DISSERTATION

EXPLORATION-BASED DESIGN METHODOLOGY USING THE THEORY OF CONSTRAINTS IN EXTENDING PLASTICS MANUFACTURING FOR NOVEL HIGH PERFORMING FABRICS

Submitted by
Aderemi Shekoni
Department of Systems Engineering

In partial fulfillment of the requirements
For the Degree of Doctor of Philosophy
Colorado State University
Fort Collins, Colorado
Summer 2022

Doctoral Committee:

Advisor: Wade Troxell

Steven Simske
Peter Young
Amy Prieto

ABSTRACT

EXPLORATION-BASED DESIGN METHODOLOGY USING THEORY OF CONSTRAINTS IN EXTENDING PLASTIC MANUFACTURING FOR NOVEL HIGH-PERFORMING FABRICS

The world of textiles is comprised of several materials. From the conventional, such as cotton and silk, to the contemporary, such as polyester and nylon, textiles have changed over time. Nonwovens, a category of material frequently referred to as the "third-generation" of textiles, have emerged as one of the most exciting breakthroughs in the textile industry during the past few years. Nonwovens, which are frequently confused with fibers, yarns, and fabrics, have evolved as a new category of versatile material with medicinal and industrial applications.

An issue associated with the use of lightweight nonwovens is their single-use, in which a fabric weight category can be employed for only one product. The number of products per weight class that can be utilized in businesses that utilize the materials is limited. Therefore, companies utilizing these textiles in their operations must engage with plastic producers to plan, implement, and develop a single weight class for a single product. This procedure is time-consuming and generates plastic waste because of unfinished fabrics. By creating a multipurpose nonwoven fabric, organizations will be able to improve their operations by saving time and energy, improving profits, decreasing plastic waste, and enabling process innovation. To use a fabric with the same weight and similar physical properties in a different product, a different fabric is manufactured for that process, despite the similarity in weight and physical properties between the fabric used in the previous process and the fabric needed for the new process. Due to this limitation, the concept of redesigning nonwoven materials for different applications was conceived. Air Permeability, a barrier to airflow, is a significant component in the inability to support numerous uses. When a fabric's desired attribute is not satisfied, the fabric's air permeability can be optimized by utilizing a variety of process approaches to attain the appropriate performance qualities. This permits the use of a single fabric in a variety of items.

Due to the fabric's weight and volume, the usage of nonwoven in aviation and public works has expanded drastically. Thermal insulation is one of the most prevalent applications of nonwoven materials in the aviation industry. Nonwoven fabrics are also utilized as dynamic biofilters for filtration in public works, with an aerobic layer that aids in the recovery of alkalinity in the filtration systems used in these facilities. The two significant outcomes of this research are (1) Improvement of the airflow barrier, also known as air permeability (AP), which enables the use of a single weight class to make several goods as opposed to a single weight class for a single product, and the addition of a thermal barrier to the fabric. Permeability enhancements in nonwovens enhance the fabric's sound absorption, filtration, and heat absorption. (2) The capacity to recycle undesired nonwoven fabrics following production, as opposed to disposing of the plastic components in landfills. Nonwovens are semi-crystalline polypropylene plastics that are not easily biodegradable due to the strong chemical bond between the polypropylene polymers. Because polypropylenes, which are plastics, are not biodegradable, unused nonwoven fabrics are landfilled.

It was through the process of prototyping that a subsystem alteration was made that enabled the development of nonwoven fabric with better air permeability. Design as Exploration concepts are used to accomplish this. Reicofil I, II, III, and IV are the four nonwoven production systems used in this research to develop the novel fabric. In addition, this study has handled another issue by reusing and recycling unwanted fabrics to reduce the amount of plastic waste in landfills. An extrusion method that recycles rejected and waste fabrics were the result of these approaches. The innovative method used in developing the new nonwoven fabric is being explored for use in the production of plastic films to improve the quality of goods made with polyethylene plastic polymers.

ACKNOWLEDGEMENTS

Dr. Wade Troxell, my Ph.D. advisor, has given me consistent support, patience, drive, and tremendous knowledge and competence. His support, inspiration, help, kindness, and perseverance aided me in finishing my Ph.D. work, which included my dissertation. I am grateful for his advice and outstanding supervision, which have improved my professional development as a researcher. Members of my Ph.D. advising group, Dr. Steve Simske, Dr. Peter Young, and Dr. Amy Prieto, deserve special gratitude.

Berry Global, Inc. (BERRY) has been quite helpful. Berry Global, the world's top plastics producer, offered the resources, equipment, and availability of design methodology, parameters, procedures, and trials for this project (BERRY). I am grateful to all my friends and colleagues at Berry Global, Inc. for their kind help (BERRY). Dee Gibbs deserves special recognition for his outstanding assistance and advise during my Ph.D.

Finally, there are no words to explain how grateful I am to Sherifat Shekoni. Without her compassion and kindness, I would not have been able to complete this dissertation.

Aderemi Shekoni

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NOMENCLATURE

A	Cross sectional area of sample
A_z	Area of the extruder
a	Temperature coefficient
B	Temperature gradient
D	Screw diameter
H^*	Depth of channel
K_{eff}	Elective thermal conductivity
K_{tc}	Thermal conductivity of sample
N	Screw speed
P_c	Power consumption
P_o	Initial pressure
P_z	Final pressure
Q	Heat flow rate
R_r	Two-point correlation
r_t	Throttle ratio
S	Main heater surface
$SS_{critical}$	Critical screw speed
T_o	Initial temperature
T_x	Temperature as a function of axial distance
VA	Velocity at point A
VB	Velocity at point B
V_{bz}	Barrel z velocity
VH	Viscous heating
λ	Thickness of sample
ϕ	Flight helix angle
μ	Melt viscosity
$\Delta P/\Delta Z$	Pressure gradient
ΔT	Temperature dif

INTRODUCTION

The nonwoven industry is a significant component of the textile industry. It is the industry's backbone in many ways. It supplies materials for particular applications and other textiles in a variety of ways. The nonwoven content of a material can be determined by counting the grams of active material in each product. In most nonwovens, the active material is the fibers, filaments, and/or threads. The amount of active substance in a product is commonly referred to as its "denier." A product constructed entirely of nonwoven, for example, may have a denier of 100. The first and most visible distinction between nonwoven and traditional fabrics is their structure. Fibers are suspended in a liquid and spun into yarn to make a textile product in traditional textiles. In the nonwoven world, the opposite is true. A nonwoven is a mass of fibers that have been dried and pressed into a product.

Disposable nonwovens account for two-thirds of all nonwovens commercialized in North America, and this figure is rapidly increasing as more sectors adopt these plastic textiles (INDA, 2011). The key component of a facemask used in healthcare is disposable nonwoven fabric, and the use of nonwovens increased dramatically with COVID-19. Medical gowns, filtration products, absorbent hygiene products, sanitary wipes, disinfection wipes, construction padding materials, heat absorbent items, and protective garments are some of the most frequent end-use products utilizing disposable nonwovens. The chemical makeup of these fabrics, as well as their physical properties and inexpensive production costs, have all contributed to their increased use. Cotton and other natural fibers have long been used to make textiles. However, the emergence of current technology has greatly broadened fabric possibilities. At the moment, the most common natural fibers are spun into yarn and stitched into cloth. Nonwoven extrusion is a separate method of producing specific fabrics. A continuous thread of fibers is drawn through a die in a nonwoven extrusion process to create a finished product with a variety of properties. The continuous strand of fibers is made up of parallel fibers held together by a binder. The final result is created by driving the binder-containing strand through a die to generate the required shape and size. The die can be used to adjust the width and thickness of the end product.

Polypropylene, a semi-crystalline synthetic material, non-biodegradable polymeric polymer with cheap manufacturing costs and appealing visual and mechanical properties, is used to manufacture disposable nonwoven fabrics. In general, there are two types of plastic part production methods: continuous and cyclic. Figure 1.1 depicts the two methods. Nonwoven textile structural qualities are strongly dependent on polypropylene in terms of fiber fineness, fiber arrangement, fiber length, and mechanical and structural variances caused by production methods (Huang et al, 1993). The nonwoven extrusion method is a planar technique that involves the chemical, mechanical, and thermal bonding of fibers. The metallic screw, depicted in Figure 1.2, is a critical component of the extrusion system. By spinning while heated, the metallic screw aids in the melting of the polypropylene polymers. The heat generated in the extruder, along with the friction of contact with the polymers, results in a well-distributed molten mass, with the viscosity of the plastic melt assisting in the transition of the melt from the extruder to the die chamber.

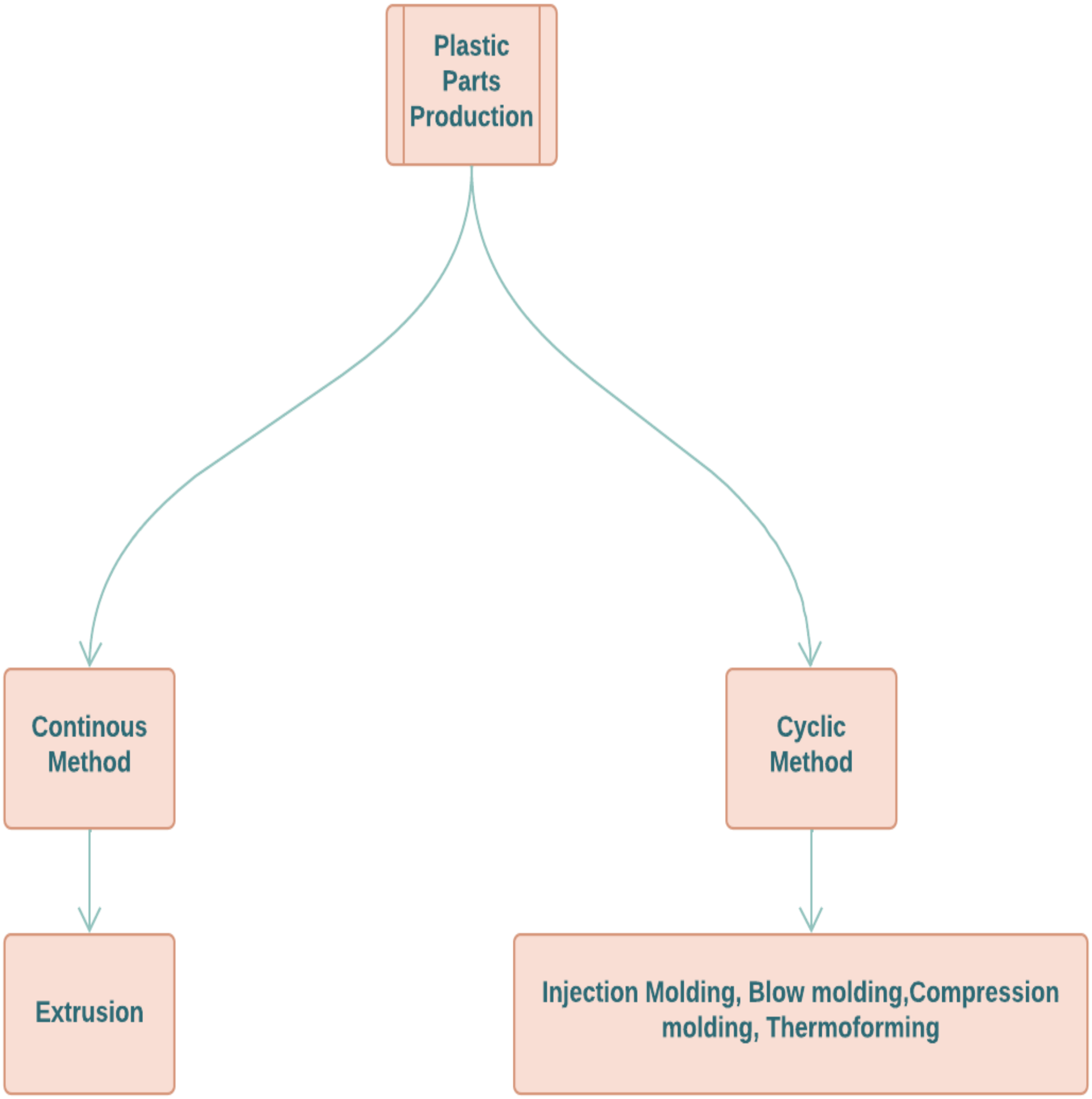


Figure 1.1 Methods of Plastic Production

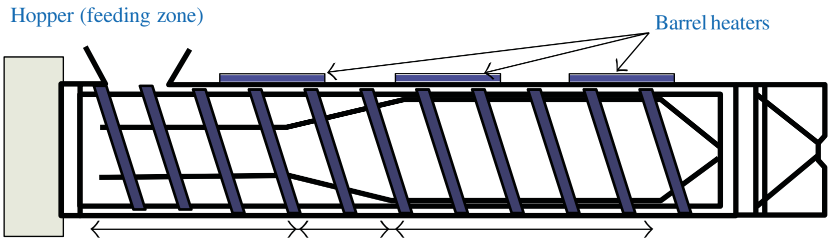


Figure 1.2 Large Screw Inside the Extruder. (Maniruzzaman et al, 2012)

The molten plastic is pushed through the die body by the pressure generated by the extruder. As molten plastic passes into a mold, it gets shaped into a certain form. The pressure is produced by the extruder and utilized by the die. The relationship between the die and die-head pressure is linear (i.e., low restriction die requires low pressure). A variety of variables in nonwoven production are determined by the physical dimensions of the desired fabric. There are numerous variations of disposable nonwovens. The classification of a nonwoven fabric is determined by its polypropylene foundation. Polypropylene's categorization is also influenced by its melt flow rate. Table 1 depicts the various forms of nonwoven fabrics that are disposable.

Spunbond polypropylene and Meltblown polypropylene are distinguished by their respective melt flow rates. The melt flow rate of Spunbond polypropylene is 35 g/10min while that of Meltblown polypropylene is 230 g/10 min (the unit of melt flow rate is g/10min). Numerous disposable nonwovens are composed of S-M-S fibers, however, the vast majority of disinfection wipes are predominantly composed of S-S fibers. Thermal insulation systems employ S-S-S nonwoven textiles, while large-scale filtering systems employ SMMS nonwoven textiles

1.1 Overview

During production, the structural integrity of disposable nonwoven fabrics is achieved through physical and chemical processes.

Table 1. Examples of disposable nonwovens

Polypropylene Type	Nonwoven Types	Name
1. Spunbond (PP) 2. Meltblown (PP)	S-S	Spunbond – Spunbond (Pure Spunbond)
	S-M-S	Spunbond-Meltblown-Spunbond
	S-M-M-S	Spunbond-Meltblown-Meltblown-Spunbond
	M-M	Meltblown-Meltblown (Pure Meltblown)
	S-S-M-S	Spunbond-Spunbond-Meltblown-Spunbond
	S-S-S	Spunbond-Spunbond-Spunbond

Nonwovens are manufactured at a high rate of approximately 100 meters per minute, depending on the age of the manufacturing system employed; the more recent the Reicofil manufacturing system, the quicker the production time. From raw materials to completed product, the production of nonwovens involves four steps.

In order to create a disposable nonwoven, a vacuum-fed resin is fed to the Material Feed, which is positioned above the extruder. The material is melted and homogenized within the extruder. The two types of extruders are single screw extruders and double screw extruders. Extruders with a single screws are Reicofil I and II, and extruders with two screws are Reicofil III and IV. There are two primary kinds of feeding: flood feeding and starvation feeding. Flood feeding is most common in single-screw extruders, while starvation feeding is more prevalent in twin-screw extruders. Figure 1.3 illustrates a computation of flood feeding in comparison to starvation feeding.

The final application of the fabric determines whether flood or starvation feeding is used. Extruders with two screws are utilized in modern nonwoven machines, whilst single-screw extruders are utilized in older machines. For effective process control and well-shaped textiles, starvation feeding is required.

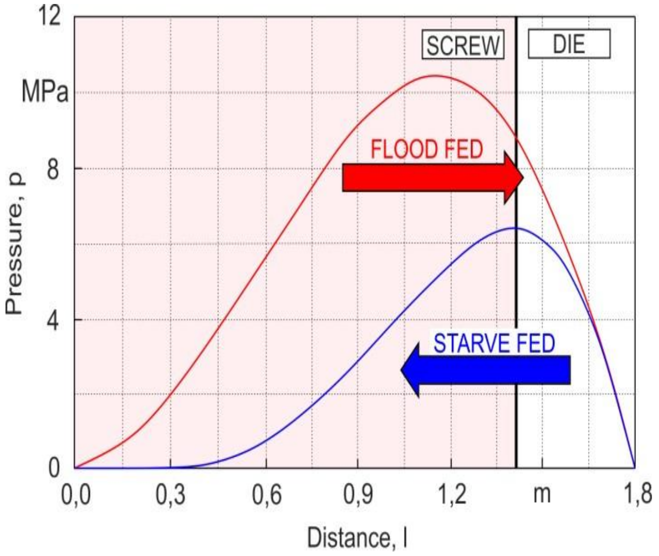


Figure 1.3 Scheme computations for flood and starve feeding adapted from Wilczyński et al,2019

Higher pressure variance is the primary disadvantage of starvation feeding when the length of the produced cloth is insufficient. In contrast, flood feeding is a cost-effective alternative. It is inexpensive, effective with pelletized polymers, and utilizes the entire extruder length.

The desired melt flow is then determined as the melt is transferred to the die chamber following the extrusion process. Gravity-generated flow and drag-induced flow are two methods for achieving the required flow of molten material. The flow mechanism of the extrusion process consists of these two types of flow. The most prevalent type of flow is the drag-induced flow, in which the frictional force between the extruder screws and the plastic, as well as the frictional force between the plastic and the barrel, move the polymer forward. As the molten mixture goes through the die body, strands of plastic are produced. Before the filaments are physically linked, they are cooled using large cylinder-shaped machines known as calendars. The term for the mechanical bonding process is calendaring. Calendaring is a nonwoven fabric finishing process in which the fabric is pressed at a high temperature and pressure through heated cylindrical rollers (Sharma, 2017). Two rollers press down on the transitional fabric from opposite ends to aid in the bonding and aesthetics of the plastic.

Depending on the type of nonwoven and the final application of the fabric, chemicals are sometimes added to nonwoven fabrics as they travel through the calendar. One example is a nonwoven material developed for use as absorbent wipes. When converted into sanitary wipes, these nonwovens are treated with absorption-enhancing surfactants. As depicted in figure 1.4, the winder mandrel receives the newly created nonwovens web as it travels through the machine, rotating at a predefined speed until the desired volume builds up on the winder. The winder mandrel captures the fabric as it emerges from the manufacturing system by winding on the mandrel. When the target volume is reached, the crane operator uses a hydraulic system to transport the mass from the winder area to the slitter waiting area, as depicted in figure 1.4. When the slitter is clear, the jumbo roll is carried to the slitter, where it is slit into required sizes based on customer specifications. The slit fabric is then wrapped and packaged for delivery.

Figure 1.4 S-M-S Nonwoven on a winder mandrel lifted by 12.5-ton crane.

1.2 Thesis Topic Overview

The development of new disposable nonwoven fabric will be utilized to illustrate and analyze design as an exploration technique in relation to the development of new disposable nonwoven textiles. Design as Exploration will be utilized in two key areas of this design and development project: a) the development of a new innovative product with limited industrial knowledge that can be applied to multiple products, and b) the modification of production equipment based on the theory of constraints as it relates to the product. SMS nonwoven fabric will be utilized since, compared to other disposable nonwovens, it has the most applications. The development of a new generation of SMS nonwoven fabric is described in a nonpragmatic manner.

Chapter 2 begins with design thinking in relation to the new nonwoven fabric. The proposed plastic fabric of the next generation is created with the user and final application in mind. We explore beyond the typical manufacturing boundaries for SMS nonwoven textiles in order to align the product development team's thought process with potential end users and end-use of the material, which takes us back to the process with the end user in mind. In addition, we use a holistic approach to the system, aligning it with the theory of constraints, in order to satisfy the stakeholders' need for the development of a 15 gsm S-M-S (Spunbond-Meltblown-Spunbond) nonwoven with an air permeability more than 27 ft3/ft2/min.

In chapter three, we use the foundations of a change in process thinking to explain the process and challenges of designing the new Synergex one SMS nonwoven material. In the construction of the 5K die, we begin with "The Goal" and how it relates to design thinking before closing off with "Design as Exploration." This chapter contrasts previous installations of lightweight nonwoven S-M-S and their associated air permeability with the current objective. The permeability of a disposable nonwoven fabric is determined by the random distribution of plastic filaments in relation to the viscosity and density of polypropylene used in its production.

In Chapter 4, we break down the development process and demonstrate how the new nonwoven fabric is manufactured. We discuss the extrusion method, polymer characteristics, pellet behavior during extrusion, and experimental design employed to produce this unique SMS nonwoven fabric.

Chapter 5 discusses the next steps in the development of disposable and reusable nonwovens. This chapter covers methods for producing biodegradable nonwovens and how Synergex One's results can benefit recycled pellets used in the creation of nonwovens. Also highlighted are advancements in the production of plastic films in relation to the polymer. The similarities between the production of nonwovens and plastic films are studied and explained.

The design as exploration theory will be utilized more frequently when examining design outcomes from the perspective of design limits and how this impacts the design cycle of generating a new nonwoven fabric. This study will focus on the relevance of design as exploration theory to the production of new innovative nonwoven designs, as it embraces the exploratory part of this theory as it relates to the development of other plastics engineering products.

1.3 Thesis Statement

This dissertation demonstrates how a design approach based on the philosophy of design as exploration led to the enhancement and/or modification of present engineering designs and nonwoven production systems to successfully generate a novel nonwoven fabric. Synergex One was established by applying a systems-based design methodology to the development of a next-generation nonwoven fabric.

