownership. While a salvage equipment value is included in calculation, it can be ignored for study estimates. The number of periods over which investment is distributed can be equal to an estimated useful or economic life of the equipment. A good rule of thumb is to use an economic life of 10 years, as companies have to invest in the latest equipment technologies to be able to produce competitive products.

The capital recovery factor, also called amortization of loans, is used in loan repayments. This means that the funds for purchasing the equipment come in the form of a loan. The amortization calculator formula is:

$$AC_{E,p} = CI_{E,p} \times \frac{i \times (1 + i)^{n_{E,p}}}{(1 + i)^{n_{E,p}} - 1} + CI_{E,p} \times k \tag{58}$$

In Equation (58), the first term represents annualized capital cost of process p -related equipment. The second term represents annual recurring payments related to equipment ownership. While in the straight-line depreciation method interests should be included in annual recurring costs, the capital recovery factor method accounts both depreciation and interests on borrowed capital.

The initial capital expenditures for purchasing equipment for process p ($CI_{E,p}$ in [$]) can be obtained by multiplying the purchased equipment cost (PEC_p in [$]) by an appropriate installation factor (IF_p in [%]) assuming that installation costs are directly proportional to equipment purchase cost as shown in Equation (59).

$$CI_{E,p} = PEC_p \times IF_p \tag{59}$$

There are no cost installation factors available in the literature that can be used directly in Equation (59). Therefore, these factors must be generated based on experts opinion or detailed analysis of the incurred installation costs for existing spunbond lines. Both direct (materials and labor) and indirect (freight, insurance, taxes and construction overheads) expenses can be considered in installation factors calculations.

For cost estimating purposes, the equipment purchased cost (PEC_p) can be obtained directly from equipment manufactures or estimated using parametric cost models (Couper, 2003; G. D. Ulrich & Vasudevan, 2009). The equipment cost obtained from a vendor is mainly preferable for cost estimating of one specific scenario. The parametric cost model evaluates equipment cost using a cost function that provides a logical and repeatable relationship between the physical and functional characteristics of equipment and its purchase cost. Usage of cost functions enables engineers to perform quick and inexpensive

equipment cost estimations, allows studying the influence of equipment design parameters on cost, and building multiple scenarios to support decision-making. The drawback of using cost functions is their relatively low accuracy, which mainly depends on the quality of underlying data. The literature search shows that there are no appropriate cost functions that will allow performing the economic study of the spunbond technology. Therefore, such cost functions must be developed.

Usually, equipment cost data are correlated as a function of equipment capacity parameters (Dysert, 2001; Humphreys, 2005) as shown in Equation (60):

$$PEC_p = f(Equipment\ Capacity\ Parameters) \tag{60}$$

The functional form and values of parameters of the cost equation (60) can be determined based on the best available historical data collected from equipment manufactures using regression analysis. The cost function, once built, estimates the cost of the machine as of a specific year that is the year the model was built. To project equipment cost from the base year to another selected year a cost index must be used. The Marshall and Swift equipment cost index and the Chemical Engineering plant cost index are recommended for use with process-equipment estimates (Couper, 2003).

Table 3-5 shows the main capacity parameters that can be used for the development of generic cost functions for the main equipment involved in spunbonding process. It is preferable to build these models for similar equipment produced by the same manufacturer (i.e., prices of spunlaying equipment may differ significantly for open or closed systems, as well as for homocomponent or bicomponent machines).

Table 3-5: Equipment capacity parameters

Machinery	**Capacity Parameters**
Dryer	Volume
Spunlaid web formation machine	Width, number of spinning beams, number of holes
Thermal calendering machine	Width
Winding	Width

For example, the capacity of the spunlaid web formation process is determined by the working width (W) of the machine and number of spinning beams (N_B) (see Section 3.1.2.2). Accordingly, the purchase cost of the spunlaid machine (PEC_{SL} in [$]) can be defined as function of these two parameters:

$$PEC_{SL} = f(W_{SL}, N_B) \tag{61}$$

When dryer is needed, the purchase cost of drying equipment can also be estimated using a parametric cost model (i.e., $PEC_{DR} = f(\vartheta_{DR})$, where ϑ_{DR} is a dryer volume in m^3. However, the dryer is an integral part of the spunlaid module. Thus, a production capacity of the drying module is defined by desired capacity of spunlaid machine. Therefore, assuming that the ratio of the cost of drying equipment to that of the spunlaid machine ($f_{DR/SL}$ in [%]) is constant, the cost of the drying equipment (PEC_{DR} in [$]) can simply be estimated as a fraction of the spunlaid machine cost:

$$PEC_{DR} = f_{DR/SL} \times PEC_{SL} \tag{62}$$

The logic model for the spunlaid process equipment cost estimation is shown in Figure 3-5.

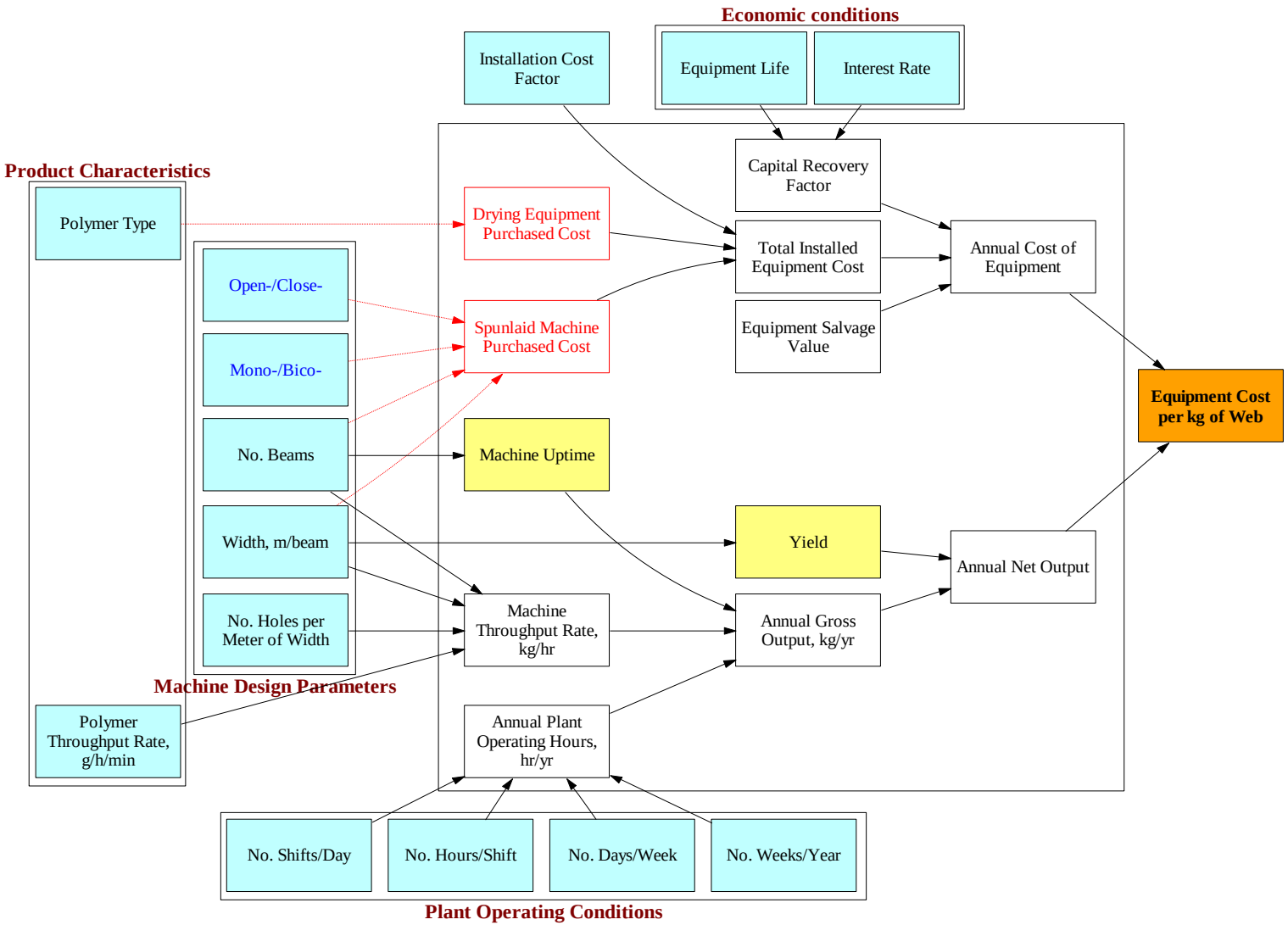


Figure 3-5: Logic diagram for the spunlaid process equipment cost estimation

3.1.2.3.5 Tooling cost (Spin pack assembly)

A spin pack assembly is an important component of the spunlaid machine that converts the molten polymer(s) into endless filaments of defined type, size, and shape. Spin pack is a design tool that adds flexibility to the spunlaid process (e.g., by changing spin pack fibers with different shape can be produced in homocomponent system or produce nonwoven mats of various bicomponent fibers configuration in bicomponent system). Spin pack assembly is expensive. Its cost varies from a few thousands to a few hundreds of thousands of dollars depending on size, complexity, choice of construction material, etc. Thus, the capital investment in spin packs and spinnerets may contribute significantly to the cost of the final product, especially for low or medium volume products that use complex, custom designed spin packs. Therefore, spinpack assembly cost is considered as a tooling cost of the spunlaid process and is modeled separately from the cost of main equipment to add more flexibility to the cost model. Figure 3-6 and Figure 3-7 show the proposed schemes of calculation logic.

Cost contribution of tooling per unit of output ($C_{T,SL}$ in [$/kg]) is calculated by dividing annualized tooling cost ($AC_{T,SL}$ in [$/y]) by annual net final product output of the facility (AQ_{Line}^{Net}) as shown in Equation (63). In turn, annualized tooling cost may be calculated using any of the methods described in Section 3.1.2.3.4, for example straight-line depreciation as shown in Equation (64).

$$C_{T,SL} = \frac{AC_{T,SL}}{AQ_{Line}^{Net}} \tag{63}$$

$$AC_{T,SL} = \frac{CI_{T,SL}}{n_T} \tag{64}$$

where $CI_{T,SL}$ is the total capital investment in tooling, and n_T is a number of years used to distribute total tooling investment. The number of years depends on a specific case and can be equal to product lifetime (if tooling is dedicated to the product) or tooling productive life (if tooling is not dedicated to the product).

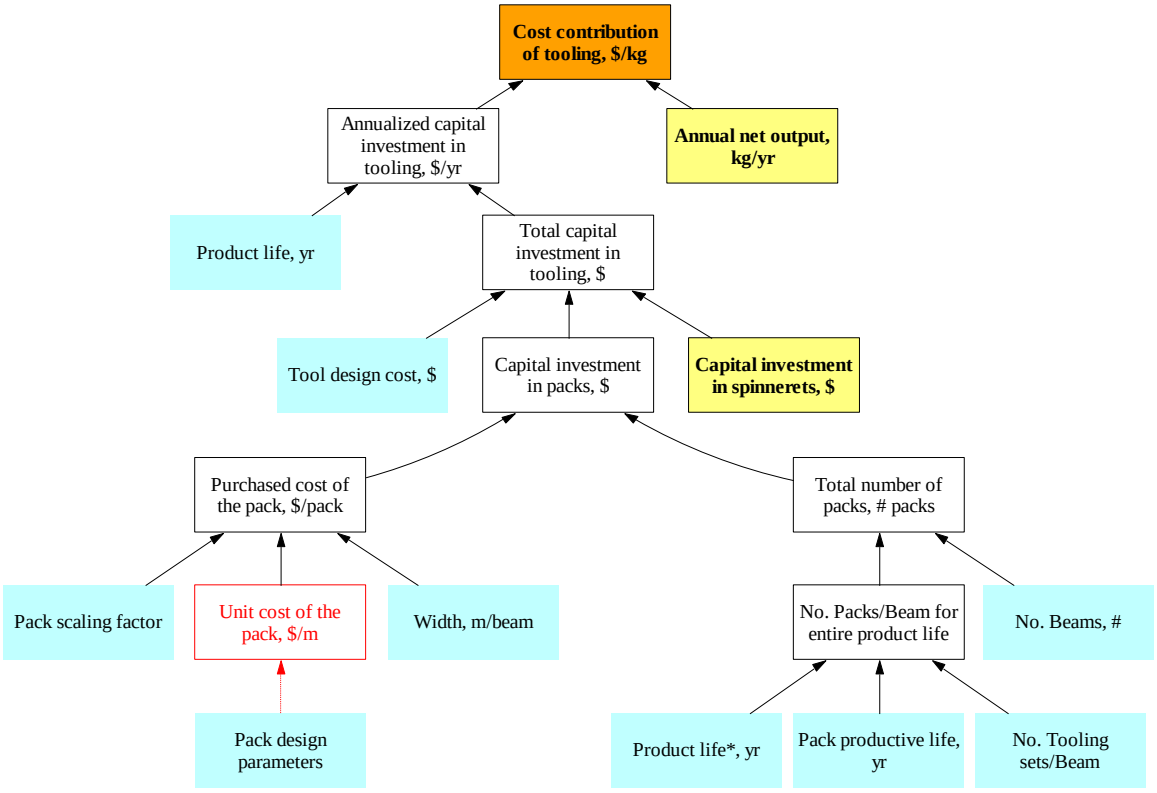


Figure 3-6: Logic diagram for spin pack cost estimation

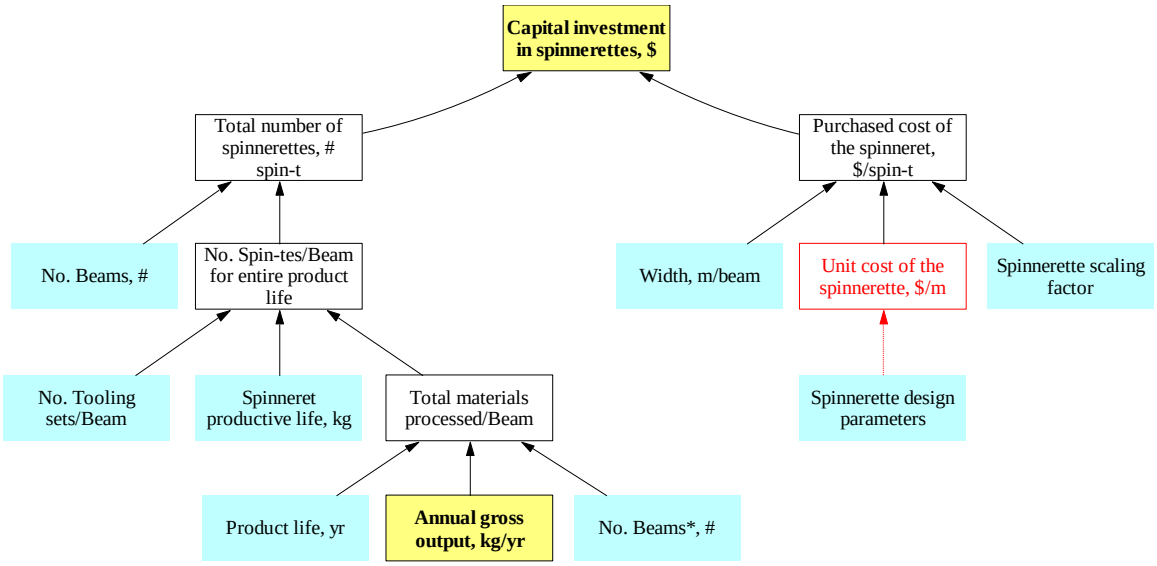


Figure 3-7: Logic diagram for spinnerette cost estimation

Capital investment in spin pack assemblies can be estimated in several ways depending on information available and accuracy required. The simplest and quickest way is to calculate this cost as a fraction (f_T) of investment in spunlaid machine ($CI_{EQ,SL}$) as shown in Equation (65). f_T can be estimated based on historical information for a specific type of spunlaid equipment (i.e., for homocomponent or bicomponent machine).

$$CI_{T,SL} = f_T \times CI_{EQ,SL} \tag{65}$$

Another way to calculate capital investment in tooling is to use a detailed model, which accounts for design cost (TDC) and costs of spin packs (CI_{Pack}) and spinnerettes ($CI_{Spin-te}$) as shown in Equation (66). Design cost of tooling may be negligible for standard tooling sets, but it may be extremely high for custom designed and complex spin pack

assemblies. Costs of spin packs and spinnerets are separated into different terms because they may have different lifetimes.

$$CI_{T,SL} = TDC + CI_{Pack} + CI_{Spin-te} \quad (66)$$

To estimate capital investment in spin packs (CI_{Pack}) and spinnerettes ($CI_{Spin-te}$), the total number of packs (TN_{Pack}) and spinnerettes ($TN_{Spin-te}$) are multiplied by corresponding purchased price (PC_{Pack} and $PC_{Spin-te}$) as shown in Equations (67) and (68) respectively.

$$CI_{Pack} = TN_{Pack} \times PC_{Pack} \quad (67)$$

$$CI_{Spin-te} = TN_{Spin-te} \times PC_{Spin-te} \quad (68)$$

Total number of spin packs and spinnerets depends on the number of spinning beams (N_B) and number of tooling sets per beam ($N_{Pack/B}$ and $N_{Spin-te/B}$) required, as shown in Equations (69) and (70).

$$TN_{Pack} = N_{Pack/B} \times N_B \quad (69)$$

$$TN_{Spin-te} = N_{Spin-te/B} \times N_B \quad (70)$$

The number of tooling sets per beam may be greater than one, since spin packs and spinnerettes must be cleaned regularly with significant cleaning time (e.g., 12-16 hours per pack) and companies may have several interchanging tooling sets (N_T) to decrease line downtime. In addition, this number depends on product (LT_{Prod}) and tooling (LT_{Pack} and $LT_{Spin-te}$) lifetimes. If tooling is dedicated to the specific product a number of sets required for product lifetime should be calculated as rounded up ($\lceil \ \rceil$) ratio of product lifetime to tooling lifetime adjusted for the number of interchanging sets as shown in Equations (71) and (72).

$$N_{Pack/B} = \left\lceil \frac{LT_{Prod}}{LT_{Pack} \times N_T} \right\rceil \times N_T \quad (71)$$

$$N_{Spin-te/B} = \left\lceil \frac{LT_{Prod}}{LT_{Spin-te} \times N_T} \right\rceil \times N_T \quad (72)$$

It is assumed that the purchase cost of the pack (PC_{Pack}) or spinnerette ($PC_{Spin-te}$) depends on per meter cost ($PC_{Pack/m}$ and $PC_{Spin-te/m}$) and working width (W) as shown in Equations (73) and (74). This dependency may be nonlinear, which may be used to model economy of scale in tooling with higher working width. Values of scaling factors (f_{Pack} and $f_{Spin-te}$) that are lower than one represent economy of scale and can be estimated by comparing prices of packs (spinnerettes) of the same type but different working widths.

$$PC_{Pack} = PC_{Pack/m} \times W^{f_{Pack}} \quad (73)$$

$$PC_{Spin-te} = PC_{Spin-te/m} \times W^{f_{Spin-te}} \quad (74)$$

The purchase cost of the pack ($PC_{Pack/m}$) or spinnerette ($PC_{Spin-te/m}$) per meter may differ depending on tooling manufacturing technology and pricing policies of various toolmakers. The best approach is to contact a toolmaker for a price quote for a specific type of tooling. If historical information about purchased prices of tooling with different design parameters is available, per meter price can be estimated as functions of these parameters (see Equations (75) and (76)).

$$P_{Pack} = f(Pack\ Design\ Parameters) \quad (75)$$

$$P_{Spin-te} = f(Spinnerette\ Design\ Parameters) \quad (76)$$

Examples of design parameters that may influence per meter cost of spin pack and spinnerette are listed in Table 3-6.

Table 3-6: Tooling design parameters

	Design Parameters (Cost Drivers)
Pack	Homocomponent/multicomponent, construction material, complexity, etc.
Spinnerette	Construction material, hole shape (round/irregular), hole diameter, L/D ratio, accuracy of hole diameter, accuracy of capillary length, hole density, coating, etc.

3.1.2.3.6 Plant floor space cost

Since the spunbond equipment, operators, input/output materials, and conveyors require space in a manufacturing plant, the space-related costs must be included in product cost calculation. To calculate the cost contribution of plant floor space to cost of unit of product ($C_{S,p}$ in [$/kg]) the annual cost of plant floor space ($AC_{S,p}$ in [$/y]) must be divided by an annual net output of the spunbond line under consideration (AQ_{Line}^{Net} in [kg/y]) as shown in Equation (77). In turn, the annual cost of plant floor space can be determined by multiplying the total floor area occupied by process p machinery (A_p in [m^2]) by an appropriate annual space cost rate (SP in [$/$m^2$]) as shown in Equation (78).

$$C_{S,p} = \frac{AC_{S,p}}{AQ_{Line}^{Net}} \tag{77}$$

$$AC_{S,p} = A_p \times SP \tag{78}$$

The annual cost of space (SP in [$/$m^2$]) may include space rate, cost of utilities such as water and energy used for heating ventilation and air conditioning, illumination, the cost of security and building maintenance, and other costs directly related to the factory floor space occupied by the process. This number can be easily obtained from real estate agents or

market reports provided by specialized research agencies (e.g., RSMeans, www.rsmeans.com; Cushman&Wakefield, http://www.cushwake.com).

