

DEVELOPMENT OF A NOVEL METHOD OF FABRIC MANUFACTURE FOR DESIGN PRACTICE
(An Investigation of Fibre on Yarn Surface Entanglement)

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A thesis submitted in partial fulfilment of the requirements of Nottingham Trent University
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ABSTRACT

Textiles are one of mankind's most used products, the earliest references are to the use of plants and then animal skins, these resources were the main source of shelter and protection for the body. Currently, textile fabrics are produced either using yarns or fibres, yarns are manufactured using two ancient fabric construction practices known as knitting and weaving whereas fibres are based on fibre bonding or fibre entangling; the resultant fabrics are known as nonwoven. Since the origin of textiles, the manufacturing techniques have continued to utilise these three methods: weaving, knitting and nonwoven.

This thesis demonstrates the development of a novel technique to manufacture textile fabrics, which I call 'Fibre on Yarn Surface Entanglement' (FOYSE). The registered process FOYSE® has been initiated through testing methods to consider how to entangle, and to explore scale and design applications. Two textile structures and tools to create them have been pioneered and these demonstrate suitability for fabric surfaces commonly used for woven and knitted textiles. The first material is registered as Zephlinear® and the second is trademarked as Hover-Text™. These innovative textiles are an ideal structure to accommodate future demands caused by advancing technology within industry. Zephlinear is a structure suitable to support smart and intelligent textiles as demand grows for advancing wearable fabrics. Hover-Text is an ideal structure to accommodate the demand for sustainable activewear. Mixed methods is the methodology used in this research. Tensile testing provided quantitative data and structured questionnaires were used to provide qualitative data. Twelve samples underwent tensile tests and were confirmed to meet the British Test Standard ISO 2062. Each sample showed slight variations in results. For example, two samples tested in the weft direction showed a difference of 40% strain capacity. It was assumed the irregularity was the result of differing quantities of fibre on the yarn surface used for entanglement. The results from the qualitative data provided information on how individuals understood the variance of fabrics manufactured by FOYSE in relation to known fabric surfaces. In addition to the development of a novel technology, this thesis also introduces novel tools and techniques.

The FOYSE production process provides advancement to knowledge regarding how fabric from yarn can be assembled into textiles outside of the two known construction methods. Therefore, the present work introduces a fourth class of fabric surface. Thus, removing the limitations of the three known methods of manufacturing textiles. In addition, this thesis demonstrates a proof of concept for novel tools and machinery used to speed up and automate the FOYSE manufacturing process.

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RESEARCH ACTIVITIES

Patent, publications, conference proceedings, presentations, exhibitions, and awards produced during the research, are listed below:

I. Patent

1. Zephlinear LTD Fabric Manufacture, patent number: Patent Application No. 1706938.6, 2017.

II. Publications and conference proceedings

1. Reynolds, S. (2021), E-textiles the Need to Breathe: A Novel Manufacturing Process and Textile for Lightweight Transparent Sustainable E-textiles and Wearables SPWID 2021, The Seventh International Conference of Smart Portable, Wearable, Implantable and Disability oriented Devices and Systems. Conference proceedings.
http://personales.upv.es/thinkmind/dl/conferences/spwid/spwid_2021/spwid_2021_1_40_80019.pdf

III. Presentations

1. Reynolds, S. (2021), Textiles the Need to Transcend the Known: Rejection of traditional textiles to embrace futuristic fabric applications for the advancement of humanity: A novel manufacturing process and textile that interconnects fibre entanglement and digital delivery for the rapid additive manufacturing of true textiles. Digital Art and Interpersonal Interaction: BCU Steamhouse: Connections
<https://steamhouse.org.uk/event/digital-art-and-interpersonal-interaction-bcu-steamhouse-connections/>

IV. Exhibitions

1. Reynolds, S. (2018), The University of Pennsylvania Fisher Fine Arts Library Material Collection
<https://library.artstor.org/#/search/zephlinear;page=1;size=72;donatinginstitutionids=%5B10017%5D>
2. Exhibition of FOYSE apparel displayed at the White Gallery, ExCel London

V. Awards

1. Reynolds, S. (2016), Wool Innovation Prize by The Merchants of the Staple of England and The Worshipful Company of Woolmen.
<https://merchantsofthestapleofengland.co.uk/2018/01/16/wool-innovation-prize-2016/>
<https://www.woolmen.com/wool-innovation-prize-2017/>
2. Reynolds, S. (2021) The Seventh International Conference of Smart Portable, Wearable, Implantable and Disability oriented Devices and Systems. Best Paper Award at The Seventh International Conference of Smart Portable, Wearable, Implantable and Disability oriented Devices and Systems.
<https://www.iaaria.org/conferences2021/AwardsSPWID21.html>

INTRODUCTION

There are three textile fabric manufacturing processes in use today across the global industry having emerged through numerous historic innovations. Textile fabrics are one of mankind's most essential materials. Plant fibres and animal skins are the earliest materials used for protection and comfort for our bodies and homes. The use of plant fibres and animal skins has evolved, and in some cases, they have been combined with newer synthetic and cellulosic regenerated fibres which led to a new generation of manmade fibres. The resulting fabrics maintain the features of natural fibres and skins but with added benefits brought through the addition of these new fibres. Initially, plants were manufactured into thread and then woven; similarly, furs and animal hair were carded and/or spun into yarn and then either bonded or woven into various textiles. As we became more skilful with the manufacturing process, we also developed innovations in the production of apparatus to help automate the manufacturing of fabrics. Currently, manufacturing methods are limited to three practices: weaving, knitting and nonwoven created by fibre bonding or entanglement¹ and there has been minimal innovation in how fabrics are formed. My role as a researcher and inventor is to explore the potential of adding a process, which involves first bonding the fibre by spinning and then bonding the yarn by the inventive step of surface entanglement. My position as an entrepreneur provided the finance and time to conduct the research. The hypothesis is that this new process would add an additional fabric surface and a production method, which will advance current fabric manufacturing restraints by introducing yarn surface entanglement as a fourth class of construction method. This formed the research question: Can fibre on yarn surface be entangled to create a new fabric surface and introduce a fourth class of textile and manufacturing process?

My formative years as a designer maker stemmed from my exposure to textile manufacture at a very early age. My mother was a nurse by day and my father a bricklayer by night. Between them they also operated a small textile business. It was typical of Windrush immigrants in the UK (United Kingdom) to have multiple income streams to support their family. I transitioned from personal design practice within textiles many years prior to this research, however my passion for textile innovation remains. My life's journey, education and experience supported the distinctive roles evident in this research. Namely that of a researcher, inventor, and designer which I encapsulate as an entrepreneur.

¹ Fibre bonding is connecting synthetic fibre by a heat or air process. Fibre entanglement is connecting natural fibre using needle punching or wet finishing.

CHAPTER 1: RESEARCH CONTEXT

1.1 Background of the Study

Motivation for this research was to provide an additional fabric surface that provided visual distinction from designs created from the known processes – weave, knit and nonwovens. In addition, this fabric would provide a manufacturing method that would answer the problem of the seamless insertion of elements, including E-yarns, used in electronic textiles. The instigation of this project emerged from an event when I was observing wool yarn from knitted garments connecting after undergoing the wet finishing process². This repeated occurrence was an initial annoyance, the design structure I was creating was intended to have an appearance of unconnected floating yarn. However, without any encouragement the fibres on the yarn would entangle. It was clear that the fibres connecting the yarn had little strength and could easily be separated by using little force and I became intrigued with this phenomenon and began to explore it further. This eventually formulated the hypothesis for this research. I then began investigating methods to reproduce this occurrence but with a desire to increase the strength of the entanglement. My role as a designer working with wool of various types has given me expert insight and knowledge as to how these fibres and yarns performed. When I operated as a knitwear designer maker, I served a variety of market levels. This included serving independent boutiques and global design houses, such as DKNY, which helped develop my expertise. Examples in Figures 1.1 and 1.2 demonstrate some of my practice in these cases via a Shima Seiki computerised knitting machine. Examples in Figures 1.3 and 1.4 demonstrate work using hand craft techniques utilising a domestic knitting machine.



Figure 1.1: Shetland wool collection

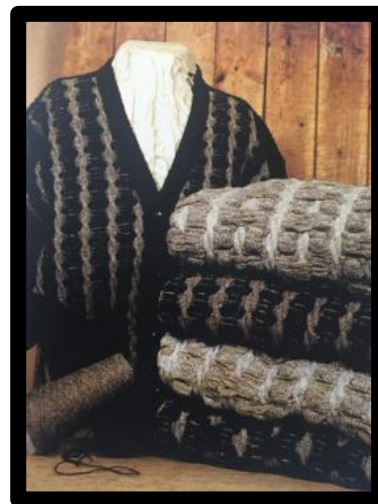


Figure 1.2: Shetland wool collection

² Wet finishing is usually the final step in some textile manufacturing processes. It is used to improve the look, performance, or softness of the finished textile.



Figure 1.3: Cashmere collection.



Figure 1.4: Lambswool collection.

The clothing in all these figures were put through a wet finishing process for completion. The knowledge of using a chemical solution to finish knitted apparel contributed to this research. The strength of the solution and the application methods of the chemical application were significant variables tested within the experimentation process to establish the strength of the new process.

My recent years consist of working cross-disciplinary, namely, within interior design and real estate which also provided knowledge that was advantageous to completing this research. For example, the initial research area for the project was to investigate how the yarn surface fibre entanglement process could be manufactured efficiently and possibly automated. A major step in the yarn surface fibre entanglement fabric production was to encourage fibres in the surface of a yarn to uncurl from the yarn while keeping the twist structure. Manual brushing was tested using various tools to accomplish this process. Regardless of the tools experimented with to uncurl fibre from the yarn, it was a laborious process. My experience of using handheld powered tools, led me to investigate attaching various hairbrush heads to a powered driver. This experiment was successful due to the increased speed at which fibre could be teased from the yarn.

1.2 Research Approach

The approach to the research question was particularistic;³ A holistic approach was adopted to understand the mechanism of the entangling of fibres protruding from woollen yarns and to define the manufacturing rules. The development of novel tools and the iteration of experiments were undertaken to advance the production process. Speed and scale of production are factors directly associated with commercialisation of textile products. The knowledge necessary to transitioning the novel process from a craft practice to commercial and industrial production had to be investigated. As noted by Khalifa:

Understanding the engineering design process is important for managing the design activity process and to aid product development and improvements. In addition, the design process assignments are defined by the creation process, product performance, and the resulting quality (Khalifa 2013).

The research expounded in this thesis is a combination of the product development (novel fabric surface) and engineering design process (tools to aid in the manufacture). Significantly, the creative process, product performance and the usability of both product and process were contributing factors to verify or falsify the hypothesis of crafting a textile fabric by entangling the surface fibre on yarn.

As the research process being developed was drawing on both product and engineering approaches as well as aesthetic and functional outcomes, I was keen to explore if there were examples that existed which articulated these synergies and tensions. In Figure 1.3 there is a model which clearly conveys how consumer products that engage in both product design and engineering processes are used to develop new consumer products. This design spectrum supports the nature of the research which involves product, process, and tools to aid FOYSE manufacture. In this research it was clear that there was a relationship between the amount of fibre protruding from the yarn surface and quantity of pH 9 solution used to aid in entangling the fibres on yarn surfaces.

The development process for FOYSE is directed toward establishing a fourth class of textile fabric, consumer reaction has some weight in the research. Therefore, it was important to investigate both the aesthetic and the functional properties of FOYSE fabrics. The balance between industrial design and technical design is in relationship with each other and then the consumer product is what makes the Caldecote product design spectrums connect to this research.

³ Exclusive attention or devotion to one's own interests.

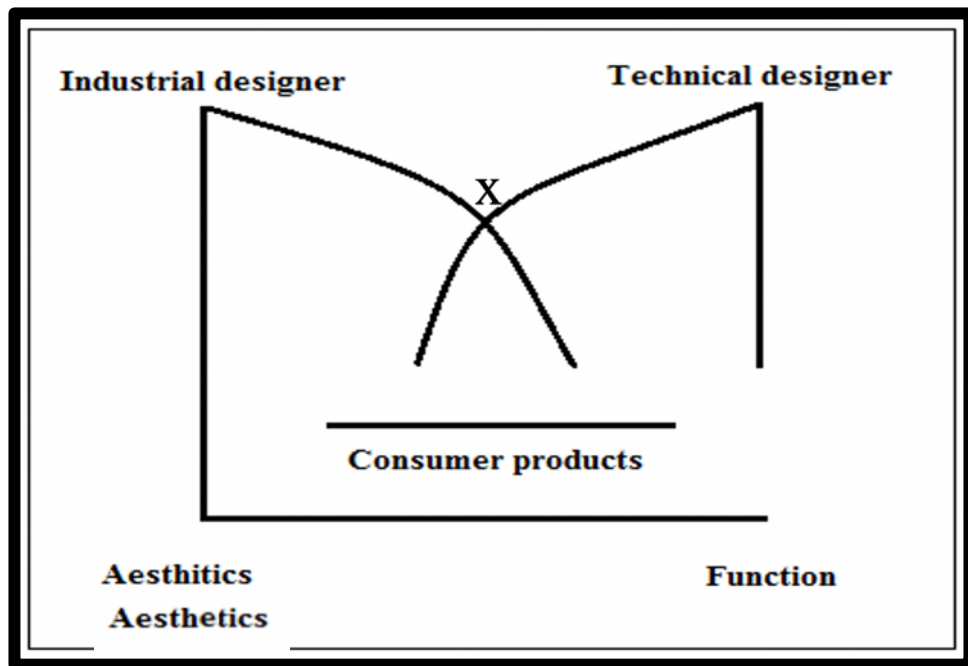


Figure 1.5: Design spectrum – adopted from Caldecote 1989 (Khalifa 2013).

A product that relies mostly on aesthetics, such as garments and interior fabrics, is within the design spectrum of an industrial designer. Products that are function dominant, such as automobile engines, building foundations; [and] technical textiles are within the domain of engineers (Khalifa 2013). Some fabrics that require significant stretch and retraction such as lingerie require engineering type skills. The 'X' in Figure 1.3 is a symbol to illustrate that as a researcher I situate myself in the centre of both domains: an industrial and technical designer as aesthetics and function are equal considerations for this research. Textile designers work with what is known, namely weaving, knitting and fibre bonding. An industrial designer, by definition, bridges the gap between what is and what is not possible. The term hybrid designer is applicable to my role in the research as both design and development skills are used. Consumer products rely on both engineers and industrial designers to flourish. Engineers for execution and function according to required specifications and on industrial designers for aesthetics. The level to which each discipline dominates the design varies from product to product (Khalifa 2013). Figure 1.4 is an illustration of the design spectrum for both disciplines. These factors have direct application to the methodology used to address the research questions.

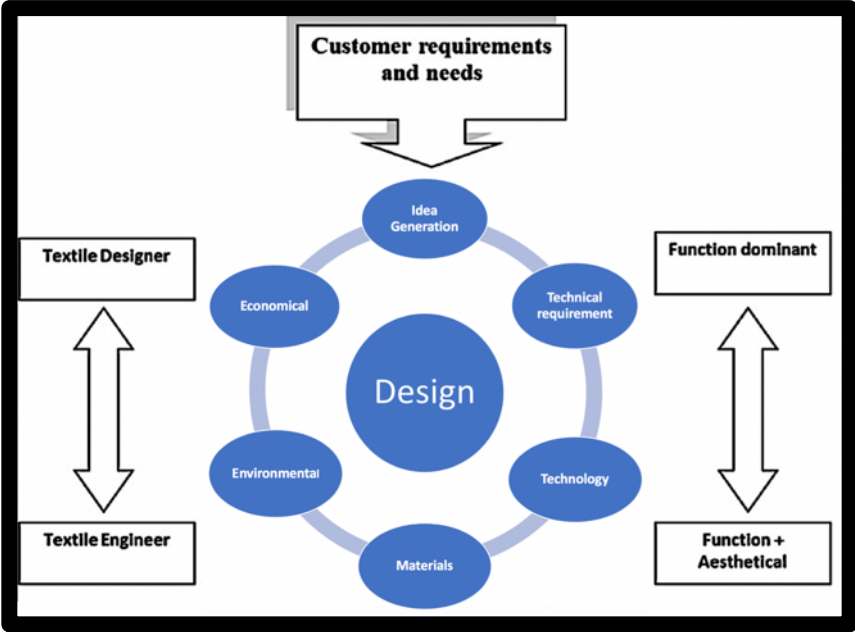


Figure 1.6: Technical Textile Design Spectrum (Khalifa 2013).

The approach used to address the research problem is presented in the image below. Empirical and literature research insights were triangulated with the experimental practice to explore and address the questions throughout the written thesis.

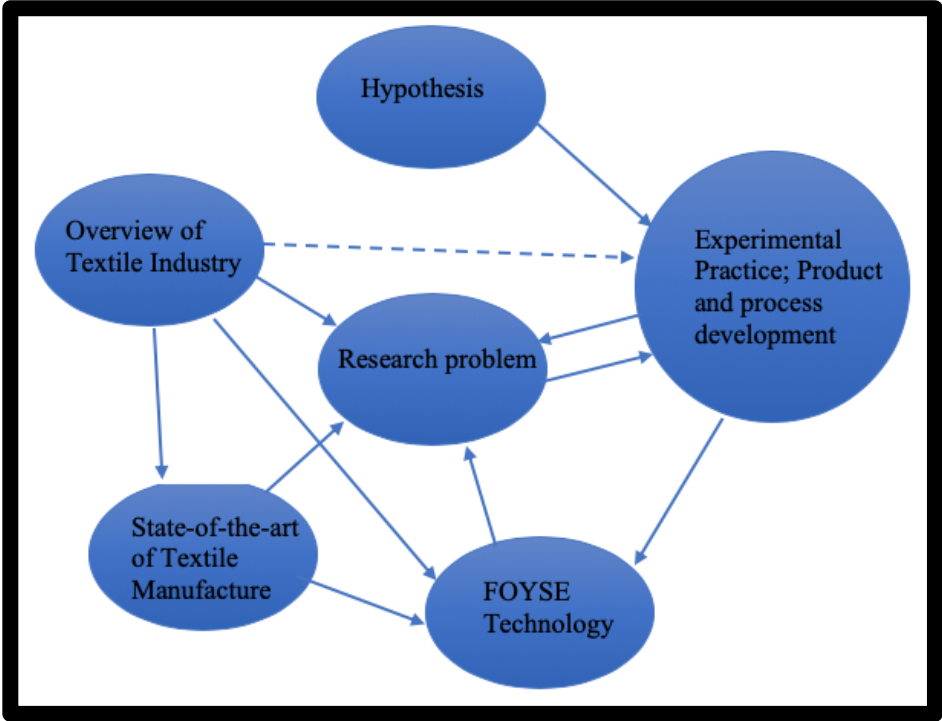


Figure 1.7: An overview of the research approach used to address the research problem.

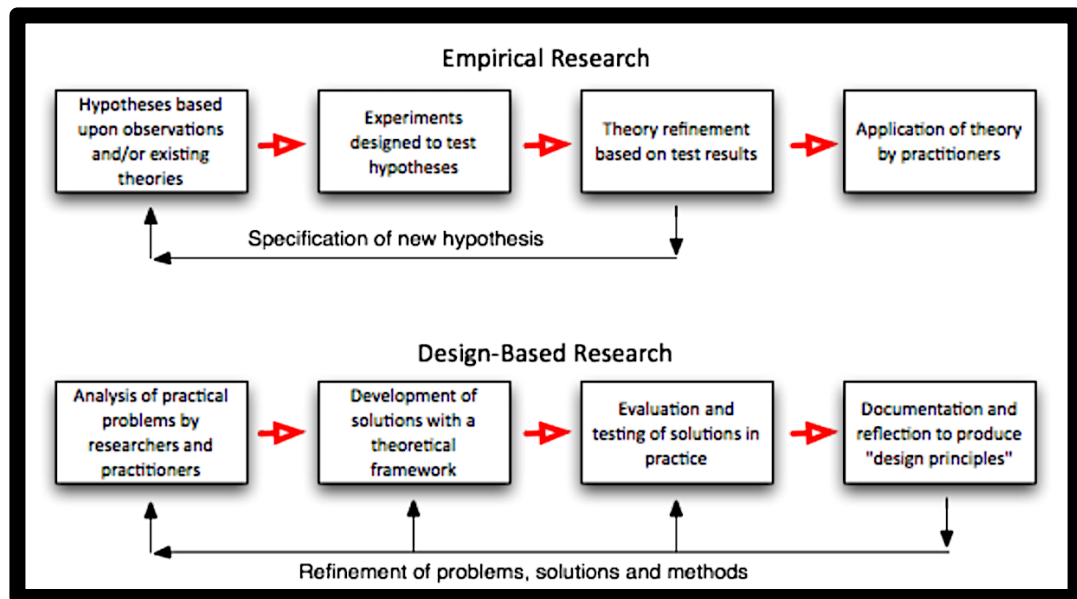


Figure 1.8: Empirical research vs. Design-based research (Porter and Norjkorloo 2014).

Research methodology is a systematic approach to collect and evaluate data in the research process. Empirical research and design-based research processes were both considered. The purpose of data collection for this research is to test the hypothesis which derived from an observation. The research is not founded on analysis of practical problems by researchers and practitioners which is design-based research. The research derived from a passion to understand and investigate the phenomenon of surface fibre on yarn entangling. Therefore, the Design-based research process is not suitable for use as the underpinning research methodology. Empirical research is the underpinning research methodology to be used in this study. Empirical research is based on observation and measurement of phenomena, as directly experienced by the researcher as illustrated in figure 1.8.

1.3 Novel Manufacturing Process Overview

As this is a new manufacturing method, I wanted to clearly demark it from other construction processes and subsequently named it FOYSE®. This is an acronym for Fibre on Yarn Surface Entanglement. This construction is yarn based but has an inventive step of the incorporation of fibre bonding. The “bonding” is caused by entangling natural fibres which are limited to the fibre on the surface of the yarn. The FOYSE process has been used to test and explore samples using 100% wool and a wool/mix yarn. The breadth of experimentation is to demonstrate evidence of the new manufacturing process’s ability to create material that is suitable for varied design applications and to explore its potential limitations and strengths. Research has also been conducted to assess market potential by identifying product advantage in the form of difference from current fabrics.

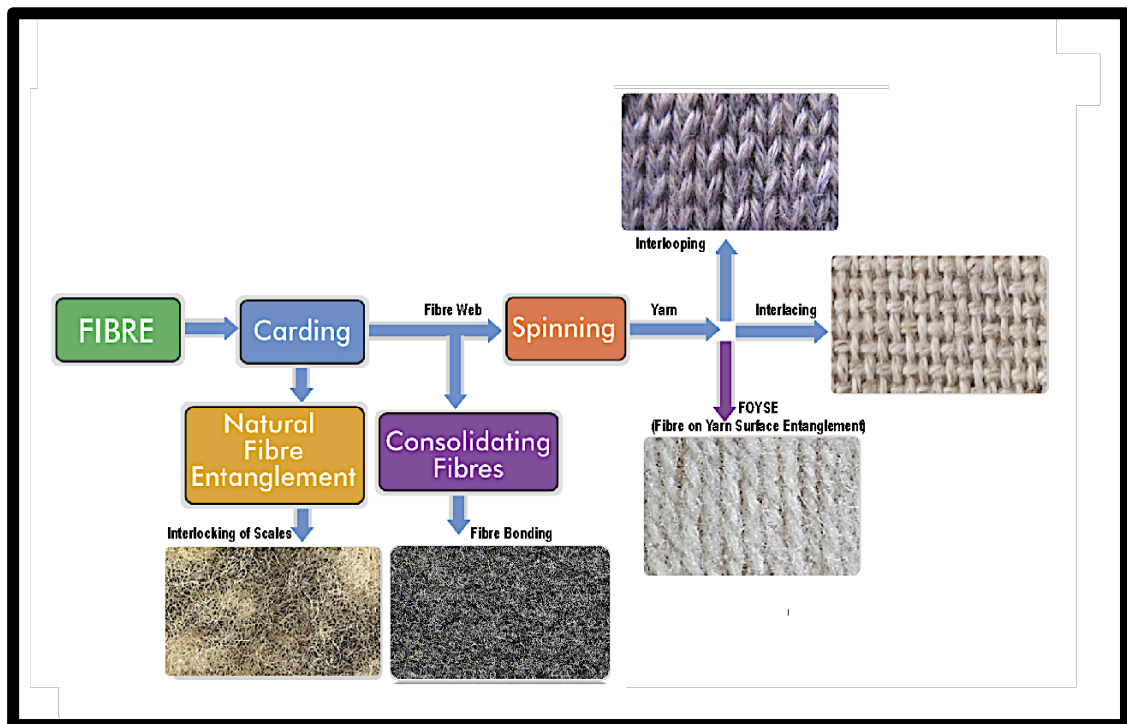


Figure 1.9: Fabric processes of the three classes of fabric construction and Zephlinear created by FOYSE.