The statement is, *"How can we use existing nonwoven manufacturing technologies to develop a new generation nonwoven fabric for the 15gsm weight class with enhanced physical attributes suitable for many end-use applications across multiple industries?"*

As a result of Synergex One, there are currently two ways to the production of disposable nonwovens. Using flowcharts, Figures 1.6 and 1.7 demonstrate, respectively, the conventional and novel approaches. The traditional method employs the RF-1 and RF-2 manufacturing systems for heavyweight nonwovens (60 gsm and above) and the RF-3 and RF-4 manufacturing systems for lightweight nonwovens, i.e., 59gsm and below. The main differences between the RF-3 and RF-4 are their manufacturing speed and their ability to produce nonwovens from raw cotton. Plans to perform research and development on biodegradable nonwovens have created a discussion concerning raw cotton. The RF-3 cannot manufacture biodegradable nonwovens utilizing plastic polymers and cotton, and it is slightly slower than the RF-4. Using the inventive strategy, any of the RF manufacturing systems can be used to make both heavyweight and lightweight products, but RF-1 and RF-2 are slower. The new strategy entails altering the RF-3 and RF-4's subsystems to get the desired outcome. The advent of the 5K die has made this possible, as the 5K die is now the only die used in the RF-4 nonwoven production system (figure 1.7). We utilize both the 4K and the 5K for the RF-3, depending on the type of nonwoven product and its intended application. To produce the RF-3's fabrics, the dies are interchanged as needed. Target values of air permeability determine whether a 4K or 5K die is utilized. Reicofil manufactured all the nonwoven technologies used in this research (figure 1.5).

Figure 1.5 Reicofil Product Logo

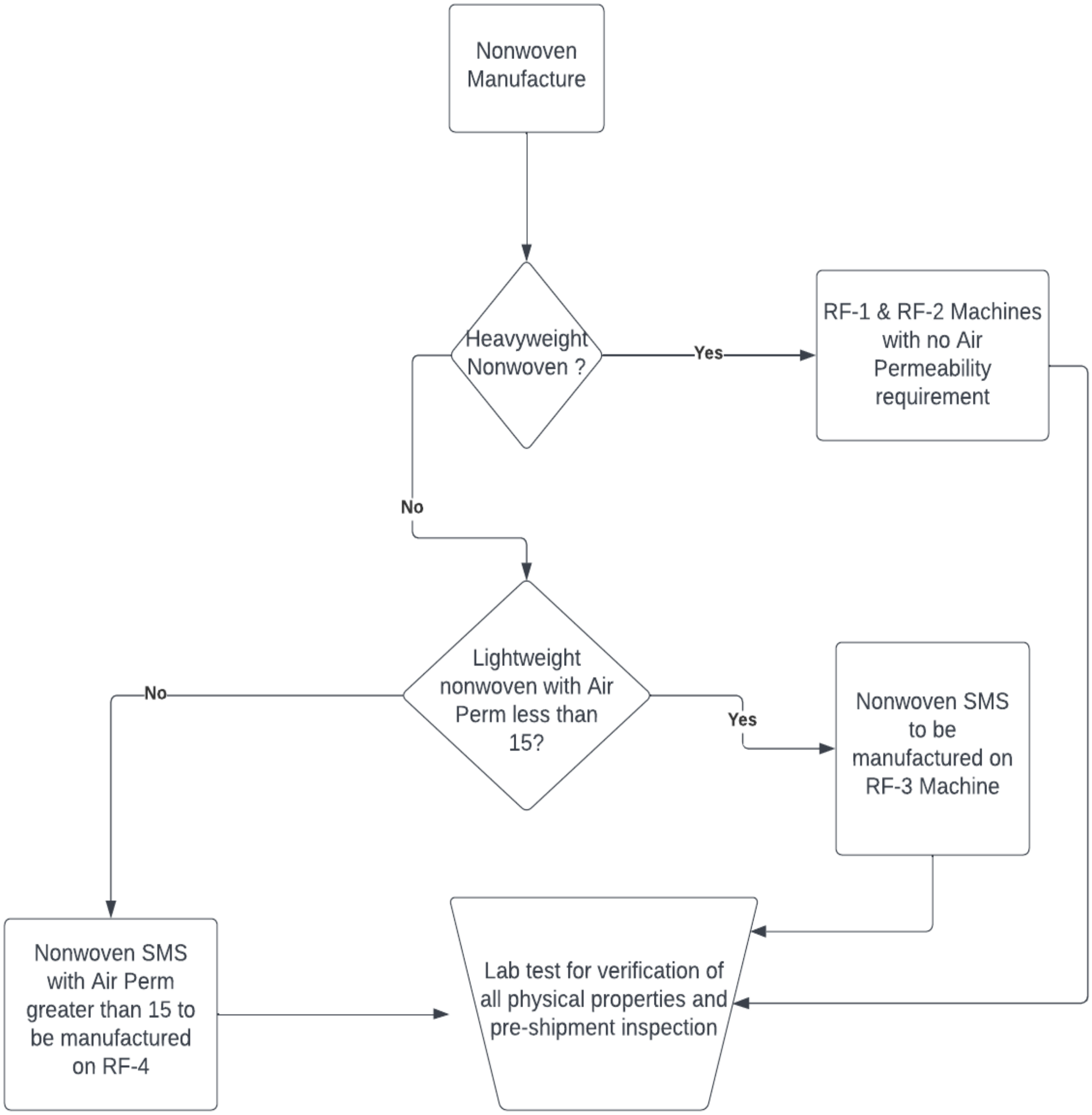


Figure 1.6 Conventional Disposable Nonwoven Manufacture Flow Diagram

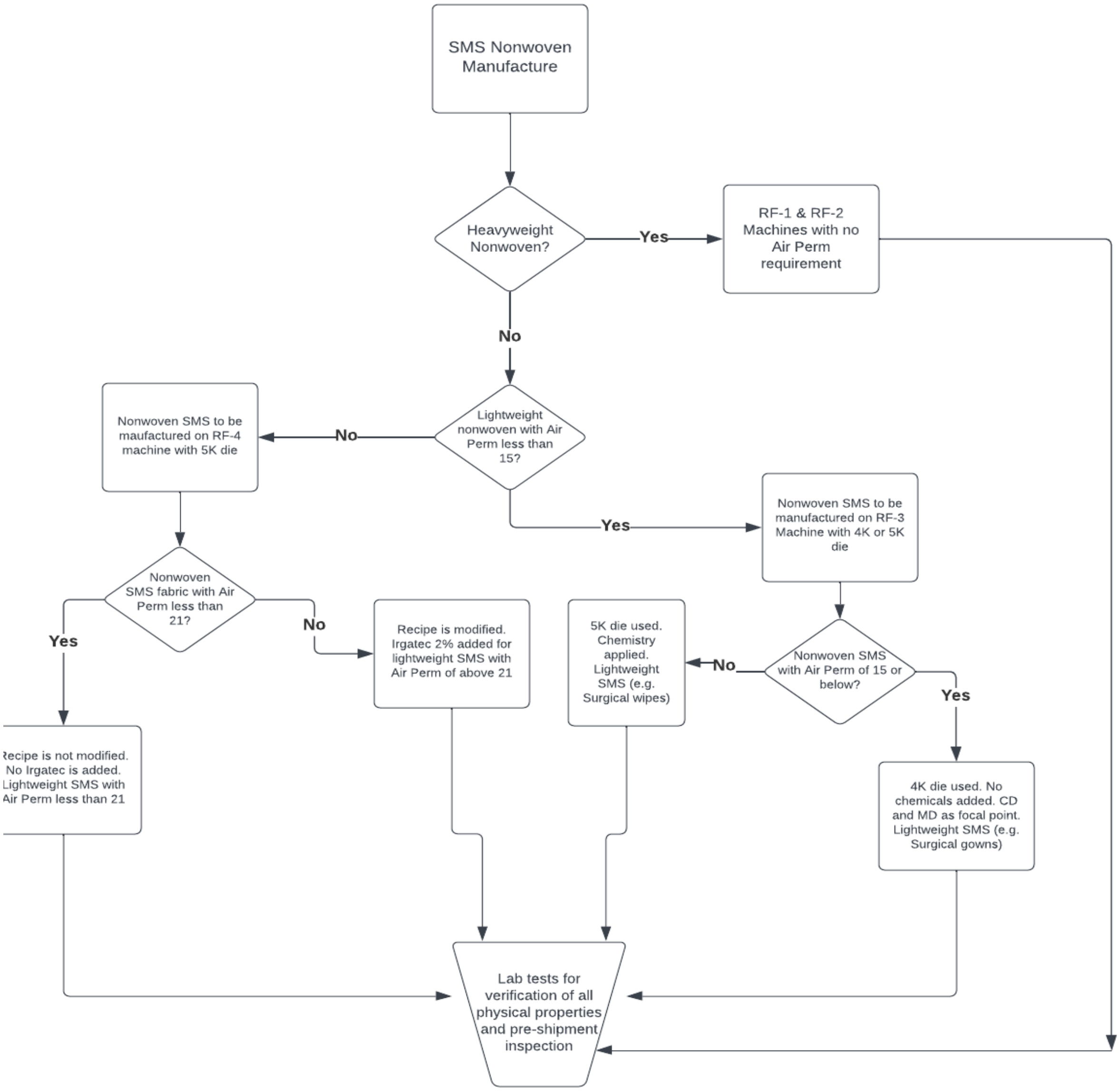


Figure 1.7 New Simple Nonwoven Manufacture Flow Diagram

2. BACKGROUND

2.1 Design Thinking

Design thinking is an empathic method of considering a proposed product from the consumer's or end-user's perspective. Nonwovens are utilized in numerous industries; consequently, client perception of the product is crucial. "Design thinking is a discipline that combines the sensibility and technique of a designer to connect people's desires with what is technologically feasible and a viable business strategy that can be transformed into customer value and market potential" (Brown, 2008). In a Harvard Business Review article published in June 2008, Tim Brown discusses the importance of Design Thinking in generating novel ideas that lead to the creation of new products. Tim explains the impact of IDEO, a company that employs design thinking. The primary premise of IDEO is founded on the personality profile of a design thinker, which begins with empathy and goes via integrative thinking, optimism, experimentalism, and cooperation to aid in the creation of new product concepts. "Design Thinking" is utilized by IDEO to promote the creation of new products. IDEO creates products, service environments, and digital experiences utilizing design thinking. The process detailed in the article is comparable to that used to create Synergex One. The three stages of the procedure are Inspiration, Ideation, and Implementation. Synergex One was motivated by a previous accomplishment involving the modification of a formula to create a sanitary wipe manufactured from recycled polypropylene. Examining the capabilities of the manufacturing systems led to the ideation phase of the process. Implementation is the process of merging techniques and alternatives to produce a new plastic nonwoven fabric.

To incorporate Design Thinking into Synergex's innovation, we followed all eight processes outlined in the Design Thinking book. The eight steps include the following:

I. Begin from the beginning. II. Employ a human-centered approach. III. Experiment frequently and early. IV. Seek external support. V. Combine large and small projects. VII. Identify talent in whatever way possible. VIII. Design for the Cycle.

Design Thinking is present in Synergex One's development. The initial objective was to produce a lightweight fluid barrier fabric that would assist the client obtain a commercial contract. However, owing to Design Thinking, a multipurpose fabric with numerous end-use applications was created.

2.2 Nonwovens

Nonwovens are anisotropic materials whose fiber distribution and orientation are connected to the mechanical strength of the web (Mohammadi et al, 2003). Nonwovens are web structures produced by combining mechanical, thermal, chemical, and/or solvent methods to bind together fibers or plastic filaments. Polypropylene, the nonwovens' basis material, is a homopolymer with syndiotactic methyl groups, indicating that the methyl (CH3) groups are alternatively positioned throughout the carbon chain. Spunbound and Meltblown are the primary constituents of a vast array of nonwoven materials (Table 1). Depending on the final use, Spunbond and Meltblown polymers are mixed in a variety of ways to produce the required nonwoven material. Table 1 demonstrates several instances of such combinations. Meltblown polymers are produced by incorporating micro-denier and/or nanofibers into a polymer melt and then extruding polypropylene via tiny pores surrounded by a high-velocity blowing gas. Inadequate process controls during the production of nonwovens may result in the formation of defective fabrics. Examples of failures include meltbown fly (an aesthetic defect), fiber rupture, polymer drips, and others. The orientation of the web's nonwoven fibers corresponds to a predetermined statistical distribution (Woo et al, 1994).

Nonwovens differ significantly from conventional web textiles in terms of the services they provide when compared to non-polypropylene materials such as cotton textiles. Tensile strength is an essential property of nonwoven materials. The tensile strength of a nonwoven fabric can be measured in two ways. There are two types of tensile: MD Tensile, which is the vertical direction, and CD Tensile, which is the cross direction tensile or horizontal direction. When comparing nonwovens to cotton-based textiles, the following characteristics are considered: I Bacterial and Viral Droplet Barrier (ii) Thermal Insulation (iii) Acoustical Insulation (iv) Absorbency (v) Liquid Repellency (vi) Softness and Durability, and (vii) Filtration Barrier.

2.2.1 Bacterial & Viral droplets barrier

Nonwoven textiles are essential as a bacterial and viral droplet barrier, as demonstrated in hospitals where disposable nonwoven fabrics are used as medical gowns and hospital bed linens to protect personnel and patients from infectious microbes (gram-positive, gram negative, microfungus, etc.). Antimicrobial compounds can cling to the fabric of S-M-S nonwovens, protecting caregivers and patients against opportunistic germs. To combat illnesses caused by these germs, manufacturers of medical gear and hospital linens have fluorinated the fabrics. When fluorine is added to the nonwoven fabric, it becomes hydrophobic, making it particularly efficient as a barrier against the illnesses described above. The effect of fluorination on fabric, which strengthens its antibacterial barrier against microorganisms, is depicted in Table 2.

Table 2. Effects of Fluorination on SMS Nonwoven fabric according to ASTM E 2149

Fluorinating mixture and treatment duration	Bacteria & microfungus amount increase (%) / antimicrobial effect		
	Bacteria		Microfungus
	Escherichia coli	*Staphylococcus aureus*	*Candida albicans*
Pristine PPNWF	100 / absence of antimicrobial effect		
$9\%F_2+9\%O_2+82\%N_2$, 30 min.	14 / low antimicrobial effect	56 / absence of antimicrobial effect	0 / excellent antimicrobial effect
$10\%F_2+90\%N_2$ 30 min.	6 / good antimicrobial effect	0 / excellent antimicrobial effect	59 / absence of antimicrobial effect

2.2.2 Thermal Insulation

In avionics engineering, nonwoven textiles are increasingly used as thermal insulation fabrics. The structure of nonwovens makes them an excellent solution for thermal insulation. Nonwovens significantly limit heat transmission due to the density of the fabric and the polymer structural arrangement that prevents heat from passing through it. Thermal conductivity is a sort of heat transmission in which energy is transported from a region with a higher temperature to one with a lower temperature (Piekaar & Clarenburg, 1967). The Fourier Heat Transfer Equation (Piekaar & Clarenburg, 1968);

$$Q = AK_{tc}\,[\Delta T/\lambda] = -\,AK_{tc}\,[dT / d\lambda] \;\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ (2.1)$$

Where K_{tc} = thermal conductivity of sample, A = cross sectional area of the sample, ΔT = temperature difference, Q = heat flow rate, λ = thickness of the sample, and $\Delta T / \lambda$ = gradient of temperature in the X direction.

For air, vacuum, inert gas, and other situations, the nonwoven fabric's temperature range of effectiveness is -292F to 1202F. (Mohammadi & Lee-Banks, 2003). For effective thermal conductivity, the governing equation is

$$K_{eff} = Q/S \left[\frac{1}{(\Delta T/\lambda)_1 + (\Delta T/\lambda)_2} \right] \;\ldots\ldots\ldots\ldots\ldots\ (2.2)$$

Where K_{eff} = elective thermal conductivity, Q = heat generated by the electrical source, S= main heater surface area, λ = thickness of the samples, ΔT = temperature gradient.

When nonwoven textiles are employed as thermal insulators, the material insulates heat by obstructing the heat conduction channel. The fabric's insulating characteristics improve as the density of the nonwoven fabric increases.

2.2.3 Acoustical Insulation

As acoustical insulation fabrics, nonwoven textiles are applied in the musical instrument sector. Nonwoven fabrics are utilized in acoustics due to their expansive overall surface area (Kourtides et al, 1988). To insulate or absorb sound waves, nonwoven materials are employed as liners in musical instruments such as loudspeakers, guitars, and other instruments. Nonwovens are effective acoustic insulators due to their surface area, which is governed by the denier and cross-sectional shape of the fibers. Because of their capacity to absorb sound, nonwoven materials are often used in recording studios. The greater the fabric density, the more opportunities there are for sound waves to make contact with the fabric's fibers, hence isolating the sound effect from nearby locations.

2.2.4 Absorbency

There are nonwoven textiles that are hydrophobic and hydrophilic. The hydrophobicity or hydrophilicity of the fabric is determined by the manufacturing process's base chemistry. Fluorination of nonwoven fabric, as described in 2.2.1, renders the fabric resistant to water and other liquids. In the instance of absorbency, surfactants are utilized to make the fabric very absorbent. Utilizing hydrophilic nonwoven applications, personal hygiene products, diapers, and cleaning wipes are produced.

2.2.5 Liquid Repellence

Hydrophobic fabric is a nonwoven fabric that repels liquids. This type of material has a low absorption rate and high stability, making it water-resistant. Hydrophobic nonwovens are utilized in products that are intended to generate a moisture-resistant dry barrier.

2.2.6 Softness & Strength

The chemical bond of the polymer used in nonwoven fabric's manufacture gives it its strength. The softness of a nonwoven fabric is determined by its density. Most lightweight nonwoven textiles are soft due to the fiber arrangement in the fabric, whereas heavier weights are coarse. A nonwoven fabric can be utilized in a range of industries since it retains its strength regardless of how soft or coarse it is.

2.2.7 Filtration Barrier

In municipal water treatment plants and wastewater treatment plants, nonwoven textiles are applied. For membrane filtering, nonwoven fabrics are used instead of mesh screens, and gravity pressure is employed instead of a pump (Seo et al, 2002). The nonwoven structure enables it to operate as a sludge barrier in the water, making it an economical filtration medium for these facilities. Figure 2.2 demonstrates how the Meltblown in the SMS acts as an additional barrier, restricting the introduction of pollutants using low gravity filtration strategy. The filtration process for nonwoven materials is straightforward. The pore size of an SMS fabric, which is approximately 100µm, decreases when exposed to sludge or other kinds of impurities, preventing the contaminants from passing through the filter.

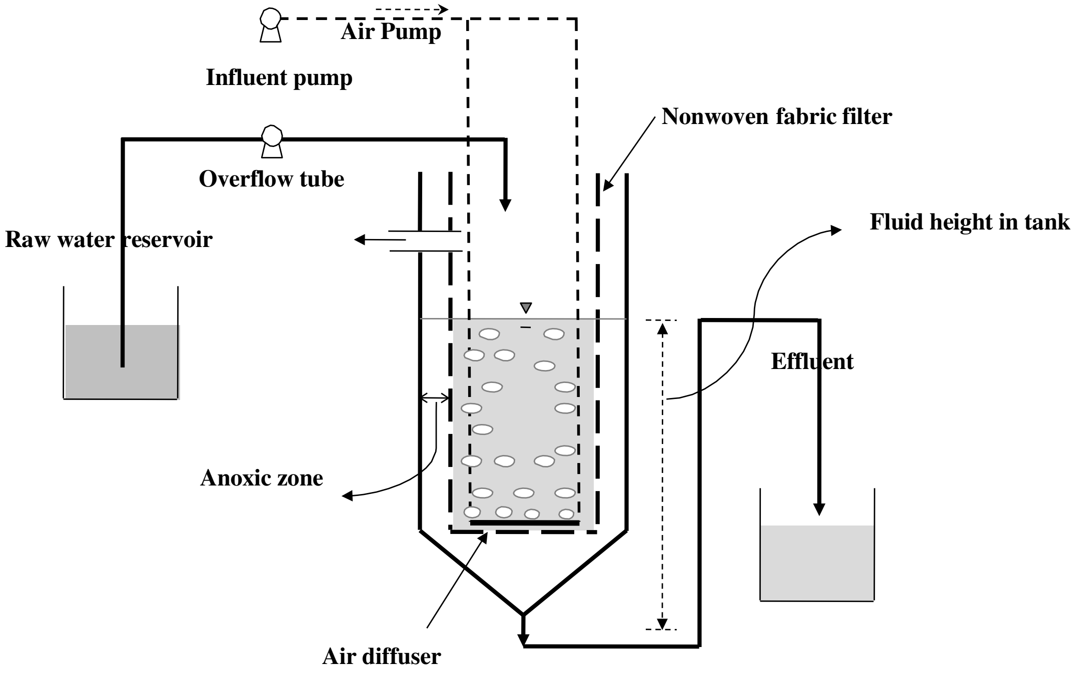


Figure 2.1 Low gravity nonwoven fabric water filtration.

2.3 Making a SMS Nonwoven- System Approach

From a systems perspective, the extruder, die chamber, and calendar are three critical components of the manufacturing system that lead to the manufacture of high-quality nonwoven materials. How these three subsystems interact during the production of nonwoven fabrics affects the material's quality. If the fibers are not properly extruded, they may clog the Die Chamber, and clogged dies result in polymer drips that hinder SMS bonding at the calendar. The inverter breaker plates regulate the uniformity of the melt flow for efficient extrusion. The inverter breaker plates with the screen pack and the screw belt permit a high flow because the breaker plates improve the flow of the molten mass through the die. This has a direct effect on the quality of the extruded product. Filtering contaminants from the molten mass, the screen pack serves to increase barrel pressure for better mixing by filtering out impurities.