The amount of floor space required by machine can be estimated as a function of its size as shown in Equation (79). Table 3-7 shows some size parameters for the equipment involved in the spunbonding process For example, the plant area required by a spunlaid web formation process could be defined as function of working width (W) of the machine and number of spinning beams (N_B) as shown in Equation (80).

$$A_p = f(Machine\ Size\ Parameters) \tag{79}$$

$$A_{SL} = f(W_{SL}, N_B) \tag{80}$$

Regression analysis could be used to determine the functional form and values of parameters of the equation using historical data collected from industry sources (e.g. building floor plans of already built spunbonding plants).

Table 3-7: Space parameters

Machinery	**Size Parameters**
Dryer	Volume
Spunlaid web formation machine	Width, Number of spinning beams
Thermal calendering machine	Width
Winding	Width

3.1.2.3.7 Maintenance

Maintenance cost category includes costs of labor and materials, as well as maintenance contracts associated with keeping the process equipment running or restoring it to the desired operating condition. Proper maintenance of equipment can significantly reduce

the overall operating cost, while boosting the productivity of the line. Regular maintenance allows avoiding breakdowns and unplanned line shutdowns, excessive set-up, changeovers and adjustments, idling and minor stoppages, running at reduced speed, startup losses, and quality defects. The cost of maintaining equipment varies considerable depending on equipment age and condition, location and maintenance strategy implemented in a company. The cost of maintenance of process p per unit of product ($C_{M,p}$ in [$/kg]) is calculated by equally distributing the total annual cost of maintenance ($AC_{M,p}$ in [$/y]) over the net annual output of the line (AQ_{Line}^{Net} in [kg/y]):

$$C_{M,p} = \frac{AC_{M,p}}{AQ_{Line}^{Net}} \tag{81}$$

In general, maintenance of the spunbonding line may be separated into two types: capital and routine maintenance. Therefore, annual cost of maintenance ($AC_{M,p}$ in [$/y]) is a sum of annual costs of capital ($AC_{M,p}^{Cap}$) and regular ($AC_{M,p}^{Reg}$) maintenances as shown in Equation (94).

$$AC_{M,p} = AC_{M,p}^{Reg} + AC_{M,p}^{Cap} \tag{82}$$

Capital maintenance is usually performed once per year when the entire plant is closed. During this maintenance the main components of the production line are inspected and worn out components are replaced by specially trained or outsourced team. The cost of this maintenance for a process p can be estimated as a fixed percentage (CMF_p in [%]) of total capital investment in equipment ($CI_{E,p}$ in [$]) as shown in Equation (83). For simple plants with relatively mild and noncorrosive conditions, capital maintenance factor of 3 to 5% should be adequate (Humphreys, 2005).

$$AC_{M,p}^{Cap} = CMF_p \times CI_{E,p} \quad (83)$$

The routine maintenance of the spunbonding plants is performed several times within a year. During this maintenance the production line is stopped for several hours, spunlaying equipment is purged, and spin packs are changed. Annual cost of regular maintenance ($AC_{M,p}^{Reg}$) for process p is a product of number maintenances per year (N_M) and cost to perform one maintenance (RMC_p) as shown in Equation (84).

$$AC_{M,p}^{Reg} = N_M \times RMC_p \quad (84)$$

The cost of one regular maintenance (RMC_p) may include expandable materials and parts, labor, and utilities used. In this model, it is assumed that maintenance labor is fixed and its cost does not depend on the number of maintenance performed. Therefore, the cost of maintenance labor is accounted for in the total labor cost in Section 3.1.2.3.2 and is not considered here. Each time when the line is stopped/started some losses raw materials may occur. The cost of these losses is considered as a part of material cost in Section 3.1.2.3.1 and is not included in cost of maintenance.

Among all processes, the cleaning of the spunlaying equipment is the main reason to perform regular maintenance. Therefore, the cost of maintenance for this process has the most complex structure and further explanation of maintenance costs is conducted in application to spunlaying equipment. Equation (85) shows that this cost consists of machine set-up cost (RMC_{SL}^{Setup}), purging cost (RMC_{SL}^{Purge}) and packs cleaning cost ($RMC_{SL}^{PackCleaning}$). Since labor and losses of raw materials are not included in maintenance

cost, cost of set-up is equal to cost of utilities used during line star-up/shut-down as shown in Equation (86).

$$RMC_{SL} = RMC_{SL}^{Setup} + RMC_{SL}^{Purge} + RMC_{SL}^{PackCleaning} \quad (85)$$

$$RMC_{SL}^{Setup} = \left(UR_{El,SL} \times UP_{El} + UR_{W,SL} \times UP_{W}\right) \times t_{Setup} \quad (86)$$

where $UR_{El,SL}$ and $UR_{W,SL}$ are hourly consumption rates of electricity and water by the spunlaying machine correspondingly, UP_{El} and UP_{W} are utilities unit prices, and t_{Setup} is a total time to shut-down and start-up the line.

The cost of spunlaid machine purging includes cost of utilities calculated similarly to the set-up case and cost of purge polymer used as shown in Equation (87):

$$\begin{aligned} RMC_{SL}^{Purge} = {} & \left(UR_{El,SL} \times UP_{El} + UR_{W,SL} \times UP_{W}\right) \times t_{Purge} \\ & + Q_{SL}^{In} \times t_{Purge} \times \left(P_{Purge} + C_{D}\right) \end{aligned} \quad (87)$$

where t_{Purge} is the spunlaid machine purge time, Q_{SL}^{In} is a material consumption rate of the machine, P_{Purge} is the price of purge polymer and C_{D} is the disposal cost of used purge polymer.

Finally, the cost of spinpack cleaning is a product of number of spin packs to clean, which is equal to the number of beams (N_B), and cost to clean one spinpack ($C_{PackCleaning}$):

$$RMC_{SL}^{PackCleaning} = C_{PackCleaning} \times N_{B} \quad (88)$$

The calculation of spin pack cleaning cost is discussed in more details in the Section 3.1.2.3.8.

3.1.2.3.8 Spin pack cleaning cost model

Spin packs have to be changed and cleaned at regular intervals to keep performance and efficiency of the spunbond line at optimum level. The spin pack life highly depends on polymer melt quality and purity, typically 20 to 45 days. Pressure increase across the filter media, leaks and run ability problems are the most common reasons for pack changes. Each time the spin pack has to be changed material wastage occurs, accompanied by increased production costs due to cleaning and replacing it. The cost of servicing spin packs must be included into the cost model since it increases production cost.

A typical spin pack cleaning process has three main steps. First, the spin pack must be carefully removed and disassembled, and then the spinpack components are placed in a thermal cleaning furnace where they are cooked at high temperatures for some time to melt off and remove all organics. Temperatures and cycle time usually varies with polymer type. This is the most critical stage as improper cleaning in an oven can lead to long post treatment. After the furnace phase, the parts are allowed to cool, unload and cleaned mechanically with scrub pad or brush to remove the loose inorganic materials as ash and scale and then may be placed into ultrasonic cleaning tank for additional cleaning. The last cleaning phase is spraying the pack using high-pressure water, followed by drying. Then, spin pack components must be carefully inspected for cleanliness and damage. The maximum attention must be paid to spinneret plate. This traditionally is done by light box, however it is highly recommended to use automatic spinneret inspection system. Finally, spin pack is reassembled. New screen packs and seals are installed, plates are aligned and stacked, assembly bolts are coated with anti-seize compound and tightened to proper torque. Clean

spinpack must be preheated in a convection oven before being reintroduced back into production. The major steps of the spin pack cleaning process are shown in Figure 3-8.

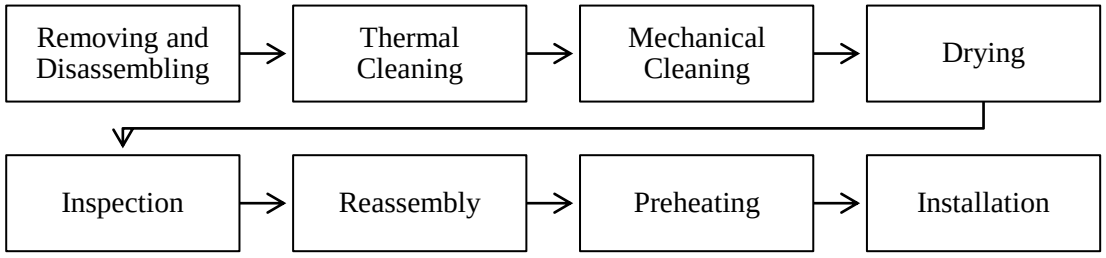


Figure 3-8: Spin pack cleaning process

The total cost of cleaning and maintaining a spin pack (PCC in [$/pack]) is a sum of costs of pack expendables (i.e., pack screens, sealing gaskets, etc.) (C_{Exp}^{PC}), dedicated labor (C_L^{PC}), pack cleaning equipment (C_E^{PC}), utilities (C_U^{PC}), and space (C_S^{PC}) as shown below:

$$PCC = C_{Exp}^{PC} + C_L^{PC} + C_E^{PC} + C_U^{PC} + C_S^{PC} \tag{89}$$

Cost of expendable materials and parts is calculated by adding the cost of each component. If there is a special team that is dedicated to spinpack cleaning only, then the labor cost per cleaning of one spinpack is calculated according to Equation (90):

$$C_L^{PC} = \frac{L^{PC} \times APT_{L^{PC}} \times LR^{PC}}{N_M \times N_B} \tag{90}$$

where L^{PC} is a number of persons in a cleaning crew, $APT_{L^{PC}}$ is the annual paid time, LR^{PC} is the wage rate, N_M is the number of maintenances per year, and N_B is the number of spinning beams. In this equation, numerator is the total annual cost of labor, and denominator is a number of spin packs cleaned per year.

The cost of equipment per cleaning of one spinpack (C_E^{PC}) is calculated as total capital investment in pack cleaning equipment (CI_E^{PC}) distributed over it productive (economic) lifetime (n_E^{PC}) in years and then over the number of packs cleaned per year ($N_M \times N_B$) as shown below:

$$C_E^{PC} = \frac{CI_E^{PC}/n_E^{PC}}{N_M \times N_B} \tag{91}$$

Cost of utilities per cleaning of one spinpack (C_U^{PC}) is a sum of costs of each type of utility (e.g., electricity, gas, water, compressed air) used by each cleaning process:

$$C_U^{PC} = \sum_p \sum_u UR_{u,p}^{PC} \times UP_u \times t_p^{PC} \tag{92}$$

where $UR_{u,p}^{PC}$ is the consumption rate of utility u by cleaning process p, UP_u is the price of utility u, t_p^{PC} is the time that spinpack spends in process p.

Finally, the cost of space per cleaning of one spinpack (C_S^{PC}) is calculated as annual cost of space dedicated to cleaning area ($A^{PC} \times SP$) distributed over the number of packs cleaned per year ($N_M \times N_B$) as shown below:

$$C_S^{PC} = \frac{A^{PC} \times SP}{N_M \times N_B} \tag{93}$$

where A^{PC} is the area occupied by the spin pack cleaning operations in m^2, SP is the annual price of space in \$/m^2. In the next section, the cost model implementation in MS Excel spreadsheet will be discussed.

3.2 COST MODEL IMPLEMENTATION IN MS EXCEL

The cost model formulated in Section 3.1.2 has been implemented in a MS Excel spreadsheet to automate the calculations and analysis of the results. The workbook consists of three main worksheets, including the cost model itself, supporting estimation sub-models of the parameters and a detailed report of the cost breakdown structure. A screen shot of the "Cost Model" worksheet (not all content shown) is presented in Figure 3-9. A detailed cost model worksheet is shown in Appendix B. It is separated into three sections, namely controls, a brief report of the results and cost model inputs and calculations grouped into logical blocks. The control section contains several command buttons to call the data input form, save/load models, and run design of experiments and Monte-Carlo simulations. This functionality will be discussed later. The product cost summary section displays brief results of the model in terms of total and process specific annual and per unit costs, to allow user to see the effect of the input parameters on the costs.

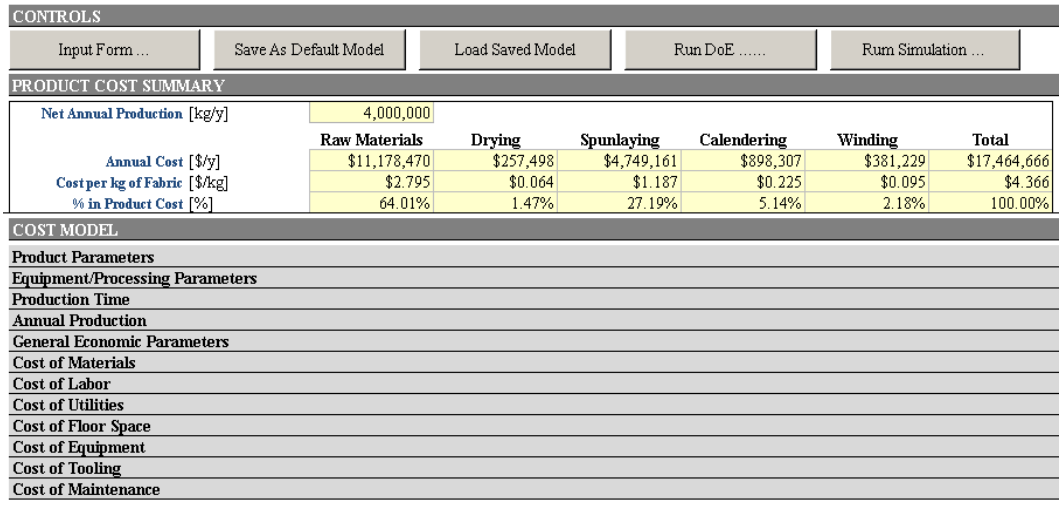


Figure 3-9: Clipped layout of the "Cost Model" worksheet

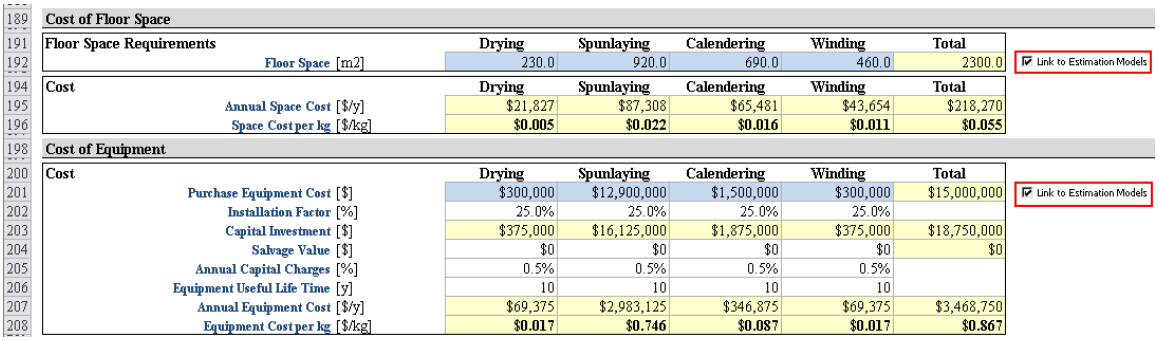
The last section of the "Cost Model" worksheet is the cost model implementation. The blocks of information in this section, in most parts, correspond to the order of the model formulation in Section 3.1.2. Figure 3-10 shows the blocks for the specification of product parameters and spunlaying process parameters as an example. The user enters information into the unfilled bordered cells and the values of parameters relevant to each block are calculated in the filled cells. For example, changing the value of the polymer flow rate in the row 38 of spunlaying parameters will change the specific throughput, filament take-up velocity and production rate in rows 40-43 according to Equations (5), (6), and (4), correspondingly.

17	**Product Parameters**						
19	Fiber Technology	Bicomponent					
20	Fiber Cross Section	Round					
21	Fiber Configuration	Sheath Core					
22	Fiber Linear Density [deniers]	1.5					
23	Fabric Basis Weight [g/m2]	100					
25	**Fiber Composition**	**Component A**			**Component B**		
26	Component Weight % in Fiber [%]	75.0%			25.0%		
27		**Polymer A**	**Additive A1**	**Additive A2**	**Polymer B**	**Additive B1**	**Additive B2**
28	Materials [%]	PET			PA 6		
29	Materials Weight % in Component [%]	100.00%	0.00%	0.00%	100.00%	0.00%	0.00%
30	Materials Weight % in Fiber [%]	75.00%	0.00%	0.00%	25.00%	0.00%	0.00%
32	**Equipment/Processing Parameters**						
34	**Spunlaying**						
35	Working Width [m]	3.4					
36	Number of Beams [# beams]	1					
37	Number of Holes [# holes/m/beam]	4000					
38	Polymer Mass Flow Rate [g/hole/min]	0.70					
39	Yield [%]	100.0%					
40	Specific Throughput [kg/h/m/beam]	168.00					
41	Fiber Take-up Velocity [m/min]	4200.00					
43	Production Rate [kg/h]	571.20					
44	Requires Drying Equipment	Yes					

Figure 3-10: Example of the cost model data-input blocks

Some model inputs, for example, floor space requirements or purchase equipment costs in rows 192 and 201 in Figure 3-11, can be directly specified by the user or these values can be linked to estimation sub-models. When the user checks the "Link to Estimation

Models" check box, the input parameters become linked to the corresponding estimation sub-models on the "Estimation Models" worksheet. The linking option is useful when exact values of inputs are unknown or when the user wants these values to be updated in response to changes in other input parameters. For example, the cost of equipment depends on the working width of the line. When purchase equipment costs are not linked to the estimation sub-model, the user has to alter these costs manually after each change of the working width. In contrast, when purchase equipment costs are linked to the estimation sub-model, they are automatically recalculated.



189	**Cost of Floor Space**						
191	**Floor Space Requirements**		**Drying**	**Spunlaying**	**Calendering**	**Winding**	**Total**
192	**Floor Space**	[m2]	230.0	920.0	690.0	460.0	2300.0
194	**Cost**		**Drying**	**Spunlaying**	**Calendering**	**Winding**	**Total**
195	**Annual Space Cost**	[$/y]	$21,827	$87,308	$65,481	$43,654	$218,270
196	**Space Cost per kg**	[$/kg]	**$0.005**	**$0.022**	**$0.016**	**$0.011**	**$0.055**
198	**Cost of Equipment**						
200	**Cost**		**Drying**	**Spunlaying**	**Calendering**	**Winding**	**Total**
201	**Purchase Equipment Cost**	[$]	$300,000	$12,900,000	$1,500,000	$300,000	$15,000,000
202	**Installation Factor**	[%]	25.0%	25.0%	25.0%	25.0%	
203	**Capital Investment**	[$]	$375,000	$16,125,000	$1,875,000	$375,000	$18,750,000
204	**Salvage Value**	[$]	$0	$0	$0	$0	$0
205	**Annual Capital Charges**	[%]	0.5%	0.5%	0.5%	0.5%	
206	**Equipment Useful Life Time**	[y]	10	10	10	10	
207	**Annual Equipment Cost**	[$/y]	$69,375	$2,983,125	$346,875	$69,375	$3,468,750
208	**Equipment Cost per kg**	[$/kg]	**$0.017**	**$0.746**	**$0.087**	**$0.017**	**$0.867**

Link to Estimation Models

Link to Estimation Models

Figure 3-11: Example of estimated model inputs

In addition to the space requirements and purchase equipment cost sub-models, the "Estimation Models" worksheet contains estimations of labor requirements, utilities consumption rates, tooling costs, and spinpack cleaning costs, that may also be linked to the main model if needed. The sub-model for estimation of the purchase equipment cost is shows in Figure 3-12. This model scales up the cost of the 1.7-meter wide line accounting for "new"

equipment parameters specified in the model and several adjustment factors that may be used to include (dis)economy of scale in the calculations.

Estimation of Purchase Equipment Cost	Base	New			
Width [m]	1.7	3.4			
# Beams [#]	1.0	1.0			
# of Holes	4000.0	4000.0			
Polymers to Dry [kg/h]	285.6	571.2			
	Drying	Spunlaying	Calendering	Winding	Total
Distribution By Processes	2.0%	86.0%	10.0%	2.0%	100.0%
Base Equipment Cost	$ 150,000	$ 6,450,000	$ 750,000	$ 150,000	$ 7,500,000
Drying Throughput Adjustment Factor	1.00				
Width Adjustment Factor		1.00	1.00	1.00	
# Beams Adjustment Factor		1.00			
# of Holes Adjustment Factor		-			
Purchase Equipment Cost	$300,000	$12,900,000	$1,500,000	$300,000	$15,000,000

Figure 3-12: Example of parameters estimation sub-model

After all input parameters of the model are specified, the detailed cost breakdown structure is reported in the "Cost Model Results" worksheet as shown in Figure 3-13. The report includes annual production costs, costs per kilogram and square meter of final fabric and cost distribution in the context of processing steps and cost elements. The figure also shows that each row of the report can be further expanded to see the contribution of each cost element to a process cost, or the contribution of each process to the total cost of a cost element.