Figure 1.9 demonstrates traditional textile manufacturing and FOYSE, where textile fibres are bound together to form fabric structures. The conversion from fibre to textile fabrics is achieved in steps, and the key process of these steps is illustrated. A fibre web is formed using staple fibres in the carding process. Nonwoven fabrics are produced by consolidating carded fibre web.⁴ Woven and knitted fabrics are manufactured using yarns spun from carded fibre. Two fabric structures have been manufactured using the FOYSE process to demonstrate design capability named Zephlinear and a second structure named Hover-Tex. The name Zephlinear is derived from two words Zephyr and Linear and applied when the FOYSE process is used to manufacture a textile with one layer of yarn as in Figure 1.6. Hover-Tex will be discussed further in this thesis.

Yarns spun from staple fibres have fibres protruding from the yarn surface, referred to as 'yarn hairiness' which are caused due to partial anchoring of the fibres within the yarn structure. In the FOYSE process, the protruding fibres of woollen yarns are raised from the yarn and entangled to create a textile fabric. There are several important differences between the current nonwoven and FOYSE construction process. Figure 1.6 shows that unlike known nonwoven fabrics the spinning process is a significant part of FOYSE manufacturing.

⁴ Nonwoven can also be created by entangling natural fibre directly from carding.

FOYSE first iteration comprised of the following manufacturing process:

- a. Laying out lengths of spun wool yarns in a parallel array.
- b. Raising fibres on the surface of each length of yarn in the array by brushing the yarn surface. Using hairy yarn such as mohair can reduce or eliminate the brushing process.
- c. Wetting the yarns in the array to encourage the entanglement of surface fibres of yarns in the array.
- d. Manually or via a washing machine repeated agitating and rinsing the array of surface fibres on yarn to increase the entanglement of surface fibres of yarns in the array.
- e. Drying the wet yarns in the array.

An example of Zephlinear manufacture created by FOYSE is detailed below. In this example, surface fibre entanglement strength is obtained with the use of a washing machine. The method will now be described by referring to the accompanying figures.

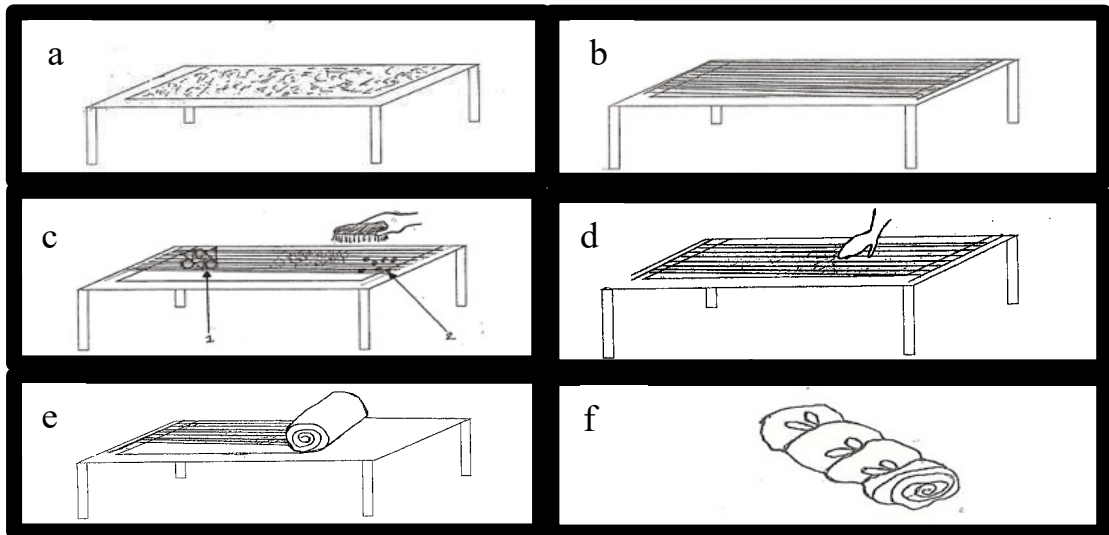


Figure 1.10: (a-f), a) Towelling cloth is placed on a table-top, b) Parallel array of wool yarn is laid and secured with tape on to the towelling cloth, c) Yarn is brushed to raise surface fibres. Image at points 1 and 2 illustrate embellishments, such as beads which can be added at this point to create a design feature, d) Water and on average 5ml pH 9 solution is added by hand to the surface fibres on the yarn, e) Towelling cloth is then tightly rolled to tension the yarns, f) Towelling cloth is secured with rope to ensure yarn ends stay in position.

At this point, the bundle is placed into a washing machine and put on a 40-degree centigrade wash cycle. Within chapter 2.1.9. further modifications of FOYSE technology will be apparent without departing from the scope of the 6 stages described above.

From initial experimentation and sampling of the FOYSE process, two very distinct fabric surfaces were created. The first is a fabric structure created by a single parallel array of yarn as seen in Figure 1.13 and Figure 1.14 named Zephlinear. The second, is a fabric structure created by a vertical base layer of parallel yarn coupled with a top layer placed horizontally to create a 90-degree angle seen in Figure 1.15 and Figure 1.16 named Hover-Tex. Zephlinear's structure gives a distinctive linear appearance, the entanglement of the fibres can be observed in Figures 1.13 and 1.14, which is created by FOYSE.

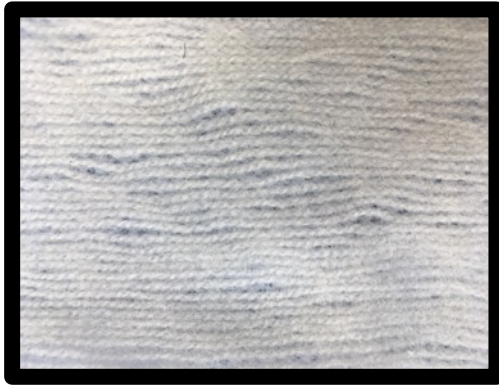


Figure 1.11: Normal view of Zephlinear.

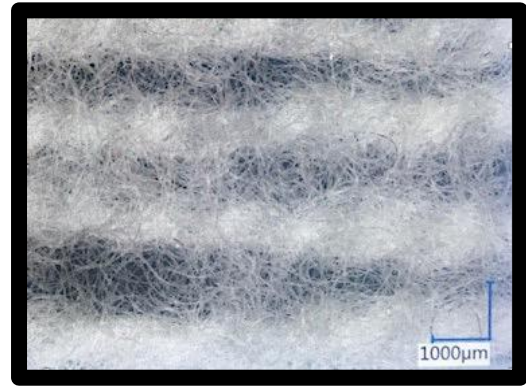


Figure 1.12: Microscopic view of Zephlinear.

A second layer of parallel yarns can be placed at a 90-degree angle. This fabric surface gives the perception of woven material. Under microscopic view the horizontal layer of yarns appears to hover above the base layer of yarn (the vertical layer of yarns).

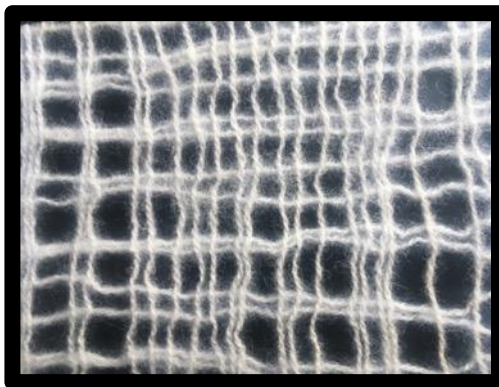


Figure 1.13: Normal view of Hover-Tex

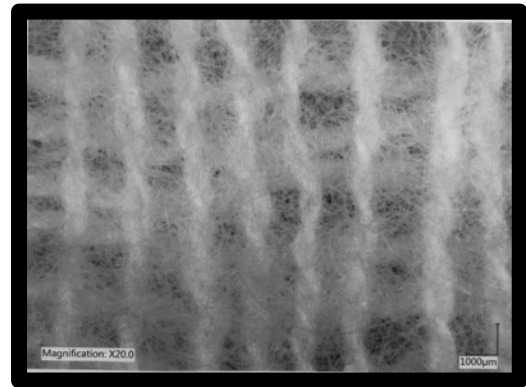


Figure 1.14: Microscopic view of Hover-Tex.

1.4 Contribution to knowledge

The technology and fabric investigated in this research provides a novel textile structure with a distinctive linear appearance, that has a “fibre entangled channel” either side of a yarn as in Figure 1.3. The “fibre entangled channel” could be utilised to embed components that has the potential to increase capacity for functionality and creative use. Alternatively, components can be embedded within the actual yarn structure. Applying a second layer of yarn advances the FOYSE structure by providing space for embedding items between the two layers as in Figure 1.15. These items could be electronics or nanocomposites. This would therefore offer an uncomplicated method to produce smart and intelligent fabrics. The manufacture of nonwoven fabrics involves less steps due to the manufacturing process not requiring conversion of fibres to yarn. In addition, the current nonwoven production process involves the random placement of individual fibres to be bonded or entangled to create a fibre web. In contrast, the FOYSE process provides the ability to precisely place fibres, due to them being attached to the yarn surface. Additionally, the advancement of entangling only the fibres protruding from the yarn surface enables engineering of a structure that can be systematically designed to meet specific performance requirements. One example being the fibres released from the yarn can be completed to an extent that affects the density of the final fabric surface. This function can increase or decrease the containment of heat released from the body. This is particularly imperative regarding fabrics with measurable ventilation and insulation properties. It is also my intention to explore the gap in knowledge regarding the limitation of existing textile production processes.

1.5 Textile Market Application

Textiles is a large, global, and complex industry with numerous fields of practice which contribute to a global and competitive industry from raw material to consumer product (Briggs-Goode and Townsend 2010). The size of the textile industry is in direct proportion to the demand which spans across manufacture, technological development, and application of the final product (Briggs-Goode and Townsend 2010). These factors contribute to the current generation of textiles, including technical textiles being passive (Dias and Arafa 2011). In value, the textile industry is currently worth nearly \$3,000 trillion and the global textile consumption is estimated at \$30 million per year (Business Vibes 2015). These Figures include textile, clothing, footwear, and luxury fashion, along with the production processes in design and manufacture. This data is relevant to this research as it gives scale to the level of diversity in these industries. In line with the cross-disciplinary nature of woven, knitted, and nonwoven manufacturing process, FOYSE can also be used to manufacture fabrics to meet a variety of end uses. The research demonstrates that FOYSE is capable of manufacturing fabrics that have comparable characteristics to woven, knit and nonwoven fabrics. This

indicates that fabric surfaces produced by FOYSE manufacturing have the potential to be used across the breadth of the industry.

Year	billion	% Growth
2016	785.9	3.3%
2017	822.2	4.6%
2018	861.4	4.8%
2019	902.5	4.8%
2020	948.2	5.1%
2021	992.0	4.6%
CAGR: 2016–21		4.8%

SOURCE: MARKETLINE MARKETLINE

Table 1.1: Global apparel & non-apparel manufacturing current market value and forecast:
\$ billion 2016- 21 (Lu 2018).

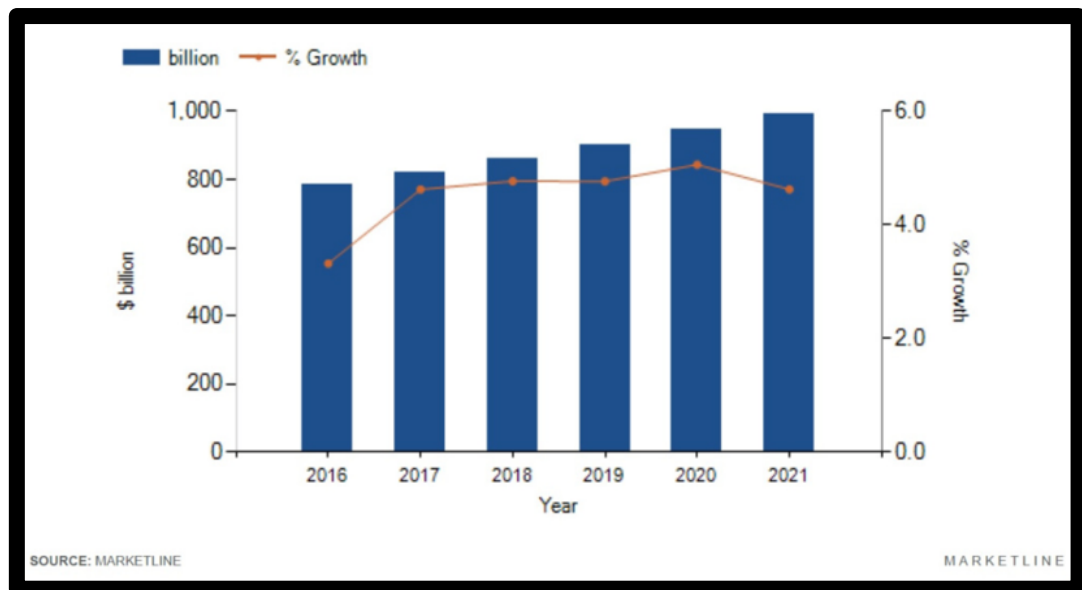


Figure 1.15: Global apparel & non-apparel manufacturing current market value and forecast:
\$ billion 2016- 21 (Lu 2018).

From table 1.1 and Figure 1.15, it is apparent that the global apparel & non-apparel manufacturing show considerable growth when considering their position within the textile market size and value. This sector is

forecast to reach \$992 billion in value by 2021, a major increase of 26.2% since 2016. The combined annual growth rate of the market during the period of 2016 and 2021 is forecast to be 4.8% (Lu 2018). These projections were set prior to the COVID-19 pandemic, which, in line with previous global plagues, will have an overall negative effect on the global economy. Hayakawa stated that labour-intensive industries such as textiles were likely to suffer from the negative impacts of COVID-19 in exporting countries (Hayakawa and Mukunoki 2021). Their reasoning was that these industries were likely to suffer from the negative effects of workplace-closure or work-from-home orders. COVID-19 was also named responsible for demand loss which resulted in excess supply. This led to lower prices in household appliances, vehicles, and textiles etc. (Hayakawa and Mukunoki 2021). Despite the challenges of COVID-19, it is proposed that FOYSE could have an effective impact within this sector of the textile market, providing an alternative method of textile fabric manufacture.

Fast fashion is responsible for much of the growth in this field, as fashion retailers aim to quickly capture current fashion trends expressed on the catwalk (Anwar 2017). An additional interpretation states that fast fashion is not only how fast designs move from runway to outlet and finally to purchaser; but also, from the purchaser to the rubbish heap, thus adopting the now commonly used name of 'throwaway fashion' (Harrabin 2019). Thus, impacting textile manufacturing and leading to concerns about the environmental impact of over production and waste. Sustainable fashion is a movement and process of fostering change to fashion products and the fashion system towards greater environmental integrity and social justice. Sustainable fashion concerns more than addressing fashion textiles or products used in society, it also comprises addressing the circular systems of fashion (Zsakay 2018). While this research project does not focus on sustainability, it is noteworthy that the FOYSE process uses natural yarns and could be considered eco-friendly. FOYSE also has the potential for manufacturing on a batch basis, allowing designers to create standalone fabrics that could be sold in sections as small as 4-inch strips, which subsequently could be used to embellish, update, or change a ready-made garment.

The textile industry is a growing sector and estimated to hold continual relevance within our social structure. Technical development and design capacity are two areas of focus for the study with the wider investigation of new product and process acceptability. Technical development is limited to what influences the strength and structure of FOYSE fabrics. Design capacity is limited to elements that influence fabric appearance and performance.

1.6 The Aims and Objective of the Research Project

There are six aims for this research containing elements within them:

- 1) Establish a stable method for producing fabric using FOYSE.
- 2) To explore the technical parameters – yarn types, scale, strength:
 - a) What influences the fabric appearance and strength?
 - b) Creation of a portfolio of samples to test versatility and practicality of FOYSE for design practice.
 - c) To investigate the design of apparatus to aid in the manufacturing process.
- 3) To test the tensile strength and the limits of the fabric produced.
- 4) To develop a collection of samples experimenting with yarn type to test versatility and creativity.
- 5) Develop textiles, hand-held tools and apparatus to aid in FOYSE manufacturing and test their suitability as a product in the fashion, textile, craft and education market.
- 6) Understand potential of FOYSE materials and consumer reactions to the fabrics.

Objectives:

- a) Obtain methods to control fabric appearance, strength and texture to support end use identification.
- b) Identify methods to aid production to present FOYSE fabrics as an economical option to the known three classes of fabric.

Record response from mixed methodology of usefulness of FOYSE.

The research is framed in the scientific method of investigation, using my experience of observing a phenomenon and asking questions. The empirical cycle was used to formulate the hypothesis which became the point of investigation to falsify or verify.

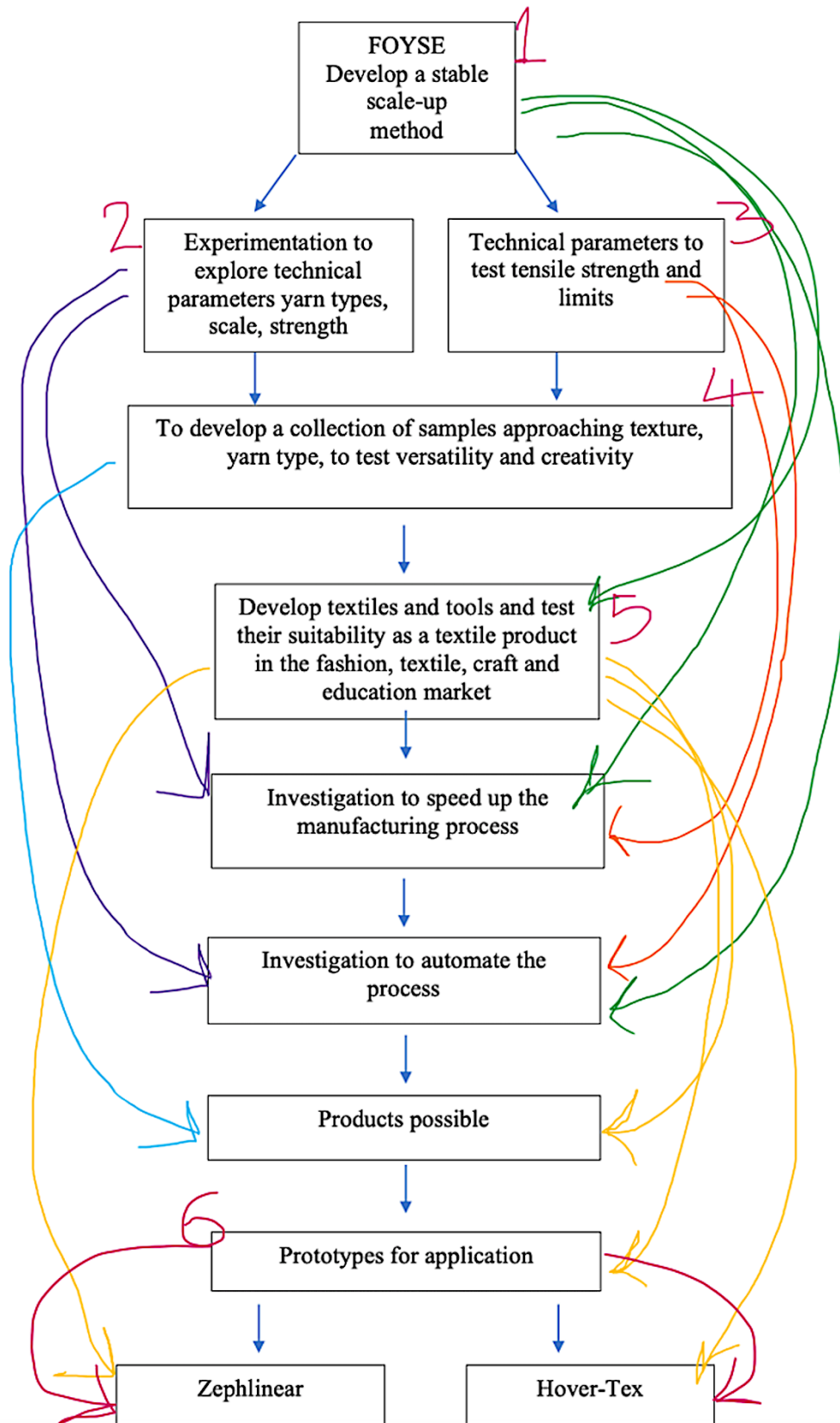


Figure 1.16: Chart of product and technology development in relation to research aims.

1.7 Structure of the Thesis

This thesis comprises of nine chapters in total and following on from Chapter 1, the content of each chapter is as follows:

Chapter 2: LITERATURE REVIEW: Overview of Major Advances

A literature review opens this chapter highlighting textile advancements from 25,000 BCE to the 21st Century. Four specific areas of literature are researched, textile development of the three known manufacturing techniques, tools utilised for textile manufacture, social and economic events affected by textile industry developments. The end of the chapter is focused on the FOYSE fabric construction process.

Chapter 3: METHODOLOGY

Addresses and identifies the program of enquiry in which the research was conducted: the scientific method, the approach taken to answer, 'the problem', namely deductive reasoning and the framing of the research. These methods intertwined between development of product and process to investigate the hypothesis; research design embedded within experimental design practice and finally discussion on the mixed method methodology adopted to approach the inquiry.

Chapter 4: A DETAILED STUDY OF THE FOYSE MANUFACTURING PROCESS

An overview of the FOYSE process from conception to the argument for its position as a fourth class of textile. This proceeded to an analysis of the causes and parameters that influence appearance and strength through a detailed description of the FOYSE process and known fabric manufacturing. This is followed by an overview of the preliminary research commencing by discussing the framework used in Chapter 3.

CHAPTER 5: A DETAILED STUDY OF MATERIAL PROPERTIES OF TEXTILES MANUFACTURED BY FOYSE

Continuing from the manual manufacture of FOYSE contained in chapter 2 and further detailed in chapter 4. Chapter 5 focuses on the investigation of the FOYSE product and process. The chapter outlines the areas which were experimental such as the testing of manual novel tools and the speeding up of the manufacturing process to enhance the automation of the FOYSE process. Finally, this chapter concludes with the analysis and reflection on the results.

CHAPTER 6: PROOF OF CONCEPT FOR SCALE OF MANUFACTURE

The purpose of this chapter is to identify if FOYSE can be scaled in size with increased speed and efficiency. This is a necessity if FOYSE manufacture is to be commercially viable. Apparatus to aid FOYSE manufacture detailed in chapter 4 is the premise on which the concept is developed. The aim is to transition FOYSE manufacturing from a craft discipline to a process capable of production by mechanical means.

CHAPTER 7: POTENTIAL APPLICATIONS

In this chapter, methods to transfer the new knowledge within the textile community and education establishments are presented. A detailed description of the Guild methodology for knowledge and skill transfer is described including the benefits of applying the model to FOYSE dissemination. Research results relating to what fabrics created by FOYSE can be used for is given in image form and a brief description.