2.4 Spunbond Extrusion

Spunbond nonwovens are produced using a continuous extrusion method in which the Spunbond resin is heated until molten. As seen in figure 2.2, heat is delivered above the recrystallization temperature of the resin, and heat generation is enhanced by utilizing the screw in the extruder. The mold is penetrated with molten resin material. As spinnerets, the molten fibers emerge from the die and are collected on a fiber collector, a cylindrical roll.

2.5 Meltblown Extrusion

Meltblown nonwovens are produced using a continuous extrusion technique in which the Meltblown resin is heated and melted. The supplied heat exceeds the temperature at which the resin recrystallizes. The mold is penetrated with molten resin material. The molten fibers emerge from the die as spinnerets, which are gathered on a fiber collector, a cylindrical roll.

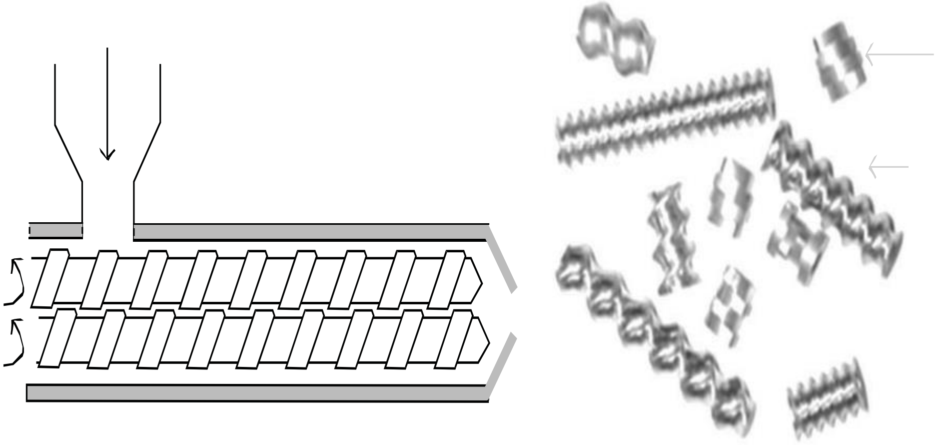


Figure 2.2: Generalized twin screw in extruders. (Maniruzzaman et al, 2012)

2.6 Die body and Web Collector

The die and a mixture of cold and pressured air that chills the forming resin fibers on the web collector are the key determinants of fiber formation. The die body has a substantial effect on how the nonwoven emerges. The track on the die dictates the layout and distribution of the web.

2.7 Calendaring- Web bonding

In Reicofil machines, the fiber web obtained after the extrusion process is calendared by two substantial cylindrical structures. Two calendars on the nonwoven fabric aid with bonding and pattern formation. The calendar is essential for the creation of an SMS since it guarantees that all three components are produced and integrated correctly. The calendar allows for the proper bonding of Spunbond-Meltblown-Spunbond during SMS material production. Two metal canisters with a cylindrical shape are pushed together at a pressure of 600 psi.

2.8 Making a Nonwoven

The polypropylene's clogging characteristics become worse as its melt-flow increases. Meltblown polypropylene in an SMS nonwoven fabric possesses a high melt-flow rate, enabling it to function as a fluid barrier. For nonwovens made with Meltblown polymers, a precise recipe for the nonwoven fabric is created. Additives are utilized in the production of S-M-S (Spunbond-Meltblown-Spunbond) products to allow the molten mass to flow freely. Virgin resins and polymers have never been utilized in conjunction with by-products from natural gas and/or crude oil operations. A silo is used to store virgin resin at the manufacturing facility. The silo is inert since it is designed to store virgin resin until the extrusion process is initiated, at which point a pneumatic system employs air and pressure to move the resins to the related extrusion unit in preparation for extrusion. The hopper system transfers resin from the silo to the extruder, which uses heat to melt the resin (450F minimum temp).

Resin filaments are dispersed from the molten mass in the Die chamber, and the apron collects them prior to delivering them to the press roll. The materials placed on the apron are pressed by the Press roll, which then advances toward the calendar. Calendar rollers grab and press fabric for the purposes of bonding and imprinting a pattern. The newly manufactured fabric is dried in the dryer, and the new web is collected on the winder. A 12.5-ton crane moves a jumbo roll from the winder to the slitter, where it is slit into a variety of roll sizes. Following slitting, the product is transported to a wrapper for packaging. This is an elementary and general description of how nonwovens are manufactured.

2.9 Motivation

"The ability to design creates civilizations" [Smithers 1992, p.2]. For many businesses, advancements in engineering and innovation are essential motivators, necessitating the need for novel product development strategies. To build a technical system that complies with industry standards, system parameters must be carefully evaluated. The original idea for this project was the desire to address a problem using engineering concepts. The efficacy of design thinking in adjusting design parameters to improve a present product while keeping the end-user in mind prompted the idea of utilizing Design as Exploration to create a new nonwoven SMS.

2.10 Design Contraints

At 125 Pascal, RF-3 (Reicofil III) and RF-4 (Reicofil IV) technologies are utilized to manufacture lightweight nonwovens with high air permeability. Prior to this study, the highest air perm achieved using RF-4 technology was 21 ft3 /ft2 /min at 125 Pa. Low levels of antioxidants (AOx) in final products have an impact on the Air Permeability of the fabric. According to BERRY's corporate R&D and Product Development team, designing a new generation nonwoven with improved air perm and tensile strength may involve asking the OEM (original equipment manufacturer) to create a new generation Reicofil nonwoven machine. The Product Development team determined that a new Reicofil machine is required to achieve the desired SMS air perm target of > 27 ft3/ft2/min at 125 Pa for materials with a basis weight of 15 gsm (grams per square meter). Given the fact that the melt flow rate (MFR) of the meltblown Polypropylene resin used to manufacture the nonwovens is between 220 and 230 MFR, it introduces a new constraint. Moreover, the new RF-5 technology will cost BERRY an additional $150 million.

2.11 Design as Exploration

To create the new lightweight S-M-S nonwoven, we begin by revisiting our initial constraint statement and analyzing the nature of the design challenge while keeping the design requirements in mind. We have the first limitation, which is the same as the initial need, R initial, with Design as Exploration as the design process. The applied exploratory abstraction paradigm is depicted in Figure 2.3

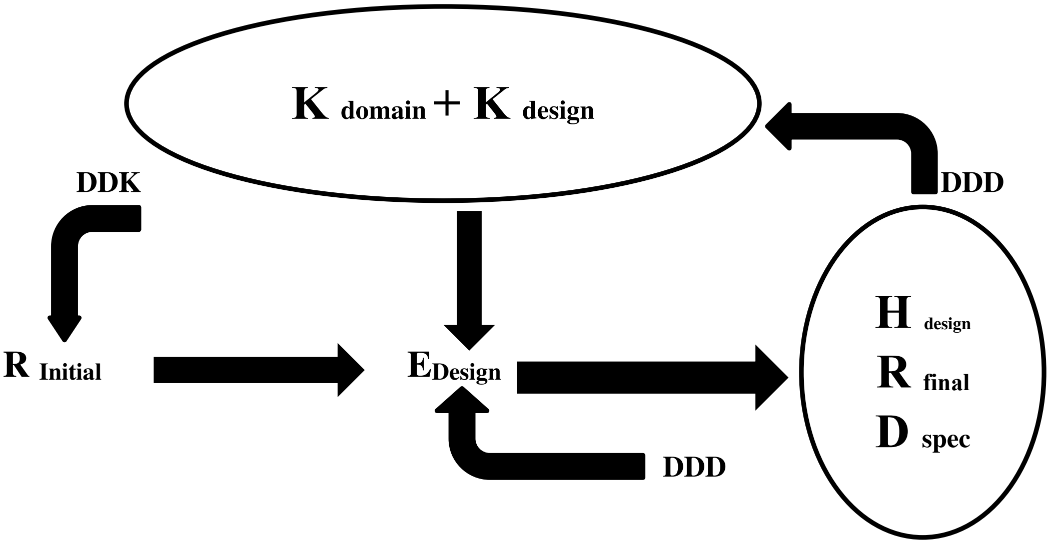


Figure 2.3 Exploration abstraction model adapted from Troxell & Troxell, 2014

Antioxidants were added to recycled pellets to improve polymer fibers, utilizing the knowledge gained from K design. Antioxidants are utilized in the production of RF-3 and RF-4 technologies. The high temperature of extrusion is a major factor in the decomposition of antioxidants. A high shear rate is a significant factor in the decomposition of antioxidants in resin. During extrusion, the shear rate influences both the antioxidant content and viscosity of the resin. In Meltblown resins, the peroxide rate is high. Meltblown PP resin's peroxides break more polymer chains throughout the manufacturing process. Irgatec CR 76 IC aids in the decrease of the peroxide effect as well as the MFR (melt flow rate) effect. Sub-400 ppm quantities of antioxidants are detrimental to the process. The procedure of adding antioxidants into recycled pellets from the Plant's recycler has been initiated.

2.12 Theory of Constraints

No Reicofil (RF) machines have produced a lightweight SMS nonwoven material with an Air Perm of greater than 27 ft3/ft2/min at 125 Pascal or 0.01813 Psi. This is a significant constraint (Pound per square inch).

Determining the constraint (R initial).

Low antioxidant levels affect S-M-S Air Perm values - **Exploiting the Constraint** (K design).

At 125 Pa, the air permeability of lightweight materials (59gsm and below) is superior to that of heavier materials (60gsm and above) – **Exploiting the Constraint** (K domain)

All RF technologies can satisfy the CD (cross direction) and MD (machine direction) requirements- **Subordinating all non-constraints** (K design)

We focus on why RF-3 and RF-4 technologies produce lightweight materials with improved air permeability and how to further investigate the process capability of these two RF technologies. –**Elevate the constraint (H design + E design).**

3 THE GOAL, THEORY OF CONSTRAINTS & DESIGN AS EXPLORATION

3.1 The Goal

"In my opinion, the key to being a competent scientist is not intelligence. Enough already! All we need to do is examine reality and think logically and clearly about it. "The decisive aspect is having the courage to address discrepancies between what we observe and deduce and how things are done" (Goldratt & Cox, 2016). The objective is to generate profit for Berry Global through the development of a new SMS product based on existing procedures. The design team began employing Dr. Goldratt's Theory of Constraints, as outlined in The Objective. To generate our desired S-M-S nonwoven with an air permeability of greater than 27 ft3/ft2/min at 125 Pa, we focused on design as a crucial aspect of the nonwoven production process. We identified the limitation (why do we have this limitation?). To ensure that the limitation has a direct effect on the desired output, evaluation methods of process designs that circumvent the limitation are utilized. Examine the limitation through the design lens and concentrate on ways to circumvent it.

3.2 Plastic Behavior during extrusion

As the first step in designing a novel nonwoven fabric, we concentrated on plastic behavior during extrusion to design and manufacture Synergex One. The fundamental functions of an extruder include conveying solids, melting, mixing, degassing, melt conveying, and pressure development of polypropylene pellets. Solids can be transported using either gravity-induced or drag-induced conveyance. The feed hopper and feed throat are responsible for gravity-induced conveying, while the screw is responsible for drag-induced conveying. The nonwoven fabric is affected by the temperature of the barrel, pellet size, shape, and distribution, compound fillers and additives, material screw, and surface roughness of the barrel and screw. The development team seeks methods and strategies to enhance the fabric's physical properties to meet the requirements of the end user.

The pressure increases exponentially along the length of an extruder's chamber. The frictional heat produced is proportional to the pressure within the chamber. We have

$$P(z)=P_o \exp(A_z) \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (3.1)$$

Where P_o = initial pressure, A_z = Area of the extruder chamber, P_z = Final pressure

The frictional heat generation formula is frictional force multiplied by relative velocity. The general operating concept of a twin-screw extruder is that when pressure increases, frictional heat increases, temperature increases, and the polymer melts faster. As solids to solids break the link of the polymer, the pressure decreases exponentially.

When the barrel friction is greater than the screw friction, the conveying rate is less volatile, resulting in a more stable process or scenario. To achieve significant barrel friction, two fundamental hits are required. Changing the barrel's temperature has a negligible effect, while barrel surface machine grooves have a significant impact. The temperature of the initial zone of the barrel can be altered to increase friction (figure 3.1), which simultaneously increases motor load and decreases pressure variation.

The following are fundamental characteristics of Synergex One: I Air Permeability must be more than 27 ft 3/ft 2 /min at 125 Pascal (ii) CD and MD tensile strength must be 34(N/50mm) at 1-30. For lightweight materials, both RF-3 and RF-4 procedures may attain CD and MD tensile values of 34 N/50mm. After analyzing the structure of the problem to be solved, we began studying methods to generate a new product using our current process, its capabilities, and with "The Goal" in mind.

3.3 Design as Exploration Synergex One breakdown:

a. Heavy weight nonwoven materials manufactured with RF-2 technology have an extremely low air perm at 125 Pa for SMS products (H design).

b. Lighter weight SMS materials manufactured with RF-3 and RF-4 technologies have an air perm in the range of 18 to 21 ft3/ft2/min at 125 Pa. (E design)

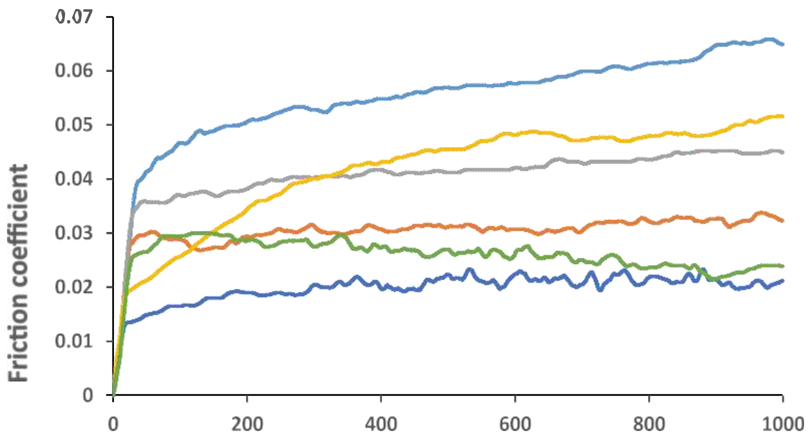


Figure 3.1 Coefficient of Friction in extruder barrel. BERRY©

c. RF2 technology uses 3.4K die; RF3 and RF4 technologies uses 3.7K die (**E design**)

d. The die body in the die chamber is the same size across all RF technologies; the dies used in each technology only differs in the number of holes in each die. (**E design**)

e. The 3.7K die was the newest die installment by Reicofil (**H design**)

f. The RF-3 which runs lighter weight materials has a 3.7K Die and the R4 installment has a 3.7K Die. Looking at process data there is a **direct correlation** with the number of holes in the Die and the quality of the Air Perm. (**K domain + K design**)

g. RF technologies with 3.7K die achieves air perm of 21ft^3/ft^2/min at 125 Pa for SMS materials

h. Berry makes die slabs in-house

i. Data shows the higher the number of holes in the die, the better the air perm in the SMS material (randomized fiber web distribution)

j. Design a 4K die to compare and use on RF4 technology. Compare the air perm to the 3.7K die

k. Use Design of Experiments to run trials using the 4K die

l. If the results are better than the 3.7K die, design a 5K die and compare results with the 4K die

3.4 Design as Exploration- The 5K die

Die is a crucial component in plastic extrusion because it influences how uniformly the polypropylene molten mass emerges from the chamber. Figure 3.4 depicts the configuration and placement of dies within the die chamber. A variety of settings within the die chamber control the output of the plastic fibers. Using design thinking and Design as Exploration methodology, the choice was taken to tweak one of the die chamber's features to build and construct a 5K die. We designed a 5.4 K die for evaluation in the Reicofil RF-3 and RF-4 machines.

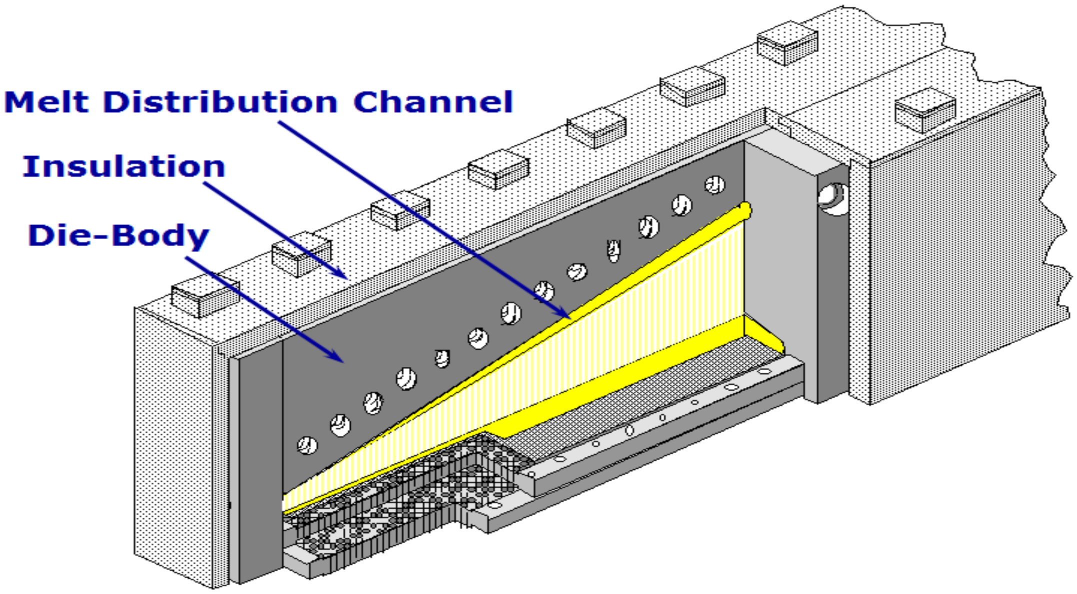


Figure 3.2: Components of the SMS Die Body Assembly. BERRY©

As part of an effort to create a high-quality product, the proposed 5K die (Die with 5,400 holes) will enable the fabrication of a more uniformly distributed web formation of the new nonwoven by increasing its permeability. We began with the 4K die and then progressed to the 5K die. OEM (original equipment manufacturer) designed the 3.7K die for the RF-3 and RF-4 machines. It is important to note that all Reicofil nonwoven machines have identically sized die chambers and dies of identical length. We designed the 5K die in collaboration with the original equipment manufacturer, and the materials produced on the line with the 5K die consistently outperform other lightweight nonwoven materials. The development of the 5K die is portrayed in figure 3.3 below.

Figure 3.3 5K Die in Development at BERRY (Berry Global, Inc. ©

3.5 Processes leading to Synergex One development

Dr. Goldratt's The Goal facilitated the discussion of what manufacturing is all about. Manufacturing is an enterprise, and the purpose of every enterprise is to generate a profit. Businesses provide value or solve issues to generate a profit, and manufacturing comes inside this category. With The Goal as a guide, the BERRY team was able to discover the limitations of lightweight SMS materials in terms of permeability. We examined the production bottlenecks in relation to the limitations. With design thinking and the end-user in mind, the process of fabric development is explored in depth. Design as Exploration assists in leveraging the constraints utilizing the exploration abstraction model, resulting in system modification following the analysis. Synergex One, a new generation of lightweight nonwoven fabric, was produced by modifying the system and optimizing process controls.

4. DISCUSSION OF PROCESS DETAILS

4.1 Polymer Characteristics During Extrusion

Modifying the operating circumstances and technical parameters used in the production of the new nonwoven is a multistep process that begins with the establishment of a stable product. A vital aspect of achieving a stable product is ensuring that the barrel friction variation in the extruder is greater than the screw friction variation. This is achieved by altering the temperature of the first barrel zone to increase friction, resulting in a larger motor load and reduced pressure variation, as shown in Figure 4.1. Using a grooved sleeve, polymers must also be transferred into the extrusion sleeve.

The grooved sleeve is only used in the extruder's feed section and is intended to move in the axial direction. This provides for efficient cooling of the grooved component, which is crucial for maintaining product integrity. The grooved sleeve improves pellet transportation by allowing for high barrel friction and low screw friction. In the second stage, the pellets are melted in an extruder. The pellets can be melted in one of two ways in an extruder. It is possible to have both continuous and dispersed melting. This product is manufactured by dispersed melting, also known as dispersed solids melting. All solid particles are dispersed across a solid substrate by means of twin screws.

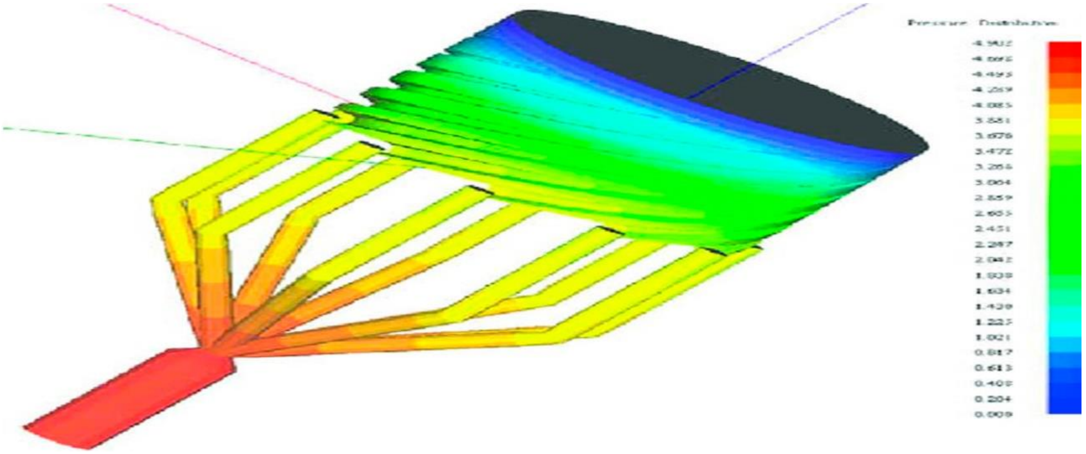


Figure 4.1 Pressure variation of polymers by SPIRAL CAD modelling polymer. (Hyvärinen et al,2020).