	A	B	C	D	E	F	G
2			Product Cost Structure				
3		Cost by Processing Steps		annual	per kg	per m2	%
4		Raw Materials		$ 11,178,470	$ 2.79	$ 0.28	64.0%
14		Spunlaying		$ 5,006,659	$ 1.25	$ 0.13	28.7%
16			Labor	$ 627,948	$ 0.157	$ 0.016	13%
17			Utilities	$ 399,281	$ 0.100	$ 0.010	8%
18			Floor Space	$ 109,135	$ 0.027	$ 0.003	2%
19			Equipment	$ 3,052,500	$ 0.763	$ 0.076	61%
20			Tooling	$ 244,800	$ 0.061	$ 0.006	5%
21			Maintenance	$ 572,996	$ 0.143	$ 0.014	11%
22			Total	$ 5,006,659	$ 1.25	$ 0.13	100%
24		Calendering		$ 898,307	$ 0.22	$ 0.02	5.1%
34		Winding		$ 381,229	$ 0.10	$ 0.01	2.2%
44		**Total**		**$ 17,464,666**	**$ 4.37**	**$ 0.437**	**100.0%**
45							
46		Cost by Cost Elements		annual	per kg	per m2	%
47		Raw Materials		$ 11,178,470	$ 2.79	$ 0.28	64.0%
48		Labor		$ 1,143,282	$ 0.29	$ 0.03	6.5%
50			Spunlaying	$ 627,948	$ 0.157	$ 0.016	55%
51			Calendering	$ 263,594	$ 0.066	$ 0.007	23%
52			Winding	$ 251,740	$ 0.063	$ 0.006	22%
53			Total	$ 1,143,282	$ 0.29	$ 0.03	100%
55		Utilities		$ 570,047	$ 0.14	$ 0.01	3.3%
62		Floor Space		$ 218,270	$ 0.05	$ 0.01	1.2%
69		Equipment		$ 3,468,750	$ 0.87	$ 0.09	19.9%
76		Tooling		$ 244,800	$ 0.06	$ 0.01	1.4%
83		Maintenance		$ 641,047	$ 0.16	$ 0.02	3.7%
90		**Total**		**$ 17,464,666**	**$ 4.37**	**$ 0.44**	**100.0%**

Figure 3-13: Example of detailed costing report

As was mentioned at the beginning of this discussion, the cost model has several tools to automate the model data input and analysis of the results. These tools can be called with command buttons located at the top of the cost model worksheet, as shown in Figure 3-9. While all input parameters in the form may be specified in the Excel worksheet itself, the user may also use the specially designed input form. The form allows the user to fill in the required information step-by-step. The form for the specification of the general economic parameters is shown in Figure 3-14, as an example. Similar forms are designed for all information blocks.

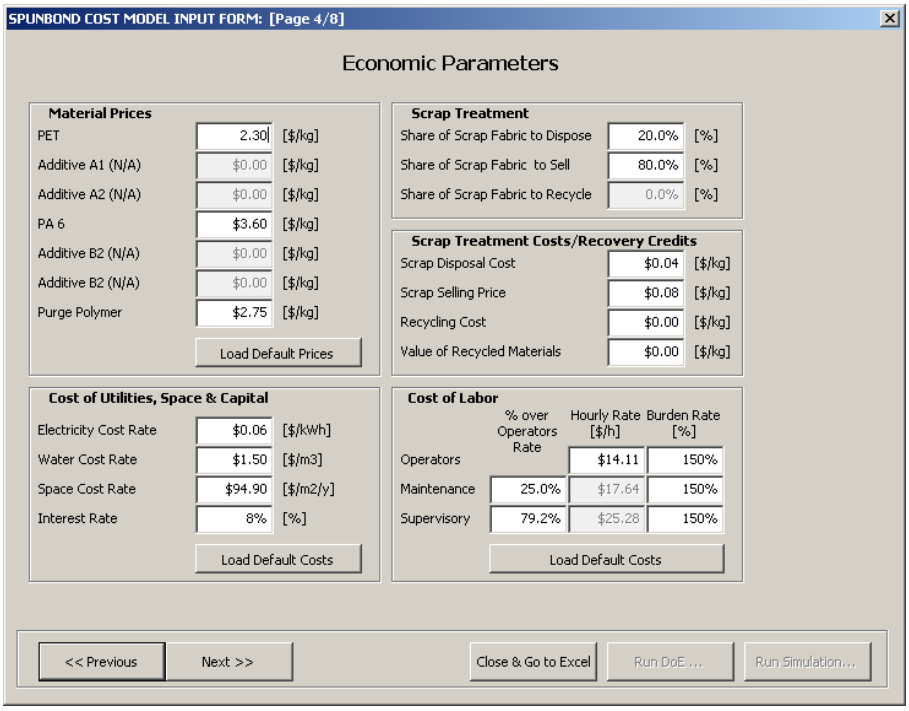


Figure 3-14: Example of the cost model input form

In addition to calling the input form, the cost model controls allow the input parameters of some scenario to be saved to a separate worksheet using the "Save As Default Model" command button. This information can be loaded using the "Load Saved Model" command button to return all model parameters to their last default values. The "Run DoE…" command button at the top of the control panel of the model calls the design of experiment specification form, as shown in Figure 3-15. Using this form, the user can select a set of factors to study and specify value levels for each factor, as well as, select the responses of the experiment. When the user hits the "Run DoE" button, the program will input each combination of factors levels into the cost model, and will record the corresponding values of the response fields.

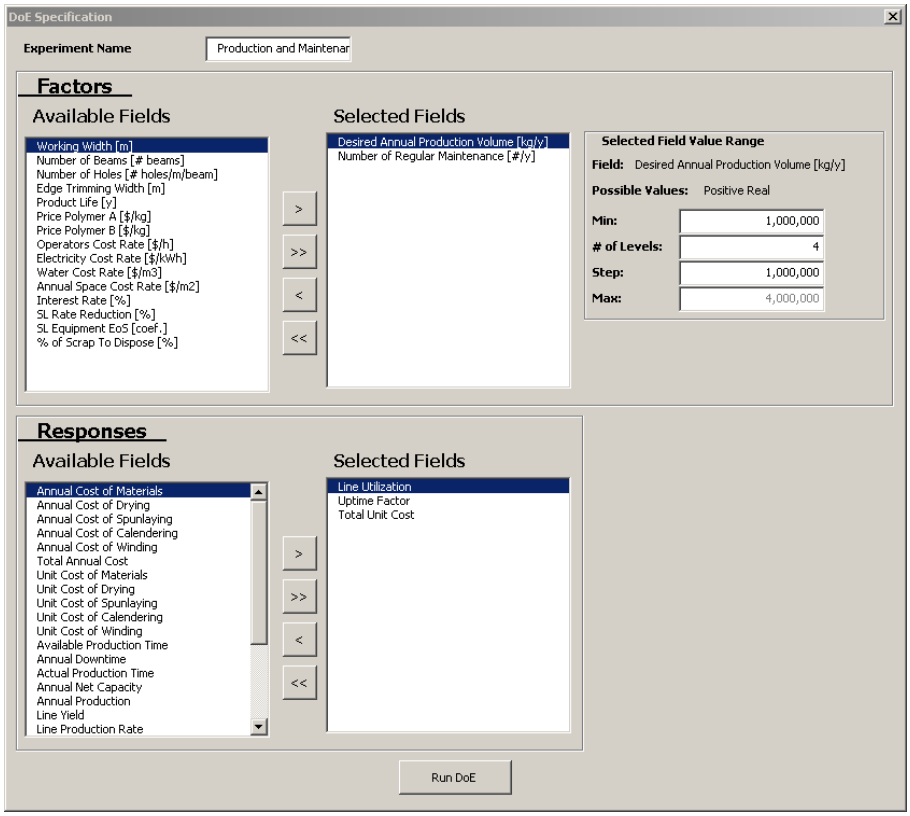


Figure 3-15: Design of experiment specification form

For example, the desired annual production rate and number of maintenances per year were selected as experiment factors on the figure. The first factor is set to vary from one million to four million kilograms per year with the step of one million, which results in four levels for this factor. The number of maintenances is set to be 12, 24, and 36 maintenances per year. Line utilization, uptime factor, and unit cost of product were selected as experiment responses. For these inputs, the result of the experiments will be values of the responses for twelve combinations of annual production rate and number of maintenances per year. This example of the design of experiment for the first six combinations of parameters is shown in Figure 3-16.

	A	B	C	D	E	F
1		Desired Annual Production Volume	Number of Regular Maintenance	Line Utilization	Uptime Factor	Total Unit Cost
2	1	1,000,000	12	22.4%	98.9%	$8.680
3	2	2,000,000	12	44.8%	98.9%	$5.804
4	3	3,000,000	12	67.2%	98.9%	$4.845
5	4	4,000,000	12	89.6%	98.9%	$4.366
6	5	1,000,000	24	22.7%	97.7%	$8.744
7	6	2,000,000	24	45.3%	97.7%	$5.836

Figure 3-16: Example of Design of Experiment outputs

The results of the design of experiment may be plotted graphically to better identify the cost behavior. For the example above, the unit cost behavior as a function of annual production can be plotted for different numbers of maintenances per year. In addition, the results may be used to identify effects of parameters or combination of parameters on unit cost of product.

The second analytical tool is a Monte-Carlo simulation of the cost model. The form to specify parameters of the simulation is shown in Figure 3-17. This window can be called with the "Run Simulation …" command button from the cost model controls. Analogously to the design of experiment, the user has to select factors and responses for the simulation. For each factor, the user defines an assumed random distribution and specifies its parameters. For example, the simulation form shown in the figure contains the price of polymer A as a factor, which has uniform distribution from 2.25 to 2.35 dollars per kilogram. During the simulation run, values of factors are sampled from the corresponding random distributions based on the random numbers seed specified by the user. These sampled values are used as model input parameters. Together with the resulting values of the response fields, they are recorded in

table form on a new worksheet. The number of rows is equal to the number of replications specified by the user.

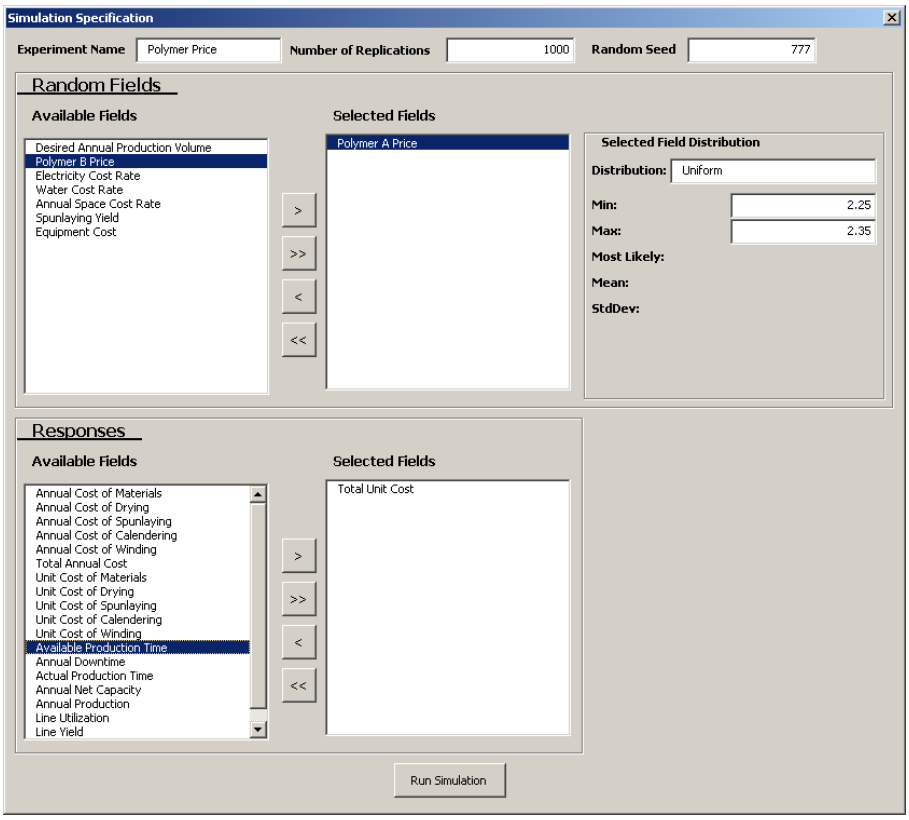


Figure 3-17: Simulation specification form

The main purpose of the simulation tool is to identify the expected values of responses and associated risks under uncertainty in the input factors. The reported values of the responses can be used to construct histograms, fit distributions, estimate mean values, standard deviations, and confidence intervals. In the next section, the developed cost modeling and analysis tool is used to illustrate its application for cost estimation and the analysis of the spunbond process.

3.3 APPLICATION OF THE COST TOOL

In this section, several examples are discussed to illustrate possible applications of the model for cost analysis of the spunbond process. While there may be many other questions that could be studied with this type of model, the examples shown in this section were selected based on information availability, which had limited the depth of the model. The discussion starts from definition of the base-case used in the analysis, as well as specification of all input information and second-order equations. Then the base-case is analyzed in respect to cost breakdown structure, cost sensitivity to input parameters, and the effect of line utilization and uncertainty on unit costs. Finally, an optimization study is conducted to find the optimal maintenance policy.

3.3.1 Base-case definition and input information

For the purpose of the analysis, a thermally bonded spunlaid nonwoven fabric produced of bicomponent filaments (PET core / PA 6 sheath) was selected as a sample product. Such a product combines the useful properties of both polymers, such as good dyeability, abrasion resistance, moisture absorption of nylon, with the good flexibility and high modulus of polyester. The resulting high strength, tear-resistant, moldable, dimensionally and thermally stable fabric can be used for commercial carpeting, automotive and roofing applications. It was assumed that the annual demand for the fabric will be 4000 tonnes, and the product will be produced for 10 years. The summary of product characteristics is shown in Table 3-8.

Table 3-8: Product characteristics

Parameters	**Value**	**Units**
Fiber technology	Bicomponent	
Fiber cross section	Round	
Fiber configuration	Core / Sheath	
Materials	PET / PA6	
Composition (Core-/Sheath ratio)	75 / 25	[%]
Fiber linear density	1.5	[denier]
Fabric basis weight	100	[g/m^2]
Annual demand	4000	[tonnes/y]
Product life-time	10	[y]

For the base-case scenario, the assumed working schedule of the spunbond line is 24 hours a day (three shifts per day), 7 days a week for a total of 50 working weeks per year. The remaining 2 weeks is used to perform annual capital maintenance. In addition, the line is shut down once per month for 1 shift (8 hours) to perform regular maintenance. This time includes time for machines shutdown/startup (2 hours), purging of the spunlaid equipment (1 hour), and spinpack change time (5 hours per spinpack). This working schedule results in the maximum available production time of 8,400 hours per year with the uptime factor of 98.9% or 8,304 hours of actual annual production time. Table 3-9 summarizes the base-case working schedule of the line.

Table 3-9: Base-case working schedule for a spunbond line

Parameters	**Value**	**Units**
Number of working hours per day	24	[h/day]
Number of working days per week	7	[days/week]
Number of working weeks per year	50	[weeks/y]
Duration of capital maintenance	2	[weeks/y]
Number of regular maintenance	12	[maint./y]
Duration of one regular maintenance, including:	8	[h/maint.]
- line shutdown/startup time	2	[h/stop]
- spunlaid machine purge time	1	[h/stop]
- spinpack change time	5	[h/maint./beam]
Maximum available production time	8,400	[h/y]
Maintenance downtime	96	[h/y]
Actual production time	8,304	[h/y]
Uptime factor	98.9%	[%]

To produce a nonwoven web comprised of 1.5 denier fibers, the polymer throughput rate should be kept at 0.7 gram per hole per minute. Since the basis weight of the web is 100 gram per square meter, a single spinning beam machine is chosen. Based on these parameters and the expected working schedule of the line, it was calculated that a 3.4 meter wide spunbond line with 4,000 holes per meter of spinning width is enough to meet the expected demand. Assuming that material losses occur at the edge trimming step only (i.e., yields of drying, spunlaying, and thermal calendering steps are 100%), the maximum production capacity for such line is approximately 4,500 tonnes per year. Production conditions, spunbond line specifications, and resulting annual capacity of the line are summarized in Table 3-10.

Table 3-10: Process/equipment parameters and capacity

Parameters	Units	Value
Polymer flow rate	0.7	[g/hole/min]
Number of spinning beams	1	
Number of holes	4,000	[holes/m/beam]
Working width	3.4	[m]
Edge trimming width	0.2	[m]
Net fabric width	3.2	[m]
Line specific throughput	168	[kg/h/m/beam]
Gross production rate*	571.2	[kg/h]
Line yield*	94.1	[%]
Net production rate*	537.6	[kg/h]
Annual net capacity of the line	4,464,230	[kg/y]

* Steady state values

The manufacturing line under consideration consists of three main pieces of equipment including the spunlaid machine, thermal calender and winder. In addition, since both polymers are hydroscopic, it was assumed that the production line requires a separate drying step before fiber spinning and includes two dryers. As was discussed in Section 3.1.2.3.4, the purchase price of spunbond equipment depends on many parameters including system type (homocomponent, bicomponent), technology (open, closed system), manufacturer, working width, number of spinning beams, etc. To build the purchased equipment cost function, information about the different types of equipment and corresponding prices should be collected. However, this information is a commercial trade secret and is difficult to obtain. Therefore, a simplified version of the equipment cost estimation function was used in this study.

The purchase price of one specific spunbond line, suitable for production of a given product but with lower capacity (Base Line) than needed, was obtained from an equipment manufacturer. Based on expert opinion this price was allocated to equipment required at each production steps as shown in Table 3-11. Then the price of each piece of equipment was scaled-up using Equation (94):

$$PEC_p = PEC_p^{Base} \times \prod \left(\frac{F_i}{F_i^{Base}} \right)^{n_i} \quad (94)$$

where PEC_p and PEC_p^{Base} are the scaled-up and base purchase costs of equipment for process p correspondingly, F_i and F_i^{Base} values of capacity parameters i for scaled-up and base equipment, and n_i is economy of scale exponent. A value of n_i equal to one means that the cost of equipment increases proportionally to the capacity factor i, values between zero and one represent economy of scale, values greater than one represent diseconomy of scale. Chosen capacity factors for each type of equipment are shown in Table 3-11. All economy of scale exponents were set to one due to the lack of information about actual economy of scale.

Table 3-11: Spunbond line price distribution between processing equipment

Equipment type	Polymer drying system (2 sets)	Spunlaid web formation machine	Thermobonding calender	Master roll winder
Cost distribution	2%	86%	10%	2%
Capacity factors	Raw materials usage rate	Working width, number of spinning beams	Working width	Working width

The resulting purchase costs of the equipment are shown in Table 3-12. It was also assumed, that the installation cost is 25% of purchased equipment cost and the economic lifetime of equipment is 10 years. For the purpose of the study, the equipment salvage value was set to zero.

Table 3-12: Spunbond equipment capital investment data

Equipment	Purchased Cost	Installation Factor	Capital Investments	Equipment Life
Polymer drying system (2 sets)	$300k	25%	$375k	10 years
Bicomponent spunlaid web formation machine	$12,900k	25%	$16,125k	10 years
Thermal calendering machine	$1,500k	25%	$1,875k	10 years
Winder	$300k	25%	$375k	10 years
Total line	$15,000k	-	$18,750k	-

In addition to the equipment, the cost of tooling may significantly contribute to the total capital investment in the spunbond line. While calendering and winding may require some special tooling, it is assumed that their costs are insignificant and the only tooling investment considered in the model is the cost of the spinning packs and spinnerets used in spunlaying. Based on expert opinion the cost of spinpack for bicomponent fiber production was estimated to be $4,000 per inch ($160k per meter). The cost of a spinnerette was estimated to be $10 per hole (e.g., one meter of spinneret with 4000 holes will cost $40k). It was assumed that 2 sets of spinpack and spinnerette are bought to reduce line downtime

during maintenance (i.e., to exclude spinpack cleaning time from maintenance time). Table 3-13 summarizes tooling capital investment requirements.

Table 3-13: Tooling capital investment data

Tooling	Purchased Cost, $/m	Number of Sets	Capital Investments
Spin Pack	$160k	2	$1,088k
Spinnerette	$40k	2	$272k
Total	$200k	-	$1,360k

To estimate the number of operators required for the spunbond line it was assumed that the line requires one lead operator per line and one operator per meter of working width. Therefore, 3.4 meter wide spunbond line required 5 operators to work in 3 shifts. To allocate the cost of operating labor to each production step, it was assumed that lead operator is allocated uniformly to each process (i.e., 0.25 persons per shift per piece of equipment). Half of the operators are dedicated to dying/spunlaying with 90% of the time spend on spunlaying machine, and the second half of the operators are dedicated to thermal calendering/winding units in proportion 50% to 50%. It was also assumed that one maintenance person is needed for the line less than 3.4 meter wide, and 2 maintenance employees are required for larger lines. Maintenance labor was distributed to each production step proportionally to capital investment in the corresponding equipment. In addition, one technical manager was included into calculation and assigned to each production step in proportion to the number of operators. Both maintenance and supervisory personnel are assumed to work one shift per day. Table 3-14 summarizes labor requirements.

Table 3-14: Labor requirements for the spunbond production

Equipment	Lead Operator	Operators	Maintenance Labor	Supervision
	[persons/shift]			
Polymer drying	0.25	0.20	0.04	0.09
Spunlaying	0.25	1.80	1.72	0.41
Calendering	0.25	1.00	0.20	0.25
Winding	0.25	1.00	0.04	0.25
Total line	1.00	4.00	2.00	1.00
Number of working shifts	3	3	1	1

Electricity and water were considered as the main utilities used in the spunbonding process. Specific energy consumption for the entire line was estimated as 2 kWh per kilogram of materials process (i.e., PET 75%, PA6 25%). Based on this number, and the expected production rate of the analyzed spunbonding line, the steady state electricity consumption of the line is 1,142.4 kW. These rate was approximately distributes between the production equipment involved, based on similar equipment specifications which are publicly available. The consumption of water of the Base Line was scaled-up proportionally to the production rates and was evenly distributed between the spunlaying and calendering steps. The space dedicated to the spunbond line was assumed to be 25,000 square feet (~2,300 m^2) based on several news articles concerning recently opened spunbond plants in the US. This space was roughly allocated to the production steps in proportion to the dimensions of similar equipment obtained from publicly available specifications. The resulting consumption of electricity, water and space requirements are shown in Table 3-15.