CHAPTER 8: PROJECT OUTPUTS AND DISSEMINATION

In this section of the thesis, intellectual property as a result of this research is stated. The chapter also details academic and commercial libraries that have provided a platform for FOYSE fabrics to be viewed globally.

CHAPTER 9: CONCLUSION

Commencing with a summary of this thesis, this chapter firstly presents the technology and resulting products that went through the investigation process. Followed by results derived through the research process, namely the limitation of the three currently known textile manufacturing processes. The conclusion then goes on to highlight the findings that all known manufacturing processes were discovered; the research contribution to knowledge; and finally future work to be undertaken concludes this chapter.



Figure 1.17: FOYSE fabrics modelled on mannequin.

CHAPTER 2: LITERATURE REVIEW: Overview of Major Advances

2.1 Introduction

The proposed new fabric and the investigation of the FOYSE process would fit into a new classification of material types which might generally be known as an expansion of 'nonwoven' category of textiles. Therefore, I have considered this broad classification to compare and contrast with FOYSE. Textile advancements are presented covering four specific areas: Literature relating to economic and social developments, new textile fabrics and societal shifts. These four areas are important to the research as they demonstrate a fundamental position regarding how and at what speed textile manufacture and fabrics have developed. These four areas were also chosen as they provide a holistic approach to textile manufacturing.

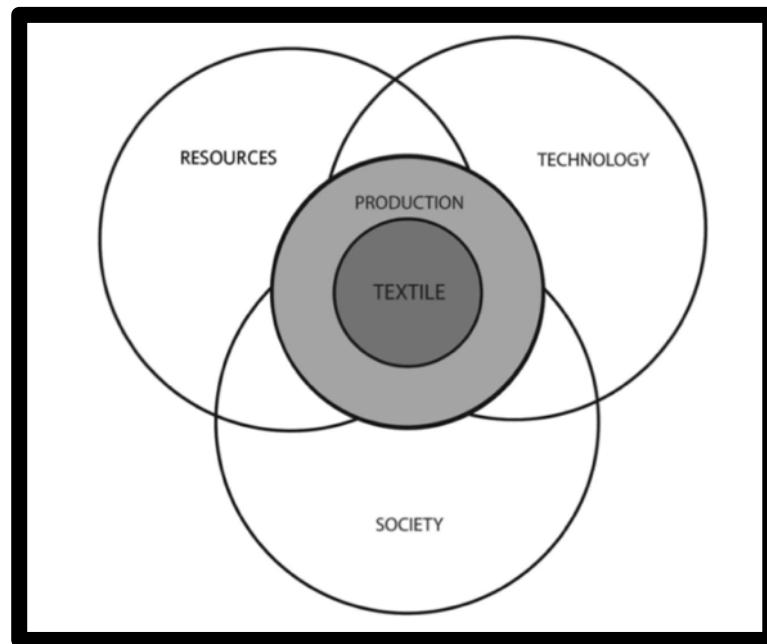


Figure 2.1: Graphic work Marianne Bloch Hensen. Source: Old Textiles – New Possibilities (Strand et al., 2010).

This holistic approach is supported by researcher Eva Strand who wrote 'Textiles express who we are – our gender, age, family affiliation, social status, occupation, religion, and ethnicity. Knowledge of textile history is hence a key to our understanding of a multitude of human issues' (Strand et al., 2010). A model of textile and the production of textile demonstrates the synergy between technology, resources, and society as presented in the Venn diagram Figure 2.1.

This holistic approach is also recognised more broadly and has impacted research completed in international contexts:

Handmade clothing and environmental textile products with their aesthetic and social meanings represent the oldest forms of human culture. The development of mass-produced textiles has posed, on the other hand, increasingly important economic and expert consumer issues in relation to the large-scale industrial production and commercial business of mass-produced textiles. In contrast, handmade, self-directed, creative activity with manually operated tools has gained more psychological significance and value in the life of the common, modern individual, as well as an educational factor for children ... that textile crafts can be divided into a science investigating designing and making-up processes, with which economic, technological, historical, and aesthetic factors can be taken into consideration (Kaukinen 2009).

Kaukinen continues to analyse this multifaceted scientific field lying between diverse sciences within this field and discusses four domains of clothing and environmental textiles which are (1) textile technology, especially handwork or work done by hand (2) the designing of textile products (3) the textile economy and (4) textile history (Kaukinen 2009).

Every material and raw material has its own techniques and technologies. Material must be understood more widely in craft science because it communicates with both cultural and technological information between the maker and consumer. This is illustrated in Figure 2.1 (Kaukinen 2009). Within my research, the socio-cultural design tasks were continually reflected upon in my role as the researcher within an institution.⁵ All textile materials have individual functions stemming from the techniques and technologies used in the product and process. Figure 2.2 clearly emphasises that craft science communicates between the maker and consumer culturally and technologically.

⁵ In essence, institutional spheres are the macro-level structural and cultural milieus in which lower-order phenomena (e.g., fields; organisations; encounters) are organised and connected (Abrutyn 2016).

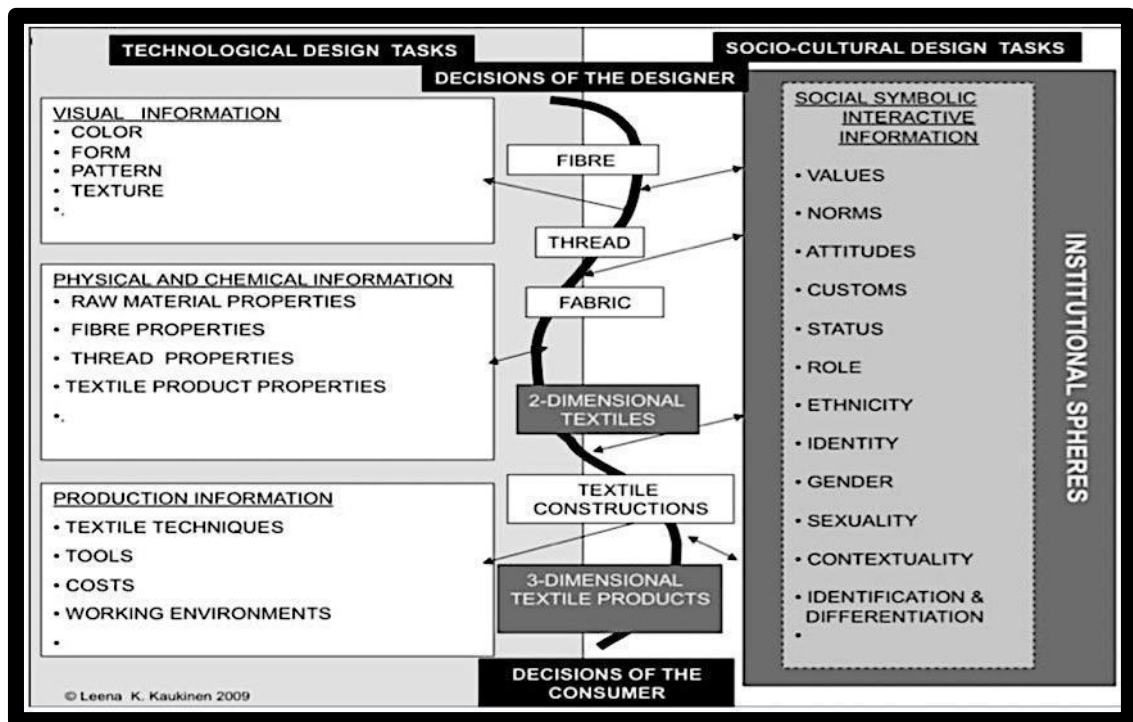


Figure: 2.2: Cultural and technological information between the maker and consumer (Kaukinen 2009).

The Figure represents textile fibres, their properties and expressivity in the technological and cultural dimensions as related to design tasks. All these issues must be addressed in the communication and decision-making process between the designer and the consumer (Kaukinen 2009). Therefore, this chapter will outline this holistic approach: manufacturing techniques which include understanding raw materials used for manufacturing textiles; advancements of textile fabrics incorporating tools utilised for manufacture; and social and economic events which involves building the relationship between maker and consumer. This literature review provides an overview of existing knowledge and outlines the gap in knowledge within textile manufacture and development with consideration to relevant social and economic events that have and continue to impact textiles. Further evidence of the continuation of textiles across all aspects of society is the growing demand of smart textiles. In summary of this introduction, textile manufacture, raw materials, social context, and economic context are entwined within the literature review.

2.1.1 History of Textile Manufacturing

The earliest evidence of textile manufacture is of string (an impression in clay) dated 25000 BCE. Current fabric manufacturing techniques using yarn are limited to two ancient practices known as knitting and weaving. The earliest woven fragments have been found and dated 7000 BCE. Recovered knitted cotton socks have been dated from between 11th and 13th centuries CE (Barber 1992). Nonwoven fabrics are created from fibre webs that have not been spun into yarn. Remains have been found of sophisticated nonwoven cloth (felt) dating 6500 BCE (Batra and Pourdeyhimi 2012). The first record of manufacturing using an apparatus are basic weaving looms that date back to 4400 BCE. The looms were found from excavations in Central Europe and were made during the Neolithic period. The apparatus was a simple vertical structure that had weights at the end of the warp. The looms were typically angled and placed against a firm structure such as a wall or beam as illustrated in Figure 2.3. The warp-weighted loom produces material that has both a warp and weft, fundamentals of woven material. However, the warp-weighted loom has a major difference from the typical loom of today. The actual warp is secured at 90 degrees to each other (Crowfoot 1936). This discovery of the earliest apparatus used to weave cloth coincides with the earliest record of cloth manufacture in a larger scale using an object other than personal handheld tools (Murray 1994). A typical loom of this type was used by the Greeks and was constructed with 'an upper beam only and the warp threads were bunched at the lower end and weighted with metal or clay balls to keep them taut' (Roth 1913). The image is an 'Illustration [discovered] on a skyphos (A Van Branteghem vase in the Ashmolean Museum, Oxford) from H. B. Walters' paper on Odysseus & Kirke on a Boeotian vase, Jour. Hellenic Studies, 1892-3' (Roth 1913).

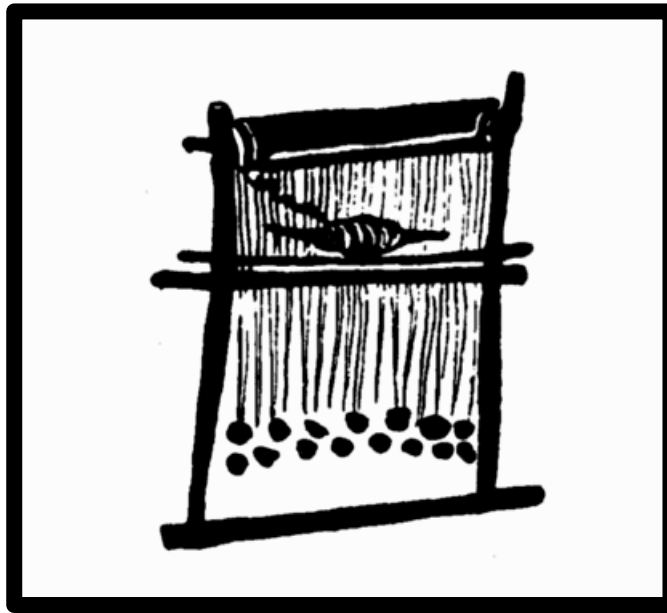


Figure 2.3: Greek loom with spool and warp weights (Roth 1913).

By 3000 BCE cotton was being grown, spun and woven into cloth in several countries across the globe. Cotton for fabric manufacture was being grown on a wide scale spectrum in the subcontinent known as Bharatavarsha (Gnawali 2014) today Pakistan and western India (Temin 1988). Natives of Egypt's Nile valley were manufacturing and wearing cotton apparel during this same period. By 2700 BCE, the Chinese Xia dynasty had discovered how to cultivate silkworms and develop looms, specifically to weave fine silk cloth (Dingleet al., 2005). Creating specialist apparatus to aid a new production process has proven to be a common practice in history.

During the same era, linen was found on an Egyptian mummy woven at 540 threads per inch. The fabric was well made and no different in appearance as Linen fabric made today (Schwarz and Kovačević 2017). As one of the oldest cultivated plants in human history and previously time consuming to manufacture, linen survived through the ages and is still a well utilised textile today (Bonneville1994).

The manufacturing of textiles advanced over time regarding speed and size of production, in addition, methods to decorate fabric surfaces also advanced. In 327 BCE, Alexander the Great commented on the beautiful decorative printed cotton being produced in India (Broudy 1993). By 300 BCE, we see an extensive global textile trade established by the domination of the Ancient Greeks and Romans (Gehani 1998). The ability to 'scale up' fabric production size and increase speed of production increased the applications that textiles could be used for such as huge cotton awning's (Kaukinen 2009). It is still a major factor as to whether a new method or process is deemed commercially viable, therefore scalability is a major factor of the research.

Whilst the technology for weaving continued to develop regarding quality and scale of product produced, the Middle Ages saw mankind's knowledge advance. Fragments of a new form of textiles dated 200 – 256 CE were excavated in present-day Syria (Fisher 1981). The new textile was made from yarn, although, unlike woven textiles it had been created using one continuous strand of yarn. The new fabric was unlike woven material not only in manufacture but also in appearance and functionality. The most significant difference between the two textiles was that the woven fabrics provided a material surface with limited stretch. However, the new textile had considerable stretch when compared to the rigidity of woven cloth. The early remains of the new material were celebrated for many years as the first knitted textiles in history (see Figure 2.4). However, this newly identified technology for making material was later found to be nålbinding a fabric surface created from a method of knotting (Sagona 2018). Nålbinding is thought to have derived from a different form of knitting found in 'Coptic socks' from Egypt, dating to around the year 1000 CE (Theaker 2006). The determining difference identified as knitting uses two needles making loops within loops, whereas nålbinding knots string together with one needle.⁶ Continual investigation, research and study into textiles allowed this knowledge to be revealed, which highlights the importance of textile research and development. Below is an image of fully formed socks made from the nålbinding method of garment construction dated 250 – 420 CE (Sagona 2018). The earliest known examples of knitting are knitted Egyptian socks found in Egypt and dates between 11th and 14th centuries CE (see Figure 2.5).

⁶ However, it is believed knitting derived from nålbinding centuries later which is the reason for the fact both knitting and nålbinding produce almost identical looking fabric surfaces.



Figure 2.4: Nalbanded socks (Collections.vam.ac.uk 2020)



Figure 2.5: Cotton socks found in Egypt. From L to R: Textile Museum, ca. 1100 – 1200 CE; Victoria and Albert Museum, ca. 1100 – 1300 CE; Textile Museum, ca. 1300 CE (Julz 2015).

Both woven and knitted fabrics have their own strengths and limitations, and these qualities lend themselves to specific applications. For example, woven for items requiring limited stretch such as formal jackets, and knitted for stretchy items such as pullovers. Also, individual end-uses of the two manufacturing methods are a reflection on a common understanding that ‘consumers clearly want different properties in fabrics depending on the end-use of the textile (Hollen and Saddler 1968).

Nonwoven products had progressed by 600 CE to an extent that remarkable felted items were being manufactured (see Figure 2.6). Highly sophisticated felt has been found in Siberia providing evidence that the felting process was now refined, and individuals were able to produce exceptional pieces of textiles. Intricate designs were now being created using fibres dyed with vibrant colours. During this period, the colour purple for example, was extracted from a mollusk, and was very difficult to obtain. Around 8500 mollusks were said to produce one gram of dye (Buitron 2018), and due to the complexity of the creation of the dye, its price was higher than gold (Ciccolai et al., 2020). The layering of the fibres at varying thickness was also being used to enhance the design of the final fabric (Sagona 2018). Therefore, development of felt products appears to be limited to visual appearance, durability, and 3D products. Presented in Figure 2.6 is a felted "saddle" cover (a ceremonial or burial horse cloth) found in the frozen Pazyryk tombs (Scythian) in Siberia that could be as old as 2500 years. Shoes and hats were also commonly made from the felting process.



Figure 2.6: A felted saddle cover (Hermitage Museum 2020).

Wool had become an established trade and in 768 CE the founder of the Carolingian Empire Charlemagne, also known as Charles the Great, established a silk weaving industry and imported wool from England. Charlemagne was best known for uniting Western Europe for the first time since the fall of the Roman Empire (Batra and Pourdeyhimi 2012). This is relevant as it highlights how territory ownership impacts economic development due to directly and indirectly allowing freedom of trade which affects growth and development. By 900 CE England had also established a textile trade predominately trading wool. Alfred The Great contributed to the growth of the textile industry by encouraging the expansion of the wool industry in England (François 2001).

Knitting technology had now been well developed and sophisticated cotton socks were found in Egypt that dated 1000 – 1200 BCE. These items are some of the earliest knitted pieces found to date. The socks had been created from undyed natural yarn with indigo dyed yarn. These contrasting colours are used to highlight the patterning of the socks (Lloyd 2011). The textile trade was so buoyant in England and the first annual cloth fair was held in 1153 (Schwarz and Kovačević 2017). Paintings and carvings dated 1200 BCE provide evidence that the spinning wheel was in common use, which increased the yarn available to aid in production (Choy and Davina 2014). A drawing of a young woman spinning by Lucas Van Leyden, 1513 in Figure 2.6 pictures a well-advanced spinning wheel.



Figure 2.7: Women spinning (Spinning – History & Gallery 2020).

The scale of woven material being produced had increased so much that by 1305 CE Venice had 17000 people engaged in weaving wool. This allows us to understand the scale in which the weaving industry has developed. By 1400 CE Knitting was also a common practice and famous artists were also capturing individuals weaving and knitting. An example of this is an image of Madonna Knitting by Master Bertram of Minden 1345-1415 CE (Schwarz and Kovačević 2017). The Middle Ages saw the development of the textile trade and the early establishment of communities formed exclusively for textile manufacturing.

In the period 1500 CE, the textile industry progressed dramatically due to the invention of the first knitting machine. This machine quickly became known traditionally as producing framework knitting. The machine invented by Reverend William Lee in 1589 CE was the first major stage in the mechanisation of the textile industry (Spencer 2010). His invention not only affected textile manufacturing but also sparked the industrial revolution which impacted many industries through engineering breakthroughs. This development forced new laws to be designed and implemented to accommodate the social and economic changes. Advances were also being made in other areas of the textile industry. For example, in 1600 CE textile workers in the Netherlands improved methods of dyeing and finishing cloth (Bender 2016). The Dutch East India company imported fine calico from India which incorporated meticulous designs (Munro 2011). With new textile fabrics came new technologies and machinery demonstrating the continual ability of mankind to innovate to accommodate textile advancements. One example is the advancement of the Calico printing machine dated 1835 CE.

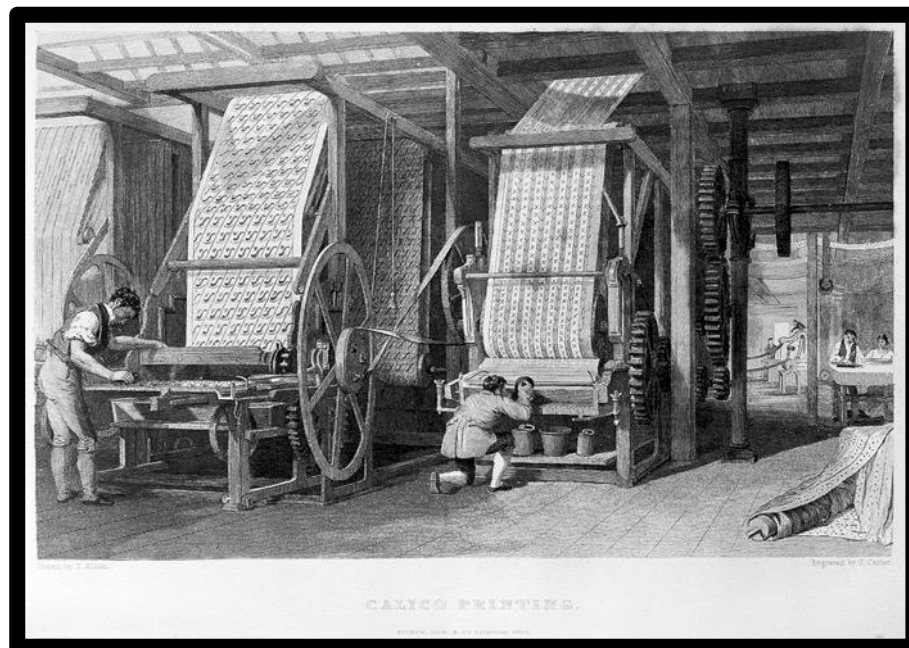


Figure 2.8: Calico printing machine (Commons.wikimedia 2014).

Social Context

Fuelled by consumer demand textiles began to have social impact and importance. Globally, textiles for apparel and interiors were being traded: intricately designed high-quality rugs, curtains, and yardage of plain finely woven fabrics for clothing were being transported around the world. Textiles were such an important trade that extreme measures were put in place to ensure the protection and preservation of this lucrative industry. Craft workers became so valuable in Europe that those who operated in that industry were restricted from free movement and individuals even lost their lives if the government felt their actions would threaten the trade. English textile craftsmen were forbidden by law to emigrate to America due to their skill being in great demand (François 2001). A model used for skill share and protection of a trade and technique are craft guilds which date back to mediaeval times. Prior to the industrial revolution craft guilds were a platform to regulate the production, price, quality, and distribution of textiles (Cummings and McMasters 2005). In chapter 6 the Guild model is discussed in detail as the preferred platform for delivering FOYSE technology and related products.

From birth to death, human lives are surrounded by fabric. We dry ourselves with towels, sleep on pillows and mattresses, lay between sheets, wear clothes, sit on fabric covered cushions and couches, walk on carpets, and cover our windows with curtains. (Petty 2014).

Overall, textiles have restricted lives (François 2001) caused deaths (Cartwright 2016) and commanded after life decisions (Hills 1989). In general, these findings have significant implications for the understanding of how textiles are reflected in a social context.

Economic Context

The 'Wool Act of 1699' is an example of the extent the government was willing to go to keep a tight grip on the textile industry. The Wool Act was proven to be a seed that fuelled rebellion and the US War of Independence from English rule 1775-1783 (Stein and Stein 2000). The conflict was not limited on an international scale but countries within Europe were also targeted. Irish weavers produced cloth less expensive than the English weavers and attempts were made to suppress them. Not only was [Irish] cloth less expensive but it was also stated their linen was superior to all others (Geary 1995). These are two examples of how textiles have proven to be an industry of economic importance.

In 1733 CE John Kay, an Englishman, invented the Flying Shuttle Loom. This loom was an improvement of existing machinery, allowing a single weaver to weave considerably wider fabrics. Another major advantage of the Flying Shuttle Loom was that it could be mechanised, allowing the loom to be automatic (Crouse

1932). James Hargreaves, in 1764 CE, invented the Spinning Jenny, which was the first machine to spin more than one piece of yarn at a time (Hills 1979). Any advancements to improve speed and lessen production costs were in great demand. Richard Arkwright, in 1769 CE, patented the Water Frame which was a spinning machine that ran on waterpower. Samuel Crompton, in 1779 CE, invented the Spinning Mule (Fernandez 1998). This was a machine that sophisticatedly combined the Spinning Jenny and the Water Frame. Edmond Cartwright invented the first Wool-Combing machine and in 1785 CE patented the first Power Loom (O'brien 1997). Over in the United States of America, advancements were also taking place at a rapid pace due to Englishmen taking advantage of modifying the 'British' technology for use in the USA. Samuel Slater was an industrialist of early English America and was known as the "Father of the American Industrial Revolution" and the "Father of the American Factory System". However, in England he was not viewed favourably and was labelled "Slater the Traitor" because he carried the British textile technology to America (Stein and Stein 2000). Eli Whitney invented the Cotton Gin in 1794 CE. The US-born inventor created the machine that greatly sped up the process of removing small seeds from cotton fibre. This machine increased the production of cotton so much, that it revolutionised the production of cotton in 1793 CE (Harris 2013). An early example of pre-computer technology also derived from the textile industry, for example, the Jacquard Loom. This was designed and had the ability to use punch cards that enabled a single weaver to produce complex patterned fabric (Kurzweil 1992). Contrary to early contentions between England and America in 1816 large numbers of power looms were being installed into factories in America (Siemens 1958). In the 1800s, the textile trade was booming to the extent that even Ireland, a relatively small country, was exporting 25 million yards of woven linen (Geary 1995).