The following steps are involved in the melting of dispersed solids which enables adequate fluid viscosity as shown in figure 4.2: i. analyze the temperature profile in the melt film ii. analyze the temperature profile in the solid bed iii. Verify the melting velocity as a means of establishing the process's energy balance iv. Integrate melting velocity across solid bed width to determine melting rate.

The behavior of the molten plastic during extrusion is influenced by the barrier screws. During the extrusion process, the screws are designed to separate the molten mass from the solid pellets. This allows for proper dispersive mixing and stable functioning by eliminating solids that has not melted. An application

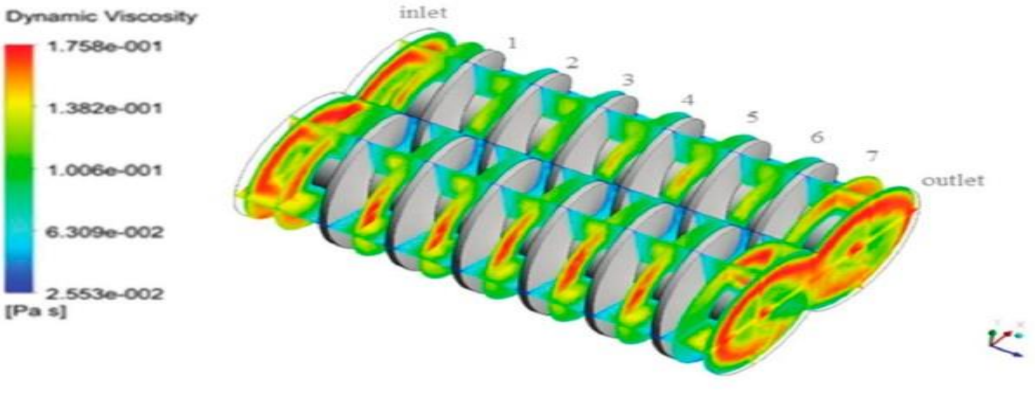


Figure 4.2 Computational model fluid viscosity. (Hyvärinen et al,2020)

melt hypothesis based on: i. preheating the feedstock in the silo; ii. increasing barrel temperature at low rpm; and iii. decreasing barrel temperature at high rpm were studied in an effort to enhance melting. High helix angle in transition section and transition sites with many flights. To improve melting performance, the barrier screws were modified to permit several flights of solid polymers (figure 4.3).

Melt conveying of polymers with distributive mixing is essential for achieving a homogeneous molten mass at the die chamber, as it lowers striation thickness, hence enabling the production of a structurally balanced nonwoven fabric from the polymer melt and reducing shear strain. During the extrusion process, the antioxidants in molten polymer are depleted, which is a major drawback. Due to shear pressure, antioxidants are also diminished. Low antioxidants have a direct influence on the air permeability of nonwoven textiles. Direct infusion in the die body is one method of managing the antioxidant (AOx) level, however this is still under consideration.

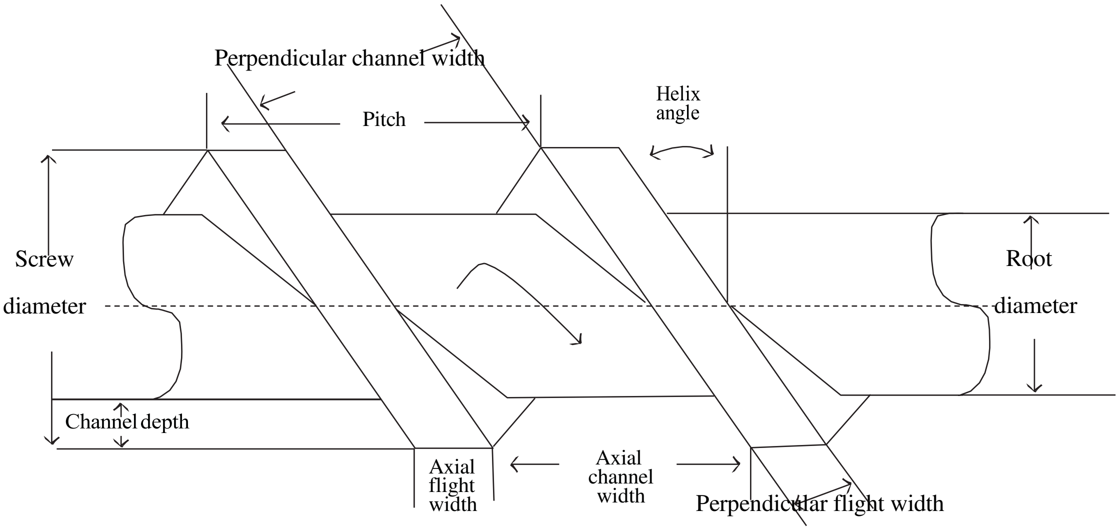


Figure 4.3 Barrier screw in the extruder. (Maniruzzman et al, 2012)

Synergex One requires distributed mixing to get the appropriate flow features. With increased metering at the extruder hopper, distributed mixing improves the melting of the pellets.

We calculate the pumping rate at the hopper using the relation below:

$$\mathbf{V=0.5WHv_{bz}}$$

where W = Width of the channel, H = Depth of the Channel

v_{bz} = Barrel z velocity, $\Delta P/\Delta z$ = pressure gradient

μ = melt viscosity

$$V = 0.5WHv_{bz} \text{………………. …... (4.1)}$$

$$H^* = [(2\mu V_{bz}) / \Delta Z]^{1/2} \text{………………. (4.2)}$$

The channel depth is crucial in determining how well the extrusion operation is running. When the channel depth, H*, is large, the viscosity in the molten mass is high. H* is little when the pressure in the barrel rises (P), and H* is small when the metering length, (z), is short. H* is large when the screw speed is high. The phase one technical analysis of the behavior of polypropylene polymers during extrusion came to the following conclusions: i. optimal depth is favorable to how the plastic acts during extrusion ii. The molten polymer performs best when the barrel temperature is low, and the screw temperature is high.

4.2 Synergex One (Case Study)

Honeywell Industries approached Berry Global, Inc. in April 2020 with the proposal for BERRY to produce a new generation of S-M-S nonwoven fabric capable of use in multiple industries (e.g., Filtration Systems material, N-95 mask material, etc.). Honeywell procurement team requested an S-M-S with enhanced air permeability and tensile strength. Air permeability is critical for lightweight nonwovens used in wipes, diapers, and N-95 masks. To achieve the objective of establishing a new generation of nonwoven fabrics, the BERRY Product Development, Research and Development, and Process Engineering teams began working on methods to develop a new nonwoven with enhanced air permeability and other critical properties. In preparation for the development of the new plastic product, BERRY defined a risk mitigation strategy to manufacture a robust new generation fabric with the fabric's integrity maintained throughout use with physical characteristics to improve the material's functionality. Integrity, as defined by Boritz (2005), is "the maintenance and guarantee of the accuracy and consistency of a system across its entire life cycle; it is a crucial aspect of system design, implementation, and use" (p.261). This project, led by Aderemi Shekoni had defined strategies which are:

I. Technical Review of the engineering process

II. Oversight for technical components of the manufacturing system

III. Product Prototyping to determine functionality

IV. Verification and validation testing

Technical Review: This approach helps in focusing on the system design of the desired product as well as the requirements of the client. The resins that are utilized in the material, in addition to the manner in which the Spunbond PP, Meltblown PP, and additives are combined throughout the extrusion process, both of which need to be taken into consideration in order to produce a long-lasting lightweight nonwoven.

Oversight of the manufacturing system's technical components: The production of a new generation of nonwoven fabric will be the focus of this study, which will make use of BERRY's existing Reicofil machines. In order to realize the objective of generating this brand-new product, the plan calls for the system's components and subsystems to be modified and optimized.

Product prototyping: Building a prototype is required for this aspect of the plan so that the functionality of the system's subsystems can be evaluated under a variety of settings in determining how long-lasting the new product will be. In this stage, the prototype process is utilized to evaluate how the newly developed nonwoven material will function in real-world scenarios.

Verification and validation test: The verification and validation test is the foundation of the mitigation plan. Vulnerability and destructive tests are carried out during the design process of a new product. These tests are used to detect areas of weakness throughout the design phase.

New generation fabric development for N-95 masks, sound absorption, avionics and air purification systems or filters is the objective of this case study. An important CTQ (critical to quality) parameter called Air Permeability with an increased value compared to the upper specification limit achieved for lightweight SMS fabrics is required. Air permeability using RF4 technology at the time of the request was 21ft3/ft2/min. As can be seen by comparing the data from all four of the RF technologies, the newer technologies provide lighter materials (59gsm and below) with higher Air Permeability (i.e., RF3 and RF4). Heavyweight materials are produced with the use of older technology (60gsm and beyond). Because of the inadequate random distribution of fibers in nonwoven textiles, all current RF approaches have failed to reach a flow rate greater than 21 ft3/ft2/min. Inadequate random distribution in the fabric reduces permeability. The lack of sufficient random distribution can be attributed to the die's method of dispersing the melt. A better distribution leads to a higher level of randomness, which improves air permeability. RF-3 and RF-4 dies have a greater random distribution of fibers than RF-1 and RF-2 dies.

When it comes to RF technology, the size and dimensions of the die chamber are uniform. Throughout the evolution of Reicofil machines, the size of the die chamber has remained unchanged. The difference is the number of pinholes in the body of the die; older technologies' dies have 3,000 pinholes, while newer technologies' dies have 3,700 pinholes. Dies with 3,000 pinholes are known as 3K dies, whereas those with 3,700 holes are known as 3.7K dies. The link between pinholes and high air permeability in lightweight materials is a major conclusion drawn from historical data. In terms of air permeability, RF methods utilizing 3K dies achieved no more than 17 ft 3/ft2 /min. RF technologies with 4K dies obtained between 18 and 21 ft3 /ft2 /min in air perm. The Synergex one must have an air permeability of at least 27ft3/ft2/min. To prevent influencing the differential pressure target of 5.2 mmH2 O/cm2, the machine direction and cross direction tensile strength specifications must also be met.

The manufacture of the nonwoven die is completed in-house with the pinning of the die. For the purpose of experimenting with design of experiments, fresh die slabs to make new die bodies were supplied. The 4K die is the initial to be manufactured (die body with four thousand holes). Design of experiments

(DOE) was utilized to determine which of the tests would help us achieve an air permeability of >27 ft3/ft2/min.

4.3 Design of Experiments

As part of our effort to build a new nonwoven with enhanced physical properties, we have devised a trial design involving 15 separate running conditions and three distinct die bodies: the 3.7K die, the 4K die, and the 5K die. The DOE consists of three phases (1,2, and 3).

4.4 Design of Experiments- Stage One

As may be seen in table three that follows, the phase one trial plan incorporates the run orders 5,8,13, and 15 respectively. After that, the throughput of the spin pump was evaluated, and then the diffuser plates were cleaned, which required taking apart the apron and suction screens and then reassembling them.

Table 3: DOE experiments (run conditions) for Synergex One

Run Order	PtType	Die Blocks	Speed, rev/ min	Energy, %	Gap, Mil
3	2	1	625	55	1
5	2	1	400	75	1
12	2	1	625	95	1
14	2	1	850	75	1
1	0	1	625	75	3.5
2	0	1	625	75	3.5
4	2	1	850	95	3.5
6	2	1	850	55	3.5
8	2	1	400	55	3.5
9	0	1	625	75	3.5
13	2	1	400	95	3.5
7	2	1	625	95	6
10	2	1	625	55	6

11	2	1	850	75	6
15	2	1	400	75	6

In the third stage, the resin type must be recognized and aligned. In this phase, Braskem (Appendix X) is the resin employed. Step four requires matching all heat zones to OEM standards, followed by the replacement of the S and E rolls' calendar oils. The sixth step is setting the calendar pressure to 600 psi. The seventh step entails commencing and completing a total calcium carbonate purge of the die chamber. Step 8 is essential to the trial phase since it introduces the die body. This phase's die body is the 4K die. After adding the 4K die, we increased the apron speed to 400 rpm to increase throughput by 45 pounds per hour (process settings).

4.5 DOE Stage Two

The phase two trial design is depicted in Table 3, which includes run orders 1,2,3,7,9,10,11, and 12. Following an evaluation of the spin pump's output, the diffuser plates were cleaned by removing and replacing the apron and suction screens. In the third stage, the resin type must be recognized and aligned. In this phase, the resin Exxon 3185 is employed. Step four requires matching all heat zones to OEM standards, followed by the replacement of the S and E rolls' calendar oils. The sixth step is setting the calendar pressure to 650 psi. The seventh step entails commencing and completing a total calcium carbonate purge of the die chamber. Step 8 is essential to the trial phase since it introduces the die body. For this phase, the 4K die serves as the die body. After installing the 4K die, the apron speed is increased from 400 to 650 revolutions per minute, resulting in a 60-pound-per-hour increase in throughput (process settings).

4.6 DOE Stage Three

The run orders 4, 6, and 14 in table three are included in the trial plan for phase three. Following an evaluation of the spin pump's output, the diffuser plates were cleaned by removing and replacing the apron and suction screens. In the third stage, the resin type must be recognized and aligned. Braskem resin is employed at this phase. Comparing the computed heat from process modification exercises to OEM recommendations constitutes the fourth step. The calendar oils for both the S and E rolls were then replaced. The sixth step is setting the calendar pressure to 700 psi. The seventh step entails commencing and completing a total calcium carbonate purge of the die chamber. Step 8 is essential to the trial phase since it introduces the die body. For this phase, the 5.4K die serves as the die body. After installing the 5K die, we increased apron speed to 850rpm and output by 80lb/hr. (process settings).

4.7 Developing Synergex One

During the height of the global epidemic known as COVID-19, an alliance between two Fortune 500 companies led to the invention of Synergex-One. "Air Permeability," a fundamental physical characteristic of nonwovens, was one of the critical quality requirements for the novel nonwoven material. The client requested that BERRY build an innovative nonwoven with an air permeability greater than 27 ft3/ft2/min. Specifying requirements is the first step in the system development process. Initial step in the system design process is the requirements analysis. The purpose of requirement analysis is to assess the system's requirements specifications. This is attained by consistency testing, automatic error detection, and the provision of system capabilities (Potts et al, 1994). Prior to the Synergex One project, BERRY had not achieved an air perm of > 27ft3/ft2/min in a lightweight SMS nonwoven fabric using the available Reicofil technology.

4.8 Design as Exploration

"By combining formal and verbal explorations with the hypothesis model, a design technique is provided that blends both pragmatic and creative approaches." (Julia, 1986). Synergex One was created utilizing the Design as Exploration methodology.

Exploring the polymer melt flow and thermal properties of the plastic resin is one of the four essential phases for efficiently developing this innovative nonwoven based on the Design-as-Exploration methodology. ii. Examining the development of melt temperature in screw extruders. iii Investigating polymer definite mixing techniques. iv Creating a 5K Die by analyzing the interplay between the die and the random fiber distribution in nonwoven textiles.

It is crucial that we analyze the limitations of nonwovens development notwithstanding the success of Synergex one production. Nonwoven fabrics are nonreactive. Nonwoven fabrics are resistant to chemical reactions, which is one of their distinguishing features. During the development of Synergex one, we began working on a new generation of diaper nonwovens. The objective of the project was to develop a multipurpose, nonwoven diaper material where surfactant is used as an in-process treatment for absorbent nonwoven diaper materials to provide adequate fluid absorption during use. The goal of the project was to create a multi-use, higher gradient S-S-S nonwoven absorption diaper that parents of young children would only need to change once per day. Our intention was to increase the volume of surfactants used during processing to alter the surface tension of the diaper components, but the technique was unsuccessful. Due to the disruption of the induced surface tension caused by the extra surfactants, increasing the volume further degrades the fabric. Even though the project did not go according to plan, we were able to learn from it. Design as exploration enables system developers to think creatively, but there is no assurance this will lead to the desired development outcomes.

4.9 Polymer Melt Flow and Thermal Properties of the Plastic Resin

Polymer melt flow and thermal properties of polypropylene polymers are critical when determining the optimal process parameters for the manufacture of nonwovens. There are three categories of plastics: high-temperature plastics, engineering plastics, and commodity plastics. Semi-crystalline polypropylene, which is used to create nonwovens, is a commodity plastic. During extrusion, there are two forms of flow: drag flow and pressure flow. The relative movement of the molten polymer's boundary along the screw channel causes drag flow, while pressure flow is created by pressure variations in the die body. Process control of these two flows is critical for the polymer filaments produced in the die chamber. Moreover, these two flows enable polymer melt velocity to vary (figure 4.4), which effects shear strain during production. The shear strain increases as the tensile strength of the resultant nonwoven decreases.

The tensile strength of nonwovens is an essential physical characteristic for preserving the material's integrity during post-production conversions. Tensile strength is determined by the viscosity of the flowing molten mass during extrusion. Cross direction tensile (CD tensile) and machine direction tensile (MD tensile) are directly affected by shear strain. Total shear deformation is the result of shear strain, which is defined as the difference in flow direction distance divided by the normal distance (Shear strain = (Shear rate) * (shear duration)).

Shear rate = (vA-vB)/AB…………………….. (4.3)

Shear strain = (AA' – BB') / AB…………….... (4.4)

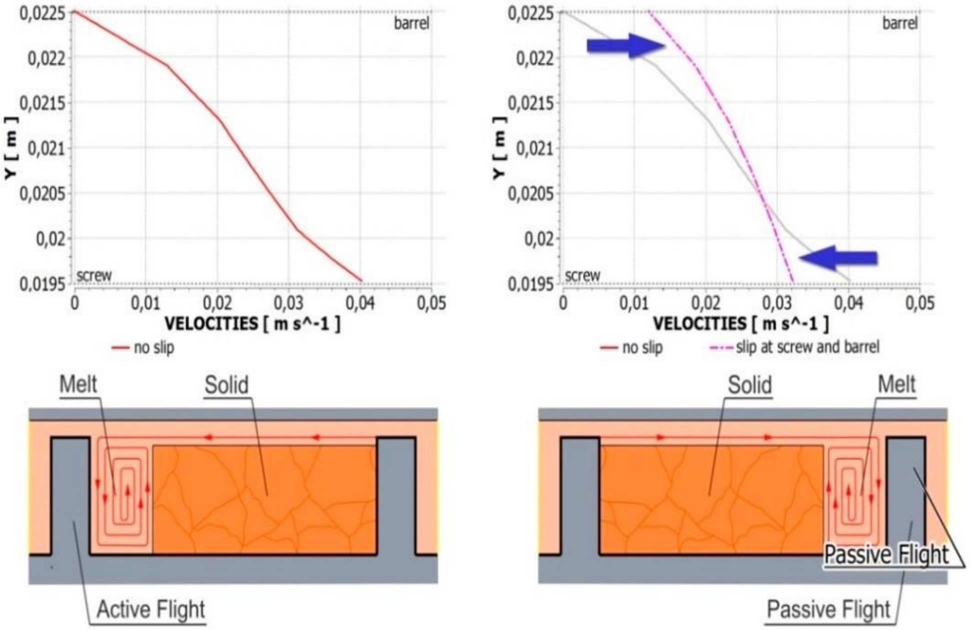


Figure 4.4 PP velocity distribution without a slip(a) and with a slip (b). (Wilczynski et al, 2019)

During the trials, the rate at which the plastic melt is exposed to shear strain is altered to determine the number of affected units in the die chamber, which influences the CD and MD tensile properties of the resulting nonwoven. To improve both tensile properties of Synergex One-15gsm, the shear rate of the molten plastic was reduced to 43 sec-1 for 10 seconds in the extruder. This resulted in a reduction of the shear strain to 430 units, a substantial decrease. The greater the viscosity of the resulting flow, the larger the flow resistance, and therefore the greater the CD and MD tensile. The elongational viscosity of a polymer after it has left the die determines its melt performance. The distribution of the fibers and the performance of the fabric outside of the CD and MD tensile properties are totally influenced by what happens to the polymer after the die. Another component of the extrusion system that we investigate is the extruder screw. It is explored how the shear rate in the channel relates to the shear rate clearing.

Shear rate in channel: $\pi ND_b \div H$…………………... (4.5)

where D is the screw outside diameter, H is the channel depth, N is the screw speed

The thermal properties of the new nonwoven textiles are essential based on their intended application. We are primarily concerned with thermal conductivity, specific heat, melting point, and induction time. The melting point (Tmp) and specific heat (CP) are the two most essential thermal parameters, as they are used for end-use conversion. By measuring the specific heat of the plastic, the differential scanning calorimeter (DSC) is used to determine the melting range and total deterioration of the fabric. Figure 4.5 illustrates the DSC range of Polypropylene.