Table 3-15: Utilities consumption rates and space requirements

Equipment	Electricity		Water		Space	
	[%]	[kW]	[%]	[m^3/h]	[%]	[m^2]
Polymer drying	12%	137.09	0%	0	10%	230
Spunlaying	60%	685.44	50%	2.27	40%	920
Calendering	27%	308.45	50%	2.27	30%	690
Winding	1%	11.42	0%	0	20%	460
Total line	100%	1,142.40	100%	4.54	100%	2,300

The model considers two types of equipment maintenance. Capital maintenance is performed once per year for 2 weeks, and the cost of this maintenance is estimated as 3% of the capital investment in equipment. Regular maintenance is performed each month for 1 shift. The cost of this maintenance includes the costs of shutdown/startup, purging of the spunlaid machine and cleaning costs of the spin packs. The shutdown/startup cost per maintenance includes the cost of electricity and water based on the consumption rates described above, multiplied by the time required for these operations (i.e., 2 hours). The purging cost includes the costs of utilities consumed by the spunlaid machine for 1 hour and the cost of purchase and disposal of purging polymer. The spin pack cleaning cost was estimated in a separate model, which accounts for cleaning equipment cost, utilities consumption and cost of expendable.

The costs of each resource considered in the model, along with the corresponding sources of information are summarized in Table 3-16. The average US market prices of polymers were used as a unit cost of raw materials. The cost rates of utilities, space and labor were obtained for North Carolina.

Table 3-16: Price of the resource for base case scenario

Resource	Value	Units
Materials		
PET[1]	2.3 (2.25 - 2.35)	[$/kg]
PA 6[2]	3.6 (3.44 - 3.75)	[$/kg]
Purge polymer[3]	2.75 (2.50 – 3)	[$/kg]
Scrap treatment		
Scrap disposal cost[4]	0.039	[$/kg]
Scrap selling price[5]	0.075 (0.05-0.1)	[$/kg]
Labor		
Operating[6] (51-6091)	14.11	[$/h]
Maintenance[6] (49-9071)	17.64	[$/h]
Supervision[6] (51-1011)	25.28	[$/h]
Burden rate[7]	150	[%]
Utilities		
Electricity[8]	0.0611	[$/kWh]
Water[9]	1.50	[$/$m^3$]
Space rental rate[10]	94.9	[$/$m^2$/y]
Interest rate[11]	8 (5-10)	[%]
Capital insurance rate	0.05	[%]

[1] RISI, Nonwovens Markets, Vol. 27, #10 (May 2012)
[2] Plastics Technology, Commodity and engineering resin prices (March 2012)
[3] Expert opinion
[4] Biocycle Magazine, The state of garbage in America, October 2010 (as of 2008)
[5] Recycler's world (www.recycle.net)
[6] U.S. Department of Labor, Bureau of Labor Statistics
[7] See appendix C
[8] US Energy Information Administration, U.S. Department of Energy (March 2012)
[9] UNC report
[10] Cushman & Wakefield, Third Quarter 2011
[11] Cost of Capital by Sector (Paper/Plastics Industry)

3.3.2 Base-case scenario cost modeling results

The main results of the base-case cost modeling are summarized in Table 3-17. The annual capacity of the line is about 4,500 tonnes and with an actual production of 4,000 tonnes the utilization of the spunbond line is about 90%. Total annual production cost is about $17.5 million, which results in $4.37 per kilogram of fabric produced.

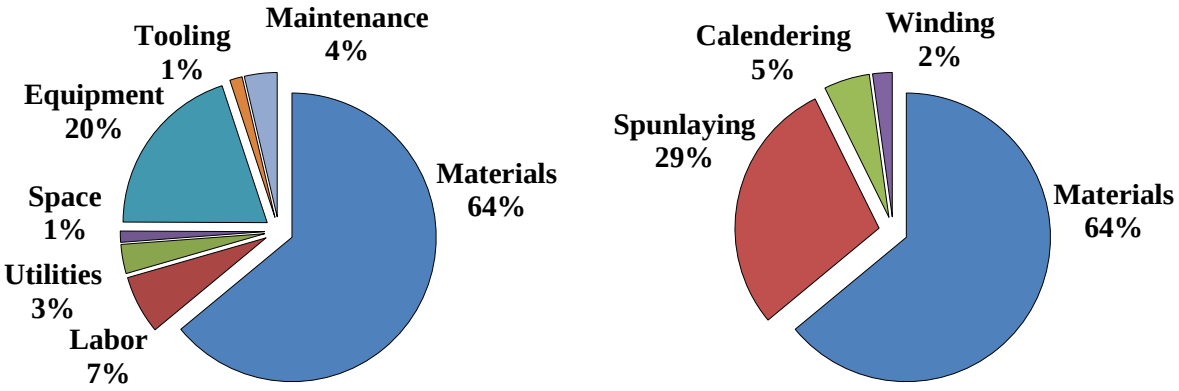
Table 3-17: Base-case cost modeling results summary

Outputs	**Value**	**Units**
Overall line yield*	94.1	[%]
Line uptime factor	98.9	[%]
Annual line net capacity	4,464,230	[kg/y]
Actual net production	4,000,000	[kg/y]
Line utilization	89.6	[%]
Total annual production cost	17,464,666	[$/y]
Cost per kilogram of fabric	4.366	[$/kg]
Cost per square meter of fabric	0.437	[$/m^2]

* Steady state values

The resulting cost structure, broken down by cost elements and processing steps, is shown in Figure 3-18 (a, b), respectively. It can be seen that raw materials comprise 64% of the total production cost. In terms of cost elements, the next largest cost contributor is the annual cost of equipment (20%), followed by the cost of labor (7%), maintenance (4%), and utilities (3%). The cost structure by production steps shows that spunlaying adds 29% to product cost, and cost of calendering and winding are significantly lower at levels of 5% and 2% correspondingly. The cost structure shows that cost minimization attempts should be

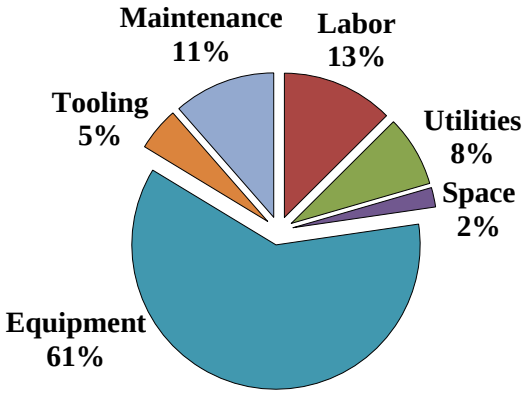
focused on reduction of materials costs and equipment prices, especially for the spunlaid machine.



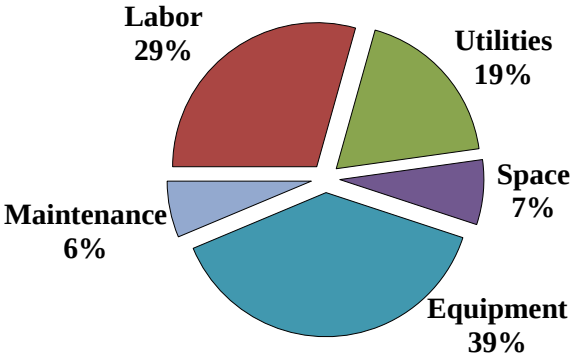
(a) by cost elements (b) by production steps

Figure 3-18: Cost distribution charts for the base case scenario

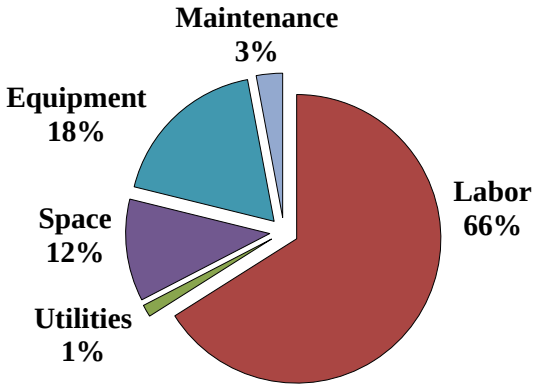
The cost model also allows for the analysis of the cost structures of each processing step by cost elements. These structures for spunlaying (including polymer drying), calendering and winding are shown in Figure 3-19 (a, b, c), respectively. It can be seen from the figures that cost structures differ significantly among processing steps. The most significant contributor for spunlaying is the cost of equipment (61%) due to expensive machinery. In calendering, the share of the equipment cost of 39% is significantly lower and is close to the cost of labor (29%) and utilities (19%). Finally, the cost of labor is the most significant element for winding due to the assumption that this process is not completely automated and that labor is required to handle finished master rolls (one operator was assigned to this process).



(a) Spunlaying (incl. Drying)



(b) Thermobonding calendering



(c) Winding

Figure 3-19: Cost distribution charts for the base case scenario for production steps

A brief analysis of cost structures revealed the dominant cost elements that need to be further investigated to define the most important cost drivers. Since raw materials comprise the most significant portion of product cost, market prices of polymers, processing yield, scrap treatment options may have significant effect on the product cost. The high cost of equipment requires the line to be utilized as much as possible. Other parameters that may influence contribution of equipment cost are line downtime and the cost of capital. To

investigate the influence of factors that drive cost elements without significant impact on line capacity, a cost response diagram for the base-case was built, as shown in Figure 3-20. This diagram shows the increase (decrease) of per unit product cost, in absolute values, in response to changes in cost factors including:

- market prices of raw materials (±20%);
- number of operators (4 and 6 operators);
- labor cost (±20%);
- utilities prices (±40%);
- cost of production space (±20%);
- cost of capital (6% and 10%);
- cost of equipment and tooling (±20%);
- edge trimming width (0.05 and 0.15 m) as a proxy for processing yield;
- scrap disposal cost and scrap selling prices (+200%).

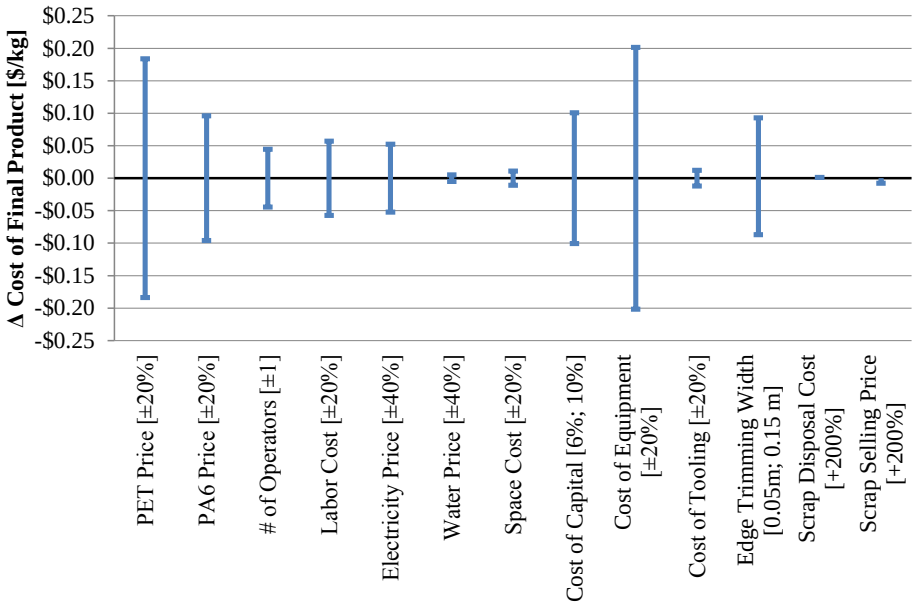


Figure 3-20: Cost variation for the base case scenario

It can be seen from Figure 3-20, that an increase (reduction) of the total equipment cost or market price of PET by 20% will increase the unit cost of final product by about 20 cents or 4-5%. Analogously, an increase (reduction) in market prices of PA6 by 20% results in change of the unit cost of product by 10 cents or about 2%. Similar effects on the unit cost are observed for the edge trimming width and cost of capital. An increase (decrease) of the edge trimming with by 5 centimeters or change of the cost of capital by 2% will result in the unit cost change by 10 cents. One percent of cost reduction can be achieved when the number of operators is reduced by one, the cost of labor is reduced by 20% or electricity prices are lowered by 40%. The effects of water prices, space and tooling costs, and waste treatment options are insignificant. To quantify the relative effects of cost drivers, and make them comparable, mid-point cost elasticity coefficients were calculated as shown in Figure 3-21.

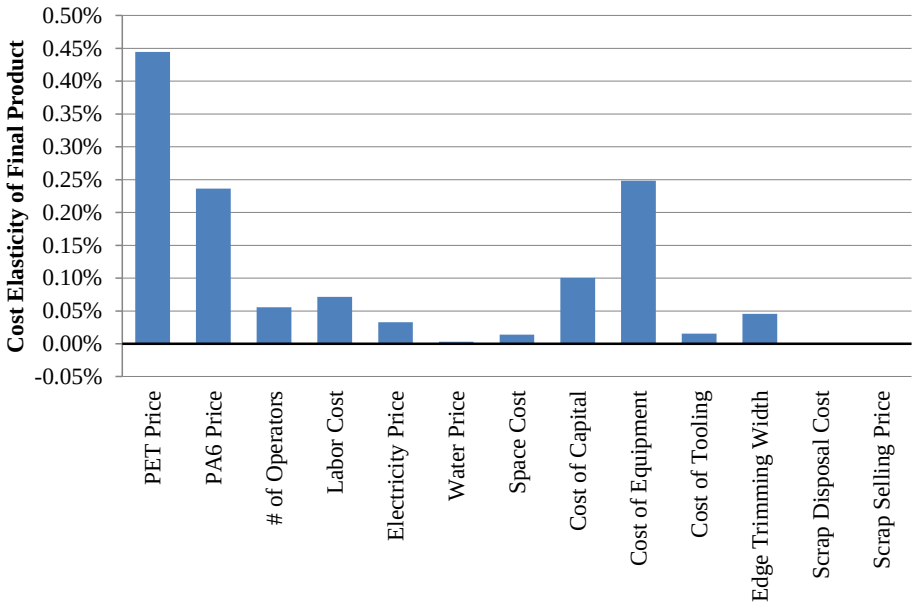


Figure 3-21: Base case unit cost elasticity

The figure shows the relative change in unit cost of final fabric in response to 1% change in cost factors. Similarly to the previous diagram, the price of PET is the most influential factor, and a 1% increase in its price will result in almost an 0.45% increase in the cost of final product. The second and the third largest drivers are the cost of equipment and the market price of PA 6, with elasticity coefficients of 0.25% and 0.24%, respectively.

3.3.3 Effects of line utilization on production cost

In the base-case analysis, it was assumed that annual demand for the product is known and constant. However, this is usually not true. Therefore, in this section the relationship between line utilization and the unit cost of the final product is investigated.

The unit cost of the product and its distribution by cost elements were calculated for different levels of actual production, staring from full line utilization or annual production of about 4,500 tonnes, gradually reducing it by 500 tonnes. The behavior of line utilization and the corresponding indices of unit cost are shown in Figure 3-22. The resulting unit costs and cost structure for nine levels of annual production are shown in Figure 3-23.

As can be seen from these figures, the utilization of the line has a significant effect on both the absolute values of unit cost and the corresponding cost structures. It can be seen from Figure 3-22, that reduction of line utilization gradually increases the unit cost of product. This increase is about 10% when the line utilization is reduced from 100% to 80%. However, the effect of further reduction in utilization grows exponentially. For example, the unit cost of the product at 11% utilization is about 3.5 times higher in comparison to the product cost at full utilization (i.e., $14.4 per unit vs. $4.2 per unit at full utilization).

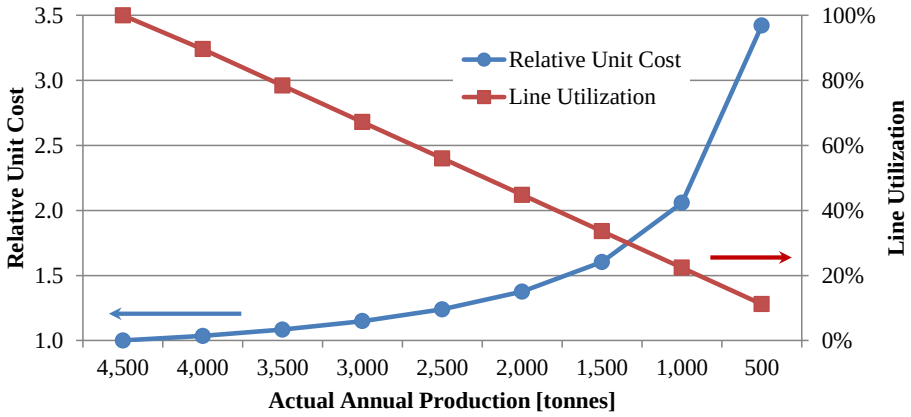
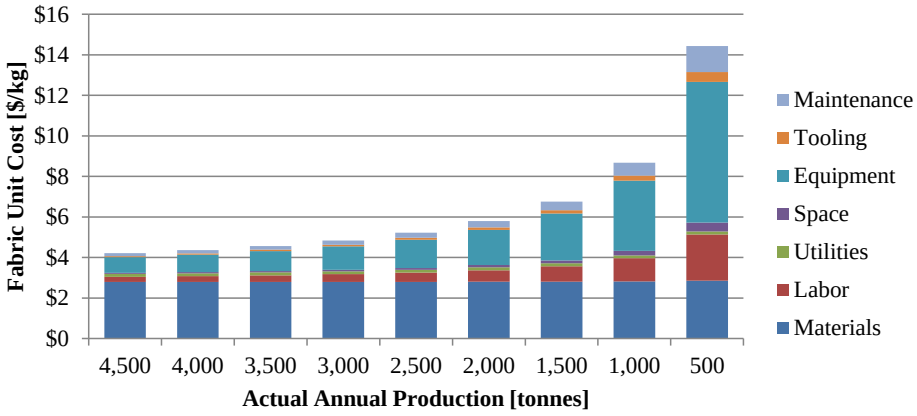
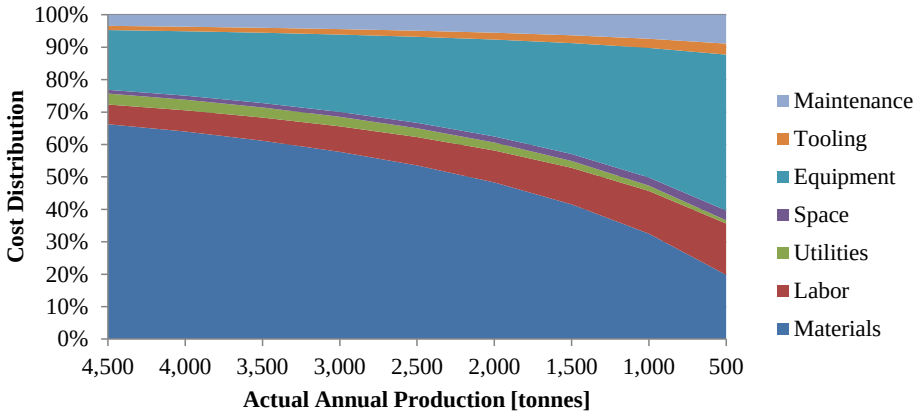


Figure 3-22: Line utilization vs. unit cost

In terms of the cost breakdown structure shown in Figure 3-23, at full utilization raw materials constitute the most significant portion of the total unit production cost. When the utilization decreases, the cost of the variable elements (i.e., materials and utilities) per unit of product stays at the same level. However, since fixed costs are distributed over a smaller amount of product, costs of fixed elements (i.e., labor, equipment, tooling, space) per unit of product increase, which leads to significant changes in the cost structure. For example, at full utilization, raw materials contribute about 65% to total unit cost, and the cost of equipment is about 20%. In contrast, when utilization is lowered to 11% (i.e., annual production is 500 tonnes) the contribution of raw materials becomes about 20%, while the share of equipment cost increases to almost 50%. Therefore, an accurate forecast of the expected demand and the selection of equipment with appropriate capacities to run production at high level of utilization is a very important decision to keep production cost at minimum.



(a) Absolute values



(b) Cost structure

Figure 3-23: Effect of changes in production volume on unit cost by cost elements

3.3.4 Effects of uncertainty in line utilization, polymer and equipment prices

The next step in the analysis is an investigation of the uncertainty in expected demand, material prices and cost of the equipment on the unit cost of the product. Such an analysis can be conducted at the initial stages of new product development, when the exact demand and cost of equipment is unknown, and market prices of materials may change

significantly due to market fluctuations. This can be tackled with case-based analysis or Monte Carlo simulation, as is shown in the following discussion.

During the data collection stage, it was found that polymer prices vary from $2.25 to $2.35 per kilogram for PET, and from $3.44 to $3.75 per kilogram for PA 6. It was also assumed that the cost of the entire line may vary in a range of plus/minus one million dollars around its base-case value of $15 million. The case-based analysis was implemented for maximum values of material prices and equipment cost (worst case), minimum level of these values (best case), and the base-case was used as the most likely case. For these three cases, the unit cost of product at different levels of desired production (line utilization) was recorded as depicted in Figure 3-24.