Automation of the nonwoven process came through a dry method of felting called needle punching. This provided the first fibre entangling process to be conducted on a commercial level. This occurred between 1870 – 1878 CE when William Bywater from Leeds, England built the first commercial needle loom. The basic components of a needle punch machine (needle loom) consist of a web feeding mechanism, a needle beam with a needle board and needles, a stripper plate, a bed plate, and a fabric take-up mechanism (Batra and Pourdeyhimi 2012). Fibre bonding continued to develop and by 1900 CE, two methods enabling automation of felt making were established: needle punching and spun lacing or jet lacing (hydro entanglement). The spun lacing or jet lacing method of felt manufacture bonds together fibres by using extremely small, high pressured water jets to produce a nonwoven fabric surface (Acar and Harper 2000). With the progression of textile manufacturing methods came a demand for improved fibre and yarns.

Raw material – Yarn Development

In 1884 CE, Hilaire Chardonnet patented the first manufactured fibre (Lēwîn 1984). Chardonnet's fibre was first produced commercially in the United States in 1910 CE under the name Artificial Silk but in today's terms Rayon (Mack 1929). Rayon was quickly accepted as a more cost-effective alternative for natural silk. The first synthetic fibre introduced to the textile industry was nylon developed by Wallace Carothers in 1935 CE at Dupont (VISTA 1998). Nylon's functionality and texture made it an ideal material to suit any number of uses. However, DuPont decided that it would focus on the ladies' fully fashioned hosiery. Research by Dupont revealed that American women purchased an average of eight pairs of stockings per year which earned Japanese silk producers over \$70 million annually (Science History Institute 2016). Once again, this new material became an alternative for silk. Further introduction of synthetic fibres came in the 1940s – 1950s CE, the main entries were Acrylic and Polyester. Carothers discovered the early formula to create Polyester but allowed it to take a back seat when he discovered Nylon. British scientists Whinfield and Dickson were the ones to advance the research and in 1941 CE patented Polyethylene terephthalate (PET or PETE) which forms the basis for polyester (Science History Institute 2017). First manufactured by Imperial Chemical Industries or (ICI) polyester became a fast alternative to cotton which became difficult to obtain after World War Two (Wolfe 2008). The first acrylic fibre to be made on a commercial scale was Orion. It was introduced into the market by Du Pont in 1950 CE. It was the second major synthetic fibre commercialised by Du Pont following nylon (Masson 1995). Initially, acrylic was hard to dye and therefore did not enter the clothing industry. However, in the fifth year after continual development, more than 70 million ladies' sweaters alone were made from the fibre (Masson 1995).

Whereas garments created from natural fibres such as wool, silk, cotton and linen were easy to identify as man-made, synthetic fibres were not. This was due to the conscious attempt to make the visual appearance of these fabrics imitate material manufactured with natural fibres. In 1960 CE, US Congress passed a Textile Fibre Production Identification Act (TFPIA). This was to resolve the problem of consumers not always being told what raw materials were used to manufacture their clothes and other textile products (Snow 2011). This would cause long-term issues due to pricing related to quality of the yarn used to manufacture the garments and launder care issues. Once again, with the introduction of new yarns, which were stronger and more resilient, came the development of more powerful and technical machinery to create fabric surfaces.

Computerisation High Speed Production Methods

Knitting machines in 1970 for the first time became controlled by computers. These machines were able to produce fabrics with high complex patterns at tremendous speeds (Spencer 2010). SHIMA SEIKI, the renowned manufacturer of powered knitting machines, manufactures machinery with a maximum speed of up to 1.1m/sec. However, the speed of these machines will vary depending on gauge, condition and the settings as the machine accommodates 10 programmable speed levels (Shima Seiki website). DuPont was the first company to open a high-energy spun-laced plant. In 1974, the plant utilised proprietary high-speed hydraulic needling (hydroentangling) technology to form the web (Yan 2016). A major aim of the hydroentanglement process was to manufacture fabrics with functionality and aesthetics comparable to woven or knitted fabrics (Berkalp et al., 2003). However, due to the unfavourable appearance of nonwoven they have not been adopted in the wearable clothing sector. Today, nonwoven machinery has progressed to the extent that it can produce fabrics at speeds up to 150m/min (Dong Yang AoLong Nonwoven Equipment Co. Ltd 2014). Textile weaving mills in the late 1980s used high-speed looms that had many tiny shuttles called darts, instead of a single shuttle developed by Sulzer (Keighley and Mark 2007). Technology had so increased that some looms wove with no shuttles at all. A jet of water and air would carry the filling through the warp up to 1000 times per minute. This was four times faster than a shuttle on a standard high-speed loom (Gries and Lutz 2018).

Fabric Production Methods for all three known fabric construction processes has dramatically advanced regarding speed of production. Materials used to create yarn and fibre for use within advanced technologies have also progressed. Textile manufacturing processes can produce limitless fabric surfaces for function and aesthetic properties. The speed in which the industry can obtain information, such as results from research, also contributes to the capacity in which knowledge and skills can be adopted to further textile developments. The current manufacturing methods have derived from the basic formations identified by century old literature and remains.

There is currently a gap in knowledge regarding fabric construction for textiles manufactured outside of the three known methods of material manufacture. This claim is supported by the following extracts from recent academic literature relating to textiles. In research relating to electronic yarns (E-yarns) and its full incorporation into textiles, only weaving and knitting processes are mentioned. Textiles consist of fibres, which are either woven or knitted to produce fabric for both protective and aesthetic purposes' (Nashed et al., 2019). Within medical textiles, again, reference regarding textile processes is limited to two methods. 'By combining one of humankind's oldest technologies, textile processing, with electroactive polymers, we

demonstrate here the feasibility of wearable, soft artificial muscles made by weaving and knitting, with tunable force and strain' (Maziz et al., 2017).

Nonwovens have several different manufacturing methods: Fibres are arranged into layers either randomly or uniformly and then felted or bonded together. Felted fibres are either entangled by heat and moisture or bonding by adhesive. More details are given within the fabric manufacture known process section. There are two established associations that have created a clear definition and benchmark for nonwoven material:

INDA: Founded in 1968, INDA is the leading global nonwovens association. INDA member companies represent the entire nonwovens value-chain.

EDANA: Formed in 1971 originally as the European Disposables and Nonwovens Association. For more than three decades EDANA has grown and evolved, to become a modern industry association with a European focus, global influence and profile today reflecting the changing dynamics of the nonwovens industry.

Definition ISO 9092:1988 & EDANA:

A nonwoven is a sheet of fibres, continuous filaments, or chopped yarns of any nature or origin, that have been formed into a web by any means, and bonded together by any means, with the exception of weaving or knitting. Felts obtained by wet milling are not nonwovens. Wetlaid webs are nonwovens provided they contain a minimum of 50% of man-made fibres or other fibres of non-vegetable origin with a length to diameter ratio equal or superior to 300, or a minimum of 30% of man-made fibres with a length to diameter ratio equal or superior to 600, and a maximum apparent density of 0.40 g/cm³. Composite structures are considered nonwovens provided their mass is constituted of at least 50% of nonwoven as per the above definitions, or if the nonwoven component plays a prevalent role (Chen 2010).

Regardless of the numerous definitions of nonwoven the material is clearly defined as being created from fibre and not a continuous yarn strand. Developments within the nonwoven industry again have been in relation to aesthetics and enhancing functionality. An example of this is a recently published paper, 'Development and Characterisation of Nonwoven Fabrics for Apparel Applications' by Institute of Materials Research and Innovation (IMRI), University of Bolton. The sections below are part of the abstract but divided into two sections. The research, although new, clearly supports the findings in this literature review that focus within textile advancements are limited to combining the existing methods (Cheemaet et al., 2018).

2.1.2 State-of-the-art of Fabric Manufacture

Textile classifications are dependent upon the technique used for its manufacture (Hearle 2005). The process to adopt differing finishers visually and functionally of textiles is still founded on the ancient three known production methods. Due to this, the three classification manufacturing methods have further subclasses. Six of these subclasses are listed in table 2.1.

Classification (structure)	Woven	Knit	Nonwoven
Sub-class (process)	Plain weave	Warp knit	Fibre entanglement
Sub-class (process)	Twill weave	Weft knit	Fibre bonding

Table 2.1: Detailing known fabric manufacture processes (Welford 1947).

The following Figures: Plain Weave with side view; Twill Weave with side view; Knit (plain) technical front; Knit (plain) technical back; Warp Knit; Fibre bonding; Fibre entanglement; are sourced from the authors undergraduate technical folder.

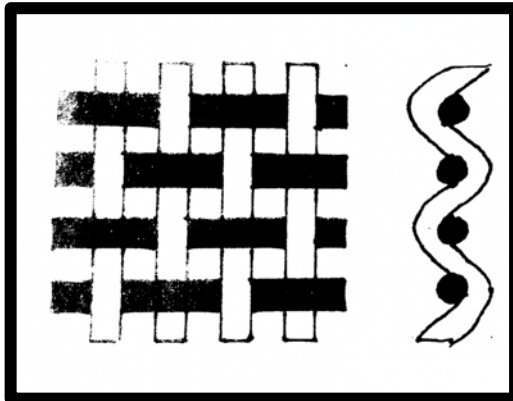


Figure 2.9: Plain Weave with side view

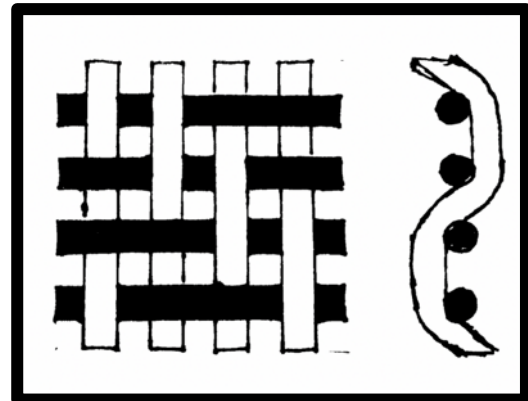


Figure 2.10: Twill Weave with side view

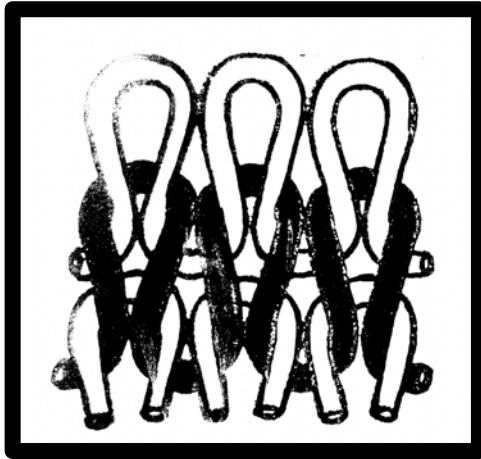


Figure 2.11: Knit (Plain, technical front)

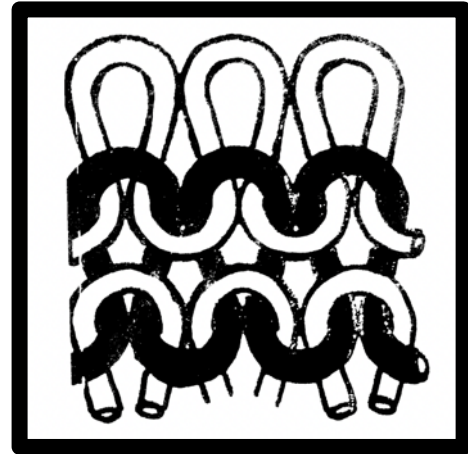


Figure 2.12: Knit (Plain, technical back)

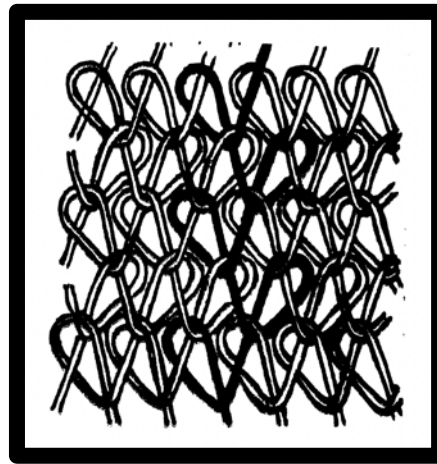


Figure 2.13: Warp Knit

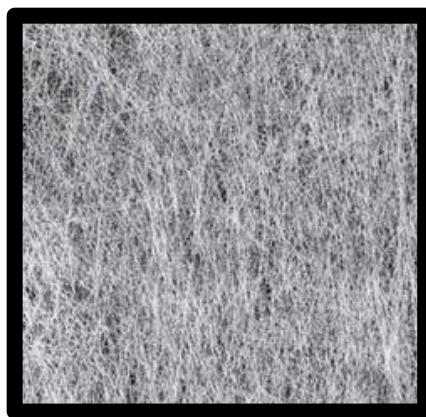


Figure 2.14. Image of nonwoven (Fibre bonding) source: Pinterest 2016

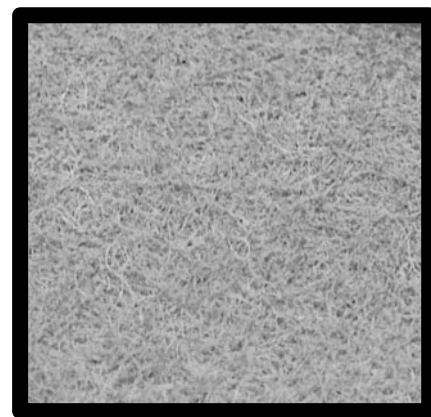


Figure 2.15. Image of nonwoven (Fibre entanglement) source: Pinterest 2019

The three processes are continually adapted to supply the naturally occurring demands of the textile industry. Fabric manufacturing processes are limited, although numerable manipulations have emerged to accommodate the need for material variation. The ever-increasing demand arises due to textile applications in almost all our activities (Taylor 1981). When a new textile is advanced to offer a new function or visual appearance there also comes the demand to speed up or simplify the new development. Speeding up the interloping, interlacing and bonding process of textile manufacture was acquired by mechanisation.

Textile versatility in use is equally matched with its diversion capability across disciplinary fields. Textiles are one of the few commodities that span across a vast collection of industries and interests including social and economic. Governmental decisions have been made as a direct result of textile products or processes as detailed earlier. Fashion and interiors are a major output for textiles due to the scope of aesthetics within the material, style, body, cover, surface, texture, drape, and resilience. However, even in Science and Technology, textiles hold importance within: 2D, 3D printing, Acoustic, Aerospace, Architecture, Automotive, Bio-couture, Biomedical Science, Biomimetic, Built Environment, Composite Surfaces, Engineering, Fashion, Health, and Wellbeing, Industrial, Interiors, Medical, Microencapsulation, Micro-technology, Product, Prosthetics, Robotic Weaving, Sensory Reactive, Smart Materials, Surface, and the Transport Industry (Loh et al., 2021). These areas required a level of manipulation to the known processes to meet market demand. The list below gives examples of the application outcome of a selection of the mentioned fields:

Agricultural (nonwoven for wind protection).

Building and construction concrete (awning, reinforcements).

Clothing (apparel).

Household (upholstery fabrics).

Industrial applications textiles (filters).

Sports and leisure (carbon- fibre composites for racquet frames).

Eco-friendly textiles (recyclable composites).

Mobility/transport (ropes, seat covers).

Geotextiles (nonwovens for drainage, reinforcement).

Packaging (nets, wrappings).

Protection (bullet-proof jackets, uniforms).

Medical (bandages, sutures).

3D Printing (Additive Manufacturing (AM) Polymer-textile composites).

However, it could be argued that varying design and enhancing the usage and efficiency of current textile production methods have limited the advancement of a novel manufacturing process. The First World War led to an exploration of the academic science of Fibres and Textiles – but the empirical design tradition remained as it was (Hearle 2005). Manufacturing developments to meet demands for smart textiles and intelligent textiles are based on known production processes. Research focus is situated within embedding or attaching new technological advancements within or to ancient textile structures. This has proven costly both in time and finance with little impact in the commercial world of wearables. For example, an E-textile Jacket worn by music artist Will.I.Am was used in a world tour of the Black Eyed Peas. The garment is said to be the most advanced jacket ever to come from Savile row⁷: a hand tailored jacket made by Hardy Amies Master tailor, Jan Cicmanec, and completely covered in, an in-house developed LED video system. The jacket can display animations at video speed from a built-in SD card (Flinders 2014). The intricate manufacturing process and the electrical components contributes to this garment not being viable for commercial use. After-care requirements such as laundering, and maintenance of parts would also be an issue.

⁷ Savile Row is a street in Mayfair, Central London. Known principally for its traditional bespoke tailoring for men.



Figure 2.16: LED jacket (Flinders 2014).

Research and development within academia and industry have sought to address the issue regarding methods of electronics integration for E-textiles. The overarching properties of concern are comfort, methods of integration and after-care around durability and laundering. Historically, electronics were first simply worn as a separate device. This was followed by electronics attached onto textiles or simply placed in pockets. Second generation of E-textiles were structurally integrated, and the third generation of textiles are functional yarns and printed electronics.

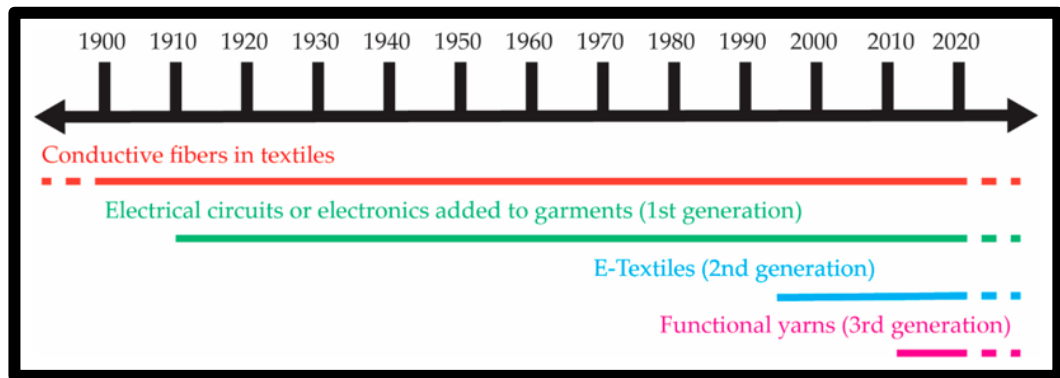


Figure 2.17: A timeline of the different generations of electronic textiles (Hughes-Riley et al., 2018).

A general overview of E-textiles will now be presented to give clarity of the term within the scope of this thesis. The basic materials needed to construct E-textiles, conductive threads and fabrics have been around for over 1000 years. Artisans have been wrapping fine metal foils, most often gold and silver, around fabric threads for centuries (Azeem and Abdul 2019). Electronic textile system architecture for E-textiles commonly has four main components:

1. Active device or sensor (electrical functionality).
2. Interconnections (wires or filaments that hook things together).
3. Processing hardware (data transmission/outputs/data storage).
4. Power (energy source).

The integration of each component is dependent on the required application. Sensors are normally required to collect and/or respond to data received from the body. This results in the need to be close to the skin with full integration for comfortability. Also, interconnections connected to the electrical reader should ideally be thoroughly integrated for the same reason (Stoppa and Chiolerio 2014). Hardware is commonly in a rigid container along with a power source. However, alternative power sources such as solar and friction are currently in development. The differing properties of electronics and textiles such as durability (bend, stretch, twist and shear) and resistant factors (resistance to abrasion, resistance to wash, chemical and sweat resistance) is a concern for e-textile development (Hardy et al., 2020). Methods to limit curves and strain within E-textile manufacturing is one concern investigated to accommodate mechanical deformation as this can cause E-yarn to fracture and/or malfunction.

2.2 Introduction to Fabric Manufacture of Known Processes

Fabric manufacturing is either preceded by yarn manufacturing, as in weaving and knitting or fibre preparation as in nonwoven. Depending on required end use, fabrics are designed to acquire multidimensional qualities regarding drape, handle, crease recovery, tear, strength, shear, air permeability, thermal resistance, and moisture vapour permeability. Textile fabrics consist of natural fibres which can be plant-based such as cotton and linen, animal-based such as wool or silk and synthetic-based such as polyester and manmade rayon. Each fibre type requires preparation prior to production according to the differing properties contained and determined end use. For example, fibre used for textile clothing 'must be flexible and capable of being creased and folded to conform to the figure and be comfortable to wear' (Taylor 1981) therefore to have creasing and crease-recovery capability is imperative for garments.

2.2.1 Yarn

A Yarn used to create a fabric surface is generally defined as fibres or filaments assembled to create a continuous strand. The strand must have strength to sustain the weaving or knitting process (Emery 1966). Fibres required for textiles require certain minimum properties. The balance of properties varies according to the required end-use. The following 10 properties are desirable characteristics of fibres or filaments:

- 1) Tensile strength – in this context, refers to the fibre along its axis and its ability to withstand stress. The force is measured by Newton's (N) and the fineness is measured by tex and stated in grams per kilometre.
- 2) Length – fibres must have a higher ratio of length to diameter which is usually comparable to longer length and higher quality. Stronger, smoother and finer yarns are typically spun from long fibres. Fibre lengths are measured in centimetres (cm).
- 3) Fineness – this describes the small diameter of the fibres as well as the flexibility and softness or its strength and rigidity.
- 4) Extensibility – this is a description of the fibres ability to stretch, extend and be able to recover. This is measured in terms of increase in length. Fibre stretch is measured as a fraction of the initial length percentage.
- 5) Durability – this relates to the fibres ability to withstand abrasion and flexibility resilience in addition to strength and elasticity.
- 6) Absorbency – this term is used to describe the fibres' ability to absorb water, which is measured in terms of dry fibres ability to absorb or regain atmosphere moisture.

- 7) Dyeability – this relates to the fibres capacity to retain dyes.
- 8) Resistance – this describes the fibres resilience against fabric care treatments such as laundering, dry-cleaning, bleaches, and stain removal chemicals. This also includes other elements and substances such as, heat, light, mildew, bacteria, fungi, acids, and alkalis.
- 9) Availability – fibres should be readily obtainable to meet demand at a reasonable price.
- 10) Friction – this characteristic describes the fibres' ability to cling together after the spinning process to enable them to have adequate surface friction.

The process used to convert staple fibres into yarn is called spinning, which is illustrated in Figure 2.16.

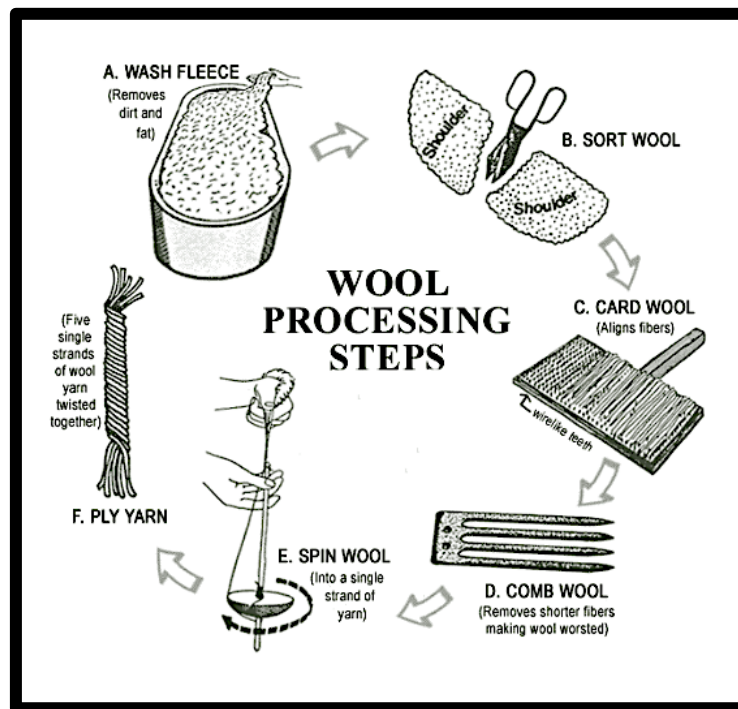


Figure 2.18: Wool Processing Steps Source: (Nejad Rugs 2007).