Melt fracture is an additional factor to consider when analyzing polymer properties. In polypropylene polymers, melt fracture occurs when the viscosity of the plastic melt undergoes irreversible deformation. The deformation converts the mechanical energy generated into heat. Up to 75% of the heat produced during extrusion is caused by viscous heat. The ability to absorb fluids will be drastically reduced if the nonwoven fabric has a substantial quantity of melt fracture, as diffusivity decreases as melt fracture increases. Melt fracture is caused by the Meltblown in SMS materials. Melt fractures are uncommon in S-S (pure Spunbond) textiles. Flow rate of molten polypropylene during Meltblown production is the causative factor.

4.10 Melt Temperature Development in Screw Extruders

The extrusion system facilitates the creation of high-quality nonwoven fabrics by regulating the melt temperature for fabric development. The viscosity of the melt has a significant impact on determining the optimal operating temperature, which is why viscous heat generation is so crucial.

Shear flow amount of viscous heating depends on the shear rate in the melt and the viscosity of the melt.

VH (viscous heating) = viscosity * (shear rate)2………………………. (4.6)

VH is measured in power per unit volume, i.e., $V = \pi DHL$……………. (4.7)

D is screw outside diameter, H is channel length, and L is axial length

Since most heating in screw extruders is done by viscous heating, we look at how most heating is done during extrusion and focus on conducive heat as it relates to how we manage the temperature. Power consumption, melt consistency, specific heat, and flow rate all influence melt temperature rise (Ta).

Pc stands for power consumption and is computed as follows:

$$Pc = [mL\ (\pi\ D)^{n+2}\ N^{n+1}] \div H^{n} \quad \text{……………………………………… (4.8)}$$

Where m = consistency index, D = screw outside diameter, N = screw speed, H = channel depth (flight height).

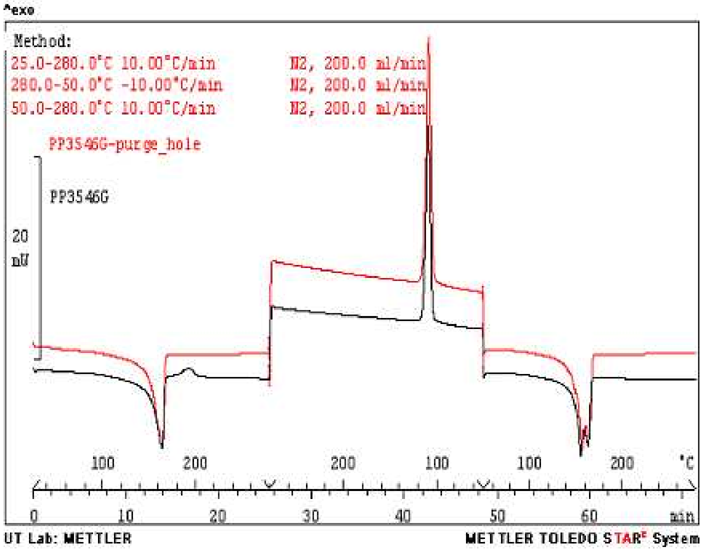


Figure 4.5 Differential Scanning Calorimeter Curve (Wang,2004)

The volumetric flow rate, $V = 0.5\ (1 - r_t)\ (\pi D^2 H N \sin \varphi \cos \varphi)$ ………………………… (4.9)

Where r_t = throttle ratio, φ = flight helix angle

To control the melt temperature during the experiments leading to Synergex One, we cross referenced the temperature during extrusion as compared to the distance of the screw and we determined temperature as a function of axial distance with the boundary condition in mind.

$T\ (x = 0) = T_0$…………………………………………………… (4.10)

$T_x = (1/a) \ln (e^{aT}{}_0 + aB_1\ xe^{aT})$………………………………….... (4.11)

Where a = temperature coefficient of viscosity, B = temperature gradient, T_x = temperature as a function of axial distance.

For low values of a, T(x) is almost linear and when we increase the values of T, the curves become non-linear. The effect of screw speed can be seen in the overall temperature in the extruder. Screw speed increases viscous heating and as a result, screw speed during extrusion increases temperature.

Additionally, increasing throttle ratio has similar effect to increasing screw speed. In controlling screw speed, development length in the extruder is important because thermal development length becomes longer than the actual metering section of the extruder if the speed is greater than 1 rev/sec (60 rpm). During the development of Synergex One, the screw speed target upper limit was 0.92 rev/sec (55 rpm).

Critical screw speed for Synergex one was:

$$SS_{critical} = [\ (q_c H^n e^{a(T_o - T_r)}) / m_r(\pi D)^{n+1}]^{1/n+1} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(4.12)$$

A point to note is viscous heating, VH, is more uniform in drag flow since shear rates in drag flow are more uniform than in pressure flow. As seen in equation 5:

$$\text{VH (viscous heating)} = \text{viscosity} * (\text{shear rate})^2 \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ (4.5)$$

In summary, throughout the development of Synergex one, all heating was achieved using viscous heating, and to cool the extrusion system, we studied the cooling profile to account for spinning difficulties caused by insufficient cooling after extrusion. As depicted in figure 4.6, the quenching chamber, which provides cooling, was misaligned as discovered through our system evaluations. The quenching chamber was adjusted and analyzed to guarantee that the resulting materials satisfy all physical property specifications (figure 4.8).

4.11 Definitive Mixing of Polymers

Synergex One-15gsm is a SMS nonwoven fabric. SMS nonwovens are composed of Spunbond and Meltblown polypropylene. Melt flow rate (MFR) is what differentiates Spunbond polypropylene from Meltblown polypropylene. Synergex one can only be created if the polymers are well combined. Meltblown MFR is greater as compared to Spunbond MFR.

We use the additive Irgatec CR 76 IC to enable appropriate Meltblown resin mixing in the polymer blend. As stated earlier, we use distributive mixing for Spunbond and Meltblown polymer blends given the fact that Irgatec CR 76 IC helps minimize interfacial tension in Meltblown polymers. When heat is applied to Meltblown polypropylene, Irgatec CR 76 IC aids in preventing the deterioration of antioxidants.

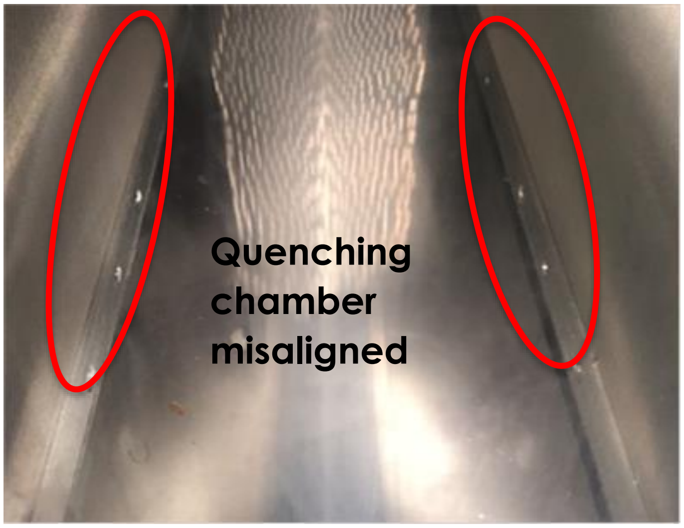


Figure 4.6 Misaligned Quenching chamber of the extruder. BERRY©

To reduce composition non-uniformity in both polymers, adequate mixing of the polymers is necessary. Figure 4.7 shows a generalized mixing method for polypropylene polymers.

The solid-to-solid structure of polypropylene pellets allows for distributive mixing, but the higher the melt flow velocity, the greater the polymer's cohesive resistance. Irgatec CR 76 IC aids in the lowering of cohesive resistance in Meltblown polymers. In the extrusion system used to produce SMS nonwovens, two extruders melt Spunbond polymers and one extruder melts Meltblown polymers (figure 4.9). Distributive mixing is crucial because it ensures that the polymer masses in all three extruders are same.

It is crucial that the percentage of Meltblown in the blend does not exceed the target for lightweight SMS fabric. The resulting material exhibits a characteristic deformation known as "Meltblown Fly" when an overflow occurs. Meltblown Fly is a fabric distortion characterized by the appearance of white plastic strips that have not disintegrated.

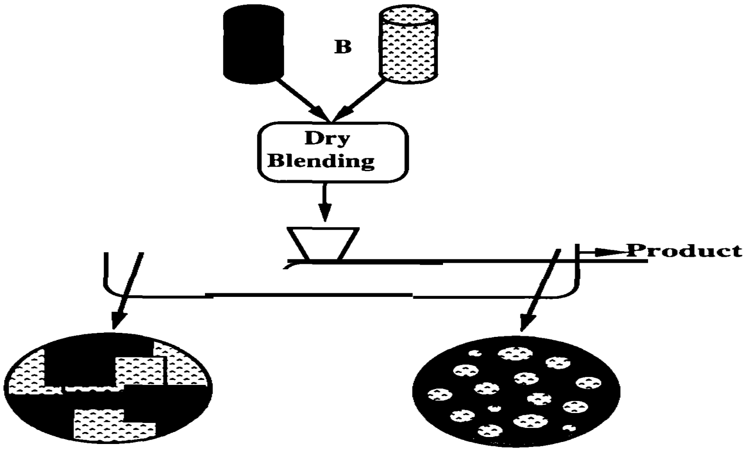


Figure 4.7 Generalized PP polymer mixing (Scott & Macosko, 1994)

Even though this has no effect on the fabric's physical properties, it is rejected for aesthetic reasons when it occurs in lightweight nonwoven materials. Aesthetics are vital for end-use applications such as diapers, medical gowns, sanitary wipes, and filter materials.

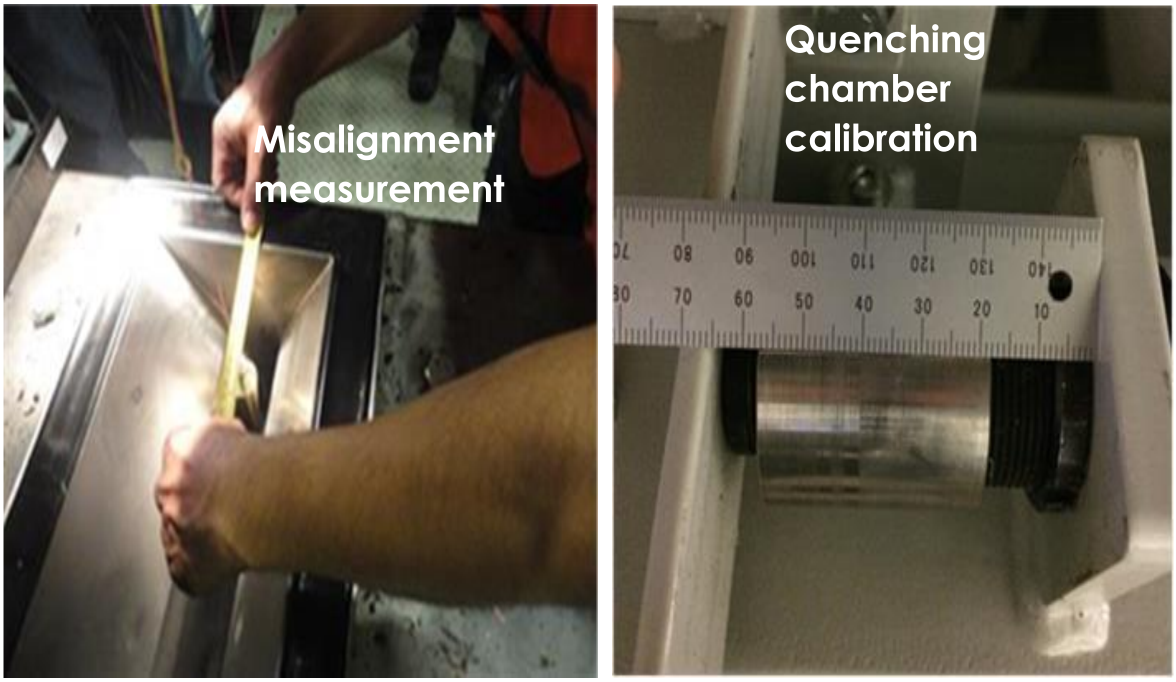


Figure 4.8 Quenching chamber realignment and calibration

Before proceeding with extrusion, we measure the texture of the spunbond polymer using the segregation scale, S, during the mixing process. S is a length scale connected with a two-point correlation, Rr.

$$Rr = [\ a(x) - a]\ [a(x+r) - a] \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots.. (4.13)$$

Where a(x) = local concentration of Spunbond

We determine that mixing in both the Spunbond and the Meltblown polymers are good enough when:

I. Striation thickness, s, is < 14μm

II. Visual observation is close to the wavelength of visible light; s = 0.5μm

We use x-grid mixers for adequate mixing of the polymers as typically done for all in-line mixing.

For efficient distributive mixing, we engage in frequent splitting and reorientation. At the metering section, residence time is vital for twin screw extruders. Residence time over the axial length of the screw is calculated as:

$$T1 = 2L/[3vb\ \sin 2\phi(1-rd)] \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots..(4.14)$$

The measurement of strain rates and strain rate exposure duration is aided by the process of distributive mixing. It is also helpful in estimating shear strain and shear strain thickness, both of which were extremely important for finding the most effective method to mix the polymers for our experiments.

4.12 The 5K Die

The creation of the 5K die for the Synergex-One is the aspect of this research that is considered to be the most important. To achieve the intended outcome, the current technology and component parts of the manufacturing systems that were already in place were modified to produce Synergex One. Although all the design choices that led up to Synergex one were important, we didn't make significant progress until we manufactured the 5K die.

Figure 4.9 Reicofil-IV SMS Production system. BERRY©

The 5K die, as indicated in Chapter 2 of this study, is as a result of Design as Exploration. The objective was to develop a lightweight SMS nonwoven with air permeability greater than 27 ft3/ft2/min, which was a crucial need for flow. The customer-required permeability target of >27 ft3/ft2/min was a flow value not previously obtained for an SMS lightweight fabric at the time. At the time of the request, RF4 technology yielded the highest permeability of 21 ft3/ft2/min. Considering data from all four technologies (RF-1, RF-2, RF3, and RF4), it is obvious that the newest machines produce lighter, more permeable materials (59gsm and below) than older ones. The RF-1 and RF-2 machines are used to make heavyweight materials (60gsm and above). Due to the end uses of the nonwovens produced by the RF-1 and RF-2 lines, the heavy weight textiles do not require a high degree of air permeability.

In disposable nonwoven manufacture, the random distribution of fibers is a constant. The fabric's quality increases with the degree of unpredictability. The RF-1 and RF-2 nonwoven systems produce the majority of non-random nonwoven fabrics due to their single-screw extruders. Fabrics produced by the current generation of RF systems (RF-3 and RF-4) with a double-screw extrusion feature a more random fiber distribution. One approach for achieving the 27 ft3/ft2/min was to chemically oxidize the fabric's surface in order to improve the degree of coarseness and orientation of the polar group in the polymer bond. This proposal was not practicable since the fabric would need to be further transformed in an oxidation chamber that BERRY did not possess. Such a procedure is prohibitively expensive in comparison to the budget for material development. Because of "The Goal," we did not proceed with the chemical oxidation strategy. The second idea, surface grafting, was made because polypropylene nonwoven fabrics lack reaction activity groups. Surface grafting requires the use of a needle-punching nonwoven production machine, which BERRY no longer operates. When comparing the permeability values of nonwoven fabrics produced on the RF-1 and RF-2 to those generated on the RF-3 and RF-4, the great idea that the die is a major determinant of how randomly the fiber is dispersed was established. The initial sketch of the 5K die is shown in Figure 4.10.

As well as the fabrication of the Reicofil die body, the pinning of the die is performed in-house. Die slabs to produce innovative die bodies are being created for the purpose of experimenting using Design of Experiments as part of this research. First to be manufactured is the 4K die. We began with the 4K die before moving on to the 5K die. The original equipment manufacturer (OEM) designed the 3.7K die for the Reicofil Machines. Die chamber size is uniform across all Reicofil technologies. We worked with the original equipment manufacturer to build the 5K die, and the materials produced on the line with the 5K die have consistently outperformed other lightweight nonwoven materials. How evenly the random fibers in the nonwoven fabric are distributed is determined by the size of the hole in the die.

When constructing the 5K die, the proposed method of pinning the center of the die, as depicted in Figure 4.13, to reduce hole density and allow for optimal flow within the die chamber was effective. This resulted in a more uniform distribution of plastic fibers traveling from the die chamber to the collector and the materials produced on the line with the 5K die have consistently outperformed other lightweight nonwoven materials. The size of the hole in the die dictates how evenly the randomized fibers in the nonwoven fabric are dispersed.

Pinning the center of the die as shown in figure 4.13 below to reduce hole density and allow for optimal flow in the die chamber was a proposed method that worked effectively when building the 5K die. The plastic fibers coming from the die chamber to the collector were more evenly distributed as a result of this.

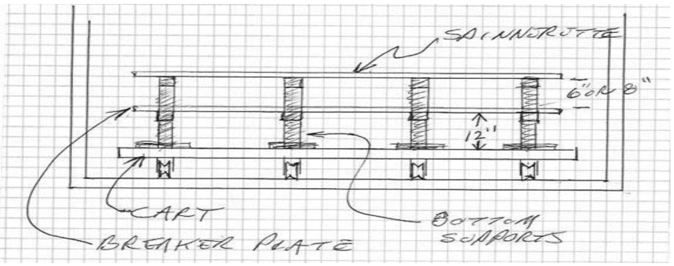


Figure 4.10 Initial draft for the 5K die. BERRY©

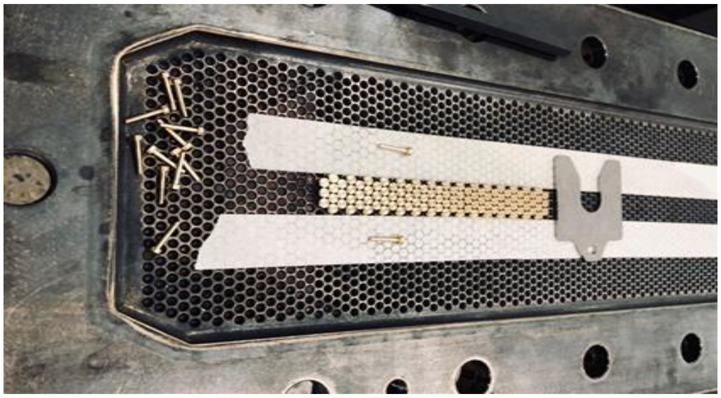
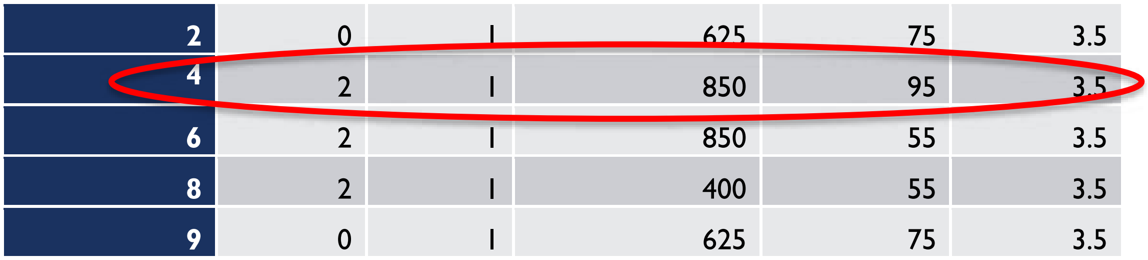


Figure 4.11 Center pinning of the 5K die. BERRY©

We determined that the 5K die was the best option for meeting the > 27ft3/ft2/min requirement without having to construct or purchase additional nonwoven manufacturing equipment. The die that shapes the plastic filaments released by the extruder is a vital subsystem or component. By designing a new form of die for the die chamber, we enhanced the filament flow. We selected run number four from the DOE's fifteen runs, as given in table 4.

Table 4 – DOE experiments (run conditions) for Synergex One



2	0	1	625	75	3.5
4	2	1	850	95	3.5
6	2	1	850	55	3.5
8	2	1	400	55	3.5
9	0	1	625	75	3.5

After employing DOE to attain the desired qualities, a capability study of the physical properties was performed. We built a product prototype based on run condition 4 and sent trial samples for penetration testing to external laboratories. In addition, we utilized ASTM-calibrated in-house Instron equipment to examine the strip and grab tensile and elongation. The material specification, table 5, was developed based on the experimental design, after which Synergex one was created.

4.13 Synergex One 15 GSM

The outcome of this study, trials, and experimental design was Synergex One 15gsm, which was accomplished using DOE run order number 4. The innovative product has an average air permeability of 32 ft3/ft2/min and a base weight of 15 gsm. Synergex one-15gsm is a versatile, high-performance plastic fabric with a variety of uses. Additionally, Synergex One is adapted and utilized for filtration applications in municipal water and wastewater facilities, automobile overhead lining systems, healthcare fluid barrier systems, musical instrument acoustic insulation, and avionics thermal insulation. BERRY trademarked Synergex One 15gs in November 2020. BERRY has collaborated with Reicofil to commercialize the 5K Die for next-generation RF technology.

Design as Exploration is responsible for the success of Synergex One and the development of the 5K die. In addition, "The Goal" helped the team to concentrate on the most crucial areas of Synergex-One development. Based on the premise that design difficulties are insufficiently stated problems, Design as Exploration emphasizes nontraditional problem-solving strategies. This indicates that design thinking can help bridge the gap when a need or solution emerges to modify an existing or intended design. By investigating the novel concept of the 5K die for plastic extrusion to create a new nonwoven, design thinking was used to concentrate on expanding the fiber dispersion of the plastic melt in order to achieve the desired air permeability of > 27ft3/ft2/min.