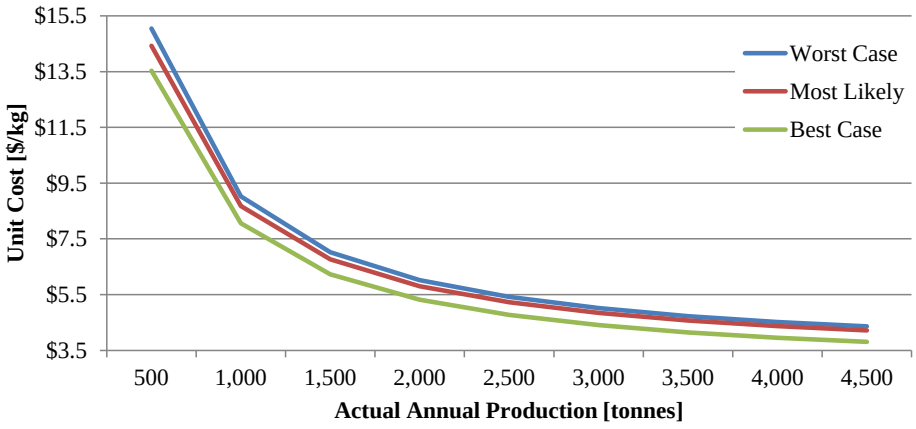


Figure 3-24: Case-based analysis of spunbond fabric cost

The figure shows significant difference between the best case and worst case product costs. The absolute and relative differences of these values are summarized in Figure 3-25.

At the lowest production volume, the worst case yields an increase in product cost by 1.5 dollars per kilogram, or 11% above the best case cost. With an increase in production, this difference reduces in absolute value, reaching about 0.5 dollars per kilogram at full utilization. In relative values, this difference increases to about 15% from the base case cost.

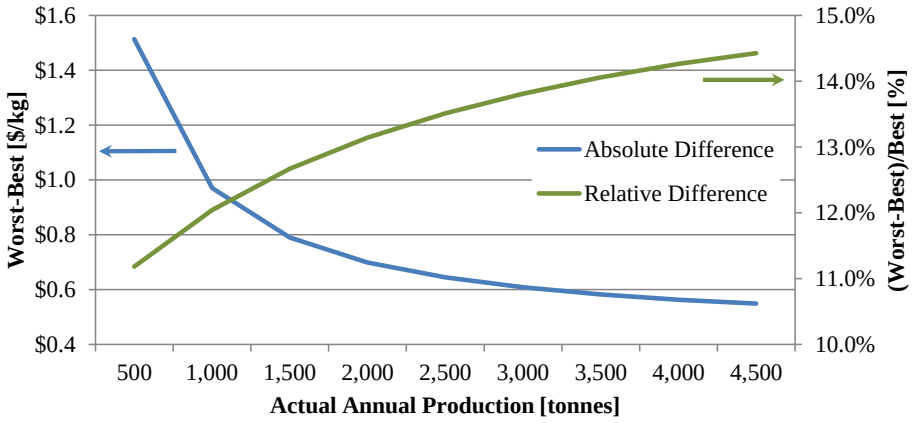


Figure 3-25: Increase in product cost in the worst case compared to the best case

The case-based analysis shows that uncertainty in the parameters may have a significant influence on the predicted product cost. However, it does not give any insight into the probability of different outcomes. Therefore, a Monte Carlo simulation was used to quantify the resulting distribution of the product cost. The distribution of expected demand (desired annual production) was assumed to be triangular, with minimum, maximum, and most likely values of 2,000, 4,464, and 4,000 tonnes, respectively. The uncertainties in polymer and equipment prices were simulated with uniform distributions. The assumed

distributions of input parameters are summarized in Table 3-18. The simulation was run for 1000 replications and the corresponding unit costs were recorded.

Table 3-18: Inputs to product cost simulation

Inputs	**Distribution**	**Min**	**Max**	**Most likely**
Demand [tonnes]	Triangular	2,000	4,464	4,000
Price PET [$/kg]	Uniform	2.25	2.35	-
Price PA 6 [$/kg]	Uniform	3.44	3.75	-
Equipment cost [$]	Uniform	14,000k	16,000k	-

The histogram of resulting unit cost distribution is shown in Figure 3-26 and the statistics are summarized in Table 3-19. The distribution is right-skewed with a long right tail. The unit cost varies from $4.147 to $5.718 with 50% of the cases being lower than the mode value of $4.345. The mean product cost is $4.625 per kilogram. However, due to skewing a median value of $4.55 per kilogram is a better approximation of expected cost. In comparison to the base case cost of $4.366, this cost is higher by 4.2%. This example shows the importance of accounting for uncertainty during the cost estimation to combine the effects of possible risks. An increase of 4.2% in unit product cost may have a significant influence on the company profitability.

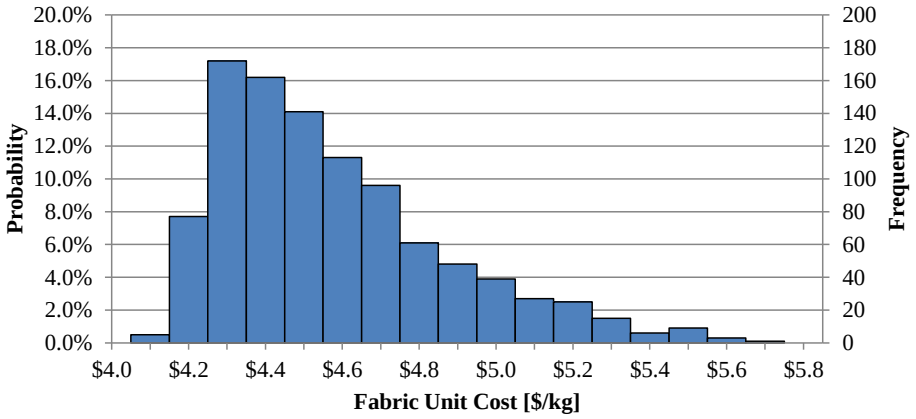


Figure 3-26: Simulated distribution of unit product cost

Table 3-19: Monte-Carlo simulation summary statistics

Unit Cost Statistics	Value
Mean	4.625
Std. Dev.	0.297
Mode	4.345
Median	4.550
Minimum	4.147
Maximum	5.718

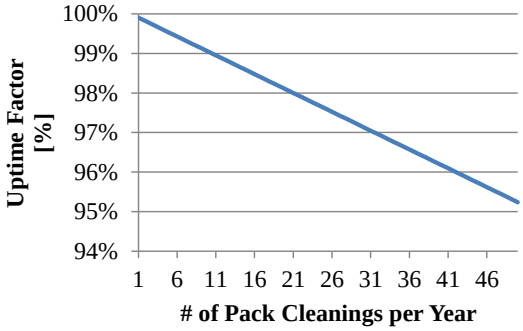
3.3.5 Analysis of maintenance policy

If the spunlaid machine operates for a significant amount of time without maintenance, the production rate should be lowered to account for polymer build up, filter and spinnerette hole blocking. This reduction in production rate reduces the annual amount of product manufactured and may have an influence on the quality of the fabric produced. To improve the production rate, spin packs should be changed and cleaned on a regular basis. In this section, the influence of the number of spinpack changes per year on the cost model

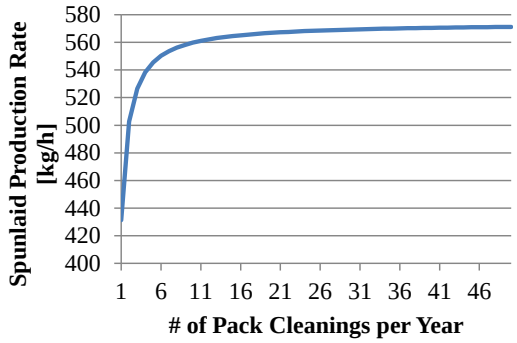
variables and unit cost of final product is investigated. The optimum number of spin pack cleanings per year is identified for different levels of the production degradation rate.

For this analysis, it is assumed that the spunbond line is run at full capacity. After first week without maintenance, there is a gradual reduction in production rate. For example, if maintenance is conducted once per four weeks, and the weekly production rate reduction is 5%, the production rates during four weeks are 100%, 95%, 90%, and 85%, correspondingly. Therefore, the average production rate of the spunlaid machine in this scenario will be 92.5% from its maximum value. The effect of the degradation on fabric quality is not considered.

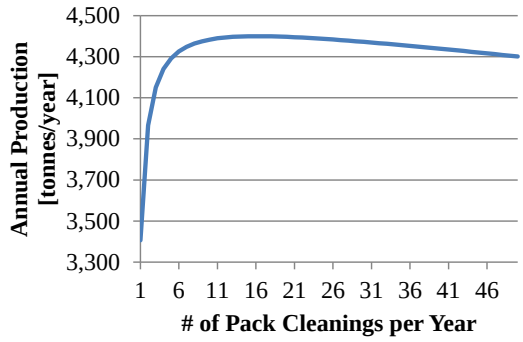
The time between maintenances is calculated as number of working weeks per year, reduced by the duration of capital maintenance and divided by number of maintenance per year. This is a user input into the model. In this scenario, the influence of the number of maintenances per year has nonlinear behavior since it affects several variables simultaneously. Figure 3-27 shows the behavior of the most important model variables as a function of the number of maintenances per year, assuming that production rate is reduced by 1% each week without maintenance. It can be seen in Figure 3-27 (a), that with an increase in the number of maintenances the uptime factor of the line linearly decreases, since each time the maintenance is performed the line must be shut down for 8 hours. On the other hand, Figure 3-27 (b) shows that more frequent pack cleaning improves the production rate of the spunlaid machine. The combined effect of decreasing the uptime and increasing the production rate on annual production volume is shown in Figure 3-27 (c). It can be seen that the annual production volume has concave shape reaching its maximum at 16 maintenances per year.



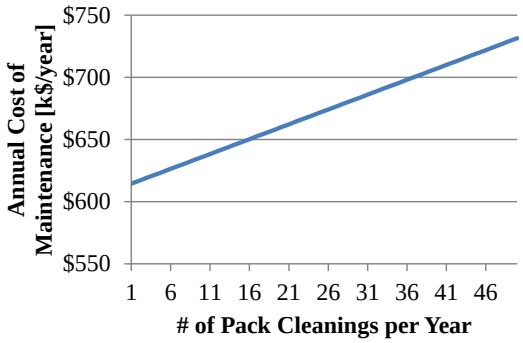
(a) Line uptime



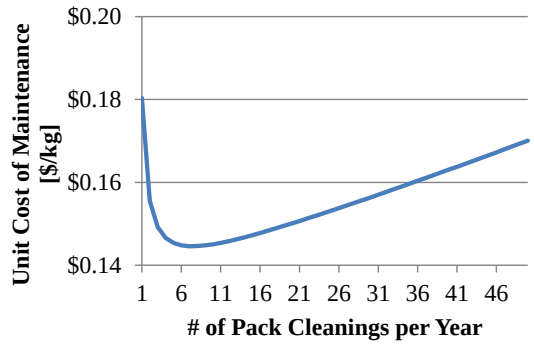
(b) Production rate



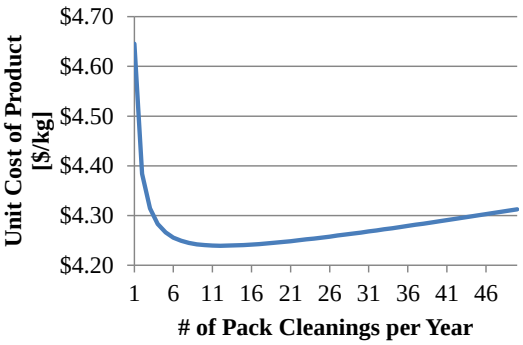
(c) Production volume



(d) Annual cost of maintenance



(e) Unit cost of maintenance



(f) Unit cost of product

Figure 3-27: The influence of the number of pack changes per year on model parameters

In addition to the influence on annual production, an increase in the number of maintenances per year increases the annual cost of maintenance, as shown on Figure 3-27 (d). Allocating the annual maintenance cost per unit of product, using the corresponding annual production, results in a convex function shown in Figure 3-27 (e). The behavior of the product cost is a combination of these effects, and is shown in Figure 3-27 (f). For this case, the minimum unit cost is found to be at 12 maintenances per year.

Similar unit cost curves were constructed for different levels of production rate degradation. These curves are shown in Figure 3-28. High values of unit cost were trimmed from the graph to emphasize the behavior around the optimal values. The vertical lines on the plot indicate the optimal maintenance policy for each case.

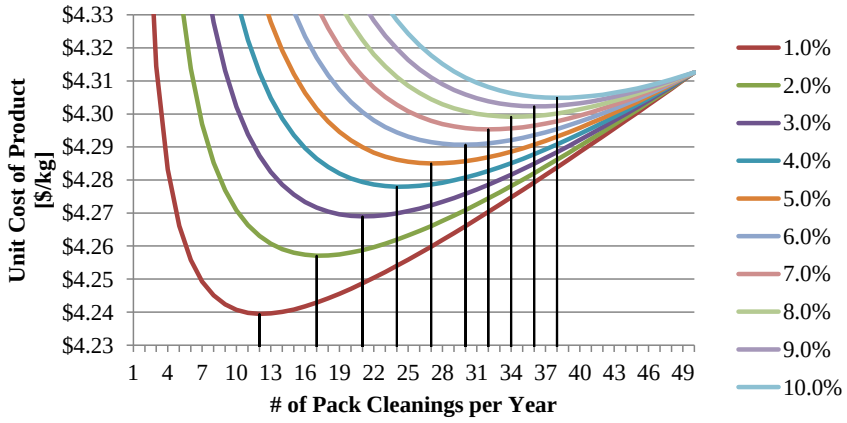


Figure 3-28: Unit cost vs. number of pack changes and reduction in production rate

Figure 3-29 summarizes the optimal maintenance polices for all ten cases considered. It can be seen that higher reductions in production capacities justifies more frequent maintenance, which grows from 12 maintenances per year for 1% weekly degradation to 38

maintenances per year for 10% weekly degradation. This case study demonstrates the importance of cost modeling and analysis for establishing the pack maintenance practice for spunbond plants and illustrates the application of cost model for the optimization of production conditions.

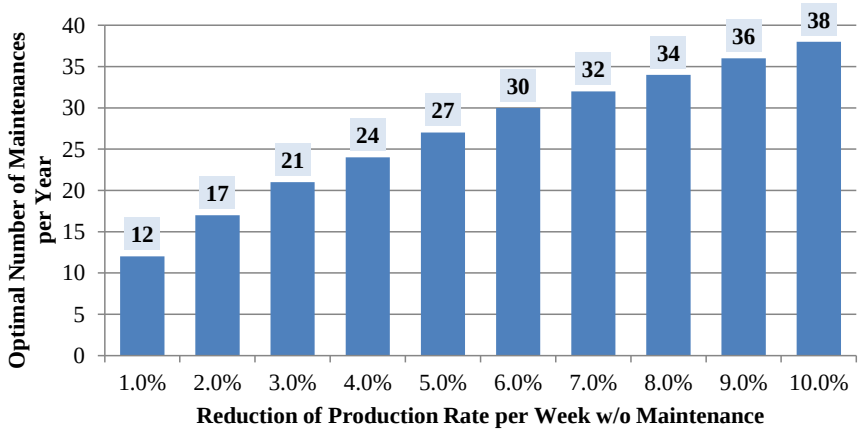


Figure 3-29: Optimal maintenance policies for different levels of production degradation

3.4 SUMMARY

In this chapter the cost model for the spunbonding process was developed. First, the model was theoretically formulated based on the published literature and understanding of the process. The model distinguishes each processing step and its cost contribution. The model equations were organized in the hierarchical structure to be able to extend the level of details for variables of interest. The model was implemented in the MS Excel to automate calculations of analysis. The validation was done by comparing model outputs with estimates obtained from the industry. Finally, the specific case for analysis was defined and economic analysis was performed.

4 FRAMEWORK FOR COST MODELING AND ANALYSIS OF NONWOVEN PRODUCTS AND PROCESSES

The manufacturing of nonwoven products generally involves several production steps, each having a set of alternative technologies that may be used. These steps may be categorized into core and supporting processes. The core production steps have an influence on the properties and functionality of a final product. This category includes web formation, bonding, and finishing. Examples of alternative technologies for each core processing step are shown in Figure 4-1. Some web formation technologies requires prior material preparation step (e.g., opening and blending of staple fibers before carding; polymer drying before spunlaying). In addition to the core production steps, a nonwoven production process may include supporting steps (e.g., winding, slitting, and packaging), that are an essential part of the production, but do not have any influence on product properties.

Table 4-1: Example of basic nonwovens manufacturing process

Web Formation	**Web Bonding**	**Finishing**
Carding	Needlepunching	Coloration
Air-laying	Hydro-entanglement	Printing
Wet-laying	Thermal bonding	Mechanical
Spunlaying	Resin bonding	Thermal
Meltblown		Chemical

The specific technologies selected for each core production step, together with any required supporting steps, are combined into a production line to achieve specific properties or functionalities of a final product. There are several established combinations of

technologies on the market. Examples of such combinations are spunlace that is air-laid web formation followed by hydro-entanglement or spunbond that includes spunlaying and thermal calendering. In addition, there is continuous research in the nonwovens industry in an effort to develop new possible combinations that will yields fabrics with unique properties. A choice of specific raw materials, web formation, bonding, and finishing technologies not only defines the properties and performance characteristics of final products, but also has a significant influence on product manufacturing costs.

Due to the variety of manufacturing technologies used for the production of nonwovens, it is difficult to develop one generic cost model that can accurately represent the specific characteristics of each production process, and their influence on production costs. Therefore, the purpose of this chapter is to introduce a generic framework that describes basic steps needed for cost model development and application, which will allow cost engineers to develop cost models for each nonwoven production process using a standardized method of cost calculation. Then, these individual models may be combined into a cost model for the entire production line.

4.1 COST MODEL DEVELOPMENT

The development of a theoretical cost model for nonwoven products is the first phase of the framework. The general cost modeling approach, described in this section, defines the main variables that are used for cost calculations and have to be further related to the specific product and process parameters under consideration.

4.1.1 General approach to cost calculation

The main idea of the cost modeling approach is to model cost of each technology (one production step) independently and then combine the resulting models into the line cost model to estimate the total production cost of a product of interest. An example production process, as it is considered in the framework, as well as mechanism of cost formation, is shown in Figure 4-1. The cost of the final product is formed by the cost of raw materials used and the production cost of each processing step. A production step consumes specific resources that may be grouped into several categories based on the resource type (e.g., utilities, equipment) or by the task that they are used for (e.g., maintenance). These groups are called cost elements, and each contributes to the total cost of a step.

As a result, the cost per unit of fabric (C_F in [$/kg]) is calculated as the ratio of total annual cost incurred (AC in [$]) to the annual net production of the line (AQ^{Net} in [kg]), as shown in Equation (95). In turn, the total annual cost is a sum of the annual cost of raw materials (AC_{RM} in [$]) used and the annual cost of each production process (AC_p in [$]) involved (see Equation (96)).

$$C_F = \frac{AC}{AQ^{Net}} \tag{95}$$

$$AC = AC_{RM} + \sum_{p} AC_p \tag{96}$$

These calculations are performed on an annual basis to account for seasonal variations in production and to average production yields, downtimes and other parameters that may vary at shorter time intervals.

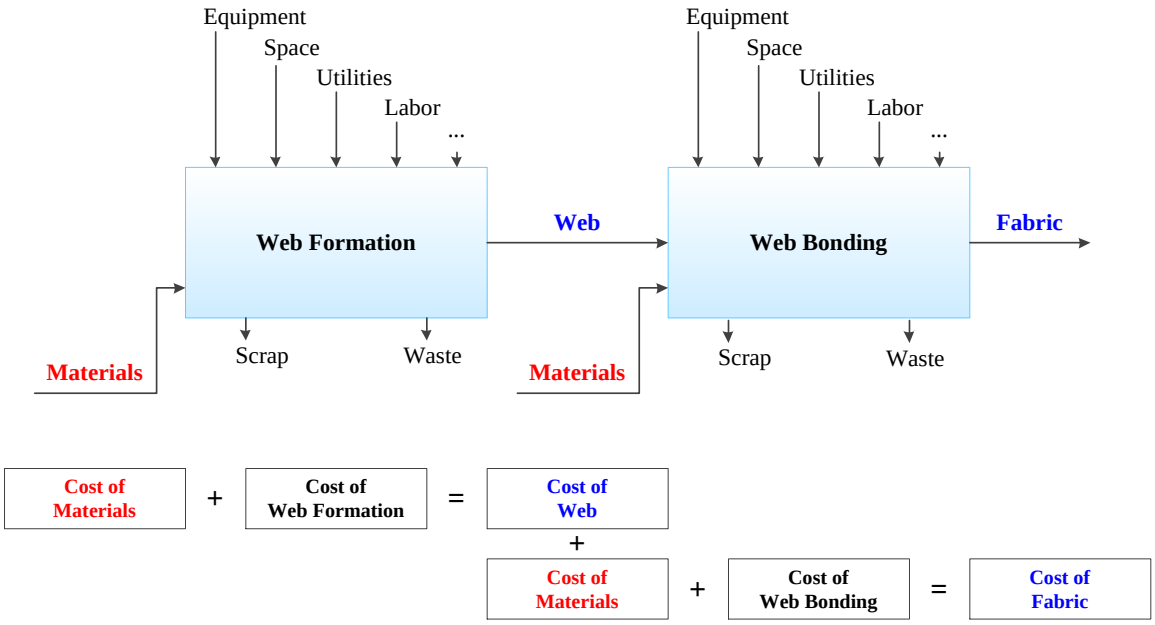


Figure 4-1: Schematics of product cost formation

The annual cost of each process is calculated using separate models for production steps that have a common structure in the top-level equations, however, each having specific details about the process embedded into the lower level equations. This makes cost models for different technologies comparable, but at the same time extendable, so any level of details can be included into the model. Such an approach reduces modeling efforts and adds flexibility, allowing step cost models to be reused in cost calculations of different production lines. Extensibility, in terms of level of details, offers the ability to conduct a detailed economic analysis, since any type of relationship between the input parameters and product costs can be accounted for. Modeling each production step separately also allows for the estimation of costs of the intermediate products, as well as identifying the cost contribution of each production step.