Yarn counts

To measure the fineness of yarns is difficult due to their compressibility; their thickness is so small in comparison to yarn length. This is also the situation with fibres used in yarn manufacture. All fibres have the same characteristic – they are very short in length, but their thickness is negligible in comparison (Dias 2015). Therefore, the fineness is expressed in terms of ‘count number’ which is an indication of weight per unit of length.

Yarns may be single, folded and cabled:

Single – Formed by twisting together staple fibres or continuous filaments.

Folded – Formed by twisting together two or more staple or continuous filament yarns.

Cabled – Formed by twisting together two or more folded yarns.

Twist is measured in turns per inch or turns per centimetre and the direction of twist may be clockwise or anti-clockwise. The direction of twist is described as either S-twist or Z -twist according to the way in which the fibres or filaments are wound around the yarn axis. If the fibres or filaments are wound from upper left to lower right (\) the yarn is S- twist and if they are wound from upper right to lower left (/) the yarn is Z – twist. As in Figure 2.19 “Unspun” fibres are yarns made of filaments and are identified as “no twist”.

Staple fibre yarns have varying amounts of twist according to the length of the fibres, the count of the yarn and the intended use. Increasing the amount of twist, up to a point, increases the strength of staple fibre yarns. Too much twist causes a shearing action and weakens the yarn.

Combed yarns with long fibres do not require as much twist as carded yarns with short fibres. Fine yarns require more twist than coarse yarns. Knitting yarns have less twist than weaving yarns.

Continuous filament yarns are stronger, in terms of tensile strength with no twist, but it is necessary to insert twist to control the separation and potential snagging of the filaments.

Counts of folded yarns

The convention for expressing the count of a folded yarn depends upon the counting system used.

For indirect systems such as woollen, worsted and cotton, two-fold twenty-fours, written $2/24$'s, means two ends each of 24's count twisted together. Ignoring contraction of the yarn, this results in a count of 12's.

For direct systems such as tex and denier, the count is expressed as $100/2$. This means that the resultant (or total) count is 100 tex and that two yarns are twisted together. Once again, if we ignore contraction caused by twist, the yarn is formed from two 50 tex yarns.

When yarns are twisted together some contraction occurs. In practice, this contraction should be considered. However, unless you are spinning your own yarn, the count, twist, etc. are determined by the yarn supplier.

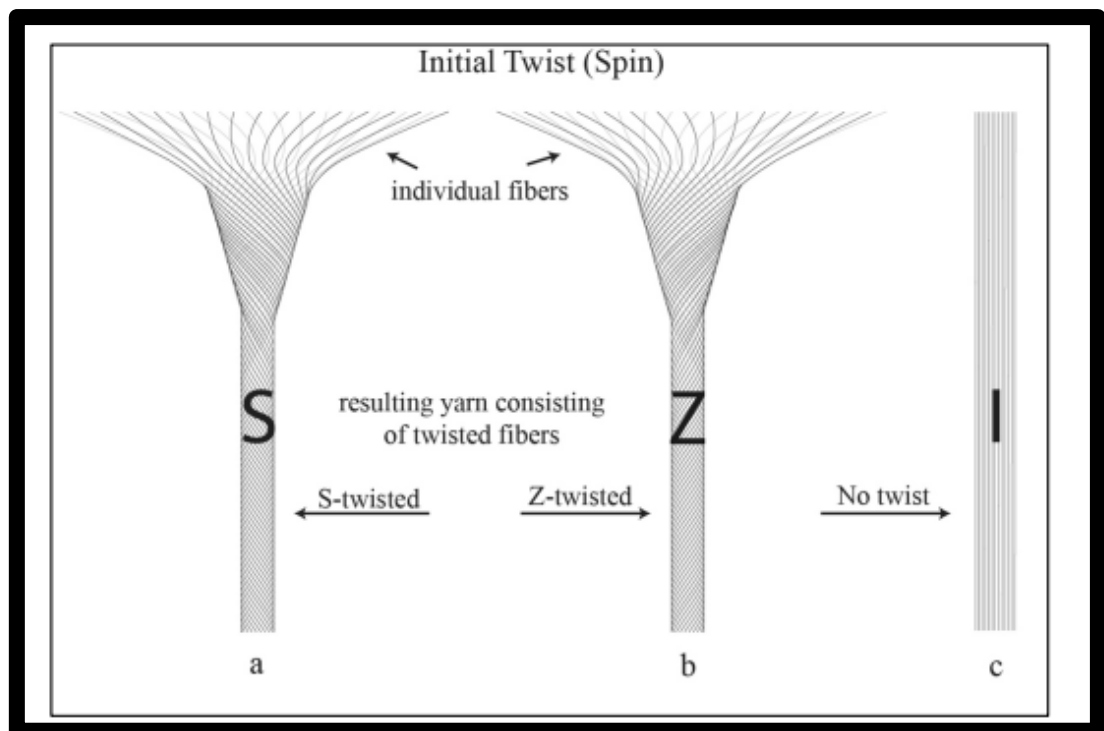


Figure 2.19: Diagram of Spin (Splitstose 2012).

Fancy Yarns

A fancy yarn is one into which deliberately produced variations are introduced. There are many methods of making such yarns, frequently by using ingenious mechanisms designed for that particular purpose. Due to the many methods used it is not possible to describe every mechanism or every yarn of this type. However, the main methods of producing them may be classified as follows:

Spinning Condenser - spun

Drawn - spun

Folding

Using conventional machinery

Using specialised machinery

Weaving

A Chenille yarn is produced by weaving a fancy (on what is known as a weft loom), which is then cut into narrow warp-way strips. The yarn produced has projecting tufts formed by the original weft yarn. The Chenille yarn is used as weft in the production of Chenille fabrics.

Dyeing

Fancy coloured yarns may be produced by techniques such as space dyeing.

The FOYSE process can utilise fancy yarns for embellishment. Samples of FOYSE fabrics have been created with six types of fancy yarns regularly used within the textile industry and are pictured in Figure 2.18. From right to left chenille, boucle, spiral, nub, slub and flock.

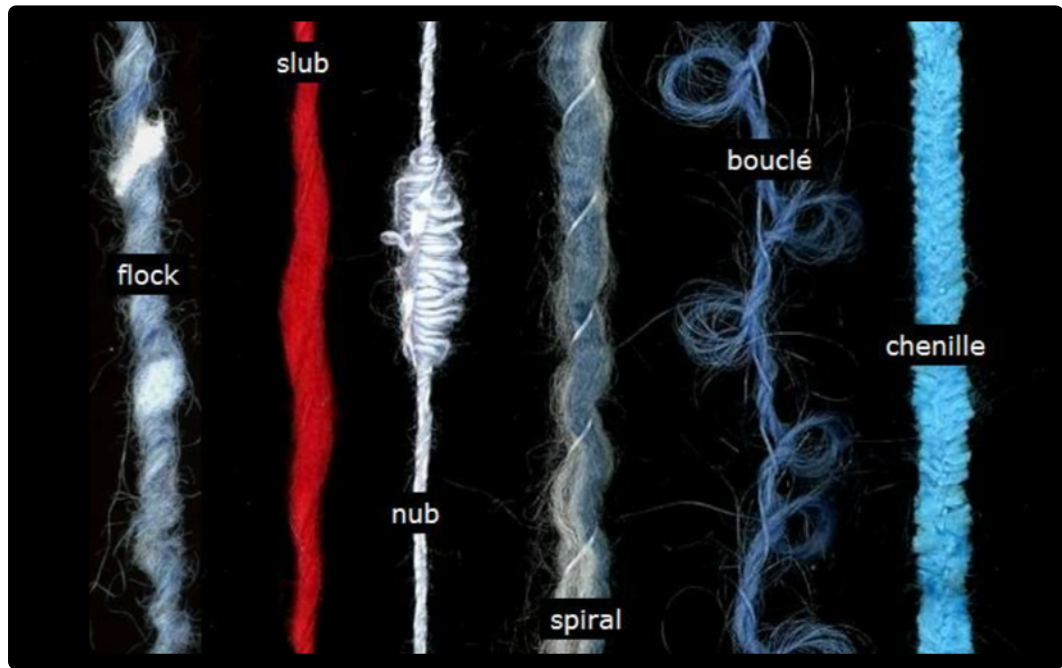


Figure 2.20: Fancy Yarn Types Source: (Watthanaphand 2020).

2.2.2 Weaving

A true weave could unravel unlike earlier structures that have been discovered but produced by twined string. This art predates woven fabric and was used for net-making to aid hunting and the carrying of supplies. True weave, unlike net created from twined string, is advantageous in that it can be mechanised with shed and bars. There are many historical references to textiles being created by long, pliable string-like elements. Impressions on clay from Pavlov, a Palaeolithic site in the Czech Republic date back as early as 25,000 BCE but should not be confused with the interlacing structure.

The first proof of true weaving occurs circa 7000 BCE at the start of the Neolithic, with impressions of plain-weave and basket-weave on clay at Jarmo (north-east Iraq) and a pseudomorph (minerals having outward characteristics of organic materials) of a plain-weave textile on a bone at Çayönü Tepesi (southern Turkey) (Barber 1991).

2.2.2 Knitting

Distinctive from weaving, a single yarn that passes from side to side produces a weft knitted fabric, each row intermeshing with the adjacent row. Weft, Rib, Interlock, and Purl are basic knitted structures with weft knit considered as the simplest method of knitting and are described as plain knit (Wilson 2001). A series of yarn passing through the length of the fabric produces warp knitted fabric, each row inter-looping with the knit on either side. The parallel placement of the yarns used for warp knit is similar to the placement of

yarns in weaving. The two different techniques produce knitted fabric with an entirely different function and finish. Weft knitting can produce complex shaped fabric with a high drape whereby warp knitted fabric can produce finer fabrics (Spencer 2001).

2.2.3 Nonwoven

Nonwoven fabric is presented in more depth due to FOYSE being constructed by fibre entanglement. Nonwovens are either fibre entangled, or fibre bonded as defined in Figure 1.6. The term nonwoven in literature is often used interchangeably to refer to the entanglement of scales on fibre and bonding of fibre or filaments. This can prove confusing, but these terms are used broadly in literature at present. However, focus is now given to nonwoven materials created by the interlocking of scales on the surface of natural fibre which is known as felt. The reason for this is that FOYSE fabric surfaces in this research are manufactured by the entanglement of the interlocking of scales on the surface of natural fibre released from the surface of yarn. Traditional fibre entangled nonwovens are created from fibre webs which have not been spun into yarn which is supported by the following definitions. Continuous agitation and pressing results in the hooking together of the fibre creating a uniform piece of felt fabric (Barber 1992). The art of making felt is completed by rolling, beating, and pressing animal hair or flocks of wool into a compact mass ensuring an even consistency (Laufer 1930). The felt process of fabric making follows the same process but may vary slightly to suit society and the environment in which they live (Burkett 1979). Using fibre of similar weights is a characteristic of felt. Tools designed to speed up the method of felt making, such as Hopper-feeders, allow a specific weight of fibre to pass into the cylinder to create a standardised web. Varying the colour of fibres used to create felt is mainly used to create design features. Felt is also the first textile that has been moulded into 3D shapes at the point of manufacture. Felt is the simplest production method of fabric construction.

At its most ancient and elemental, felt is simply entangled wool fibers, matted together. No stitches, no seams. Unique among textiles structures, felt does not rely on first turning raw fibers into yarn as weaving and knitting do; rather felt harnesses the chaos of tangles (Mullins 2009).

The second type of nonwovens are chemically formed and manufactured mechanically (Mullins 2009). Nonwovens manufactured mechanically derived and rapidly developed through the textile, paper, and plastic industries. This production method has transitioned over 50 years into a flourishing well-defined industry. 'As the demand for nonwoven has steadily increased, it has been met by the technology and ingenuity of raw materials and equipment suppliers, and nonwoven producers and converters' (Prabhu 2007). Mechanically constructed nonwoven is completed in three steps (given in Figure 2.20), with today's

machinery allowing some processes to take place concurrently. Advanced modern technology has even developed so that each stage can be completed at the same time. In addition to fibres and filaments as previously discussed, nonwoven presently is intricately engineered from solutions such as adhesive, particles, powders, and films to supply 'a multitude of functionalities' (Prabhu 2007).

Mechanically bonded fabric includes:

- Fibres that have the quality of interlock and shrink when moisture, heat and pressure are applied such as wool, hair and fur fibres
- Combining rayon or manufactured fibres with wool, hair and fur fibre
- Synthetic fibres that are produced by the needle-punch method
- Chemically bonded fabric includes:
 - Fibres that have been resin bonded using adhesives or solvents to bond a fibre web together.
 - Heat bonded is where a thermoplastic component is melted and used as a constituent that causes the fibres to bond together.

In addition, nonwoven fabrics can be created by a laminated process:

- Two very different properties can be combined to create a very different structure. A weak decorative fabric can be bonded to a fabric to increase strength, or a strong outer fabric could be bonded to a weaker fabric for insulation purposes.
- Polymer foam can be laminated to create a structure with shape retention or warmth.
- Polymer films can be bonded to waterproof fabric or create attractive decoration.

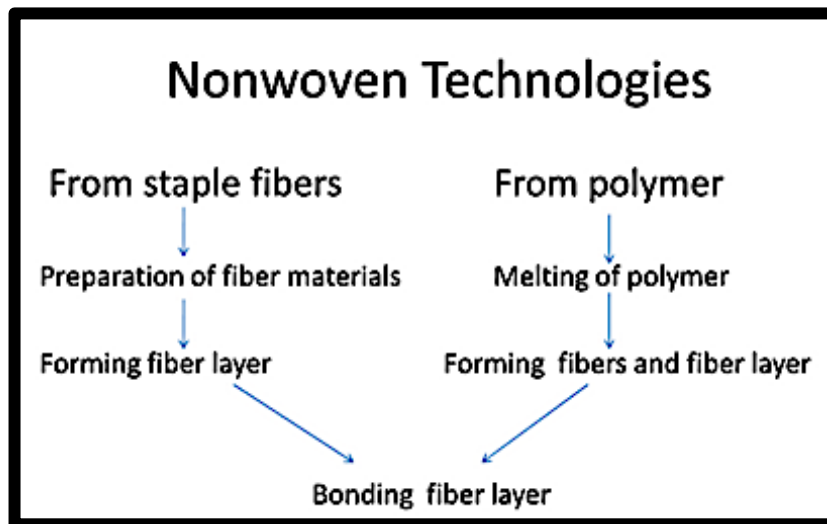


Figure 2.21: Nonwoven technology (INDA 2005).

Spunlace technology⁸ are the leading methods of manufacturing nonwoven materials as presented in Figure 2.22. The table shows an increase of spunlace nonwovens which can be attributed to an increase in technological advancement (INDA 2005). Needle – punched technologies show a smaller increase while spunbonded technologies are the least used production method and in decline. This is the result of advancements gained within hydroentanglement and needle punching methods. Extensively improved technological advancements of the quality and diversity of spunlace nonwoven is the attributed cause of this increase. The production method itself continues with simple equipment and has comparably lower manufacturing costs than other nonwovens, namely thermal resin bonded known as spunbonded.

⁸ Spunlace (Also called Hydroentanglement) is a bonding process for wet or dry fibrous webs made by either carding, air-laying or wet-laying, the resulting bonded fabric being a nonwoven (Sourcennonwovens.com 2020).

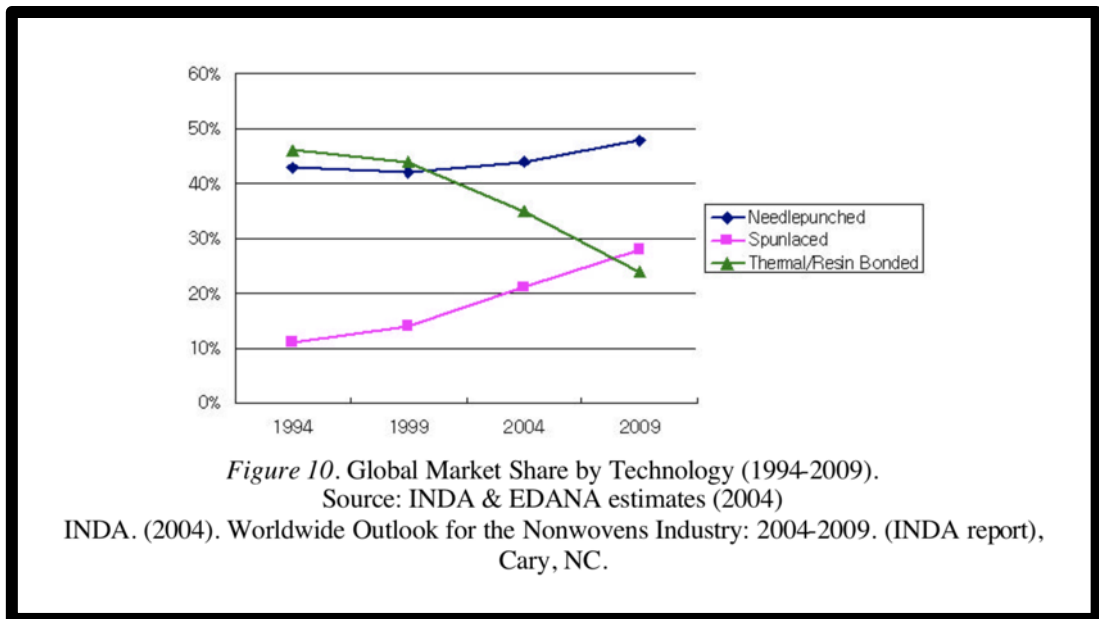


Figure 2.22: Chart to show market share of needle-punched, spunlace and spunbonded technologies. (INDA 2005).

Another contributing factor to the growth of spunlace materials is the increase of hygiene producers as they move from thermal bonded cover stock to the lower cost spunlace materials (INDA 2005). Also revealed, is an increasing demise of resin and thermal bonded nonwoven technologies. This can be attributed to the global move toward the reduction of harmful chemicals (INDA 2005).

Below is a list of advantages and disadvantages relating to the characteristics of nonwoven fabrics. The article was written by B. Maté who has been reporting on creative industries since 2007 (Maté 2014).

The advantages of bonded and fibre entangled nonwovens:

- Does not fray when cut.
- Wrinkle resistant.
- More resistant to abrasion than other fabrics.
- Great insulator due to lack of porosity as is prevalent in weave and knit.
- Less likely to erode with friction due to compact matting of fibres.

The disadvantages of bonded and fibre entangled nonwovens:

- Little or no recovery if the fabric is stretched.
- Structure sometimes feels restrictive.
- Too much stress fabric will pull apart and cannot be mended.
- Dense structure can appear unattractive.
- Cleaning felt can be problematic, therefore, hand wash or dry clean is recommended.

It is important to note that felting differs completely from fulling. To full is to apply the fibre entangling technology used to felt to a previously produced woven or knitted textile to give it the properties of a nonwoven material (Mullins 2009). The fulling process is known commercially as boiled wool.



Figure 2.23: Image of garments that have undergone the fulling process (croftmill 2021).

2.4 Summary

Having considered so far in this chapter the research approach, heritage, current manufacturing methods, and developments the following section moves to the primary research. Commencing with the phenomenon which instigated this research and the process that led to making the decision to investigate further. Literature relating to the research in textile advancements from 25,000 BCE to the 21st Century is provided. The specific areas of literature researched are textile developments of the three known manufacturing techniques, tools utilised for textile manufacture, social and economic events affected by textile industry developments. In section 2.1.8, it has been explained that the FOYSE process solves the problem of the limitation of having three classes of fabric manufacture.

CHAPTER 3: METHODOLOGY: Introduction

Textiles hold significance to everyone who wears clothes. Understanding whether the FOYSE process can manufacture textiles suitable as a viable option for creating a new generation of fabric, is investigated through the following theoretical framework.

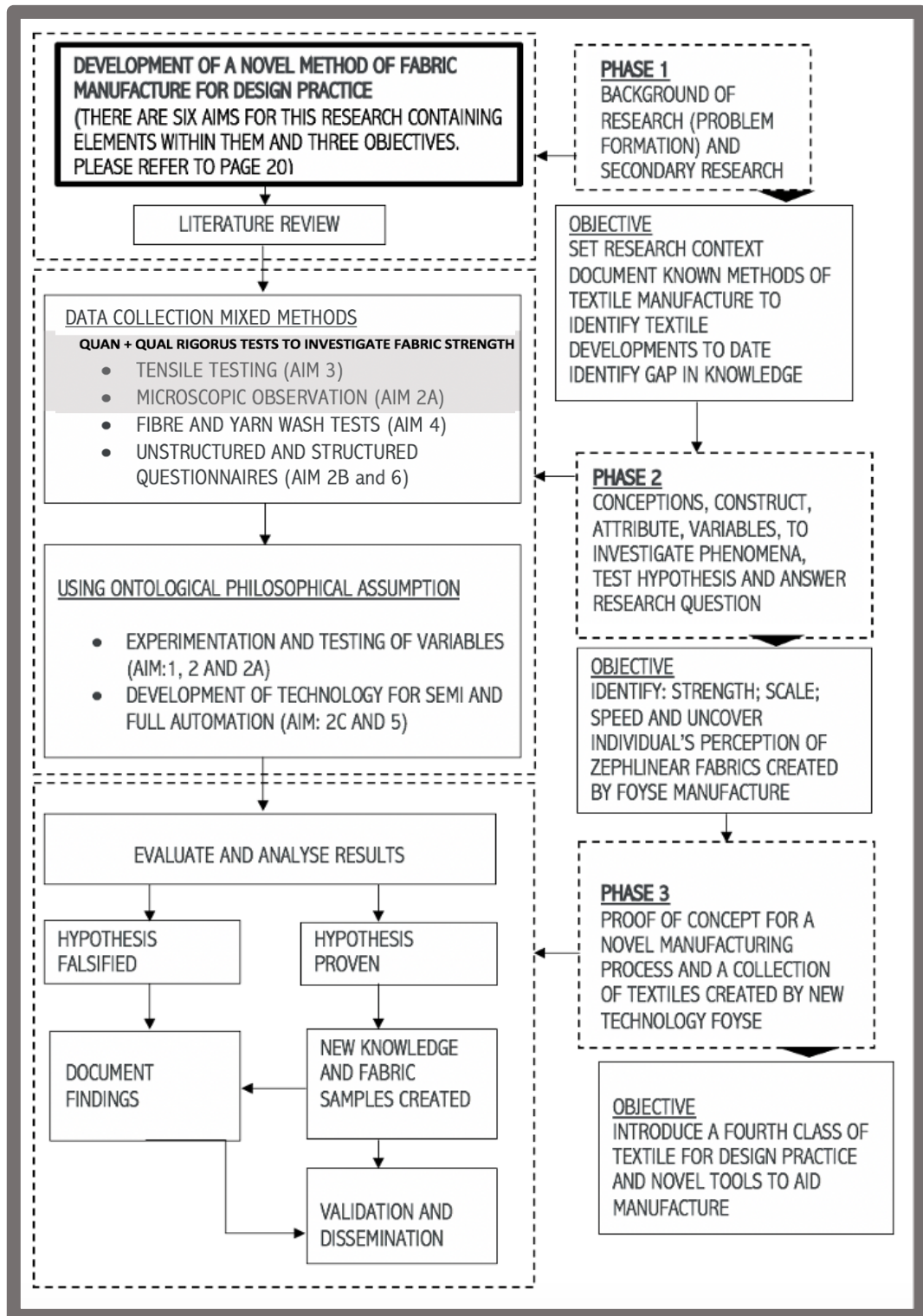


Figure 3.1: Research Framework.