Synergex One was developed using current Reicofil technology and modified versions of its components. The new "Synergex One" features enhanced air perm, tensile strength, pliability, and spray impact media. Compared to the target value of 0, the prototype material of Synergex one has an air permeability of 32 ft2/ft2/min and a spray impact score of 0.11.

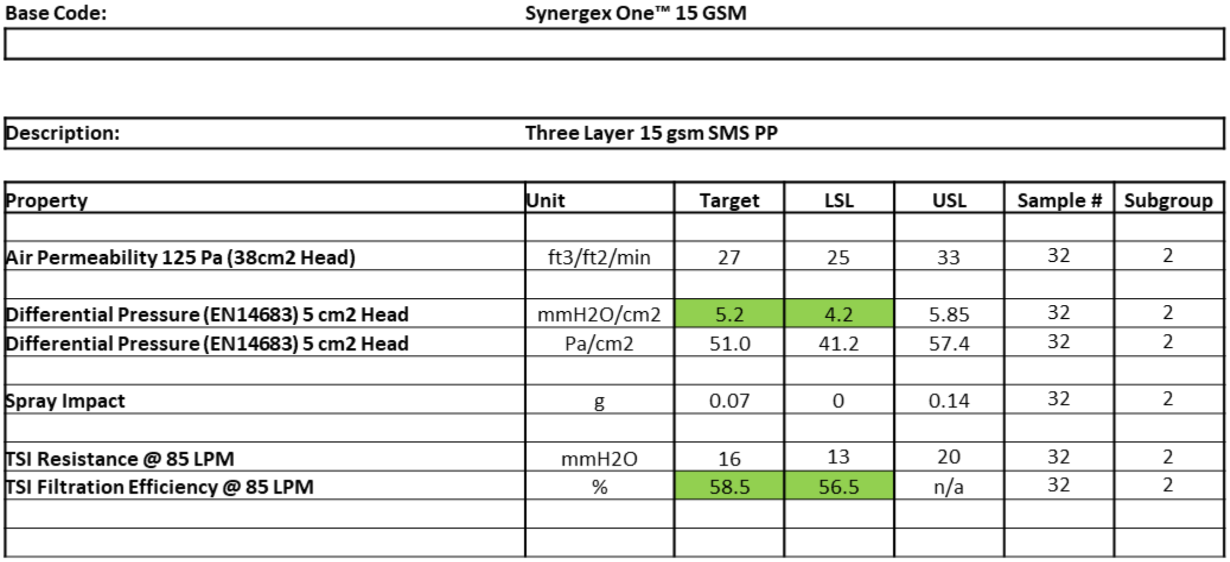
The success of Synergex One has encouraged more development projects in BERRY. BERRY is now working on sustainability projects relating to biodegradable nonwovens. Berry is currently working on a cotton-Polypropylene plastic fabric, one of the sustainability-oriented projects. Berry is also teaming with

Boomi to release a bottle made entirely of sugarcane resin in January 2023. Berry and Procter & Gamble are also collaborating on a novel S-S nonwoven for disinfecting wipes that will be ready in the summer of 2022.

5 CONCLUSION & FUTURE WORK

While keeping "The Goal" in mind, BERRY is working on other projects to improve our operations. The shift in product development methodology is crucial to the success of Synergex one development. When a system or product has been fully developed, consumers frequently consult the system requirements specification for advice on how to maximize its utility (Pohl, K., 2010, p.72). This is no longer the case at BERRY, as we now guide clients through the process by conversing with them and evaluating their ideas thoroughly.

Table 5. Synergex One Material Specification



Base Code: **Synergex One™ 15 GSM**

Description: **Three Layer 15 gsm SMS PP**

Property	**Unit**	**Target**	**LSL**	**USL**	**Sample #**	**Subgroup**
Air Permeability 125 Pa (38cm2 Head)	ft3/ft2/min	27	25	33	32	2
Differential Pressure (EN14683) 5 cm2 Head	mmH2O/cm2	5.2	4.2	5.85	32	2
Differential Pressure (EN14683) 5 cm2 Head	Pa/cm2	51.0	41.2	57.4	32	2
Spray Impact	g	0.07	0	0.14	32	2
TSI Resistance @ 85 LPM	mmH2O	16	13	20	32	2
TSI Filtration Efficiency @ 85 LPM	%	58.5	56.5	n/a	32	2

"One of the reasons clients shun the design process is because professional designers are condescending towards them. Remember that the bulk of participants are unaware of the development process and are specialists in areas where the designers are ignorant." (Gause and coworkers, 1989, page 11) According to Hsu & Woon (1998), product design is "an interactive, complex, decision-making engineering process." It typically begins with a requirement assessment, then proceeds through a series of activities to determine the best solution to the problem, and ends with a full explanation of the product (p.377). Important to the acquisition phase is the system's requirement specification. Hsu and Woon (1998) characterize this step as follows: "In general, a design consists of three phases." The initial process is the product design specification, which entails obtaining information about the product and expressing it in precise, neutral language. A typical product specification will cover topics such as performance, quality, dependability, safety, product life span, aesthetics, and ergonomics. In the second phase, known as conceptual design, the emphasis is placed on the creation of physical solutions that are in accordance with design criteria (p.377). These guidelines were adhered to by the team as they worked on the creation of Synergex-One 15 gsm. Nonwovens are only used for one end use in the past, and this decision was made based on the weight of

Figure 4.12 Synergex One Prototype Fabric. BERRY ©

the nonwoven and the kind of chemistry that was used throughout the production process. Since it may be utilized for three or more distinct applications, Synergex one is a nonwoven material that belongs to a new generation. The healthcare industry, filtering appliances, and the fluid barrier systems in public works all use Synergex one.

5.1 Recycled Polypropylene (Ongoing)

As a direct result of the increased emphasis placed on sustainability, a discussion regarding the recycling of polypropylene to lessen the amount of waste produced and cut down on the expenses of producing nonwoven materials has emerged. As a direct result of the implementation of this cutting-edge strategy, BERRY has significantly increased the amount of recycled polypropylene that it uses. In order to make financial savings and cut down on emissions of greenhouse gases, the majority of nonwoven trials in BERRY have, since the year 2020, made use of recycled polypropylene pellets. Because virgin resin (non-recycled) polypropylene has greater amounts of antioxidants (AOx), which is important for fabric quality, it is the best option for both trials and the actual manufacture of nonwoven materials. This is because antioxidants are important for maintaining the integrity of the fabric. In the course of the Synergex One project, we tried out both virgin and recycled polypropylene in a number of different applications. One of the disadvantages of utilizing recycled polypropylene is that it results in low levels of AOx in the pellets of recovered polypropylene. As a result of the shear strain that is applied to the pellets during the nonwoven production process, recycled resin-based finished nonwoven textiles have lower levels of AOx than fabrics made with virgin resins. This is one of the most important aspects. For the production of recycled pellets, SS (Spunbond-Spunbond) or SMS materials with a Meltblown content of less than 20 percent are utilized. The EREMA (figure 5.1) at BERRY is where the processing of SS or SMS recycling takes place. In order to transform SS and SMS materials back into pellets, EREMA employs a process known as reverse extrusion. The SS and/or SMS that is used in the recycling process is often composed of SMS products that have been returned or SS production batches that were rejected (customer rejects). When we look at the data, we see that for every 1000 kilograms of resin produced, there are around 90 kilos of polymer resin that are rejected after being converted to SMS or SS. In addition to that, the customer rejects amounts to an average of 10 kg of nonwoven fabric polymers. Out of the total of 1000 kilos of polypropylene resin produced, we recycle a total of 50 kg.

We came up with the idea of direct injection of AOx into recycled pellets in order to boost CTQ (critical to quality) qualities to the same level as those produced with virgin resin polypropylene. This was accomplished through the use of the Design-as-Exploration way of thinking. The melt flow rate (MFR) of recycled polypropylene resin of pure Spunbond (S-S) is 45, while the MFR of virgin polypropylene resin is only 35. Because SMS fabric contains Meltblown, recycled pellets made from SMS fabric have a melt flow rate of 50 or more.

Figure 5.1 SMS Nonwoven fabrics being fed into the Erema Recycler. BERRY ©

With the addition of the AOx injector for recycled polymers, we intend to increase the use of recycled pellets across all four technologies by employing Design as Exploration methodologies to convert 100 percent of rejected SMS and SS materials via the Erema. Figure 5.2 depicts the emergence of fresh pellets from the EREMA. We are turning defective and/or rejected nonwoven fabrics into pellets and incorporating them into our extrusion processes across all RF technologies, resulting in a substantial cost savings for the Plant. With this new technique, we're able to save the corporation $4 million annually. Three gates control the quality of the recycled pellets generated at the Erema facility. The gates are Pellet Count, Moisture Content, and Melt Flow Rate.

Pellet Count - The recycled resin particle count is a measure of the quality of the recycled pellets since it indicates uniformity and consistency. Using the analytical balance, the pellet count is measured as pellets per gram. Here, flawed pellets are segregated from the remainder of the batch.

Figure 5.2 Recycled Polypropylene pellets at the Erema. BERRY©

Moisture Content- The moisture content of recycled pellets must meet the requirements before they can be used, as it is an essential quality factor. The moisture meter is used to determine the sample's water content, which is given as a percentage.

Melt Flow Rate- For recycled pellets, the MFR is the most useful metric. The higher the MFR, the less usable the recycled pellets are. The MFR is now measured with a Tinius Olsen Plastometer, and data is recorded in grams per 10 minutes.

Specifications for Recycled Pellets: To guarantee that the relevant specifications are satisfied, each recycled polypropylene box is sampled and tested. Any package that does not fulfill the specifications is labeled as such and placed in a containment area. BERRY / PLANT standards are shown below.

BERRY standards:

Pellet Count ≅ 40-45 pellets/gram

Moisture content < 0.06%

Melt Flow Rate < 65 g/10min

Site standards from data:

Pellet Count: 19-42 pellets/gram

Moisture Content: 0.00 – 0.07%

MFR: 34.3 – 56.5 g/10min

The MFR of meltblown virgin polypropylene resins is 230. When compared to the melt flow rate of Spunbond polypropylene resin, this is extremely high. The desirable fabric for recycling is S-S (spunbond –spunbond), which is owing to the MFR of pure spunbond, which is 35 MFR. The melt-flowrate of the meltblown polypropylene in the fabric makes recycling SMS materials difficult. SMS Fabrics with a greater meltblown percentage clogs the Erema during the manufacturing of recycled pellets.

5.2 Plastic Film Extrusion (Future Work- Case study 2)

The moisture content of recycled pellets must also meet criteria for them to be used, as it is an essential quality attribute. The moisture meter is used to measure the sample's relative humidity, which is expressed as a percentage of water.

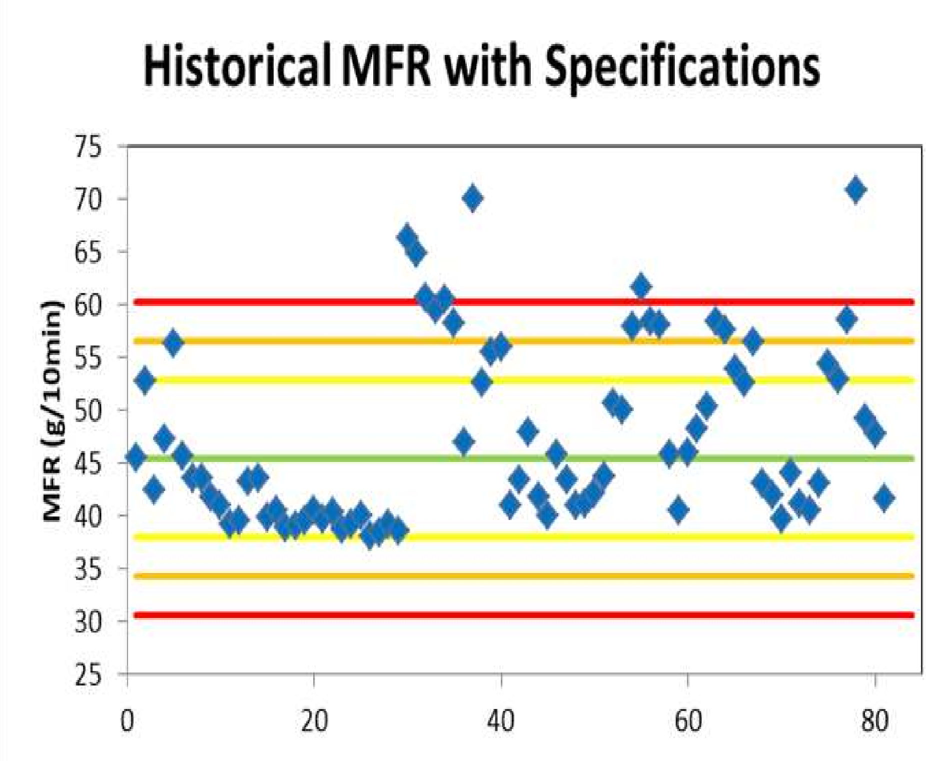


Figure 5.3 Recycled Pellets MFR (g/10min). BERRY©

The greater the meltblown content of the recycled materials, the greater the MFR of the pellets generated. Polyethylene is the polymer used in the extrusion of plastic films, and the manufacturing equipment is constructed differently. For plastic film extrusion, molten resin is transferred into an air chamber that permits the production of the film according to specifications. Nonwoven extrusion and plastic film extrusion differ in the way the resins are transformed from virgin resin to product, the plastic resins, and the extrusion system's structure and function.

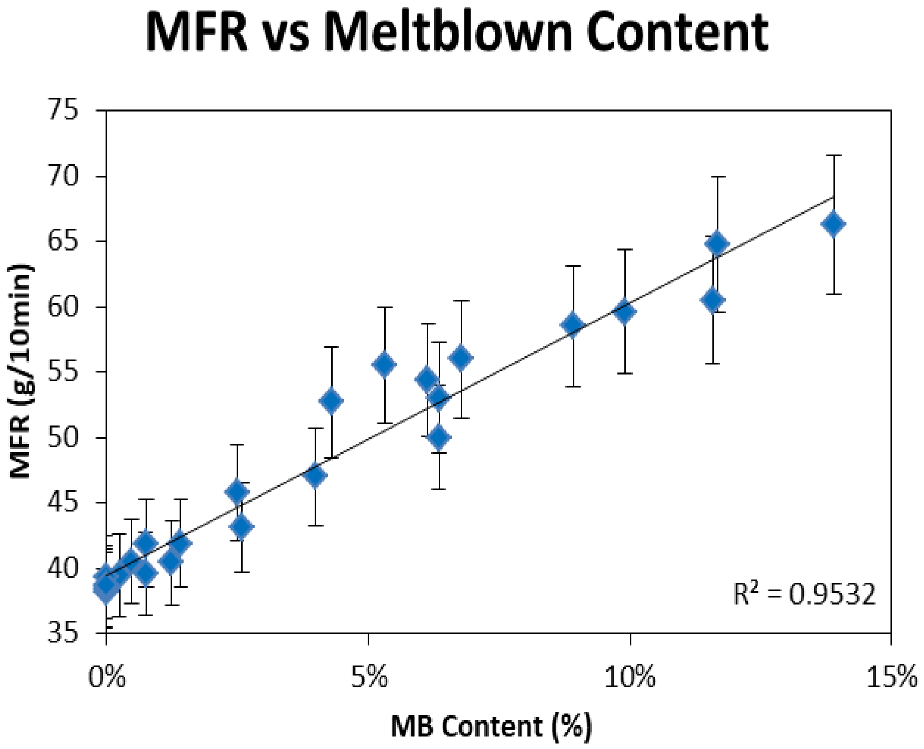


Figure 5.4 Impact of Meltblown in recycled pellets. BERRY©

Polyethylene (PET) Resin Chamber, Circular Die, and Nip Chamber are the three key components of the machine that enable the creation of plastic film during plastic film extrusion. In the polyethylene (PET) resin chamber, polyethylene polymers are extruded along with color and other additives. The circular die is where plastic film is formed, and this circular die is distinct from the circular die used for nonwoven extrusion. In the nip chamber, plastic bubbles are transformed into sheets.

Buckling is a problem that the plastic film section of BERRY is now grappling with in terms of customer complaints. The buckling of plastic film is a typical physical property defect. A variety of factors can cause buckling. Gauge control issues, air bladder shaft issues, and deforming cores as a result of misaligned lay-on pressure calibration are the primary causes. We utilized design thinking to deconstruct the plastic film manufacturing system into subsystems to better comprehend the system dynamics of blowing plastic films prior to examining strategies to drastically reduce or eliminate buckling issues. Die and nip points in the plastic film manufacturing system are associated with air bladder issues resulting from gauge control in plastic film development. Figure 5.5 illustrates the creation of plastic bubbles throughout the manufacturing process.

The monthly calibration of the manufacturing system's die for core shift concerns enables reduction of buckling but the process is time consuming affecting production time and output. Figure 5.6 depicts the buckled condition of plastic films. We will begin by focusing on the mold, as that is the source of most of the manufacturing issues we are seeing. Focusing on the die, we examine the polymer's characteristics throughout the production process.

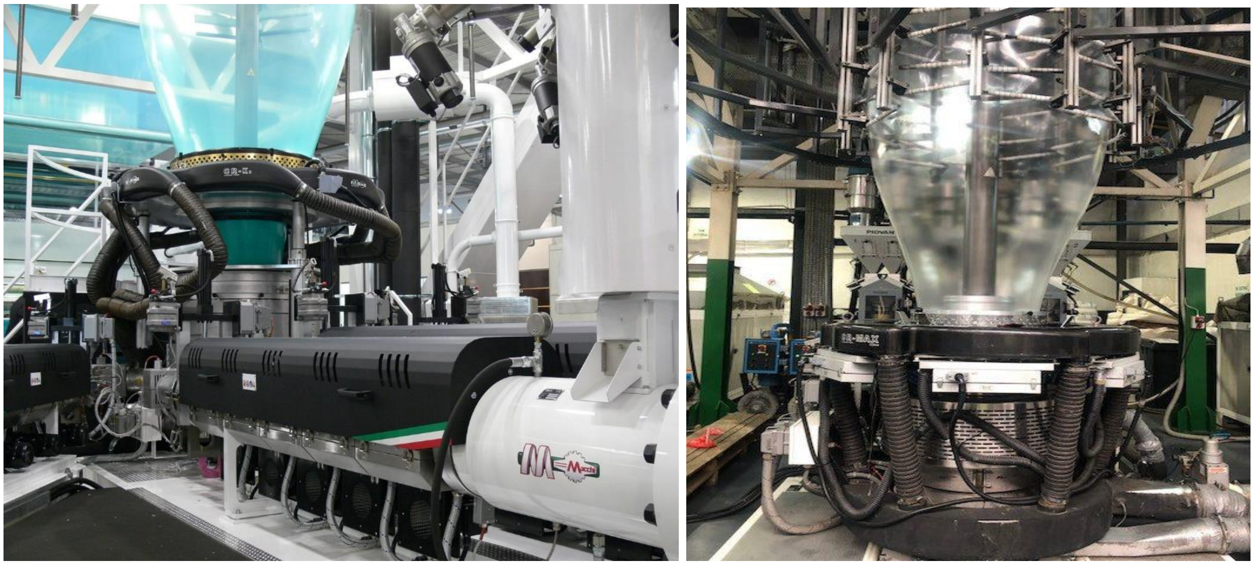


Figure 5.5 Formation of plastic film bubbles. BERRY©

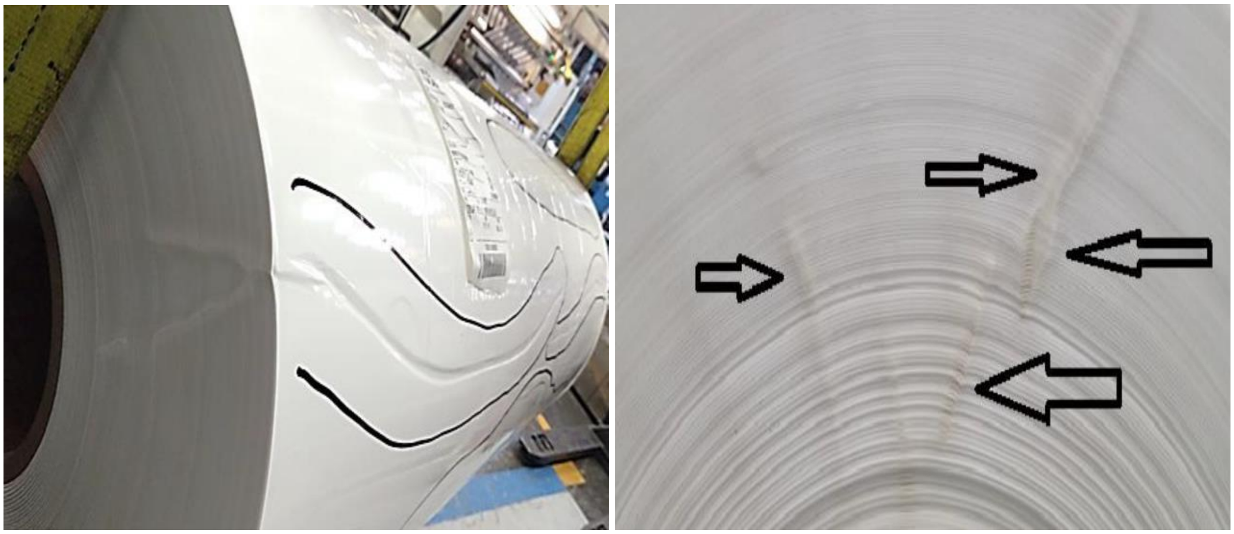


Figure 5.6 Plastic film buckling. BERRY©

In contrast to nonwoven, which is comprised of Polypropylene, plastic film is composed of Polyethylene. Polypropylene and polyethylene are among the semi-crystalline polymers. Polypropylene is resistant to organic solvents and other chemicals, while polyethylene is chemically reactive.