The approach defines components of the line cost model that need further explanation. This includes the general definition of product and production process, the cost model of the production step, the coupling of processes to obtain annual net production volume, and the annual cost of the raw materials used.

4.1.2 Specifying product and processes

Nonwoven products are characterized by structural, dimensional and compositional parameters. These parameters are defined during product development based on desired functionality and the results of trial runs. The characteristics of a final product set requirements to the production steps involved, equipment used and required processing parameters. Examples of nonwoven fabric characteristics that are important for cost modeling include raw materials, composition, fiber shape, size and length, basis weight, finishing, etc. Among these parameters, only those that are likely to have an influence on product cost should be included into the model. The selection of the parameters should be based on an understanding of the manufacturing technologies involved.

In addition to the product characteristics, the production processes that are included into the line under consideration should be clearly defined. First, all production steps involved, staring from material preparation and finishing with packaging, should be listed. Then, depending on the cost modeling purpose, some steps may be disregarded. It is also possible to aggregate some steps. For example, a spunbond line can be modeled as a single processing step if the modeler is interested in rough cost estimation for the entire product. However, if the purpose of the cost analysis is to compare two different types of spunlaying

machine (e.g., machine with “old” extruder that requires prior polymer drying versus machine with “new” extruder that dry polymer by itself), then the spunbond line should be separated into drying, spunlaying, and calendering sections. Aggregation of processes may simplify cost model development and data gathering, since the distribution of resource requirements and equipment costs between individual production steps are not needed. However, modeling each production step separately adds accuracy and flexibility to the model, with better ability to control processing variable of each production step. In addition, once developed, cost models for separate production steps can be combined in different ways for the cost estimation of other products.

4.1.3 Modeling production step

To build a cost model for a production step it should be considered as a separate module, disregarding the preceding and following production steps. The main function of the production step is to convert input materials into output products with possible scrap or waste generation. It is assumed that the step may have several inputs, which may be raw materials or intermediate products from other processes. Therefore, inputs and the output product of the step should be well defined. The output should be defined in terms of the material composition, and the requirements for inputs should be specified per unit of output (i.e., bill of materials). Such an approach allows accounting for yields of different input materials, and for materials that are used by process but do not become a part of final product. For example, for resin bonding the input materials are a nonwoven web and binder, and the output is a

bonded fabric. During the bonding, there is no weight loss in the nonwoven web (yield is equal to 100%); however there may be waste of binding material (yield is less than 100%).

Using the required inputs and composition of the output product, scrap/waste generation and corresponding yields can be calculated for each material based on material balance equations. For example, let us assume that one kilogram of output product contains a grams of material A and it is required to use b grams of material A to produce kilogram of product. Therefore, $(b - a)$ grams of material A per kilogram of output will go to waste and the yield of material A is equal to a divided by b. For processes that have one input and one output, or have the same yield for all input materials, process yield can be used instead of materials requirements.

The next step in the model formulation is to define the production rate of the process. The production rate should be functionally related to the product and equipment parameters based on a solid understanding of the process. The production rate, together with annual operating time, defines the annual capacity of the process. Annual operating time is the maximum available operating hours per year (depends on plant operating conditions) reduced by downtime. Annual production of a process is defined as a minimum among desired production level specified by the user and the process capacity. This defines the utilization, which is equal to a ratio of actual production to the process capacity. The annual usage of materials can be identified based on the bill of materials and annual production.

Once all production parameters are defined, they are used for the cost estimation of the process. The cost of a processing step is broken down into its cost elements. Table 4-2 shows the major components of production costs related to nonwoven processes. This list can

be extended, or some elements can be omitted, based on the technology modeled. These cost elements can be separated into fixed and variable. Annual costs of elements in the first category (fixed) do not depend on the quantity of fabric produced, while annual costs of elements in the second category (variable) are proportional to the annual production. In general, the annual cost of each element is an annual "requirement" for this element multiplied by its unit cost.

Table 4-2: Examples of cost elements for nonwoven processes

Variable	Fixed
Utilities (Electricity, Water) Maintenance (performed each time after certain amount of material process) Labor (low automated process) Waste treatment	Equipment/Tooling Space Maintenance (performed periodically independently from material processed) Labor (highly automated process)

Equipment cost is the first component that has to be accounted for in the process cost. To derive annual cost of equipment, the total capital investment, which includes equipment purchase and installation costs, should be allocated over its economic or productive lifetime. This can be done using depreciation or capital recovery methods as was discussed in Section 3.1.2.3.4. The resulting annual cost should be adjusted for annual payments related to ownership of the equipment (e.g., insurance). While purchase equipment cost may be directly defined by the user, for more detailed cost models it is preferable to develop a functional relationship between equipment design and capacity parameters and its purchase price.

Tooling cost is the next element, which is similar to equipment. In some cases, it can be considered as a part of the equipment cost, or may be insignificant. The only difference in tooling cost allocation, from the equipment itself, is that several sets of similar tooling may be required during the product lifetime. This may occur when tooling lifetime is lower than the lifetime of the product, or when several tooling sets are used interchangeably. In this case, the total purchase cost of tooling is the number of tooling sets required for product lifetime multiplied by the purchase price of one set. In some cases, this value can be increased by the tooling design cost, if it is significant. Again, to yield more detailed cost model, the purchase price of one tooling set may be related to product and tool design parameters.

Most nonwovens processes are highly automated. Therefore, the cost of labor can be modeled as a fixed cost. The process may require several types of labor (e.g., operators, maintenance mechanics, and supervisors), that should be identified and included into the cost model. For each labor type, daily requirements in person hours, hourly wage rates and burden rates should be specified. An annual cost of labor for each type is a product of the aforementioned parameters and the number of paid days per year. For more detailed estimates, the labor requirements should be set as a function of machine capacity parameters (e.g., working width), so they will not change with an increase in annual production for the same machine, but will increase if "bigger" equipment is considered. For processes that are labor intensive (e.g., packaging), the labor can be considered as variable so labor requirements should be modeled as a function of production volume.

Each processing step requires some plant floor space that is occupied by the main machine, workers, input/output materials, conveyors related to the process, etc. The annual cost of space is obtained by multiplying process space requirement by the annual space cost rate. This rate may be a space rental rate, or it can be calculated though the capitalization of building. It should also include the cost of non-processing utilities such as water and energy used for heating, ventilation and air conditioning, illumination, the cost of security and building maintenance, and other costs directly related to the factory floor space occupied by the process. If needed, the space requirements can be related to the machine dimensions or capacity parameters.

Maintenance of equipment is required to keep it running or restore it to the desired operating condition. Depending on the process, this cost element may include capital maintenance, regular maintenance or both. Capital maintenance is usually performed once per year, all parts of the equipment are inspected, and worn out components are replaced. The cost of capital maintenance can be estimated as a percentage of capital investment into the equipment, or detailed estimate can be made that include costs of all parts that are usually replaced, materials, labor, contracts, etc. Regular maintenance is usually performed periodically throughout the year, mostly to clean equipment components, replace expendables to improve performance of the machine. The annual cost of regular maintenance is calculated as the number of maintenances per year multiplied by cost of the one maintenance, which can be estimated in a separate cost model, if needed.

Utilities are the only variable cost element for the nonwoven production steps. Two types of utilities are typically used, namely water and electricity. To calculate the annual cost

of each type of utility its annual consumption should be multiplied by the unit price of the corresponding utility. Annual consumption can be expresses as the hourly consumption times the actual working time, or as a specific consumption rate per unit of product multiplied by the annual output of the process. For detailed estimations, hourly or specific consumption can be further related to equipment, processing, and product parameters.

In addition to major cost components, waste treatment cost may also be included in the cost of the process. Knowing the annual quantity of waste for each of the input materials, defined at the beginning of this section, the annual cost of waste treatment is a product of these quantities and the per unit cost of waste disposal. The cost of scrap treatment will be considered as part of raw materials cost at the line level.

Process can be dedicated to the product of interest thought the year, or it can be used for the manufacturing of other products when there is free capacity. In the first case, all fixed costs should be completely accounted for in the cost of the process. When the process is not dedicated, these costs should be adjusted by the process utilization, which is a fraction of annual capacity used for manufacturing the product of interest.

As was shown in the discussion of each cost element its cost calculation may include two level estimation equations. The first level equations are the resource requirement multiplied by the price of resources. The second level equations relate requirements or prices/costs to product, process, and equipment parameters. Level of details, that is a depth of analytical relationships built-in into the model, is defined by the model purpose. For example, the cost model for the same product and equipment may be designed to compare different alternatives for plant location, which actually defines cost of resources (e.g., labor

wage rate, utilities prices, etc.). In this case, there is no need to develop a relationship between product/process parameters and the consumption rates of resources or equipment/tooling cost. A single point estimate for a specific product and equipment will be enough. However, for cost models that are used to identify cost reduction potential, or to compare alternative equipment or products designs, it is preferable to build such relationships. In addition, the cost engineer should be familiar enough with the process to understand the potential significance of each resource in terms of the total product cost. More attention should be paid to modeling of resources that are likely to contribute significantly to the total product cost, while other resources may be roughly estimated.

4.1.4 Modeling the production line

When cost models for all the production steps are developed, they should be combined to create a cost model for the line of interest. The line model defines common input parameters for the models of each processing step, namely working and maintenance schedule, maximum available production time, paid time and downtime.

The first variable that should be defined when coupling cost models is the calculation of the annual net capacity of the line, which is equal to the production rate of the "bottle-neck" process (i.e., the process with the lowest capacity). The cost model for each individual step defines its capacity in terms of the step output, but not in terms of final product (e.g., the capacity of spunlaying is expressed in terms of the web, but not in terms of the bonded final fabric). Therefore, to find the annual capacity of the line it is necessary to express the capacities of each processing step in quantities of final product (i.e., how much final product

can be produced from the maximum output of a processing step assuming capacities of other steps unlimited).

This is explained diagrammatically in Figure 4-2. The numbers used in the example are for illustrative purposes and do not represent any real production process. There are two production steps in the line, namely carding and resin bonding. Carding requires 0.8 kg of PP staple fibers and 0.25 kg of PET fibers to produce 1 kg of carded web a fiber composition of 75%/25%. The carded web and binder are the input materials for resin bonding. The bonding requires 0.95 kg of carded web and 0.10 kg of binder to produce 1 kg of fabric that contains 5% of binder and 95% of web. Carding has annual capacity of 900 kg of carded web, and the capacity of resin binding is 1,000 kg per year.

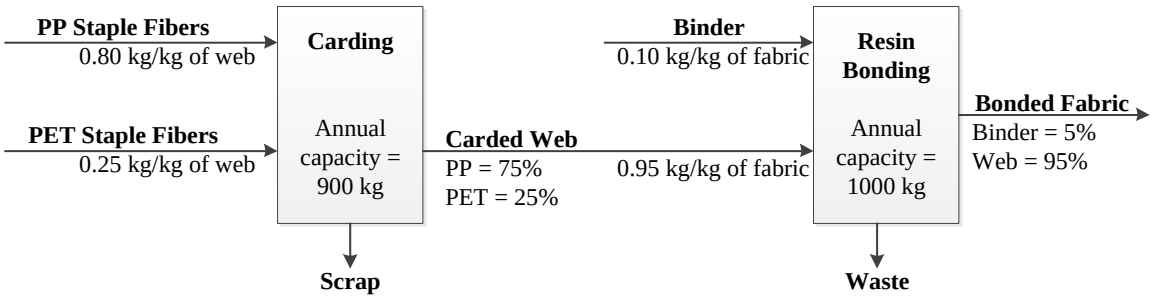


Figure 4-2: Example of models coupling

Since resin bonding produces the final product, its capacity is already expressed in terms of the final product, and is equal to 1000 kg of bonded fabric. The capacity of carding is 900 kg and 0.95 kg of carded web is required per 1 kg of bonded fabric, which results in 947 kg (900/0.95) of bonded fabric that may be produced when carding is run on full

capacity. Since the capacity of carding is lower than capacity of bonding, the line capacity is equal to the carding capacity and is 947 kg of bonded fabric per year.

Since the desired annual production output may differ from the line annual capacity, the minimum of these two values is used for the cost estimation per unit of product and annual material usage. The next step is to define the annual production of each step and the annual material usage for a given demand, as shown in Figure 4-3. It is assumed that the annul demand is 900 kg. Going backward from the final step through each previous processing step, and using the defined requirements for materials, the annual usage of each intermediate product and raw material may be estimated. In the example, resin bonding requires 90 kg of binder and 855 kg of carded web to produce 900 kg of bonded fabric. In turn, carding requires 684 kg op PP fibers and 214 kg of PET fibers to produce the web required by bonding.

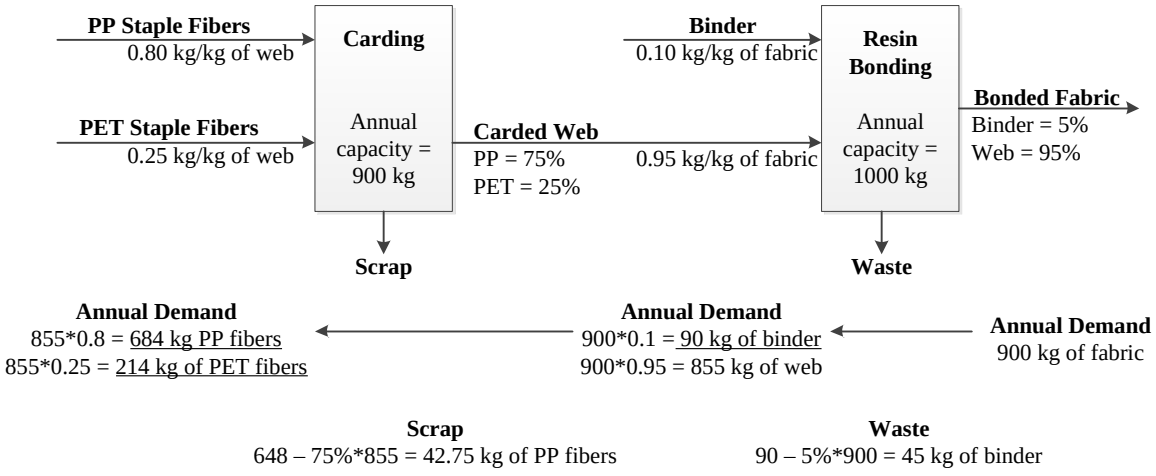


Figure 4-3: Determination of annual production for processing steps

The figure also shows how waste and scrap can be determined. For example, carding uses 684 kg of PP fibers per year. However, only 641 kg end up in the final product, resulting in scrap 43 kg. A similar calculation for the binder results in 45 kg of PET to dispose of.

Having determined the annual material usage and the corresponding price of each material, the annual cost of raw materials can be calculated. This value should be adjusted for scrap and waste treatment cost. Since scrap can be recycled back into raw materials, or sold in secondary markets, this may result in a reduction of raw materials cost. The cost of waste treatment may be included in the total cost of raw materials, or can be accounted for in the processing step where it occurs. The annual production of each processing step is passed to corresponding cost model, which returns annual cost-by-cost elements and total annual cost of a step.

4.1.5 Data gathering and model validation

The data requirements for the cost modeling can be separated into two categories: “estimation data” and “external data”. The first category includes all information required to estimate the second-order equations used in the model. The second category quantifies inputs that are external to the model and are used to define the specific case analyzed (e.g., cost of materials, utilities, labor, etc.).

The “estimation data” is used for development of the detailed cost model of a process. The main purpose of this information is to develop relationships that quantify the influence of machine, process and product parameters on resource requirements/usage and machine/tooling purchase prices. The constructions of such equations are usually based on a

statistical analysis of the problem. Therefore, the information collected should include many observations to account for different factors that may influence the variable of interest and for the variation of the variable. Due to the lack of the publicly available studies that estimate such relationships for the nonwoven processes, the only sources of the "estimation data" are the nonwoven industry (equipment manufactures and producers of nonwoven fabrics) or direct measurement/observation, if the nonwoven equipment is available. In both cases, the data collection procedure is time consuming. Additionally, the interviews or surveys of the nonwoven companies may not yield desired results, since the information collected is usually considered to be a commercial secret. Direct measurement on the available equipment may be expensive, since it requires many combinations of parameters to be tested.

In contrast to the previous category, data gathering of "external" information is easier. The cost of materials, utilities, labor wage rates, disposal cost, space rental rate and other parameters that define the economic environment of the model can be obtained from numerous publications, reports, online databases and governmental statistics. The specific sources of this information were discussed in Chapter 3.

The main purpose of the model verification is to assure that all functional relationships embedded into the model correctly reflect the effects of changes in the input parameters. The verification can be done based on theory, in consultation with industry experts or by observing behavior of the variables with different inputs, especially with their extreme values. The model validation is used to guaranty that it yields reliable results, given the assumptions stated during the development. The resultant model output can be compared with costs or market prices of similar products, or can be discussed with industry experts.

4.2 COST MODEL APPLICATION AND ANALYSIS

Once the cost model for the production process of interest is developed, and all required information is collected, the model may be utilized to analyze production costs and generate useful outcomes to support decision-making. While there are many potential applications for cost models, which depend on the specific situation being modeled and the purpose of study, several common types of analysis may be identified. Examples of cost analysis for the spunbond line were discussed in details in Section 3.3.

Product cost, and its breakdown structure, is the basic outcome that cost models provide. The estimated product cost can be used for the evaluation of economic viability and profitability of the product, for screening alternative product possibilities, and for outsourcing decisions. The resulting cost breakdown structure shows the contribution of cost elements and processes to the product cost. It can be used for the identification of potential areas (i.e., dominant cost elements and production steps) that could be further studied for cost minimization purposes. Investigating the relationships that are used to calculate costs of dominant components could provide insight into product and machines design parameters, processing variables, economic and production conditions that drive the cost of the corresponding component (e.g., see Figure 3-5 that shows factors that influence cost of spunlaying equipment). Among these drivers, the analyst should select those factors that can be readily influenced.

The effects of the selected factors on product cost can be quantified using sensitivity analysis. In this analysis, one or several input factors are varied and the resulting product costs are compared to identify the effects of the inputs. It is important that the model used for

the analysis include the detailed (second-order) equations that account for the direct and indirect influence of the inputs on product cost. For example, the materials used may not only have an influence on the cost of materials, but also on the electricity consumption rate, or may require additional equipment to be installed. To make the effects of input factors on the product cost comparable, the elasticity coefficient, which shows relative changes in the product cost in response to the 1% change in factors, may be calculated.

The next step in the cost analysis may be an optimization of the most influential controllable cost drivers to minimize the product cost. In the simplest case, the product cost can be evaluated for different levels of some factor and value of the factor that yield the minimum cost is selected as optimal. However, the interaction between several factors may have a combined influence on the product cost. Therefore, the optimization should be conducted accounting for all possible combinations of factors levels.

The previous types of analysis mainly deal with deterministic values of input parameters. However, during the product development, especially at its initial stages, many input parameters are not known exactly. In many cases, rough estimations or educated guesses are used, which may lead to invalid cost estimates. It is important to evaluate the robustness of the model to such inputs. There are two main methods to deal with uncertainty in input parameters: case based analysis and Monte Carlo simulation.

In the case based analysis, the worst, best and most likely values are identified for each uncertain parameter. To produce a possible range of product costs, as well as most likely cost, these sets of values are substituted into the model and the resulting product costs for each case are recorded. This gives a rough estimation of the risk associated with

uncertainty in input parameters. While this method is simple in implementation, it has several drawbacks. The model outcome is evaluated at three discrete points, disregarding other possible combinations of input parameters. In addition, this method does not give any insight into the probability of occurrence of each case.

A more advanced approach is the Monte Carlo simulation. It is a stochastic risk analysis, where each uncertain input is associated with some random distribution from where its values can be sampled. The estimation of these distributions is subjective and relatively complex, since it requires information about the possible values of input parameters and associated probabilities (frequencies) to be collected and fit to the theoretical distributions. When all the probability distributions for uncertain input parameters are defined, the values of these parameters are randomly generated and substituted into the model for some number of replications. The model outputs for each replication are recorded, and are then used to conduct a risk analysis. The cost distribution function (histogram) is built based on the model outcomes and shows the possible values of product costs, as well as probabilities of their occurrence. In addition, many different statistics, like mean, median, mode product cost, standard deviation, confidence intervals, etc., can be calculated based on this simulation outcome.