This will be discussed through the following section headings: 3.1 Theoretical Framework; 3.2 Tailoring Methodological Strategy to My Aims; 3.3 Applied Triangulation Methodology and Explanatory Sequential Design; 3.4 Philosophical Assumptions; 3.5 Focus Group Activity; 3.6 The Philosophical Worldview; 3.7 The Scientific Method; 3.8 Research Approach; 3.9 Methodology: Mixed Methods; 3.10 Experimental Testing to Increase Fabric Strength; 3.11 Experimental Testing to Speed Up the Manufacturing Process; 3.12 Development of Technology to Automate Manufacturing and Scalability; 3.13 Double Diamond and Engineering Framework Amalgamation; 3.14 Framework Amalgamation Summary; and finally 4 Methodology Summary.

A textile fabric must demonstrate a range of characteristics which are relevant to its application, for example drapability and breathability which affect moisture and heat transfer. However, only mechanical properties of FOYSE fabrics were investigated within the framework of this research in the form of tensile testing which records tear resistance strength and elongation. An Olympus Digital Microscope was used as a testbed to observe the entangled fibre of samples created by FOYSE. Optical microscopy, image analysis and tensile tests were conducted to investigate an assumed correlation between yarn surface entangled fibre, open areas, and material strength. Tensile testing provides quantitative data, and the Olympus Digital Microscope provides image data that is analysed qualitatively.

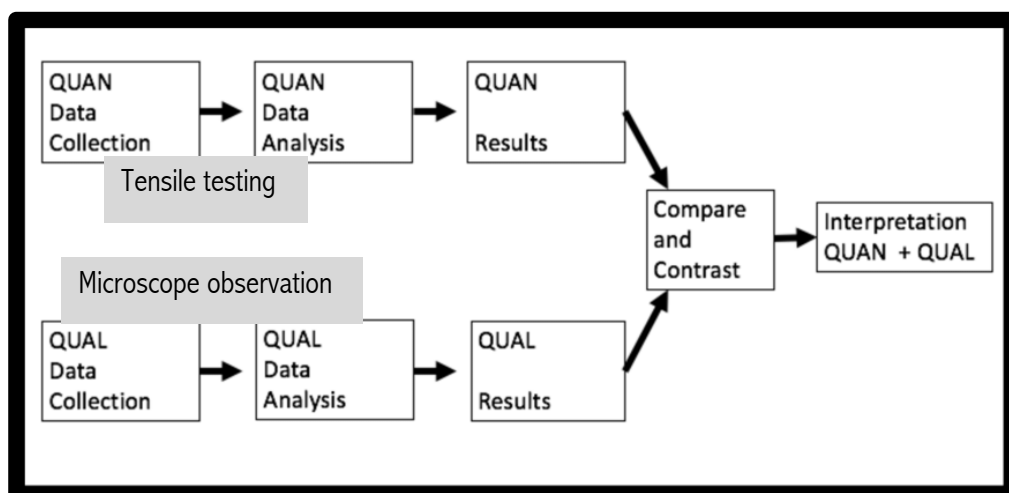


Figure 3.2: Mixed methods triangulation design.

Therefore, research aims 2A and 3 which were to investigate what influences the fabric strength used both quantitative and qualitative data collection methods. Therefore, mixed methods triangulation Figure 3.1 was used in the research. In addition, Explanatory Sequential Design was used to access divergence from fabrics created from known manufacturing methods and this is detailed in chapter 3.2, Figure 3.4.

3.1 Theoretical Framework

Having considered a range of theoretical frameworks to support this investigation, I concluded that the Mixed Method Framework developed by John Creswell would support the project most clearly. There are five essential characteristics of Mixed Methods research and when applied to this study presents a more full and concrete result (Creswell 2016). An outcome that could not be achieved by simply using qualitative methods in isolation. Mechanical testing was conducted via tensile testing which presented numeric values on the materials strength and elongation capacity. The tensile tests also identify if the FOYSE process could create fabric that had strength to be classified as a textile fabric. Qualitative methods were used to understand how individuals interpret fabric manufactured by the FOYSE process in relation to other materials. This was completed to classify fabrics created by the FOYSE process.

Five Characteristics of Mixed Methods Research:

- In response to questions/hypotheses, the collection and analysis of both quantitative and qualitative data.
- The use of rigorous procedures in conducting quantitative and qualitative research.
- The integration (or combination) of the findings from the quantitative results and the qualitative findings.
- The development of procedures in which this data collection, analysis, and integration occurs (mixed methods designs).
- The use of theory (and philosophy) as it relates to these procedures.

This research project focused on:

- Understanding the scientific knowledge underlying the mechanism of entanglement of fibres on the surface of woollen and wool mix yarns. It was important to understand the relationship between the fibre entanglements and the mechanical strength of FOYSE fabric.
- Developing the technology and tools to manufacture FOYSE.
- Test tools and fibres to create a portfolio of FOYSE samples.
- Conducting user trials to study the acceptability of the new FOYSE fabrics.
- Considering the applications and context for use of both the method and products.

3.2 Tailoring Methodological Strategy to My Aims

Identifying the suitability of fabrics manufactured by FOYSE for textile use was the priority. The strength of the fabric was essential to primary understanding to enable the decisions about yarn choice, the production methods and whether the fabric maintained its cohesion. Therefore, ‘tensile testing’ is an established method to measure the breaking point of material, providing numeric results that can be interpreted into several forms, including a graph and a numeric table.

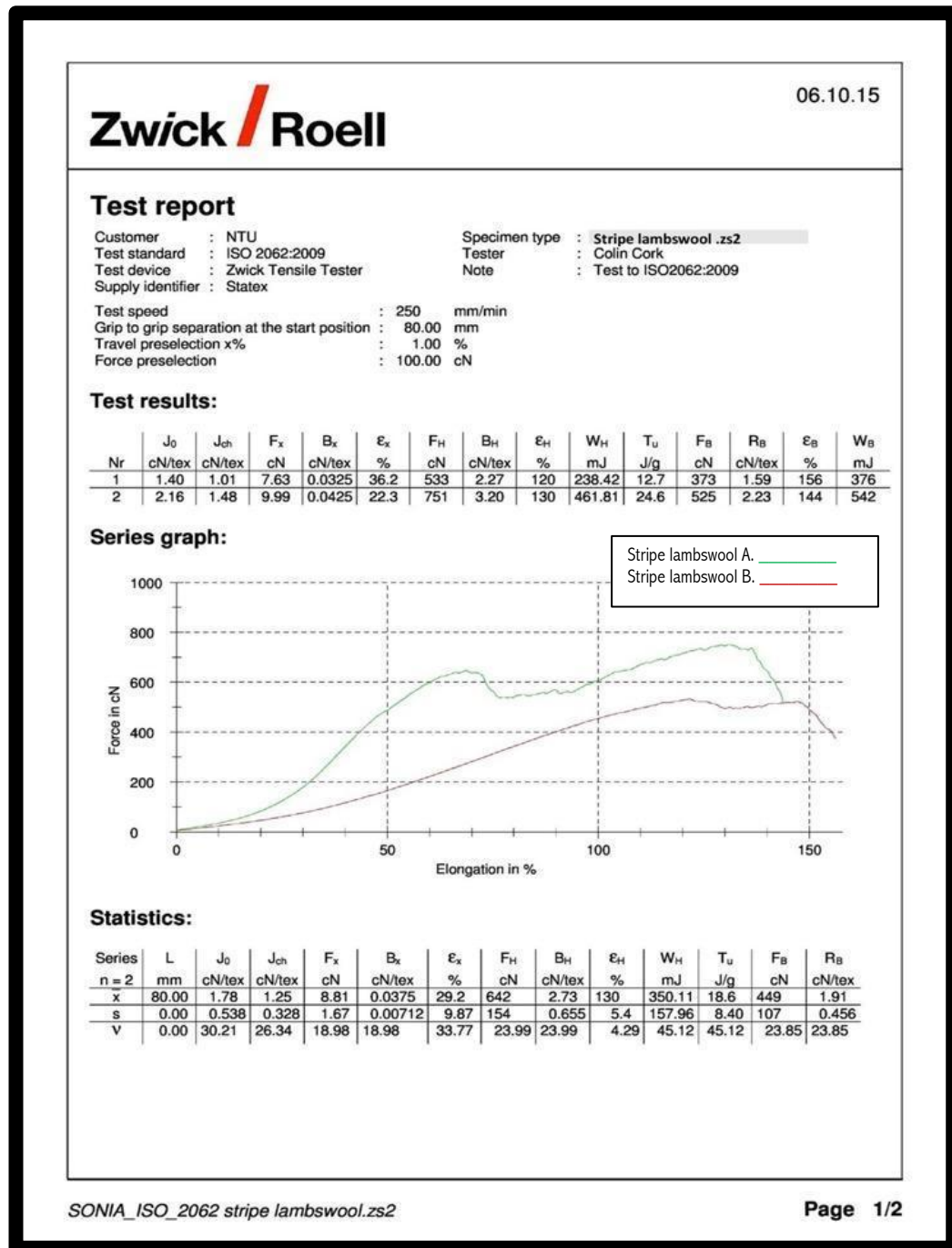


Figure 3.3: Image of tensile test results stripe lambswool.

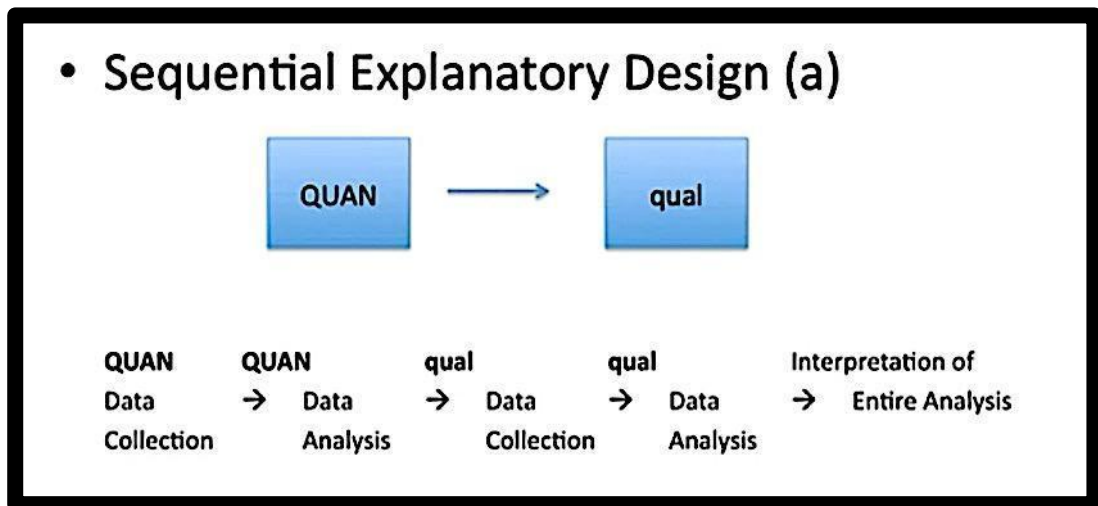


Figure 3.5: Adapted from Creswell Sequential Explanatory Design (Creswell 2009).

The Quan qual design in Figure 3.5 demonstrates the flow of the data collection; first tensile testing was used to create quantitative data and then the RepGrid technique was used to collect qualitative data. The RepGrid technique was chosen due to proving successful for this type of data collection in previous research: 'We operationalize this approach through the Repertory Grid Technique, a structured interview technique motivated by Kelly's Personal Construct Theory and propose a content-analytic procedure combining quantitative and qualitative information' (Butler Richard 2009). The qualitative data collected by the RepGrid technique will be analysed to assess divergence of the new product and process.

3.3 Applied Triangulation Methodology and Explanatory Sequential Design

It was deemed important to consider several data collection methods to obtain deeper insight into the research. A variety of methods namely tensile testing, microscopic observation and questionnaires were used to collect data on the same topic. Therefore, triangulation methodology was implemented as capturing different properties of the same materials created by FOYSE would add validity to the investigation. Tensile testing and microscopic observation were both used to identify strength of materials created by the FOYSE manufacturing process (research aim 2). The first capture of qualitative data was initiated through a presentation to students on the FOYSE process¹⁰. The students, after receiving information about the fabric and how it was developed were given the opportunity to interact with fabric samples. This interaction included the opportunity to handle and tug the samples. This access would provide some understanding on how others viewed the durability of the fabric which would impact validity for textile use. I asked them to write down any comments they had on what was presented, as I saw this as an opportunity to gather

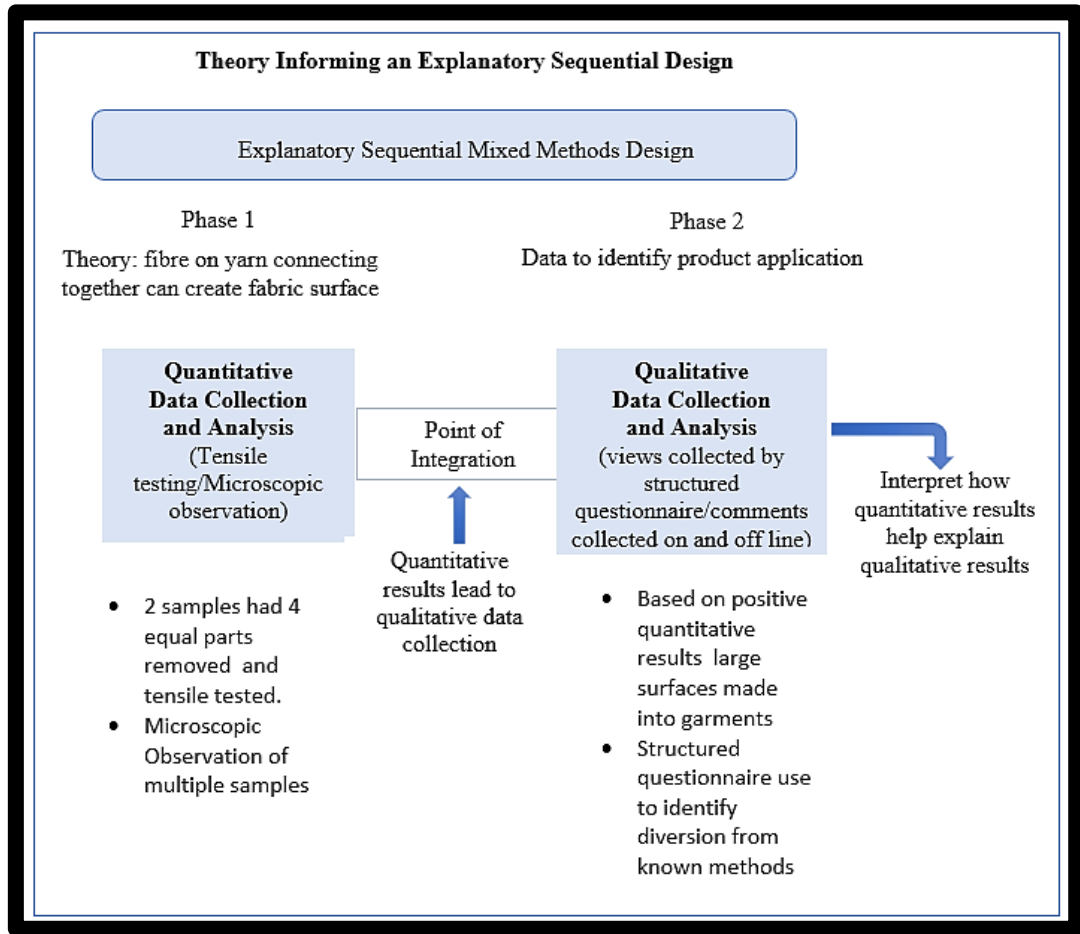
¹⁰ The FOYSE process is to connect the surface fibre on yarn with the purpose of creating a fabric surface.

information on first impressions of the process and samples. They were given the opportunity to freely express their thoughts of the novel fabric and manufacturing process. Out of 14 responses 5 words appeared more than once and are documented in the table below:

Great Idea	Innovative	Interesting	Potential	Simple
3	2	6	4	2

Table 3.1: Results from students freely given thoughts of Zephlinear.

The data collected contributed to the research by providing initial reactions that supported validation for further investigation. The words students used to describe their experience of the process, perception of the process and samples were words that are attributed to something of value. The word 'interesting' was used by 6 students and the word 'potential' was used by 4 students. This activity provided insight regarding the first impression individuals have on the FOYSE manufacturing process and products created by the process.



Point of Integration

Quantitative results lead to qualitative data collection

Interpret how quantitative results help explain qualitative results

Figure 3.6: Adaption of Creswell mixed method (Creswell 2016).

3.4 Philosophical Assumptions

The research was concerned with the identification of a phenomenon, a natural occurrence that exists. Fibres on the surface of yarn entangling was the natural occurrence observed and the foundation of this research. From observing the phenomenon, the philosophical assumption, ‘could this occurrence manufacture a fabric surface’ was made. A philosophical assumption establishes the background used for coming to conclusions or decisions. Therefore, to investigate the phenomenon of fibre on yarn surface entanglement to manufacturing a fabric for design practice, material strength and textile classification were identified as influencers. Consequently, the ontological philosophical assumption ‘What can be known about it?’ was primarily addressed quantitatively as this research method concludes reality can be described independent of human perceptions. This is true regarding identifying the strength of fabrics created by the FOYSE manufacturing process; the mechanical results cannot be influenced by an individual. Fabric strength and flexibility is the main contributor for identifying a fabric for textile use. Aesthetic properties place a textile into a classification that determines end use which is reliant on human perceptions. These two points are the reasons why mixed methods were chosen in preference over purely qualitative methods or

quantitative methods in isolation. Also, over multi-methods whereby both sources could be qualitative and therefore, the method is not mixed. The assumption that the phenomenon could produce a fabric surface was also based on prior knowledge that yarn was already a primary product used for textile manufacture.

It is important to mention that the yarns used to manufacture the samples in this research are commercially available. Therefore, it is recognised that strength tests are conducted by the manufacturers prior to the yarn going to market; to ensure the product is fit for purpose. With this understanding, the investigation assumed that the FOYSE manufacturing process had potential to degrade the strength and quality of the yarn which would affect the end fabric surface strength. This again held importance as the reality of the phenomenon manufacturing a fabric surface and textile classification are dependent on material strength and aesthetic properties.

3.5 Focus Group Activity

Research was conducted with a focus group using the repertory grid (RepGrid) interviewing technique. As a secondary data collection source, this technique created further qualitative data to uncover the individual's perception of Zephlinear fabrics created by the FOYSE process (research aim 2B and 6). This technique is frequently used to elicit qualitative data in the form of attributes, for example, characteristics that cannot easily be measured but can be observed subjectively, such as whether a textile appears flimsy or stiff. In addition to providing quantitative ratings, participants were given a numeric scale of one to five to respond to a set of questions. Due to the nature of this research, using both experimental and observational methodology should provide robust research results. The ability for the data obtained by the RepGrid to be interpreted into quantitative results is considered extremely beneficial, as the numerical results could be further used in future research or reports that were solely quantitative. George A. Kelly developed this technique as an instrument for the elicitation of personal constructs, a theory that argues 'a person's processes are psychologically channelized by the ways in which s/he anticipates events' (Kelly 1991). Kelly's writings presented the personal construct theory (PCT) as a complete, innovative and elaborated abstraction of how people make sense of their world and themselves (Butler Richard 2009). Therefore, it was concluded that the repertory grid technique¹¹ would be an appropriate method for identifying the individual's perception on fabric surfaces created by FOYSE. The technique would give data on individual views of the fabrics created by the FOYSE process and insights into how they might compare to known fabric surfaces: woven, knit and nonwoven.

¹¹ This theory for collecting information emerged from his work counselling US university students in the 1930s and was first published in 1955 (Katz 1984).

The topic for the RepGrid was narrowed to analyse the visual difference of Zephlinear created by FOYSE fabric construction. Photographic imagery of the three known fabric construction methods (woven, knit and nonwoven) were placed alongside a photographic image of a Zephlinear fabric sample. Participants were presented with a structured questionnaire in a grid format. Selected physical samples of Zephlinear fabric created by FOYSE were also presented. The RepGrid contained a list of 7 constructs and a set of three element elicitations each having three questions. Individual students, 6 in total, completed the RepGrid and the results are in Chapter 5. The elements are the three known manufacturing processes, woven, knit, and nonwoven. The five elicitations are in Table 3.2.

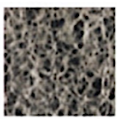


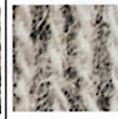
1					5
Distinct structure					Unstructured
Some structure					No structure
Loose					Stiff
Unstructured and structured combination					One structure no combination
Vertical structure mixed with entanglement					No vertical structure mixed with entanglement
More moveable					Less moveable
Durable					Un-durable

Table 3.2: List of 7 constructs used in the structured questionnaire.

The epistemological philosophical assumption for the entire research is that the relationship between the researcher and what is being studied are independent. The hypothesis can be studied without influencing or being influenced by my opinion or world view due to using a mechanical method for collecting information. Data was collected via the tensile testing and microscope instruments as required by the scientific method for data collection. Where participants were involved, data was collected in a structured manner. The manner was structured in that the participants were given set questions with a set choice of structured answers. The responses were tailored so that a response could be given with minimal time and further analysis. The axiological philosophical assumption for this research again was quantitative. Statistically, the research can be deemed as valid and reliable as the facts can be separated from values held by the researcher. The rhetorical language of the researcher is qualitative through the inductive stage of the research until the formulation of the hypothesis.

3.6 The Philosophical Worldview

The philosophical worldview proposed in the study is postpositivist:

Postpositivist hold a deterministic philosophy in which causes (probably) determine effects or outcomes. Thus, the problems studied by postpositivists reflect the need to identify and assess the causes that influence outcomes, such as those found in experiments. It is also reductionistic in that the intent is to reduce the ideas into a small, discrete set of ideas to test, such as the variables that comprise hypotheses and research questions (Creswell 2009).

The pragmatism worldview was also considered due to its ideal placement within mixed methods. In this worldview the researcher is not committed to any philosophy or way of thinking regarding knowledge, truth or reality. The focus is directed to the research question/problem. As a pragmatist the researchers focus is on the practical outcomes of the research. This is obtained by using whatever research methods are best suited to answer that question or solve the research problem. However, this thesis followed the accepted approach to research by postpositivist. An individual begins with a theory, gathers data that either reinforces or refutes the theory, and then completes necessary revisions before further tests are undertaken. This research used mixed methods sequential design which was primarily quantitative with support from qualitative data.

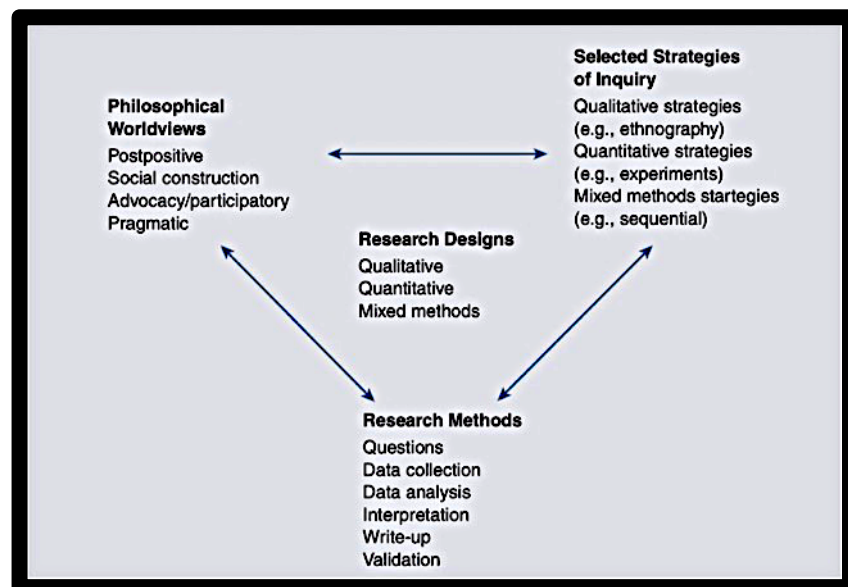


Fig 3.7: A Framework for Design - The Interconnection of Worldviews, Strategies of Inquiry, and Research Methods (Creswell 2009).