Polypropylene is a rigid, opaque material, while polyethylene is flexible and transparent. The melting point of each polymer is an additional significant factor to consider. Polyethylene has a melting temperature between 221 and 239 degrees Fahrenheit, whereas polypropylene's melting point is 266 degrees Fahrenheit. For this case study, these characteristics will be examined.

In addition, the next project I am working on is the improvement of BERRY plastic films. Another development project I am working on involves incorporating plant-based resin into BERRY's sustainability initiative. The objective is to quantify the procedure based on what was learned through the Synergex One Case Study, which employed Design as Exploration to develop new and improved nonwoven fabric. The success of Synergex One has generated further product ideas for the Berry Global Sustainability project. To generalize what I've accomplished with Synergex One Design, I'll continue using Design as Exploration from a Systems approach perspective. My ongoing research covers process enhancement and design synthesis for hybridized Cotton-Polypropylene nonwoven fabrics. At this point of the project, it is not possible to provide the specifics of this new process.

5.3 Conclusion

In conclusion, three phases, when implemented in any manufacturing organization, will produce value by improving processes, solving a problem by inventing a new product or enhancing the quality of an existing product, and eliminating bottlenecks and limits, hence saving time and money. The three phases are i) recognizing that manufacturing is a business, and the objective of every business is to generate a profit; ii) finding bottlenecks and limits in the manufacturing processes, and iii) using Design as Exploration to analyze and exploit process constraints to deliver high-quality products. This applies to any production platform or method. This is my contribution to the knowledge base.

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Appendix IA

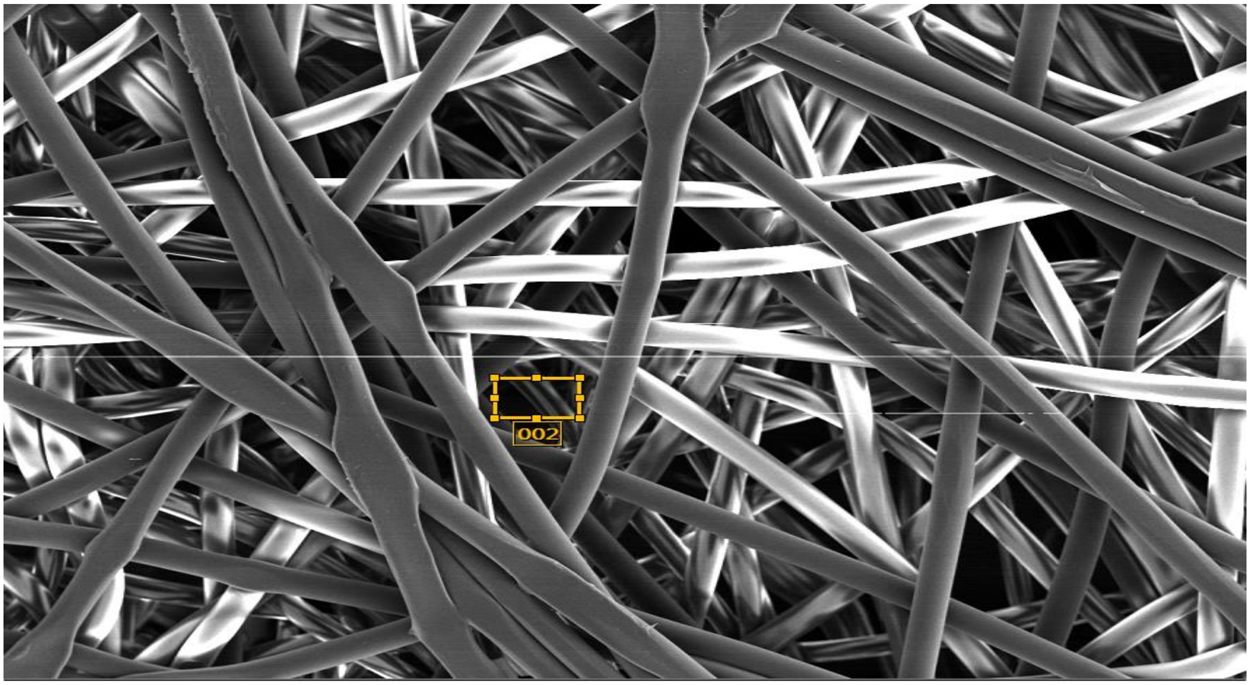
Design of Experiments Stage One-

- Synergex-One trial materials produced on RF-3 with 4K die
- Air Permeability value of the material below target (25 $ft^3/ft^2/min$)
- CD & MD tensile on target

Reicofil-3 extrusion System during Synergex-One DOE trials. BERRY©

Appendix IB

SEM (SCANNING ELECTRON MICROSCOPY) OF PROTOTYPE I

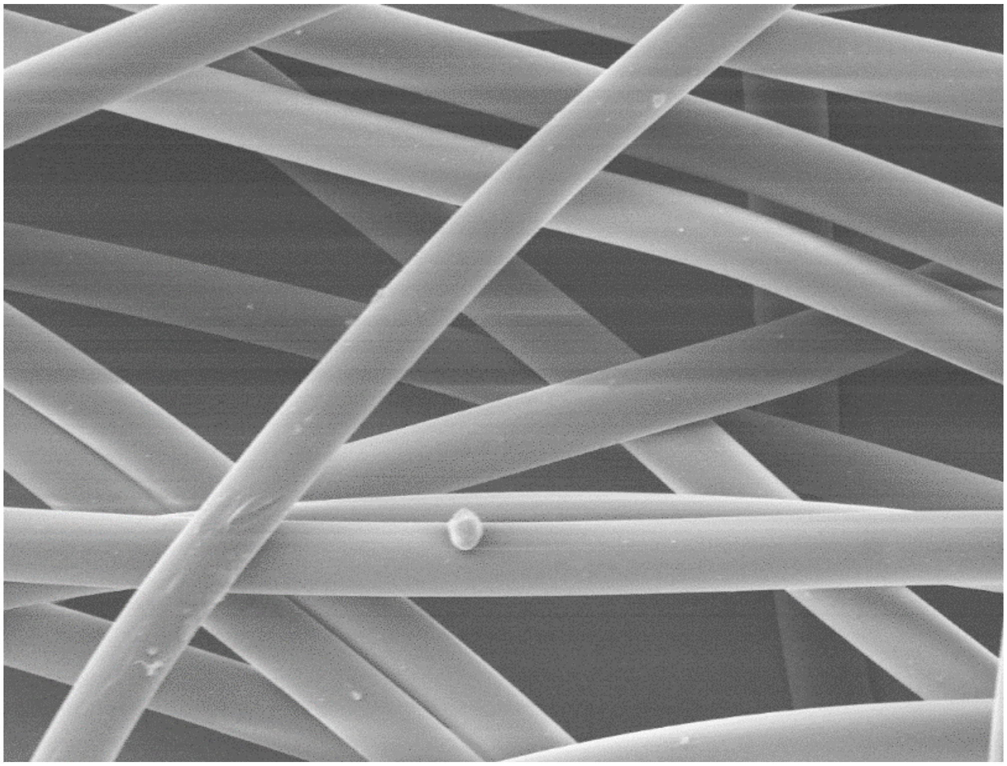


Prototype I -Fiber Diameter –Phase one DOE Trial

The scanning electron microscope of DOE trial material I. Air permeability at 25ft^3/ft^2/min

Appendix IC

SEM (SCANNING ELECTRON MICROSCOPY) OF PROTOTYPE II

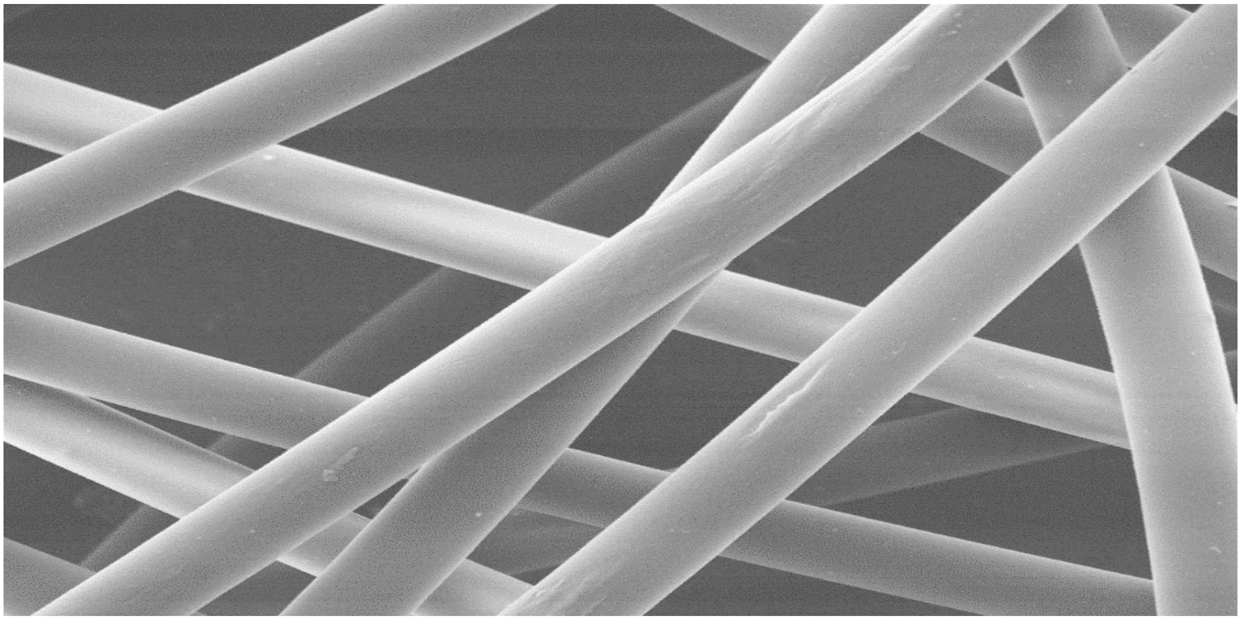


Prototype II -Fiber Diameter –Trial II DOE Material

The scanning electron micrograph of DOE trial material I. Air permeability at 28ft^3/ft^2/min

Appendix ID

SEM (SCANNING ELECTRON MICROSCOPY) OF PROTOTYPE III



Fiber Diameter –Phase III Trial Material.

The scanning electron microscope of DOE trial material I. Air permeability at 32ft^3 /ft^2 /min.

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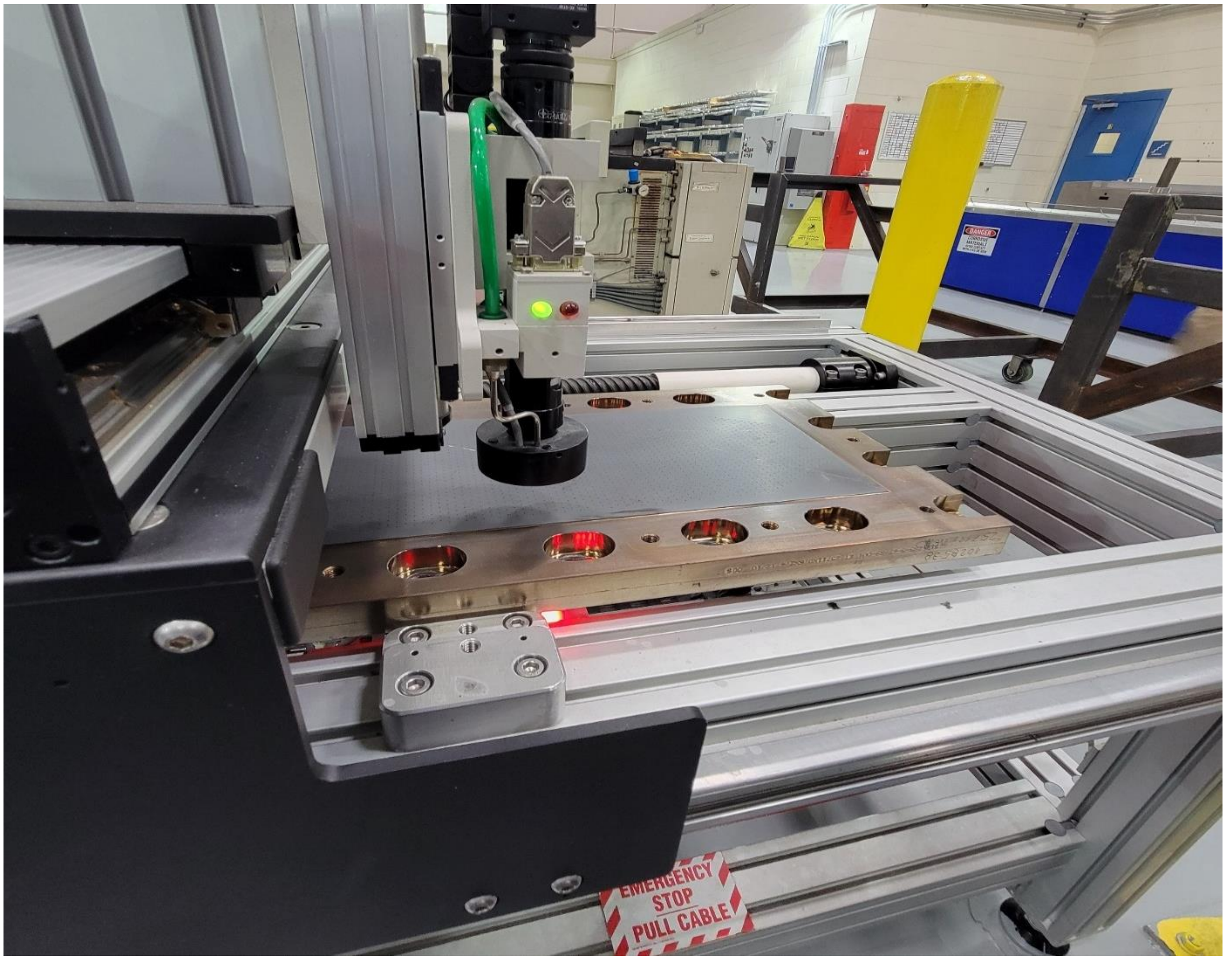
Appendix IIA

5K die development.

5400 holes carefully being created on the die slab. Each 5K die too a week to develop with overhead coat of $15,600.



Appendix IIIA

AIR-PERMEABILITY TESTING MACHINES

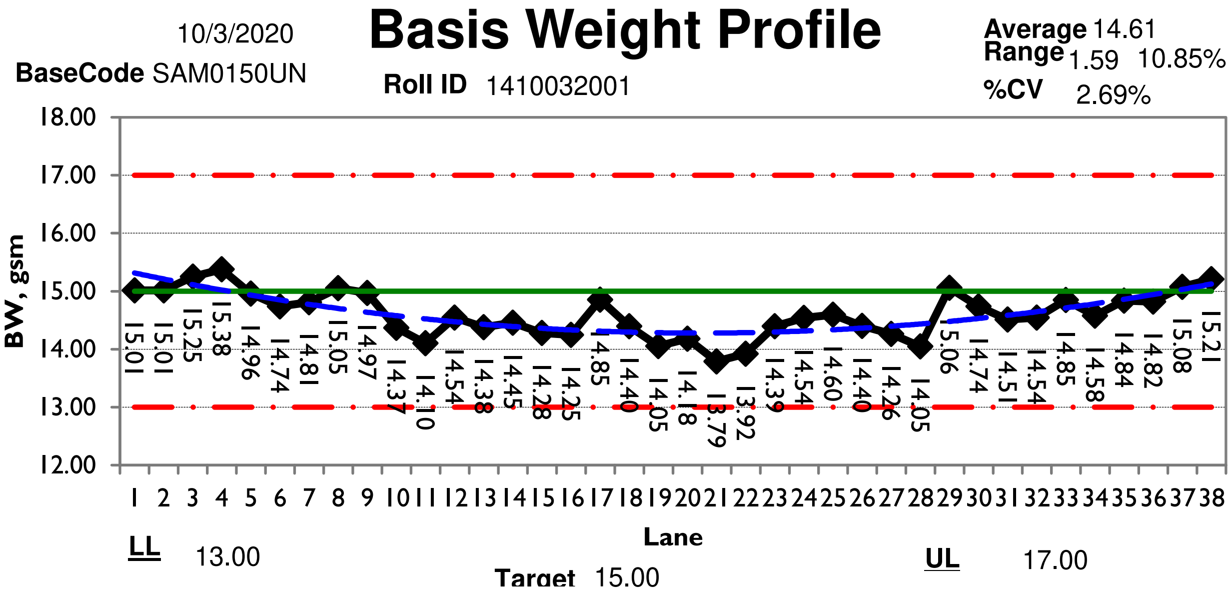
Appendix IIIB

INSTRON- CD & MD TENSILE AND ELONGATION TESTER

Synergex-One 15gsm validated completing a strip and grab tensile stress test using the Instron Machines in the lab

Appendix IVA

SYNERGEX-ONE BASIS WEIGHT PROFILE



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Appendix IVB

Synergex One-15gsm Material Specification

Base Code: **Synergex One™ 15 GSM**

Description: **Three Layer 15 gsm SMS PP**

Property	Unit	Target	LSL	USL	Sample #	Subgroup
Air Permeability 125 Pa (38cm2 Head)	ft3/ft2/min	27	25	33	32	2
Differential Pressure (EN14683) 5 cm2 Head	mmH2O/cm2	5.2	4.2	5.85	32	2
Differential Pressure (EN14683) 5 cm2 Head	Pa/cm2	51.0	41.2	57.4	32	2
Spray Impact	g	0.07	0	0.14	32	2
TSI Resistance @ 85 LPM	mmH2O	16	13	20	32	2
TSI Filtration Efficiency @ 85 LPM	%	58.5	56.5	n/a	32	2

Appendix V

Synergex-One Trial Plan

Berry

MILL TRIAL #	
MILL TRIAL NAME	**Synergex One 15gsm**
TRIAL LOCATION	**Waynesboro, VA**
TRIAL COORDINATOR	**Aderemi Shekoni, Mehmet Sinangil, Jackie Goudelock**
TRIAL DATE	**April 25, 2020**
CORRESPONDING PROJECT #	
CUSTOMER	**Honeywell**

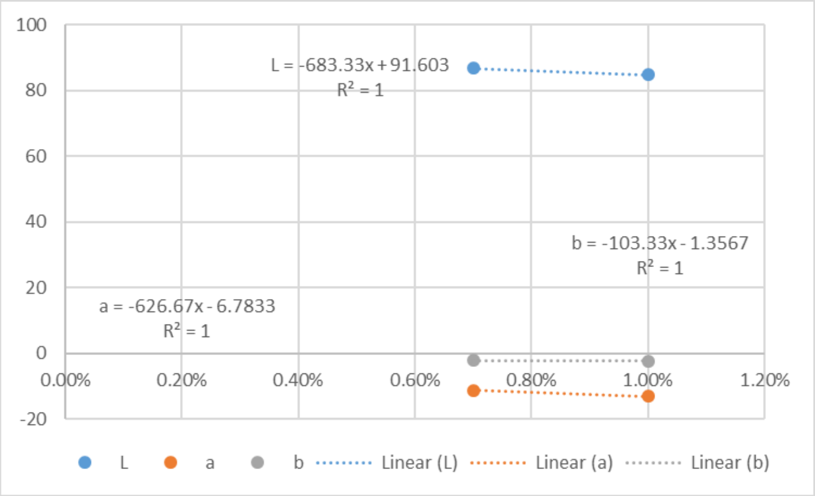
Honeywell is adding an advanced non-woven S-M-S with a lighter web to their product portfolio, called "Synergex One." Berry will attempt to meet the required CTQ requirements, non-physical properties, and L,a,b targets of this new advanced nonwoven materials. For the web color, Berry will introduce lighter teal color by reducing the concentration of the existing teal masterbatch. The best match from the initial hand sheet trial (0.7% MB) achieved a DeltaE of approximately 3.4, so the customer has requested a re-run to meet an initial target of <2 in order to be approved. The present trial is designed to meet this request.