4.3 SUMMARY

In summary, the following steps briefly describe cost model development and analysis procedure:

1. Develop cost model

1.1. Define product

1.2. Define production steps

1.3. For each production step develop a separate cost model

1.3.1. Define input materials and output product

1.3.2. Specify materials requirements and product composition

1.3.3. Relate production rate of the process to product properties and equipment parameters

1.3.4. Define cost elements

1.3.5. For each cost element

1.3.5.1. Develop first order relationships to calculate its annual cost

1.3.5.2. If needed develop second order equations

1.3.5.2.1. Collect data

1.3.5.2.2. Develop relationships

1.3.5.2.3. Validate

1.3.6. Verify and validate the model

1.4. Couple production steps cost models

1.4.1. Define annual line capacity and actual production rate

1.4.2. Find annual material usage, scrap and wastes generated

1.4.3. Estimate annual production for each step

1.4.4. Aggregate annual cost of raw materials and annual costs of each processing step as well as its cost elements into total production cost of the line

1.4.5. Verify and validate the model

2. Apply cost model

2.1. Define the base-case and gather the required data

2.2. Populate the model with the base-case data and calculate the corresponding cost of the product

2.3. Analyze the cost breakdown structure and find the dominant cost elements and productions steps

2.4. Investigate the equations that yield costs of the dominant components and find the controllable input factors

2.5. Conduct a sensitivity analysis and define the factors that have the most significant influence on product cost

2.6. For the most significant factors, conduct an optimization study and find the levels of factors that result in minimum product cost

2.7. Assess the effect of uncertainty and associated risks using case-based analysis or Monte Carlo simulation

5 CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE RESEARCH

5.1 CONCLUSIONS

The first purpose of this study was to develop a detailed cost model and perform an economic analysis of the spunbonding production process. To achieve this goal the literature review was conducted to understand the available cost modeling approaches and techniques, and to get solid understanding of the spunbond process, its components, and the relationships between its parameters. As the result of the literature review, a bottom-up, process-based cost modeling approach was chosen for model development.

The model considered only costs related to the production itself and it did not account for any plant or company overheads. It included the cost of materials and costs of core production steps involved in the spunbonding process, namely polymer drying, spunlaying, calendaring, and winding. Based on the approach, hierarchical cost models for each production step were developed and aggregated into the top-level cost model of the spunbonding line. The main cost elements for each production step were identified and their functional relationships to the product, machine, and processing variables, economic and production conditions were developed. The model allows extending and contracting the level of details, so that input variables can be directly specified by the user, or can be estimated based on other parameters using second order equations. The functional relationships embedded into the model, and the cost model itself, were verified and validated by comparing modeling results with estimations of production variables and costs obtained from industry. To automate the cost calculation and analysis, the cost modeling application was developed in the MS Excel. This software offers the user a convenient way to populate the

model with input information. In addition, it contains supporting tools to conduct the design of experiment and a Monte Carlo simulation for the cost model.

The model developed was used to perform an economic analysis of the spunbond process. To this end, a base-case scenario was established and all required information was collected from publicly available databases, reports, publications, and equipment specifications. In addition, information not available in the public domain was approximated in consultation with industry experts. The information required for the first order equations of the model were successfully collected. To develop second order relationships, an information request was sent to several equipment manufacturers. However, as most of the information requested is proprietary, or such information is not collected by the manufacturers, there were no responses. Therefore, parameters of the second order equations were estimated based on common logic and experts' opinion to allow the major trends to be reflected in the model.

The model was populated with the data collected and an economic analysis was performed. This included cost breakdown structures by cost elements and production steps, a sensitivity analysis of product cost to changes in input factors, the effects of line utilization and uncertainty on product cost, and an optimization study. The main results of the analysis can be summarized as follows:

1. The cost structure by cost elements showed that raw materials were the largest contributor (64%) of the total production costs, followed by equipment (20%) and labor (7%).

2. The cost structure by processing steps showed that spunlaying, calendaring, and winding contributes 29%, 5%, and 2% to the total production costs, respectively.
3. The sensitivity analysis revealed that polymer prices, the cost of equipment and the interest rate on borrowed capital are the most significant cost drives among the input factors considered in the analysis.
4. Line utilization in the range from 90% to 100% had insignificant effect on the product unit cost; however, further reduction in the utilization increased the unit product cost exponentially.
5. Monte Carlo simulation was used to quantify the effect of several uncertain input parameters on the distribution of cost per unit of product. It was shown that uncertainty in input parameters should be considered during cost estimation since combined effect of several variables may significantly shift the average cost of unit of product compared to the deterministic assumptions.
6. The cost model was used to conduct an optimization study to find optimal maintenance policy considering the tradeoff between maintenance cost and annual production of the line.

The second purpose of this study was to generalize the steps involved in the cost modeling and analysis of the spunbonding process into a comprehensive framework for the cost estimation of nonwoven products. The framework created defines the major steps required to develop cost models for the individual production steps of the process of interest,

the coupling of these models into the cost model of the entire line, the validation and verification of the model, data gathering and general applications of the cost model.

5.2 RESEARCH CONTRIBUTION

The work conducted in this dissertation is essentially the first academic attempt to approach the cost estimation of nonwovens. The investigation illustrated the development of a detailed, process-based cost model for the spunbonding process and demonstrated its application to cost analysis of spunbonded nonwovens. The resulting model could be used by the industry to support decision making during new product development process. This dissertation has also established a generalized research framework for cost modeling and the analysis of nonwoven products and technologies. The study provides a basis for future research in the field of cost engineering for nonwoven products.

5.3 RECOMMENDATIONS FOR FUTURE STUDIES

The following are recommendations for future studies related to this research.

1. Improvement of the cost model for the spunbonding process: Due to lack of information, simplified second order equations, which reflect only general trends, were used in the cost model for the spunbond process. The model can be improved by developing more accurate second order relationships that associate labor and space requirements, energy consumption, equipment purchase and tooling prices, along with other important variables, for each processing step to product, and equipment design parameters, and production

conditions. Detailed estimations of second order equations require that a significant amount of information to be collected and analyzed. Therefore, the development of each relationship can be conducted as a separate study.

2. Development of cost models for other nonwoven production steps: According to the approach used in this study, the cost model of the production line is a combination of individual cost models of the processing steps involved. This study discussed the cost models for spunlaying, calendering and winding processing steps that when combined form the spunbonding production line. Similar cost models could be developed for other web formation, bonding and finishing technologies utilizing the framework presented in this study.
3. Development of generic cost modeling software for nonwovens: Once cost models for alternative technologies for web formation, bonding, finishing, and other production steps are developed, they can be combined to create cost modeling scenarios representing any nonwoven production line. To simplify the coupling of different production steps and cost estimation, cost modeling software can be developed which contains a database of cost models for various production steps, and allows the user to conduct a cost analysis by easily combining them into the line of interest and specifying proper input parameters.

6 REFERENCES

Aamodt, A., & Plaza, E. (1994). Case-based reasoning: Foundational issues, methodological variations, and system approaches. *AI Communications, 7*(1), 39-59.

Anderson, D. M. (2004). *Design for manufacturability & concurrent engineering*. California: CIM Press.

Asiedu, Y., Besant, R. W., & Gu, P. (2000). Simulation-based cost estimation under economic uncertainty using kernel estimators. *International Journal of Production Research, 38*(9), 2023-2035.

Asiedu, Y., & Gu, P. (1998). Product life cycle cost analysis: State of the art review. *International Journal of Production Research, 36*(4), 883-908.

Avramenko, Y., & Kraslawski, A. (2006). Similarity concept for case-based design in process engineering. *Computers & Chemical Engineering, 30*(3), 548-557.

Baker, W. M. (1996). Take another look at activity-based costing. *Industrial Management, 38*, 19-23.

Batra, S. K., & Pourdeyhimi, B. (2012). *Introduction to nonwovens technology*. Lancaster, PA: Destech Publications. Retrieved from http://www2.lib.ncsu.edu/catalog/record/NCSU2499827

Beischel, M. E. (1990). Improving production with process value analysis: The foundation for activity based costing. *Journal of Accountancy, 170*(3), 53-57.

Ben-Arieh, D., & Qian, L. (2003). Activity-based cost management for design and development stage. *International Journal of Production Economics, 83*(2), 169-183.

Bhat, G., & Malkan, S. (2007). Polymer-laid web formation. In S. J. Russell (Ed.), *Handbook of nonwovens* (1st ed., pp. 143-200). Boca Raton, FL, USA: CRC Press LLC.

Bhat, G. S., & Malkan, S. R. (2002). Extruded continuous filament nonwovens: Advances in scientific aspects. *Journal of Applied Polymer Science, 83*(3), 572-585.

Bhatkal, R., & Busch, J. (1998). Applying technical cost modeling to the metals industry. *JOM Journal of the Minerals, Metals and Materials Society, 50*(4), 27-28.

Bird, H. M., Albano, R. E. & Townsend, W. P. (2004). *Target costing: Delighting your customers while making a profit.* Retrieved 07/04, 2009, from www.focusmag.com

Bode, J. (1998a). Decision support with neural networks in the management of research and development: Concepts and application to cost estimation. *Information and Management, 34*(1), 33-40.

Bode, J. (1998b). Neural networks for cost estimation. *Cost Engineering, 40*(1), 25-30.

Bode, J. (2000). Neural networks for cost estimation: Simulations and pilot application. *International Journal of Production Research, 38*(6), 1231-1254.

Bode, J., Ren, S., & Shi, Z. (1995). Application of 3-layer perceptrons to cost estimation. Paper presented at the *IEEE International Conference on Neural Networks, , 4*(4) 1749-1754.

Brimson, J. A. (1998). Feature costing: Beyond ABC. *Journal of Cost Management, 12*(1), 6-12.

Brown, T. (2000). Estimating product costs. *Chemical Engineering, 107*(8), 86-89.

Busch, J. (1994). Cost modeling as a technical management tool. *Research Technology Management, 37*(6), 50-56.

Busch, J. V. (1987). *Technical cost modeling of plastics fabrication processes.* (PhD, Massachusetts Institute of Technology, Dept. of Materials Science and Engineering).

Camargo, M., Rabenasolo, B., Jolly-Desodt, A. M., & Castelain, J. M. (2003). Application of the parametric cost estimation in the textile supply chain. *Journal of Textile and Apparel, Technology and Management, 3*(1), 1-12.

Caputo, A. C., & Pelagagge, P. M. (2008). Parametric and neural methods for cost estimation of process vessels. *International Journal of Production Economics, 112*(2), 934-954.

Castagne, S., Curran, R., Rothwell, A., & Price, M. (2008). A generic tool for cost estimating in aircraft design. *Research in Engineering Design, 18*(4), 149-162.

Cavalieri, S., Maccarrone, P., & Pinto, R. (2004). Parametric vs. neural network models for the estimation of production costs: A case study in the automotive industry. *International Journal of Production Economics, 91*(2), 165-177.

Celli, A. (1996). Winding technology today and tomorrow. Paper presented at the *NONWOVENS CONFERENCE,* 123-128.

Cerex Advanced Fabrics. (2008). ***Cerex® product information***. Retrieved 10/15, 2011, from http://www.cerex.com/PageView.asp?PageType=R&edit_id=172

Chen, Z., & Wang, L. (2007). A generic activity-based method for product costing in mass customization. *Journal of Manufacturing Technology Management, 18*(6), 678-700.

Cheng, C. Y. (1994). A polypropylene extrusion system for nonwoven processes, TAPPI JOURNAL, december 1994, vol. 77 (12). *Tappi Journal, 77*(12)

Cooper, R. G. (1987a). The two-stage procedure in cost accounting: Part one. *Journal of Cost Management, 1*(2), 43-51.

Cooper, R. G. (1987b). The two-stage procedure in cost accounting: Part two. *Journal of Cost Management, 1*(3), 39-45.

Cooper, R. G., & Kaplan, R. S. (1988). Measure costs right: Make the right decision. *Harvard Business Review, 66*(5), 96-103.

Cooper, R. G., & Kleinschmidt, E. J. (2003). New products: What separates winners from losers? In M. Lewis, & N. Slack (Eds.), *Operations management: Critical perspectives on business and management* (pp. 184). New York: Routledge.

Crow, K. (2002). *Achieving target cost/design-to-cost objectives.* Retrieved 07/15, 2009, from www.npd-solutions.com/dtc.html

Curran, R., Raghunathan, S., & Price, M. (2004). Review of aerospace engineering cost modelling: The genetic causal approach. *Progress in Aerospace Sciences, 40*(8), 487-534.

Daly, J. L. (2002). *Pricing for profitability: Activity-based pricing for competitive advantage* (1st ed.). New York: John Wiley & Sons, Inc.

Dixon, J. R., & Duffey, M. R. (1990). The neglect of engineering design. *California Management Review, 32*(2), 9-23.

DRM Associates. (2006). *Achieving target cost/design-to-cost objectives.* Retrieved 07/15, 2009, from www.npd-solutions.com/pdtoolkit.html

Duverlie, P., & Castelain, J. (1999). Cost estimation during design step: Parametric method versus case based reasoning method. *The International Journal of Advanced Manufacturing Technology, 15*(12), 895-906.

Ehrlenspiel, K., Kiewert, A., & Lindemann, U. (2007). *Cost-efficient design*. Berlin: Springer.

Emblemsvag, J. (2003). *Life-cycle costing: Using activity-based costing and monte carlo methods to manage future costs and risks*. Noboken, NJ: John Wiley & Sons.

Feldman, P., & Shtub, A. (2006). Model for cost estimation in a finite-capacity environment. *International Journal of Production Research, 44*(2), 305-327.

Fuchs, E. R. H., Bruce, E., Ram, R., & Kirchain, R. E. (2006). Process-based cost modeling of photonics manufacture: The cost competitiveness of monolithic integration of a 1550-nm DFB laser and an electroabsorptive modulator on an InP platform. *Journal of Lightwave Technology, 24*(8), 3175.

Fuchs, E. R. H., Field, F. R., Roth, R., & Kirchain, R. E. (2008). Strategic materials selection in the automobile body: Economic opportunities for polymer composite design. *Composites Science and Technology, 68*(9), 1989-2002.

Gagne, M. L., & Discenza, R. (1995). Target costing. *Journal of Business & Industrial Marketing, 10*(1), 16-22.

Geus, H. G., & Sommer, S. (2007). The future of spunlaid technology. *International Fiber Journal, 22*(1), 28-30.

Griful-Miquela, C. (2001). Activity-based costing methodology for third-party logistics companies. *International Advances in Economic Research, 7*(1), 133-146.

Gurney, K. (1997). *An introduction to neural networks*. London: UCL Press.

Harmon, J. (1992). Developing A turnkey nonwovens spunbond line: Part III - the fun begins. *Nonwovens Industry, March*, 40-43.

Heemstra, F. (1992). Software cost estimation. *Information and Software Technology, 34*(10), 627-639.

Holmes, R. (2011). Worldwide outlook for the nonwovens industry . *Nanofibers for the 3rd Millennium*, Raleigh, NC.

Humphreys, K. K. (2005). *Project and cost engineers' handbook* (4th ed.). New York: CRC.

INDA. (2008). *Worldwide outlook for the nonwovens industry 2007-2012.* (). Cary, NC, USA: INDA.

INDA. (2012). *About nonwovens.* Retrieved 05/14, 2012, from http://www.inda.org/about/nonwovens.html

IntertechPira. (2010). *The future of nonwovens to 2015: Global market forecasts.* ().IntertechPira.

ISPA. (2008). *Parametric cost estimating handbook.* Retrieved 04/03, 2009, from cost.jsc.nasa.gov

James, A. (1997). Principles of spin pack design: A guide to selecting components. *International Fiber Journal, 12*(2), 16-20.

James, A. (April 2000). Producing nonwoven fabrics by melt extrusion: An introduction to meltblown and spunbond processes. *International Fiber Journal,* , 32-41.

Johnson, H. T. (1991). Activity-based management: Past, present, and future. *The Engineering Economist, 36*(3), 219-238.

Kamruzzaman, J., Begg, R., & Sarker, R. A. (2006). *Artificial neural networks in finance and manufacturing*. Hershey, PA: Idea Group Pub.

Kaplan, R. S., & Anderson, S. R. (2007). *Time-driven activity-based costing: A simpler and more powerful path to higher profits* Harvard business press.

Kaplan, R. S., & Cooper, R. G. (1998). *Cost & effect: Using integrated cost systems to drive profitability and performance* (9th ed.). Boston, MA: Harvard Business Press.

Kim, G. H., An, S. H., & Kang, K. I. (2004). Comparison of construction cost estimating models based on regression analysis, neural networks, and case-based reasoning. *Building and Environment, 39*(10), 1235-1242.

Kirchain, R. (2001). Cost modeling of materials and manufacturing processes. *Encyclopedia of Materials: Science and Technology, ,* 1718-1727.

Kirchain, R., & Field, F. (2001). Process-based cost modeling: Understanding the economics of technical decisions. *Encyclopedia of Materials Science and Engineering, 2*, 1718-1727.

Kittelmann, W., & Blechschmidt, D. (2003). Extrusion nonwovens. In W. Albrecht, H. Fuchs, W. Kittelmann & J. Lünenschloss (Eds.), *Nonwoven fabrics: Raw materials, manufacture, applications, characteristics, testing processes* (pp. 188-230). Germany: WILEY-VCH Verlag GmbH & Co.

Lamboglia, E., Gaudenzi, P., & Joumier, H. (2008). Non-linear and multivariate regressions for space engineering parametric cost models. *Cost Engineering, 50*(8), 14-21.

Laukien, D. (2009). Feasibility study of spunbonds plants considering the product width. *Technical Textiles,* (2), 62-63.

Layer, A. (2003). *Case-based cost estimation: A building block for product cost management and design-for-x.* (Unpublished PhD). University of Twente, Enschede, Netherlands.

Layer, A., Ten Brinke, E., Van Houten, F., Kals, H., & Haasis, S. (2002). Recent and future trends in cost estimation. *International Journal of Computer Integrated Manufacturing, 15*(6), 499-510.

Leake, D. B. (1996). CBR in context: The present and future. In D. B. Leake (Ed.), *Case-based reasoning: Experiences, lessons and future directions* (1st ed., pp. 3-30). Menlo Park, Calif.: AAAI Press.

Lock, D. (2007). *The essentials of project management* (9th ed.). Burlington, VT: Gower Publishing.

Lu, F., & Moller, A. (1997). Influence of melt spinning speed on properties of filaments and fabrics produced in spunbonding processes. Paper presented at the *NONWOVENS CONFERENCE,* 233-238.

Malkan, S. R. (1995). An overview of spunbonding and meltblowing technologies. *Tappi Journal, 78,* 185-185.

Marir, F., & Watson, I. (1995). CBRefurb: Case-based cost estimation. Paper presented at the *Case Based Reasoning: Prospects for Applications, IEE Colloquium on,* 5/1-5/3.

Martinez, M. T., Fouletier, P., Park, K. H., & Favrel, J. (2001). Virtual enterprise-organisation, evolution and control. *International Journal of Production Economics, 74*(1-3), 225-238.

Michielsen, S., Pourdeyhimi, B., & Desai, P. (2006). Review of thermally point-bonded nonwovens: Materials, processes, and properties. *Journal of Applied Polymer Science, 99*(5), 2489-2496.

NASA. (1995). *Parametric cost estimating handbook.* Retrieved 04/05, 2009, from cost.jsc.nasa.gov/pcehhtml/pceh.htm

Niazi, A., Dai, J. S., Balabani, S., & Seneviratne, L. (2006). Product cost estimation: Technique classification and methodology review. *Journal of Manufacturing Science and Engineering, 128,* 563.

Nordson Fiber Systems.*Fiber systems technology primer: An introduction to spunbond and meltblown.* Unpublished manuscript.

Noreen, E. W., Brewer, P. C., & Garrison, R. H. (2008). *Managerial accounting for managers*. Irwin: McGraw-Hill Higher.

Park, J., & Simpson, T. W. (2005). Development of a production cost estimation framework to support product family design. *International Journal of Production Research, 43*(4), 731-772.

Pesonen, L. T. T. (2001). *Implementation of design to profit in a complex and dynamic business context.* (Unpublished PhD). University of Oulu, Finland.

Pfleeger, S. L., Wu, F., & Lewis, R. (2005). *Software cost estimation and sizing methods: Issues, and guidelines*. Santa Monica, CA: Rand Corp.

Pourmohammadi, A. (2007). Thermal bonding. In S. J. Russell (Ed.), *Handbook of nonwovens* (). Manchester, England: Crc Press.

Powell, N., & Cassill, N. (2006). New textile product development: Processes, practices, and products. *Journal of the Textile Institute, 97*(2), 155-166.

Predic, B., & Stefanovic, S. (1999). Costs management for a profitable new product development. *Economics and Organization, 1*(7), 9-16.

Qian, L., & Ben-Arieh, D. (2008). Parametric cost estimation based on activity-based costing: A case study for design and development of rotational parts. *International Journal of Production Economics, 113*(2), 805-818.

Rajkumar, R. (2003). *Decision engineering report series. cost engineering: Why, what and how?*. UK: Cranfield University.

Rehman, S., & Guenov, M. D. (1998). A methodology for modelling manufacturing costs at conceptual design. *Computers & Industrial Engineering, 35*(3-4), 623-626.

REICOFIL. (2011). *REICOFIL® bico-technologie.* Retrieved 11/05, 2011, from www.reicofil.com

Roy, R. (2003). *Cost engineering: Why, what and how?* (Unpublished Cranfield University, UK.