3.7 The Scientific Method

The scientific method used in this thesis is for investigating phenomena and acquiring new knowledge, as well as for correcting and integrating previous knowledge. The secondary research conducted identified a gap in knowledge regarding innovations for textile manufacturing outside of the state-of-the-art of woven, knit, fibre entanglement and bonding.

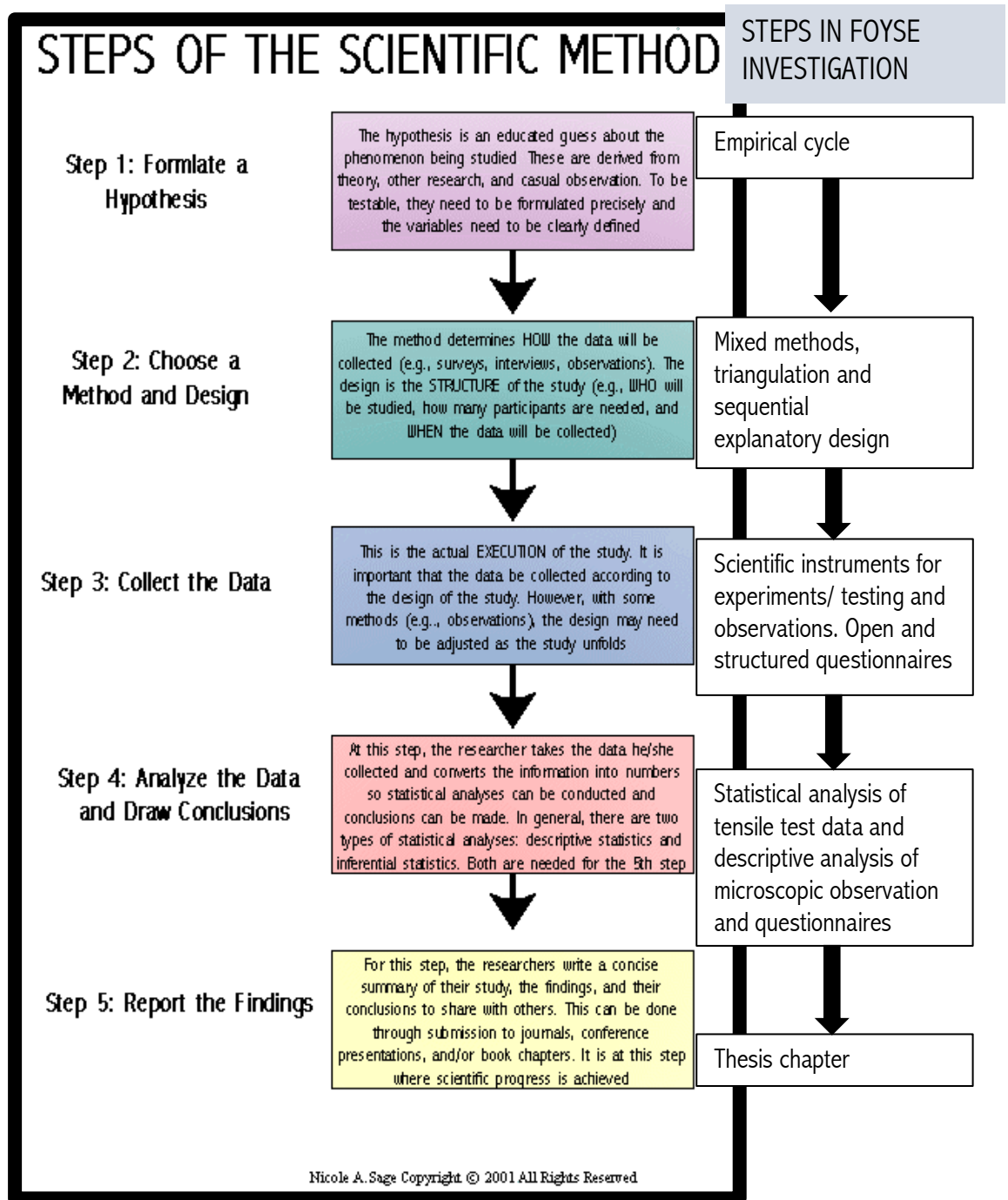


Figure 3.8: Flow Diagram of Steps of the Scientific Method (Sage 2001).

The scientific method is a procedure that has characterised natural science since the 17th century, consisting in systematic observation, measurement, and experiment, and the formulation, testing, and modification of hypotheses (Andresen 2017). This fits well within the boundary of the scientific method, for which this research area is best suited. This was due to the nature of the phenomenon and the theory under investigation. Inductive and deductive reasoning was used to establish the hypothesis. Firstly, an observation was made of fibre on yarn connecting, which is in the sphere of inductive reasoning. Secondly, the observation ignited the thought which came in the form of a statement, this could create a fabric surface, which is in the sphere of deductive reasoning. This was the beginning of the formation of the hypothesis: If fibre on yarn surface entanglement can be increased, then an additional fabric surface will be created.



Figure 3.9: Inductive and deductive reasoning used to establish hypothesis.

This process was successful for illustrating the path taken for the gaining of further scientific knowledge, and the inventing of technology and tools to aid in FOYSE manufacturing. This research followed the systematic track of collecting observable, empirical, measurable data, subject to the philosophy of reasoning. This is the process of the scientific method (Hessenbruch 2013) and illustrated in the research

development image above. The previous image presents the path taken from initial reasoning to formation of the:

Research question: Can fibre on yarn surface be entangled to create a new fabric surface and introduce a fourth class of textile manufacture?

Theory: If connecting yarns together by entangling fibres on their surface is successful, then can the surface area be increased thus creating sufficient width and lengths for commercial textile use.

Specific conclusion: Fibre on Yarn Surface Entanglement will advance current fabric manufacturing restraints by adding new tools, fabric surfaces and production methods.

The exploratory research approach was adopted for formulating the hypothesis. Explorative studies are undertaken when a new area is being investigated or when little is known about an area of interest (Midzi 2018). This approach is used to investigate the full nature of the phenomenon and other relating factors. To test the hypothesis, insight into the related premise was required to be gained. This was instrumental in setting the criteria for decision making for the research approach to be developed. In addition, it was used to focus the research problem and establish priority for further research.

The phenomena which I observed and formulated into the hypothesis, grew from an inquisitiveness to investigate the occurrence of yarn connecting when exposed to a washing process. While working as a knitwear designer one task was to hand finish the garments which included a machine wash cycle. After the wash and spin cycle, I observed that loose yarn at the end of a knitted panel would naturally attach to its neighbour. This gained my attention and sparked an interest into whether this phenomenon could be controlled, developed, and repeated. I wanted to explore this further and used 'inducting reasoning' to examine the related issues of the phenomenon. The aim was to increase the number of connecting yarns to create an industry standard fabric surface and I began to experiment with parallel yarn to test this approach. This was the first stage of the scientific method which incorporated background research in the form of examining the related issues of the phenomenon and preliminary experimenting and testing.

The stages of the Empirical Cycle according to A.D. De Groot (Wilson 2019) and the relation to FOYSE investigation are detailed below:

1. Observation - involves collecting and organising empirical data of phenomenon.
2. Induction – (Effect) the process of reaching a conclusion by considering whether a collection of broader premises supports a specific claim.

3. Deduction - (Cause) relies on logic and rationality to come to specific conclusions given general premises.
4. Testing - entails returning to empirical methods to put the hypothesis to the test.
5. Evaluation - Reflect and appraise the process.

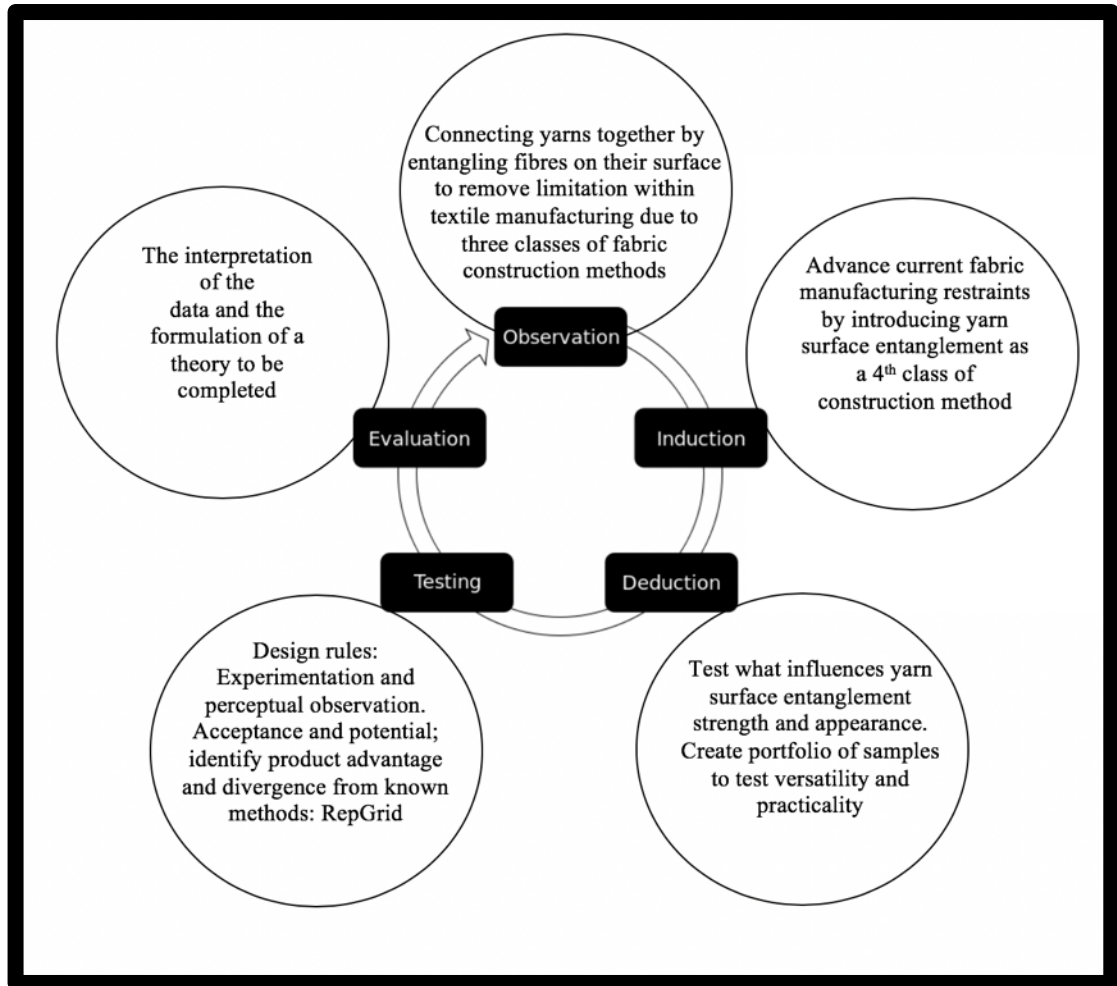


Figure 3.10: Diagram displaying research within stages of the Empirical Cycle.

The research was underpinned by adhering to the rigid structure of the scientific method which is listed below:

1. Make an observation or observations.
2. Ask questions about the observations and gather information.
3. Form a hypothesis — a tentative description of what's been observed and make predictions based on that hypothesis.
4. Test the hypothesis and predictions in an experiment that can be reproduced.

5. Analyse the data and draw conclusions; accept or reject the hypothesis or modify the hypothesis if necessary.
6. Reproduce the experiment until there are no discrepancies between observations and theory.

The deduction stage of the empirical cycle, logic and rational, concluded to test what influences fibre on yarn surface entanglement strength and appearance. A portfolio of 52 samples were created to test versatility and functionality of fabrics created by the FOYSE process. Concurrently, tools and apparatus were investigated to aid in the FOYSE manufacturing process. The tools and apparatus were developed to speed up the manufacturing process of FOYSE and establish proof of concept for automation. Proof of concept for automation was also investigated by NTU product design students. Experimentation was used to create samples of differing strength and scale. Once a suitable strength was deemed repeatable further samples were created for use in further investigation. Variables in the experimental process were manipulated to provide understanding into cause-and-effect by displaying what outcome transpires when a certain variable is manipulated.

FOYSE fabric sampling went through multiple testing and experimentation to obtain duplication. Moshe Pritsker, a former post-doctoral researcher at Harvard Medical School, told Live Science. "The reproducibility of published experiments is the foundation of science. No reproducibility – no science" (Hessenbruch 2013). In addition to the points previously mentioned, the following points also had to be met for research credibility.

- The hypothesis must be testable and falsifiable meaning (NORTH CAROLINA STATE UNIVERSITY 2007) that there must be a possible negative answer to the hypothesis.
- Research must involve deductive reasoning and inductive reasoning (Dudovskiy 2011). Deductive reasoning is the process of using true premises to reach a logical true conclusion while inductive reasoning takes the opposite approach.
- An experiment should include a dependent variable (which does not change) and an independent variable (which does change).
- An experiment should include an experimental group and a control group. The control group is what the experimental group is compared against (Bradford and Hamer 2017).

The above information is also provided in the article by Live Science previously referenced. The article is titled What is Science? by Alina Bradford. Figure 3.9 (NORTH CAROLINA STATE UNIVERSITY 2007) is an



Figure 3.12: Empirical cycle extended thought process derived from initial results.

3.8 Research Approach

The approach adopted for the hypothesis investigation is deductive as opposed to inductive or abductive approaches.

	Deduction	Induction	Abduction
Logic	In a deductive inference, when the premises are true, the conclusion must also be true	In an inductive inference, known premises are used to generate untested conclusions	In an abductive inference, known premises are used to generate testable conclusions
Generalizability	Generalising from the general to the specific	Generalising from the specific to the general	Generalising from the interactions between the specific and the general
Use of data	Data collection is used to evaluate propositions or hypotheses related to an existing theory	Data collection is used to explore a phenomenon, identify themes and patterns and create a conceptual framework	Data collection is used to explore a phenomenon, identify themes and patterns, locate these in a conceptual framework and test this through subsequent data collection and so forth
Theory	Theory falsification or verification	Theory generation and building	Theory generation or modification; incorporating existing theory where appropriate, to build new theory or modify existing theory

Figure 3.13: Differences between deductive, inductive, and abductive approaches (Dudovskiy 2011).

As in the scientific method, a hypothesis was formulated because of an observation, which prompted an investigation into a phenomenon. This method of approach was best suited to address the restraints within current manufacturing methods as the deductive approach tests the validity of assumptions (or theories/hypotheses) under investigation. The inductive approach contributes to the emergence of new theories and generalisations but does not involve formulation of hypotheses. Instead, it starts with the research question, aims and objectives. In the abductive approach, the research process is devoted to explanation of ‘incomplete observations’, ‘surprising facts’ or ‘puzzles’ specified at the beginning of the

study (Bryman and Bell 2015). Therefore, the inductive or abductive approach was not suitable for this research.

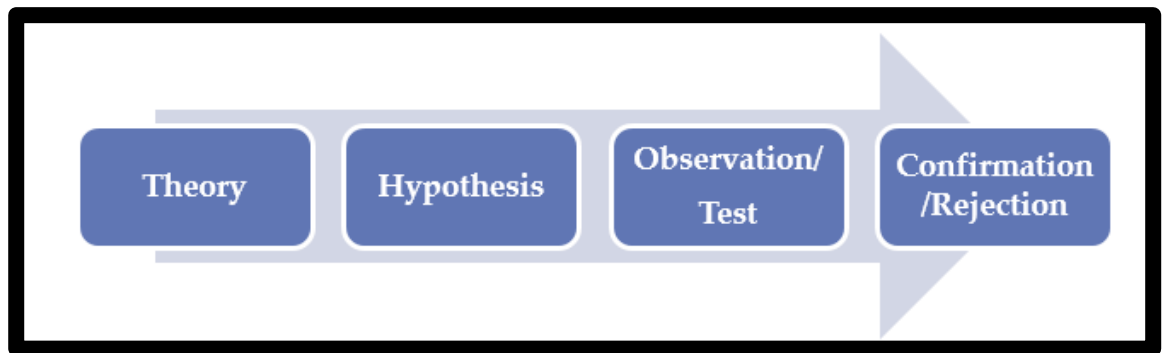


Figure 3.14: Deductive process in research approach (Dudovskiy 2011).

Investigating the phenomenon of connecting yarns together by entangling fibres on their surface results in innovation. The units of interest are limited to the technical development of the phenomenon in relation to what influences material strength and design capability. The research question asked is can fibre on yarn connecting create a new fabric surface? This led to the theory under investigation: if yarn surface fibre entangling can occur with two yarns, then theoretically, if repeated, the surface area can be increased to create a fabric surface. This led to formulating the hypothesis: if fibre on yarn surface entanglement can be increased, then an additional fabric surface will be created.

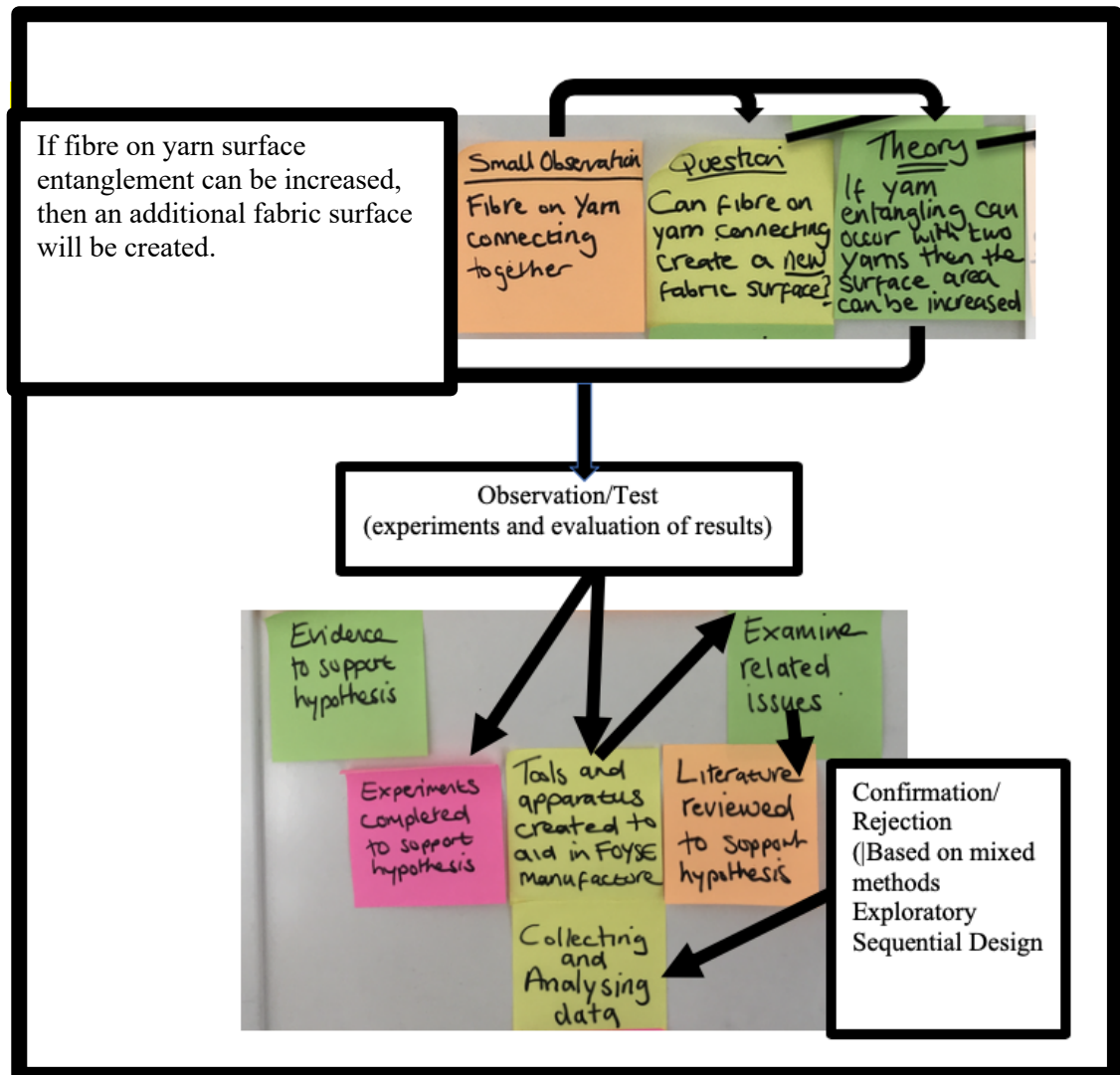


Figure 3.15: Observation/Test experiments and evaluation of results.

3.9 Methodology: Mixed Methods

The empirical evidence was analysed using mixed methods, which key features are collecting and analysing quantitative and qualitative data independently, alongside database interpretation. It involves the use of both approaches in tandem so that the overall strength of the study is greater than either qualitative or quantitative research (Creswell and Plano 2006). The hypothesis and examination of related results of the research could not be supported sufficiently by using one method. Neither qualitative or quantitative research methods used in isolation would be effective for investigating all the concepts such as visual and tactile properties, performance, and resistance properties. Combining both text and optical analysis alongside statistical analysis provides more in-depth understanding of the results. Therefore, quantitative data was collected via tensile testing to establish a numerical value to material strength. Qualitative research methods were used to establish divergence from known materials and identify characteristics for material

classification. The five areas of investigation listed could not be fully addressed by using either of the methodologies independently. The statistical results obtained from tensile testing combined with the data collected from microscopic observation and the structured questionnaires provided strong data for support of the hypothesis.

The hypothesis had five areas of inquiry which were under investigation:

- 1 Gain new knowledge and understanding of the difference of FOYSE from known methods.
- 2 Explore the technical parameters of FOYSE regarding yarn types and scalability.
- 3 To test the strength of fabrics created by the FOYSE process.
- 4 Develop fabrics/samples to test versatility and creativity.
- 5 Develop fabrics/samples and test suitability in the fashion and textile market.

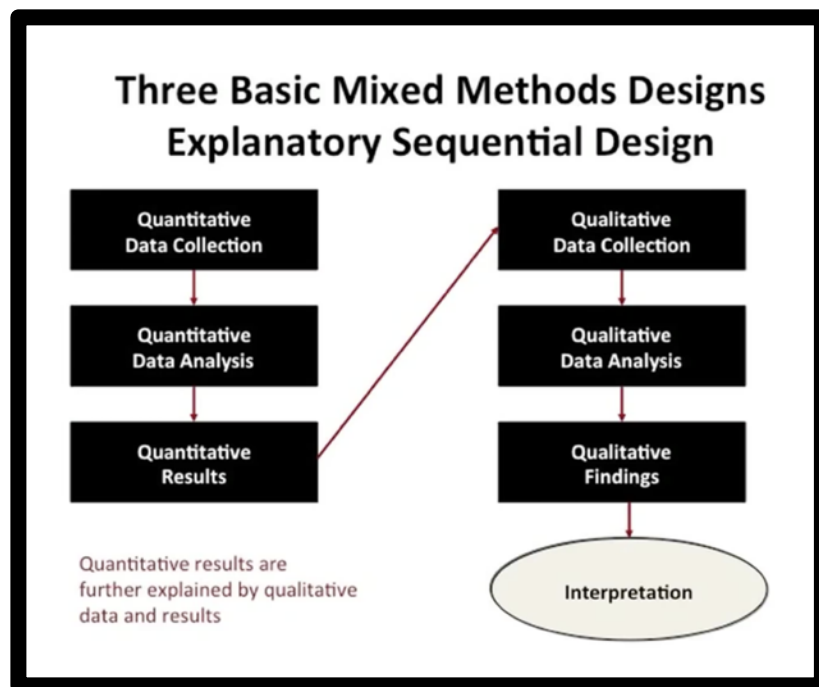


Figure 3.16: Explanatory Sequential Design (Creswell 2009).