Appendix VI

Synergex-One L-A-B Color Scale & Estimation

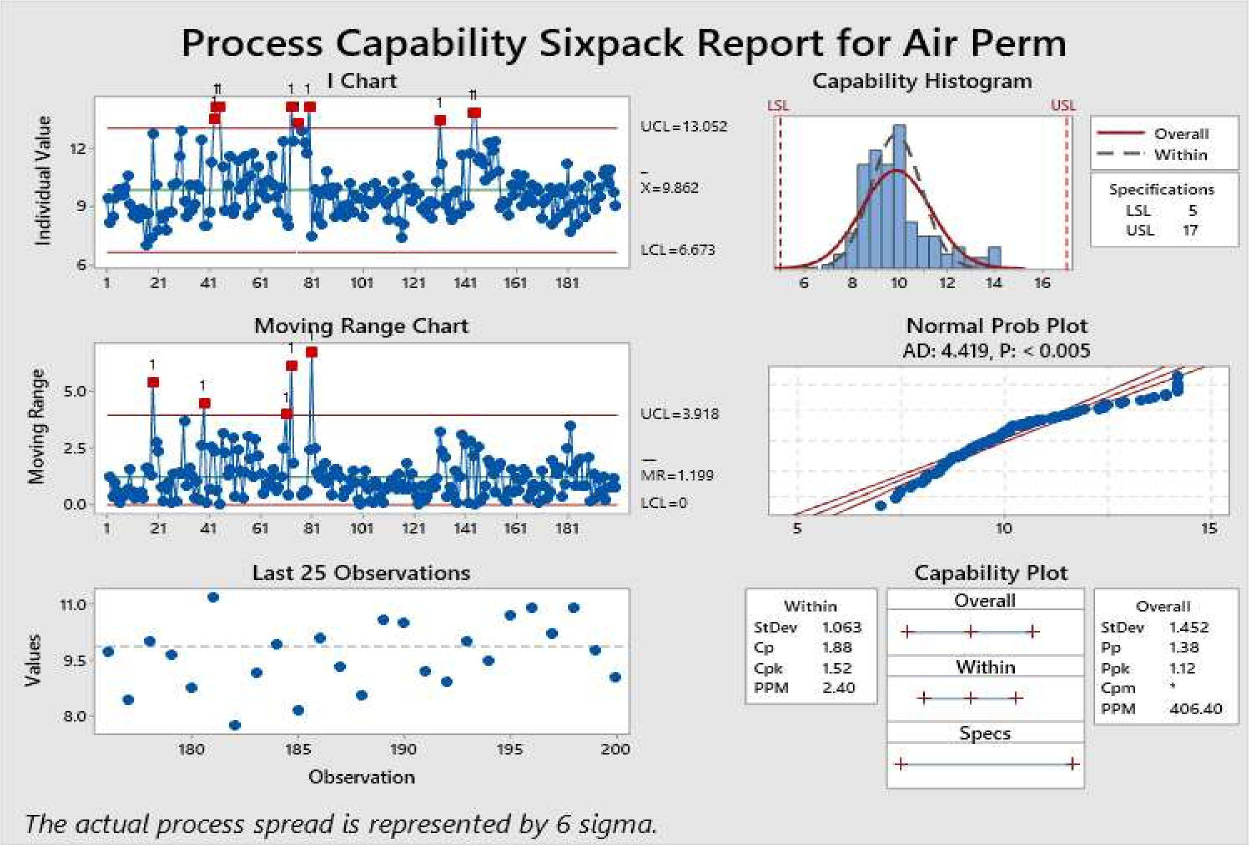
add %	L	a	b	dE
1%	84.77	-13.05	-2.39	6.12
0.70%	86.82	-11.17	-2.08	3.44
0.50%	88.19	-9.92	-1.87	1.85
0.30%	89.55	-8.66	-1.67	1.42

@ 0.5% Additive can provide close to required L, a, b targets



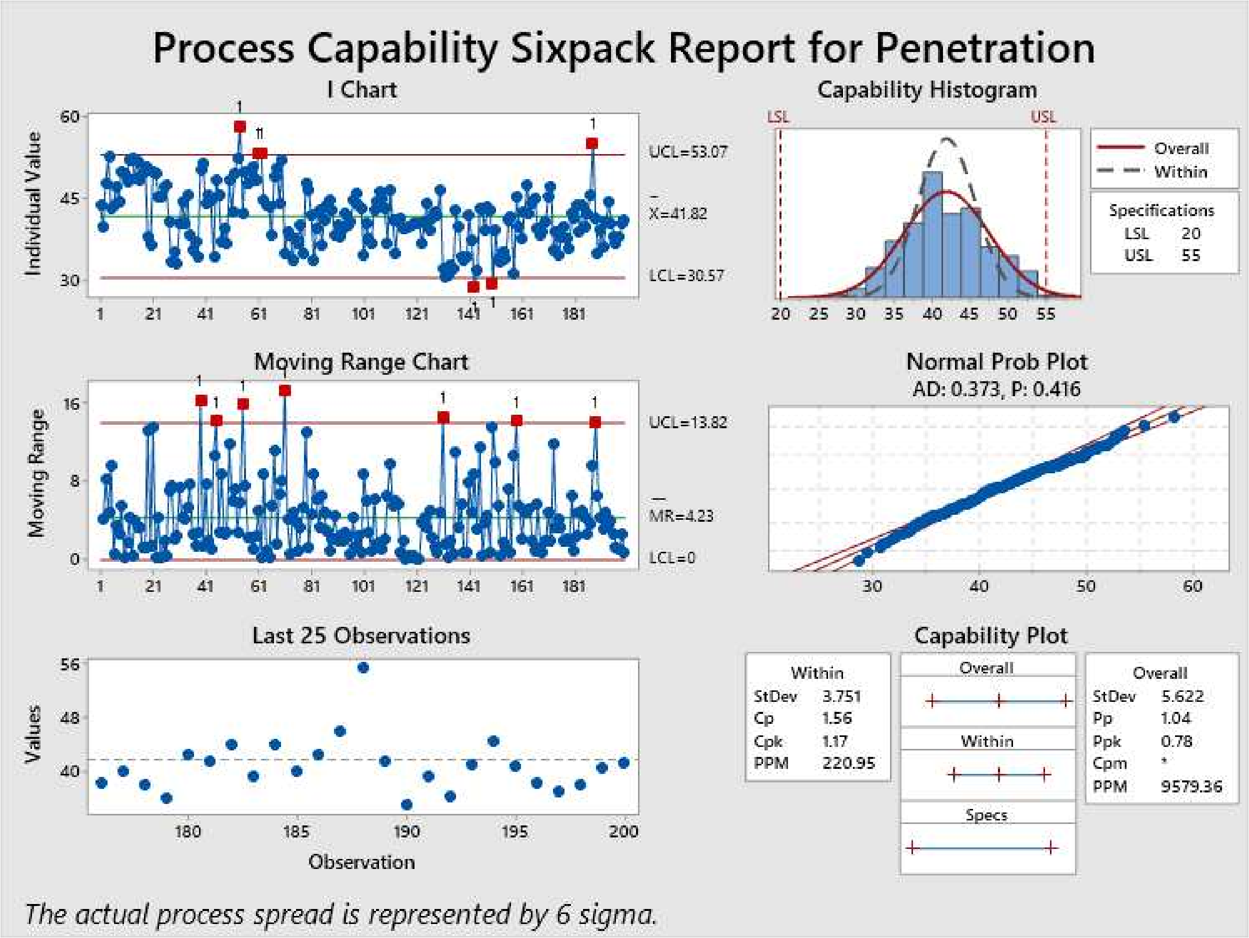
Appendix VII-A

6-PACK CAPABILITY ANALYSIS-AIR PERM (Synergex-One 15gsm)



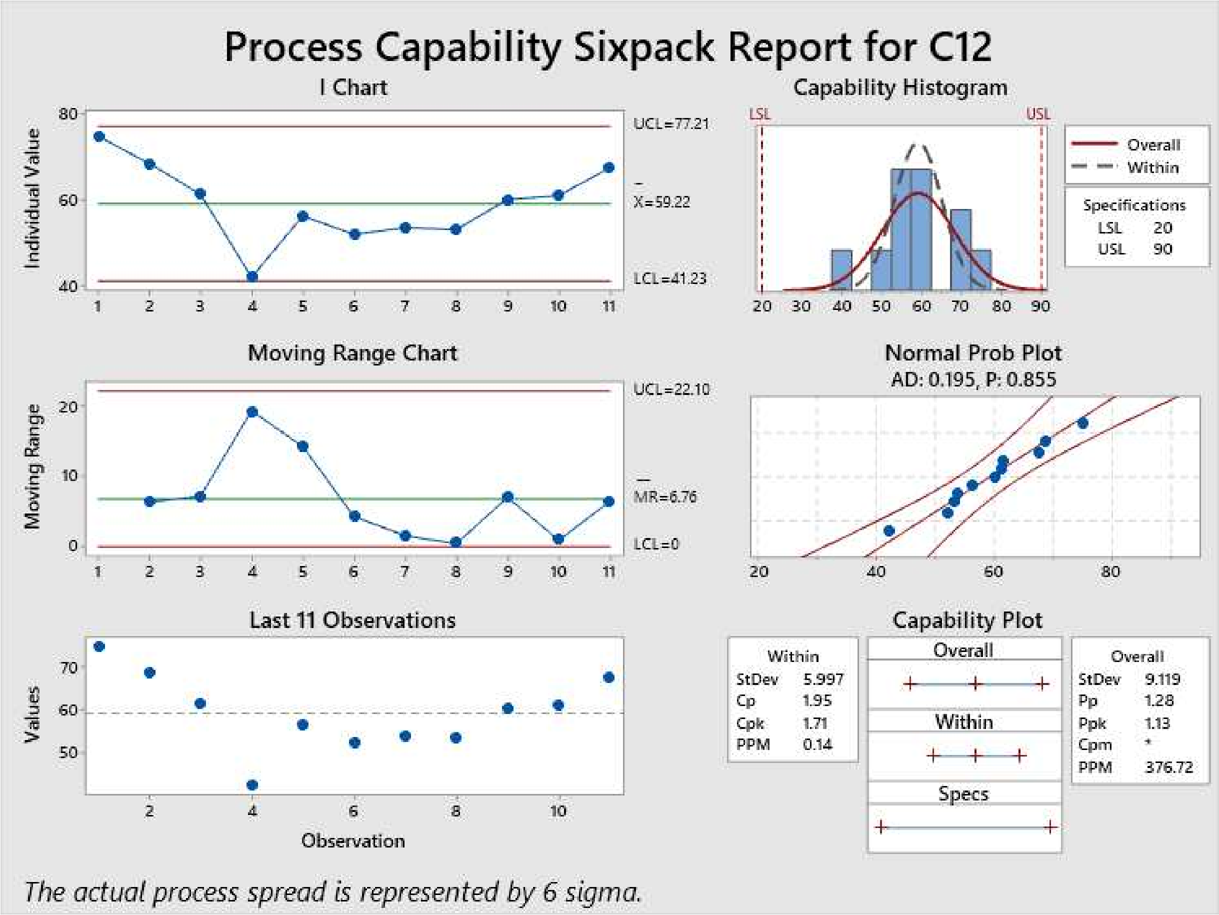
Appendix VIIB

6-pack CAPABILITY ANALYSIS- Penetration (Synergex-One 15gsm)



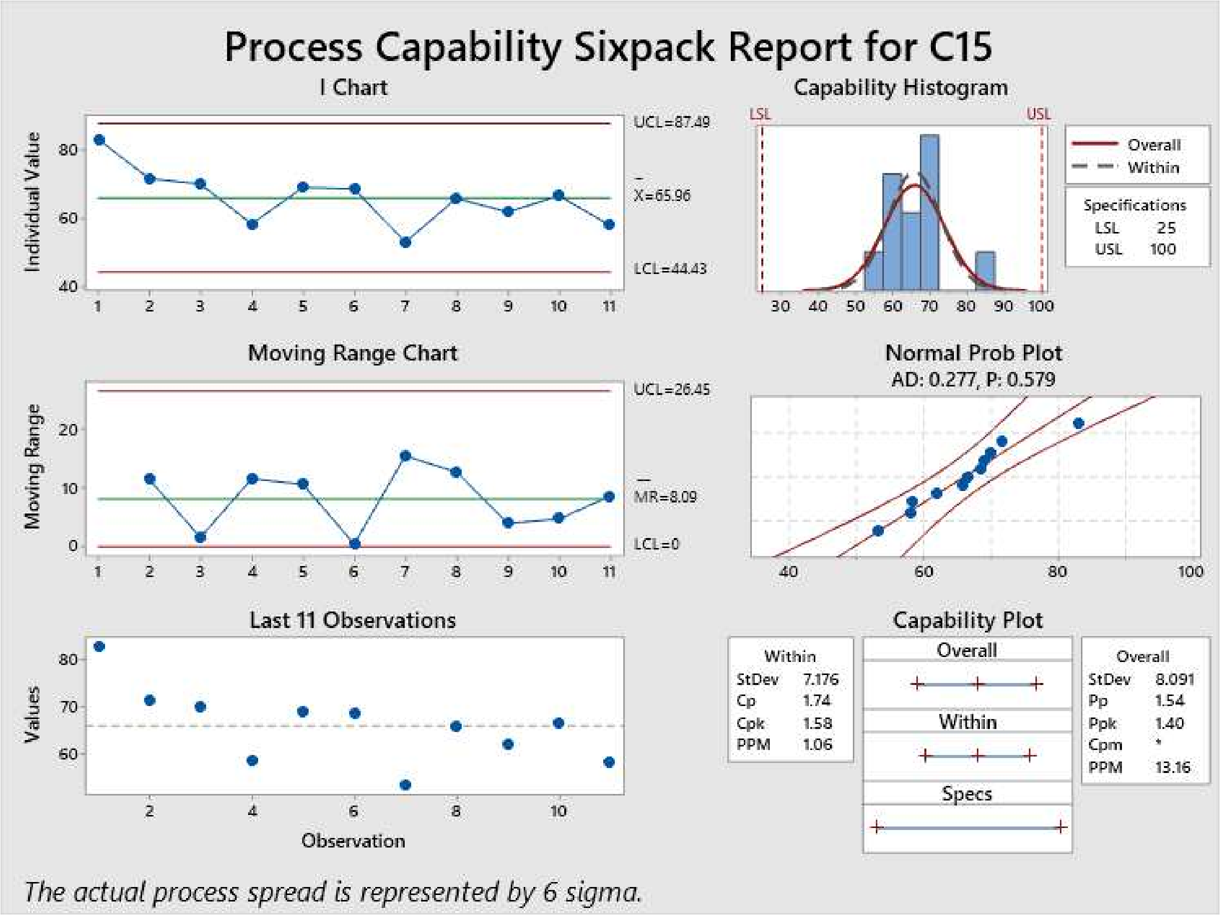
Appendix VIIC

CAPABILITY ANALYSIS – MD ELONG 2% (Synergex-One 15gsm)



Appendix VII-D

CAPABILITY ANALYSIS- CD ELONG (Synergex-One 15gsm)



Specifications

LSL	25
USL	100

Within

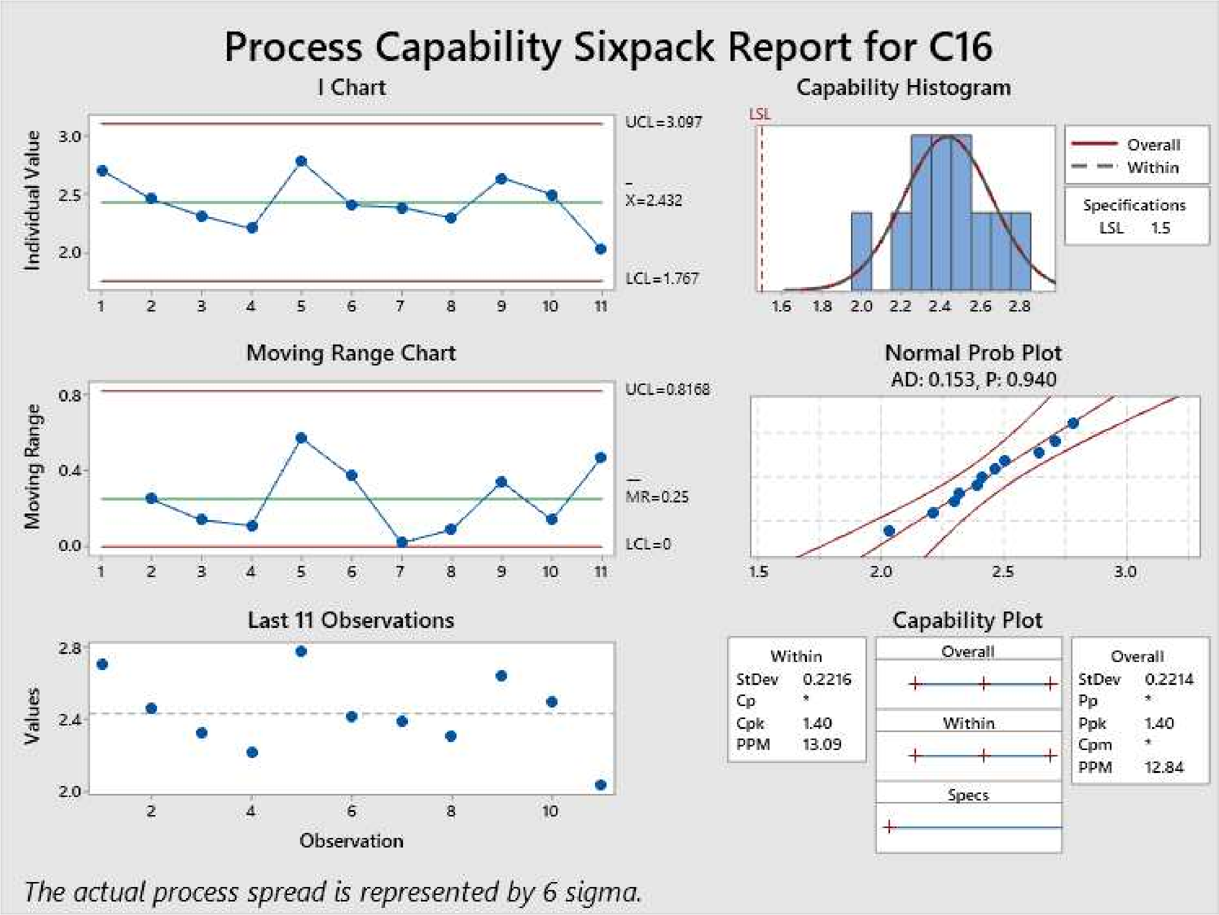
StDev	7.176
Cp	1.74
Cpk	1.58
PPM	1.06

Overall

StDev	8.091
Pp	1.54
Ppk	1.40
Cpm	*
PPM	13.16

Appendix VII-E

CAPABILITY ANALYSIS – CD TENSILE (Synergex One 15gsm)



Appendix VIII

CALENDAR OIL ANALYSIS

Reicofil-II, III, and IV Calendar oil (from left to right)

Three different oils from the calendar in nonwoven manufacturing system. The recommended oil by vendor is the D-1000 oil for the sub-system. The D-1000 allows for adequate heat conduction during calendaring of the nonwoven

Appendix IX

SMS composition is 80% Spunbond and 20% Meltblown. The Polypropylene for Spunbond resin has a melt flow rate of 35 (i.e., 35MFR). The polypropylene for meltblown resin has a melt flow rate of 230 (i.e., 230 MFR). For this research, the resin used is Braskem CP360H[1]. For all SMS, and SMMS products, we add the additive Irgatec CR 76 IC (a polymer modifier for meltblown). The percentage of Irgatec added depends on the target product (i.e. SMS or SMMS)

Synergex-One 15gsm ready for shipment. BERRY©

Appendix X

The polypropylene used for the development of Synergex-One 15gsm

Braskem

09/15/2020

BRASKEM AMERICA, INC.

C/O LEASE TRACK #29

WAYNESBORO, VA 22980

BRASKEM POLYPROPYLENE LOT ANALYSIS CERTIFICATION

The characteristics of Braskem Polypropylene shipped 09/15/2020 are as follows:

Product	CP360H
Lot Number	PACLJI1111
Production Date	09/15/2020 19:40
Railcar/Shlpper Number	UTCX053934
Net Weight, lbs.	195600
Braskem Order Number	5500040199-000040
Customer Purchase Order Number	
Seal Number(s)	174748

PARAMCTER	UNTS	RESULT	TESTMCTHOD
Melt Flow Rate	g/10 min	35.3	ASTM 01238

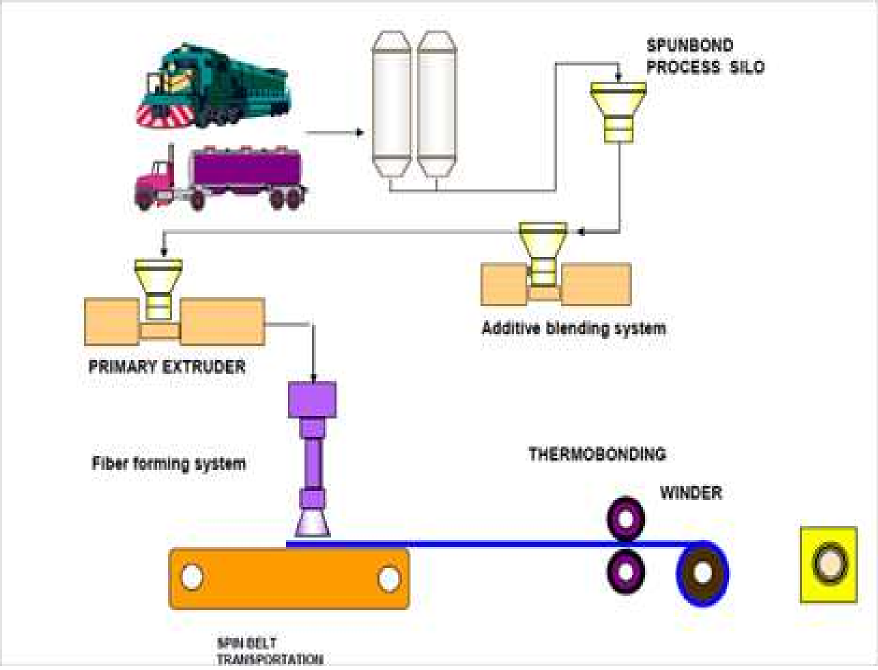
Approved and Electronically Released by: Bob Dunham
Email Address: bob.dunham@braskem.com
Office Phone: (610) 497-8248

Certificate#
Master# 2

64958

Appendix XI

SMS Manufacturing Flow (diagrammatic)



LIST OF ABBREVIATIONS

AO_x	Antioxidants
AP	Air Permeability
BERRY	Berry Global, Inc.
CTQ	Critical to Quality
GSM	Grams per square meter
MFR	Melt flow rate
PP	Polypropylene
Reicofil/RF	Reicofil Nonwoven Manufacturing system
SMS	Nonwoven fabric made with PP combinations of spunbond and meltblown