Roztocki, N., Valenzuela, J. F., Porter, J. D., & Monk, R. M. (1999). A procedure for smooth implementation of activity based costing in small companies. Paper presented at the *The American Society of Engineering Management (ASEM) National Conference*, Virginia Beach. 279-288.

Rupp, J. (2008). Spunbond & meltblown nonwovens - part two. *Textile World, May/June*, 2011.

Russell, S. J., & Textile Institute (Manchester, E. (2007). *Handbook of nonwovens* Crc Press.

Saban, K., Lanasa, J., Lackman, C., & Peace, G. (2000). Organizational learning: A critical component to new product development. *Journal of Product & Brand Management, 9*(2), 99-119.

Saravi, M., Newnes, L., Mileham, A. R., & Goh, Y. M. (2008). Estimating cost at the conceptual design stage to optimize design in terms of performance and cost. In R. Curran, S. Chou & A. Trappey (Eds.), *Collaborative product and service life cycle management for a sustainable world* (pp. 123-130). London: Springer.

Scanlan, J., Hill, T., Marsh, R., Bru, C., Dunkley, M., & Cleevely, P. (2002). Cost modelling for aircraft design optimization. *Journal of Engineering Design, 13*(3), 261-269.

Schreve, K., Schuster, H., & Basson, A. (1999). Manufacturing cost estimation during design of fabricated parts. *Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture, 213*(7), 731.

Seo, K. K., Park, J. H., Jang, D. S., & Wallace, D. (2002). Approximate estimation of the product life cycle cost using artificial neural networks in conceptual design. *The International Journal of Advanced Manufacturing Technology, 19*(6), 461-471.

Sharp, S. (2011). *Pack design and cleaning.* Unpublished manuscript.

Shi, H., & Li, W. (2008). The integrated methodology of rough set theory and artificial neural-network for construction project cost prediction. *Intelligent Information Technology Application, 2*, 60-64.

Shtub, A., & Versano, R. (1999). Estimating the cost of steel pipe bending, a comparison between neural networks and regression analysis. *International Journal of Production Economics, 62*(3), 201-207.

Shuler, B. F., & Hagewood, J. (2009). Trends in meltspinning process technology for nonwovens. *International Fiber Journal, 24*(1), 22-25.

Sievering, R., & Waltermann, H. (April 1997). Modern spin packs. *International Fiber Journal, ,* 29-30.

Singer, P. (2010). *Nonwovens: Sector report.* (Investment research). London, UK: Edison Investment Research.

Smith, A. E., & Mason, A. K. (1997). Cost estimation predictive modeling: Regression versus neural network. *The Engineering Economist, 42*(2), 137-161.

Smorada, R. S. (2002). Nonwoven fabrics, spunbonded. *Encyclopedia of polymer science and technology* () John Wiley & Sons, Inc. doi:10.1002/0471440264.pst217

Sonmez, R. (2004). Conceptual cost estimation of building projects with regression analysis and neural networks. *Canadian Journal of Civil Engineering, 31*(4), 677-683.

Stewart, R. D. (1991). *Cost estimating* (2nd ed.). New York: Wiley.

Stockton, D., & Wang, Q. (2004). Developing cost models by advanced modelling technology. *Journal of Engineering Manufacture, 218*(2), 213-224.

Taylor, I. M. (1997). Cost engineering: A feature-based approach. Paper presented at the *85th ACARD SMP Meeting,* Aalbord Denmark. 14.1-14.9.

Textile World. (2007). Albis to install world's widest spunbond line. *Textile World, March/April*

Turbak, A. F. (Ed.). (1993). *Nonwovens: Theory, process, performance, and testing*. Atlanta, GA: TAPPI Press.

Turton, R., Bailie, R. C., Whiting, W. B., & Shaeiwitz, J. A. (2008). *Analysis, synthesis and design of chemical processes* Prentice Hall.

Tyagi, R. K. (2006). New product introductions and failures under uncertainty. *International Journal of Research in Marketing, 23*(2), 199-213.

Ulrich, K., & Eppinger, S. D. (1995). *Product design and development*. New York: McGraw-Hill.

Urban, G. L., & Hauser, J. R. (1993). *Design and marketing of new products* (2 nd. ed.). Englewood Cliffs, NJ: Prentice-Hall.

Vatavuk, W. M. (2005). How to estimate operating costs. *Chemical Engineering, 112*(7), 33-37.

Verlinden, B., Duflou, J., Collin, P., & Cattrysse, D. (2008). Cost estimation for sheet metal parts using multiple regression and artificial neural networks: A case study. *International Journal of Production Economics, 111*(2), 484-492.

Wang, Q. (2007). Artificial neural networks as cost engineering methods in a collaborative manufacturing environment. *International Journal of Production Economics, 109*(1-2), 53-64.

Watson, R., & Kwak, Y. H.Parametric estimating in the knowledge age: Capitalizing on technological advances. Paper presented at the *IAMOT 2004 13th International Conference on Management of Technology,* Washington, DC.

Watzl, A. (2005). *Spunbond and spunlace - the future of nonwovens?*. Retrieved 11/10, 2010, from http://www.texdata.com/content/0527e.pdf

Weustink, I., Ten Brinke, E., Streppel, A., & Kals, H. (2000). A generic framework for cost estimation and cost control in product design. *Journal of Materials Processing Technology, 103*(1), 141-148.

Wilson, A. (2007). Development of the nonwovens industry. In S. J. Russel (Ed.), *Handbook of nonwovens* (1st ed., pp. 1-15). New York: CRC Press.

Wongvasu, N., Kamarthi, S., & Zeid, I. (2001). Case-based reasoning: Rapid cost estimation of mass-customized products. In M. M. Tseng, & F. T. Piller (Eds.), *The customer centric enterprise: Advances in mass customization and personalization* (pp. 209-229). New York: Springer.

Xu, X., Chen, J. L. Q., & Xie, S. (2006). Framework of a product lifecycle costing system. *Journal of Computing and Information Science in Engineering, 6*, 69.

Younossi, O. (2002). *Military jet engine acquisition: Technology basics and cost-estimating methodology*. California: Rand Corp.

Zamfir, M., McCulloch, J., & Pourdeyhimi, B. (2003). Recent developments in spunbonding and meltblowing: Technologies have seen variety of innovations over the years. *Nonwovens Industry,*

Zhang, Y., Fuh, J. Y. H., & Chan, W. (1996). Feature-based cost estimation for packaging products using neural networks. *Computers in Industry, 32*(1), 95-113.

Zhang, Y., & Fuh, J. (1998). A neural network approach for early cost estimation of packaging products. *Computers & Industrial Engineering, 34*(2), 433-450.

7 APPENDICES

7.1 APPENDIX A: EMPLOYEE COMPENSATION MODEL

Table 7-1: Example of simple employee compensation model

Basic Salary			
Base Hourly Wage Rate, $/h			$16.96
Total Hours Paid, h/yr	8 hours/day × 5days/week × 52weeks		2,080
Yearly Wage Paid, $/yr			*$35,277*
Paid Leave			
Total Paid Leave Hours, h/yr	(10 vacation + 6 holidays + 5 sick days) × 8 h/day		168
Actual Hours Worked, h/yr	2,080 - 168		1,912
Legally Required Benefits	**Tax Rate**	**Wage Base**	**$/yr**
Social Security	6.20%	$110,000	$2,187
Medicare	1.45%	No limit	$512
Federal Unemployment Insurance	0.60%	$7,000	$42
State Unemployment Insurance	3.42%	$20,400	$698
Workers' Compensation	$4.66	per $100	$1,644
Total Required Benefits			*$5,082*
Required Benefits Burden			*14.41%*
Optional Benefits	**Rate**		**$/yr**
Health Insurance	13.61%		$4,800
Life Insurance	0.05%		$176
Disability insurance	0.05%		$176
Retirement Contribution	3.00%		$1,058
Bonuses	2.00%		$706
Total Optional Benefits			*$6,917*
Optional Benefits Burden			*19.61%*
Annual Employee Cost, $/yr	$35,277 + $5,082 + $6,917		**$47,276**
Hourly Employee Cost, $/hr	$47,276 ÷ 1,912		**$24.73**
Burden Load Factor	$24.73 ÷ $16.96		**145.79%**

Table 7-2: North Carolina legally required benefits as of January 1, 2012

Tax Components	Rates	Notes
Social Security and Medicare (FICA)	7.65%[1]	SSI portion is 6.2% on the first $110,000 in wages Medicare portion is 1.45% with no wage limit
Federal unemployment insurance (FUTA)/	0.60%[2]	6% minus a maximum of 5.4% on the first $7000 in wages
State unemployment insurance (SUTA)	0.00% - 6.84%[3] 1.20% for new employers	SUTA tax rate and wage base varies from state to state $20,400 for North Carolina
State Disability Insurance (SDI)	0.00%[3]	Varies from state to state None for North Carolina
Worker's compensation	4.66$ per $100[4]	Varies from state to state Depends on category of employee

Sources:
[1] The Official Website of the U.S. Social Security Administration: www.socialsecurity.gov
[2] The Official Website of the U.S. Internal Revenue Service: www.irs.gov
[3] NC Department of Commerce, Division of Employment Security: www.ncesc.com
[4] Average for NC worker's compensation premium (According to US Department of Labor)

7.2 APPENDIX B: COST MODEL WORKSHEET

Product Parameters

Fiber Technology		Bicomponent
Fiber Cross Section		Round
Fiber Configuration		Sheath Core
Fiber Linear Density	[deniers]	1.5
Fabric Basis Weight	[g/m2]	100

Fiber Composition		Component A			Component B		
Component Weight % in Fiber	[%]	75.0%			25.0%		
		Polymer A	Additive A1	Additive A2	Polymer B	Additive B1	Additive B2
Materials	[%]	PET			PA 6		
Materials Weight % in Component	[%]	100.00%	0.00%	0.00%	100.00%	0.00%	0.00%
Materials Weight % in Fiber	[%]	75.00%	0.00%	0.00%	25.00%	0.00%	0.00%

Equipment/Processing Parameters

Spunlaying			
Working Width	[m]	3.4	
Number of Beams	[# beams]	1	
Number of Holes	[# holes/m/beam]	4000	
Polymer Mass Flow Rate	[g/hole/min]	0.70	
Yield	[%]	100.0%	
Specific Throughput	[kg/h/m/beam]	168.00	
Fiber Take-up Velocity	[m/min]	4200.00	
Weekly Reduction in Prod. Rate w/o Maint.	[%/week]	0.0%	100% first week
Production Rate	[kg/h]	571.20	
Requires Drying Equipment		Yes	

Drying		Polymer A	Polymer B
Need Dryer		Yes	Yes
Bulk Density	[kg/m3]	350	550
Drying Time	[h]	4	5
Drying Temperature	[oC]	120	140
Yield	[%]	100.0%	100.0%
Estimated Minimum Dryer Volume	[m3]	4.90	1.30
Actual Dryer Volume	[m3]	4.90	1.30

Calendering		
Yield	[%]	100.0%
Linear Speed	[m/min]	28.00
Production Rate	[kg/h]	571.20

Winding		
Edge Trimming Width (One Side)	[m]	0.1
Yield	[%]	94.1%
Production Rate	[kg/h]	537.60

Line		
Net Fabric Width	[m]	3.20
Line Yield	[%]	94.1%
Production Rate	[kg/h]	537.60

Material Usage Rates (Steady State)		Polymer A	Additive A1	Additive A2	Polymer B	Additive B1	Additive B2	Total
Yield Adjustment	[%]	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	
Material Usage Rate	[kg/h]	428.40	0.00	0.00	142.80	0.00	0.00	571.20
Material Usage per kg of Fabric	[kg/kg]	0.80	0.00	0.00	0.27	0.00	0.00	1.06

Production Time

Working Schedule		
Weeks per Year		52
Days per Week		7
Shifts per Day		3
Hours per Shift		8

Maintenance Schedule		
Duration of Capital Maintenance	[weeks]	2
Number of Pack Cleanings	[#/y]	12
Spin Pack Change Time	[h/beam/maint]	5
Idle Time for Spin Pack Cleaning	[h/maint]	0
Number of Stops per Year	[#/y]	12
Spunlaid Machine Purge Time	[h/maint]	1
Line Shutdown and Startup Time	[h/maint]	2

Available Production Time	[h/y]	8,400
Downtime	[h/y]	96
Actual Production Time	[h/y]	8,304
Uptime Factor	[%]	98.9%

Annual Production

Product Life	[y]	10
Annual Net Capacity	[kg/y]	4,464,230
Desired Production Source		Specific Volume
Desired Annual Production Volume	[kg/y]	4,000,000
Annual Net Production Volume	[kg/y]	4,000,000
Line Utilization	[%]	89.6%

General Economic Parameters

Material Prices		Polymer A	Additive A1	Additive A2	Polymer B	Additive B1	Additive B2	Purge Polym.
Price	[$/kg]	$2.30	$0.00	$0.00	$3.60	$0.00	$0.00	$2.75

Load Default Material Prices

Scrap Treatment Prices/Costs		
Scrap Disposal Cost	[$/kg]	$0.04
Scrap Recycling Cost	[$/kg]	$0.00
Selling Price of Scrap	[$/kg]	$0.08
Value of Recycled Scrap	[$/kg]	$0.00

Labor Cost Rates		Operators	Maintenance	Supervisory
% over Operators Rate			25.0%	79.2%
Hourly Rate	[$/h]	$14.11	$17.64	$25.28
Burden Rate	[%]	150%	150%	150%

Utilities Cost Rates		
Electricity Cost Rate	[$/kWh]	$0.06
Water Cost Rate	[$/m3]	$1.50

Floor Space Cost Rate		
Annual Space Cost Rate	[$/m2]	$94.90

Cost of Capital		
Interest Rate	[%]	8%

Cost of Materials

Materials Usage		Polymer A	Additive A1	Additive A2	Polymer B	Additive B1	Additive B2	Total
Annual Materials Used for Production	[kg/y]	3,187,500	0	0	1,062,500	0	0	4,250,000
Annual Material Lost during Shutdown/Startup	[kg/y]	10,282	0	0	3,427	0	0	13,709
Total Annual Materials Used	[kg/y]	**3,197,782**	**0**	**0**	**1,065,927**	**0**	**0**	**4,263,709**
Materials Used per kg of Fabric (incl. Losses)	[kg/kg]	**0.80**	**0.00**	**0.00**	**0.27**	**0.00**	**0.00**	**1.07**

Generated Scrap		
Annual Setup Scrap	[kg/y]	13,709
Annual Winding Scrap	[kg/y]	250,000
Annual Scrap	[kg/y]	263,709

Scrap Treatment		Disposal	Selling	Recycling
% of Scrap Directed to	[%]	20.0%	80.0%	0.0%
Scrap Treatment Cost (Benefit)	[$/y]	-$13,765.60		

Cost		Polymer A	Additive A1	Additive A2	Polymer B	Additive B1	Additive B2	Total
Annual Materials Cost (not adjusted)	[$/y]	$7,354,898	$0	$0	$3,837,338	$0	$0	$11,192,236
Annual Scrap Treatment Cost (Benefit)	[$/y]	-$9,046	$0	$0	-$4,720	$0	$0	-$13,766
Annual Materials Cost	[$/y]	$7,345,852	$0	$0	$3,832,618	$0	$0	$11,178,470
% Distribution		65.7%	0.0%	0.0%	34.3%	0.0%	0.0%	100%
Materials Costs per kg of Fabric	[$/kg]	**$1.84**	**$0.00**	**$0.00**	**$0.96**	**$0.00**	**$0.00**	**$2.795**

Cost of Labor

Labor Requirements		Operators	Maintenance	Supervisory
Number of Working Shifts	[#]	3	1	1

		Drying	Spunlaying	Calendering	Winding	Total
Operators per Shift	[#]	0.45	2.05	1.25	1.25	5.00
Maintenance per Shift	[#]	0.04	1.72	0.20	0.04	2.00
Supervision per Shift	[#]	0.09	0.41	0.25	0.25	1.00

☑ Link to Estimation Models

Cost		Drying	Spunlaying	Calendering	Winding	Total
Annual Labor Cost	[$/y]	$92,523	$535,425	$263,594	$251,740	$1,143,282
% Distribution		8.1%	46.8%	23.1%	22.0%	100%
Labor Cost per kg of Fabric	[$/kg]	**$0.023**	**$0.134**	**$0.066**	**$0.063**	**$0.286**

Cost of Utilities

Utilities Consumption Rates		Drying	Spunlaying	Calendering	Winding	Total
Electricity Rate	[kW]	137.09	685.44	308.45	11.42	1142.40
Water Rate	[m3/h]	0.00	2.27	2.27	0.00	4.54

☑ Link to Estimation Models
☑ Link to Estimation Models

Cost		Drying	Spunlaying	Calendering	Winding	Total
Annual Cost of Electricity	[$/y]	$62,322	$311,610	$140,225	$5,194	$519,350
Annual Cost of Water	[$/y]	$0	$25,349	$25,349	$0	$50,697
Annual Cost of Utilities	[$/y]	$62,322	$336,959	$165,573	$5,194	$570,047
Electricity Cost per kg		$0.016	$0.078	$0.035	$0.001	$0.130
Water Cost per kg		$0.000	$0.006	$0.006	$0.000	$0.013
% Distribution		10.9%	59.1%	29.0%	0.9%	100%
Utilities Cost per kg	[$/kg]	**$0.016**	**$0.084**	**$0.041**	**$0.001**	**$0.143**

Cost of Floor Space

Floor Space Requirements		Drying	Spunlaying	Calendering	Winding	Total
Floor Space	[m2]	230.0	920.0	690.0	460.0	2300.0

☑ Link to Estimation Models

Cost		Drying	Spunlaying	Calendering	Winding	Total
Annual Space Cost	[$/y]	$21,827	$87,308	$65,481	$43,654	$218,270
Space Cost per kg	[$/kg]	**$0.005**	**$0.022**	**$0.016**	**$0.011**	**$0.055**

Cost of Equipment

Cost		Drying	Spunlaying	Calendering	Winding	Total
Purchase Equipment Cost	[$]	$300,000	$12,900,000	$1,500,000	$300,000	$15,000,000
Installation Factor	[%]	25.0%	25.0%	25.0%	25.0%	
Capital Investment	[$]	$375,000	$16,125,000	$1,875,000	$375,000	$18,750,000
Salvage Value	[$]	$0	$0	$0	$0	$0
Annual Capital Charges	[%]	0.5%	0.5%	0.5%	0.5%	
Equipment Useful Life Time	[y]	10	10	10	10	
Annual Equipment Cost	[$/y]	$69,375	$2,983,125	$346,875	$69,375	$3,468,750
Equipment Cost per kg	[$/kg]	**$0.017**	**$0.746**	**$0.087**	**$0.017**	**$0.867**

☑ Link to Estimation Models

Cost of Tooling

Tooling Requirements & Costs		Drying	Spunlaying		Calendering	Winding
			Spinpack	Spinnerette		
# of Interchanging Sets per Beam	[#/beam]		2	2		
Tooling Life-Time	[y]	10	10	5	10	10
# of Tooling Sets per Product Life	[#]	1	2	2	1	1
Purchase Price per Set	[$/set]	$0	$544,000	$136,000	$0	$0
Total Purchase Cost	[$]	$0	$1,088,000	$272,000	$0	$0
Design Cost	[$]	$0	$0	$0	$0	$0
Other Tooling Cost	[$]	$0	$0	$0	$0	$0

☑ Link SL Tooling Cost to Estimation Models

		Drying	Spunlaying	Calendering	Winding	Total
Capital Investment in Tooling	[$]	$0	$1,360,000	$0	$0	$1,360,000
Annual Tooling Cost	[$/y]	$0	$244,800	$0	$0	$244,800
Tooling Cost per kg	[$/kg]	**$0.000**	**$0.061**	**$0.000**	**$0.000**	**$0.061**

Cost of Maintenance

Capital Maintenance		Drying	Spunlaying	Calendering	Winding	Total
Capital Maintenance Cost Factor	[%]	3%	3%	3%	3%	
Capital Maintenance Annual Cost	[$/y]	$11,250	$483,750	$56,250	$11,250	$562,500

Cost per Shutdown/Startup		Drying	Spunlaying	Calendering	Winding	Total
Purge Polymer Usage	[kg/maint]		571			
Purge Polymer Cost	[$/maint]		$1,571			
Purge Polymer Disposal Cost	[$/maint]		$22			
Electricity Cost	[$/maint]	$17	$126	$38	$1	$181
Water Cost	[$/maint]	$0	$10	$7	$0	$17
Total Cost per Shutdown/Startup	[$/maint]	$17	$1,729	$45	$1	$1,792

Cost per Maintenance		Drying	Spunlaying	Calendering	Winding	Total
Replacement Parts Cost	[$/maint]	$0	$0	$0	$0	$0
Cleaning Cost	[$/maint]	$0	$4,754	$0	$0	$4,754
Other Costs	[$/maint]	$0	$0	$0	$0	$0
Total Cost per Maintenance	[$/maint]	$0	$4,754	$0	$0	$4,754

☑ Link to Estimation Models
☑ Link to Estimation Models

Regular Maintenance & Shutdown Annual Cost	[$/y]	$201	$77,795	$534	$17	$78,547

Total Maintenance Cost		Drying	Spunlaying	Calendering	Winding	Total
Maintenance Annual Cost	[$/y]	$11,451	$561,545	$56,784	$11,267	$641,047
Maintenance Cost per kg	[$/kg]	**$0.003**	**$0.140**	**$0.014**	**$0.003**	**$0.160**