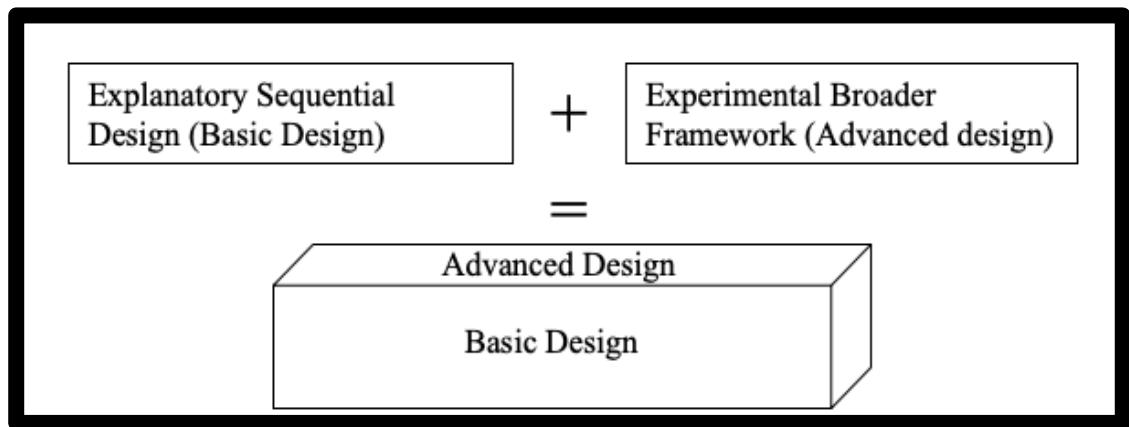


Figure 3.17: Broader Framework (Creswell 2009).

3.10 Experimental Testing to Increase Fabric Strength

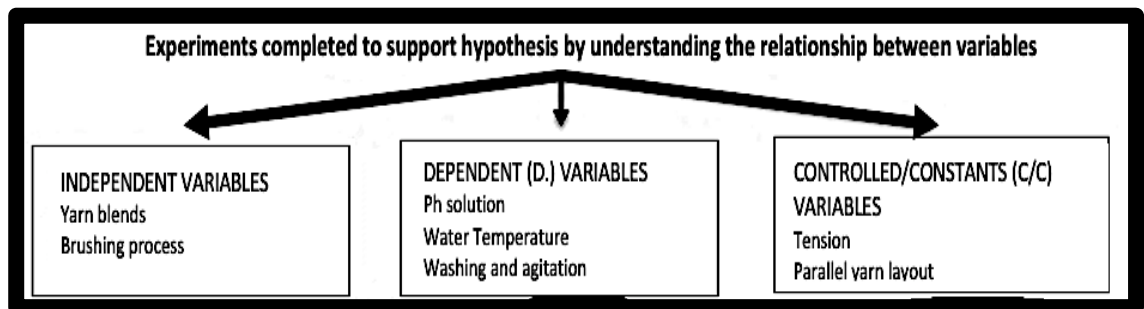


Figure 3.18: Conceptual framework.

In summary, experimentation with the manufacturing process was the method used to support the hypothesis. Therefore, the design of this research was experimental. In addition, due to the lack of previous research in this area it was also explanatory. The procedure for the experiments was to vary the steps and values of the dependent and controlled/constant variables. The relationships between the variables in the contextual framework were the basis in which the research was grounded. The procedure described above was undertaken to investigate methods to increase material strength. In support of this investigation, tools and apparatus were created and tested by experimentation. This step was needed to aid the manufacturing and sampling of FOYSE fabrics.

3.10 Experimental Testing to Speed Up the Manufacturing Process

To enable me to test and develop methods for speeding up FOYSE, the process of manufacturing, both tools and apparatus were created to aid investigation and testing. It is important to note that the development of technology to manufacture FOYSE fabrics and the development of apparatus to aid in the manufacturing of FOYSE are two distinct development processes. Consequently, the research design structure did not take on the systematic approach shown in Figure 3.16. The empirical design process was utilised for the FOYSE manufacturing process whilst the development of apparatus to aid the manufacturing of FOYSE was taking place concurrently. This resulted in the research incorporating a high level of innovation prototyping. This is used in the Stanford Design Innovation Process Model (Stanford Edu 2016). The prototyping of apparatus to aid the production of FOYSE took two distinct forms. Initially, I engaged with adapting the use of 'off-the-shelf' products to aid in raising fibre from the surface of yarn and combining them with non-related products to reinvent their use; for example, I attached a hairbrush to a power drill. However, I also developed a research project and collaborated with BSc (Hons) Product Design students, final year (level 6) and industry to establish a new proof of concept of a new machine that would enable production to be scaled and sped up.

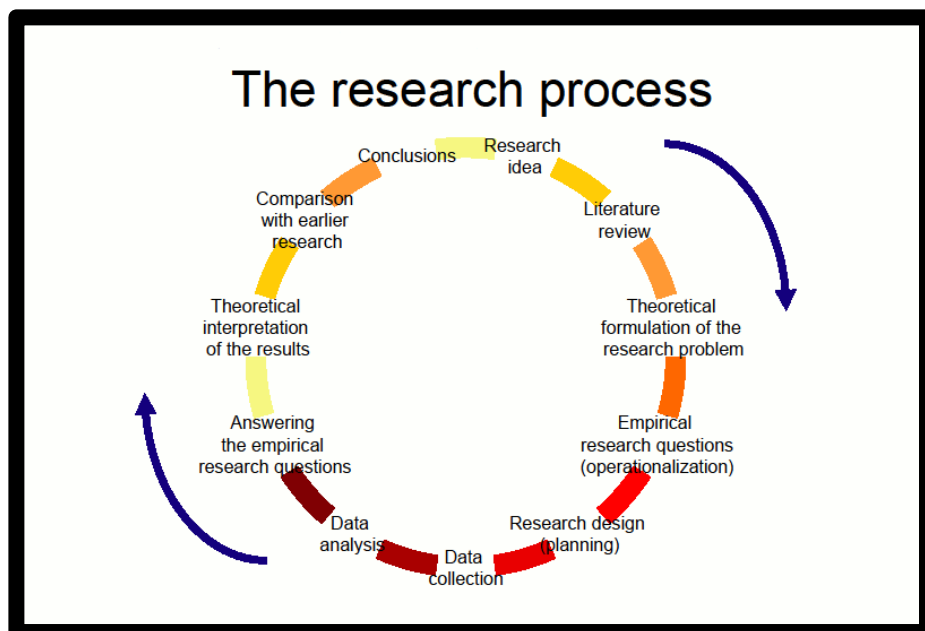


Figure 3.19: The General Methodology of Design Research Process (Alliso 2017).

Using 'off-the-shelf' products allowed the production of prototypes and testing to be conducted at a rapid speed and a reasonable cost. The initial idea was to advance current manufacturing methods to innovate a novel fabric surface. This was completed by observing current production processes and adapting them, for example, laying out a warp, as in the weaving process, but then using an entanglement process, rather than a weft to connect the yarns. Analysing existing products were identified to see how they could serve in the new process. This process underwent a continual iteration process to strengthen the fabric and design capability. When this capability was secure, fabric samples were created and tools to manufacture were produced to support the key insights.

Designing new apparatus was essential to refine the FOYSE production process. The research is textile innovation, and the design research process was conducted by incorporating the design innovation process. Minus the prototyping, the Stanford model in Figure 3.20 mirrors the empirical cycle when observing the 5 stages.

Stages in the Stanford Design Innovation Process that reflect the stages in the manufacturing of tools to aid in the automation of the FOYSE process is listed below:

1. Teams observe and interview users to better understand their needs.
2. Benchmark existing technologies and products to identify the design opportunities.
3. Extensively brainstorm to discover the obvious, crazy and novel ideas.
4. Iteratively prototype to quickly test their ideas and get a better understanding of their designs.
5. The result is a refined design concept backed with key insights.

Stage 1 of the Stanford Design Innovation process refers to individuals, whereas within this research it was applied to the development of FOYSE materials and its manufacturing process:

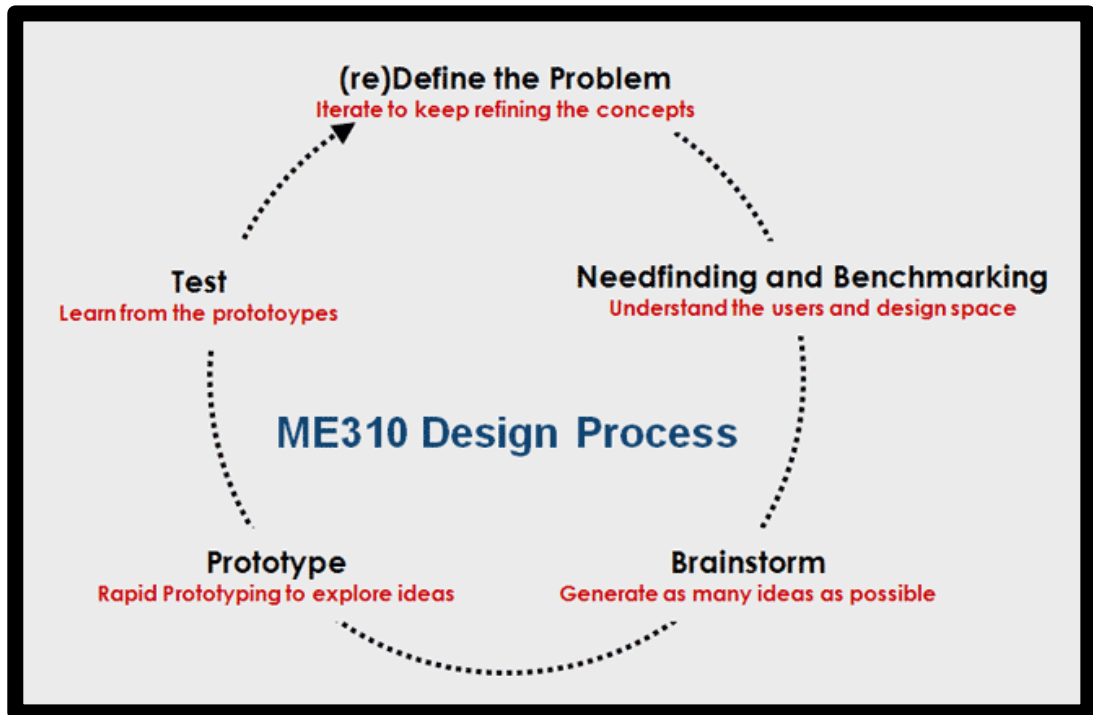


Figure 3.20: Stanford Design Innovation Process edu (Stanford Edu 2016).

The samples engineered demonstrate the compatibility of FOYSE for the general user (Bannari Amman Institute of Technology 2016). The FOYSE manufacturing process used the general methodology for design research while the apparatus to aid in manufacturing followed a typical design innovation process. Finally, investigation took place into the relationship between the three variables in Figure 3.21 which followed an engineering design model. Textile technology and engineering deals with the application of scientific and engineering principles. This is in relation to the design and control of all aspects of fibre, textile, apparel processes, its products and machinery (Bannari Amman Institute of Technology 2016). Therefore, to support the two named processes, the engineering design model was also investigated. In total three design processes were identified as having importance to the success of this investigation. The image below illustrates the relationship between the variables used for testing the hypothesis, mirrored with the process of experimentation with tools to aid in manufacturing.

By obtaining the result of a previous application in each of the variables and responding by the adjusting of tools, apparatus and measurement, data was obtained to support the hypothesis: If fibre on yarn surface entanglement can be increased, then an additional fabric surface will be created. Each iteration of the process dealt with solutions to strengthen or increase a fabric surface manufactured by the FOYSE process. For example, the varying of the brushing process and brushing tools influenced the release of the fibre on the surface of yarn. The microscopic observation provided a relationship between fibre entangled and material strength.

The conceptual design process did not take on a typical singular structure as in Figure 3.17. Instead, there were multifaceted issues related to solving the problem. The variables identified to investigate the problem are complicated issues that have lots of contributing factors when considered holistically. Each result had the potential for further in-depth investigation and generated more questions to aid in understanding the research question. Therefore, the FOYSE design process was developed and formulated to give a systematic approach to the investigation stage of the research while providing a method of segmenting each of the variables which were so closely related.

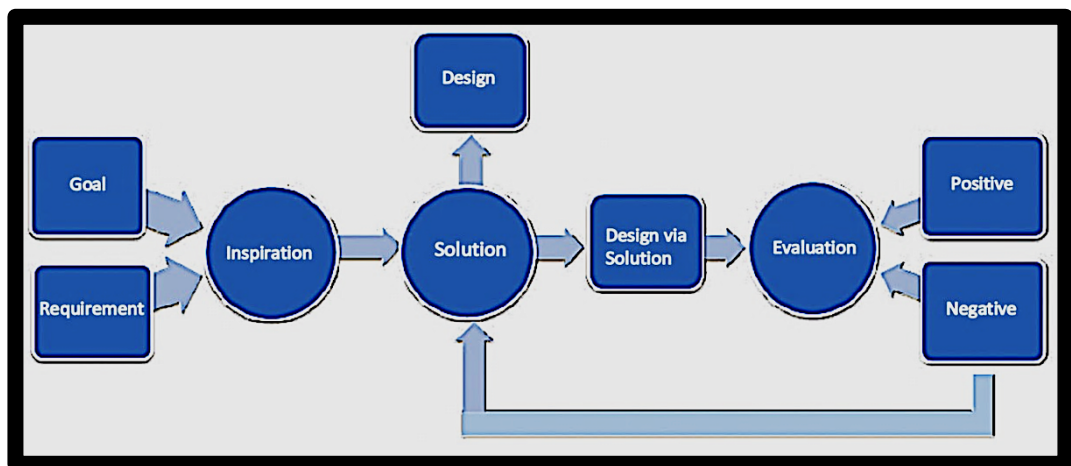


Figure 3.22: Conceptual design process for postgraduate students (AU and AU 2018).

The developed FOYSE design process was able to bring clarification about the complex processes. The main complexity was due to the volume of sampling required in the research, which was directly the result of the necessity to make multiple minor adjustments. Experiments revealed that a small change in the measurements applied in a process would make a significant change. For example, the make-up of wool and wool/mix fibres and the natural reaction could cause several variables in their tensile measurements. This would be clear when using 100% woollen yarn in comparison to a mixed yarn such as 30% silk, 70% wool, as silk is significantly stronger than wool and reacts differently when washed.

3.11 Development of Technology to Automate Manufacturing and Scalability

New tools and apparatus were prototyped with the aim of speeding up the process of manufacturing FOYSE. This resulted in a 'proof of concept' for full automation which demonstrated that the entanglement of the surface fibre raised from yarn is a repeatable process. Knowledge gained from the experimentation undertaken resulted in the development of the handheld Fibre Rise Vertical Roller. This tool increases the speed in which fibre can be teased from the surface of yarn in a uniform manner. Further tools are in development to aid each step of the FOYSE manufacturing process and will be discussed in further detail in chapter 5.

Each of the variables along with the tool and apparatus designed to aid manufacturing in the research have clear and distinctive positioning within the research design processes (Bannari Amman Institute of Technology 2016). The creation of tools and apparatus to aid in the manufacturing of FOYSE was conducted within the engineering branch of science and technology as this activity was concerned with the design, building, and use of machines, and structures (Oxford Learner's Dictionary 2010).

Textile technology or engineering deals with the application of scientific and engineering principles to the design and control of all aspects of fibre, textile and apparel processes, its products and machinery (Bannari Amman Institute of Technology 2016). This design process had a final manufacturing output of tools developed to aid in the FOYSE manufacturing process and therefore, Engineering Design Models were investigated. Prototyping tools to aid in manufacture are conducted by the repeated pulling apart of known instruments (divergence). Transforming their designed use into a reformed tool that would aid the manufacturing of FOYSE. The process was repeated each time bringing the object closer to the desired end use (convergence). This was intertwined with the development of the fabric manufacturing process and associated themes, which was the main element incorporated within this research. Therefore, the Double Diamond Model by Design Council was also investigated. This tool is a visualisation design process model which divides into four phases: Discover, Define, Develop and Deliver. Two diamonds typify a process of exploring an issue more widely or deeply (divergent thinking) followed by focused action (convergent thinking). The first diamond is targeted to help people understand, rather than simply assume, what the problem is (Design Council 2015).

3.12 Double Diamond and Engineering Framework Amalgamation

The research process which I have engaged with combines the Double Diamond Model from the Design Council and the Engineering Design Model from Engineering Design Methods by Nigel Cross. Having the Double Diamond as the foundation of the research model overlaid with the Engineering Design Model was the most appropriate method to frame the research strategy.

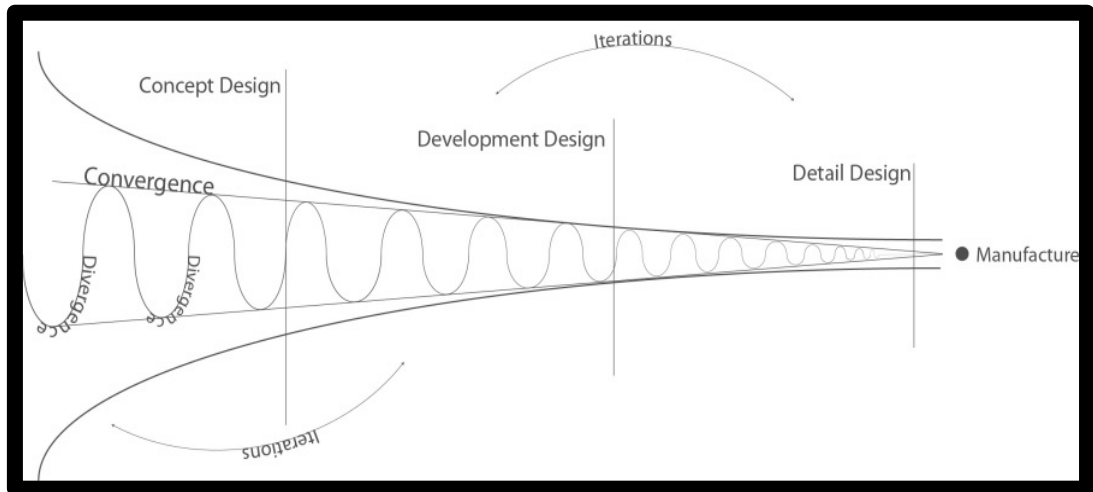


Figure 3.23: Engineering Design Methods by Nigel Cross Source: (Self 2016).

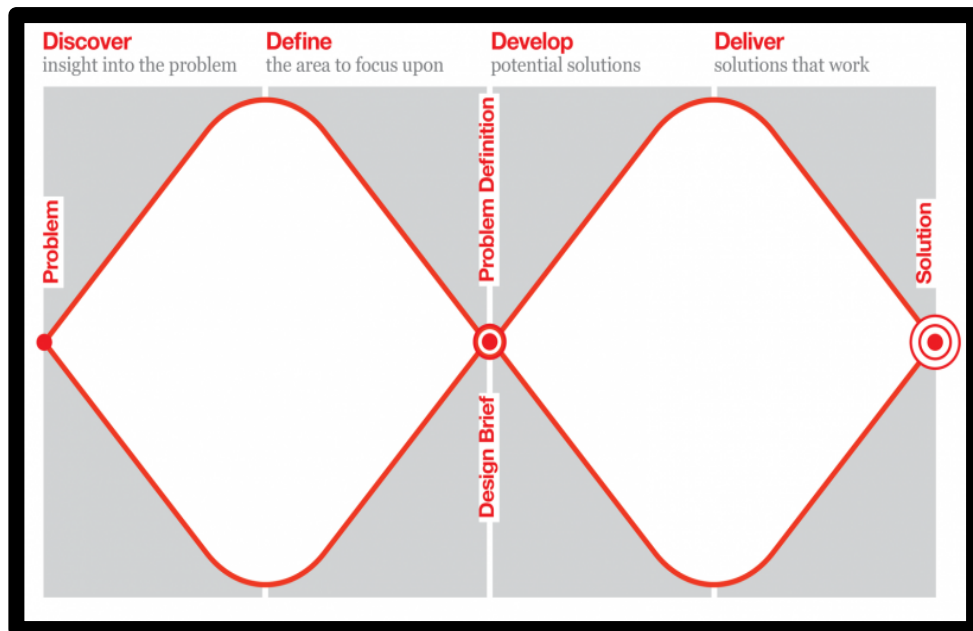


Figure 3.24: Double Diamond Model (Design Council 2015).

Combining the two models supported in gaining further clarity of the research and identifying final goals. Having the Engineering Design Model protrude through the double diamond model was a clear reflection of the research activity.

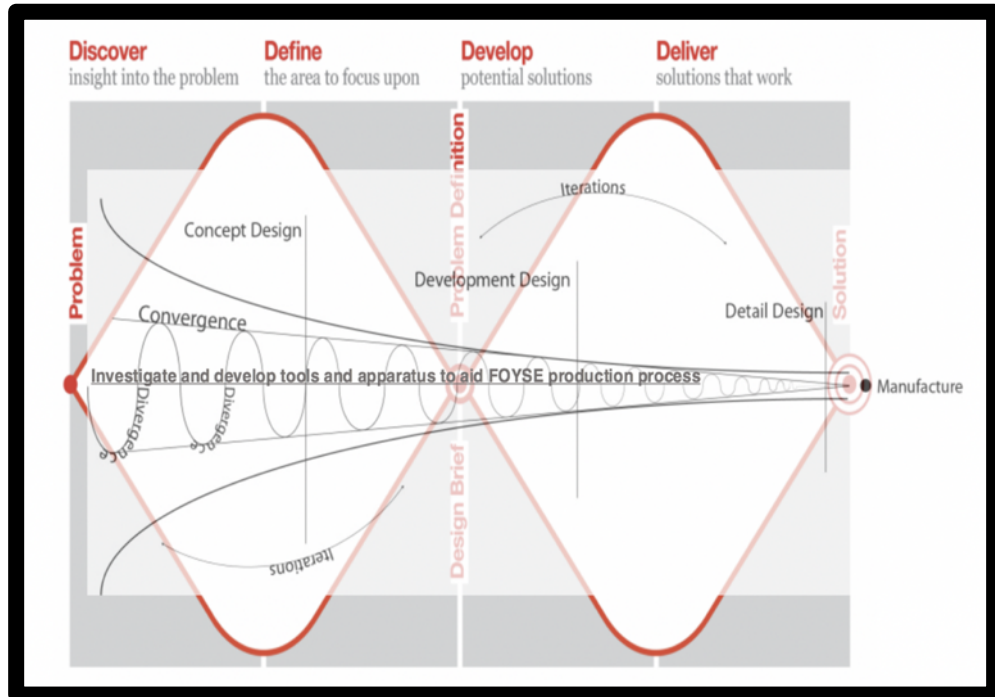


Figure 3.25: Double Diamond Model by Design Council combined with the Engineering Design Model from Engineering Design Methods by Nigel Cross.

Problem definition

DISCOVER

Limitation within textile manufacturing due to three classes of fabric construction methods
Question/insight
 Can fibre on yarn connecting create a new fabric surface?
 Adding a 4th class of fabric and process.

DEFINE

Test what influences yarn surface entanglement strength and appearance

DEVELOP

Use instruments to determine strength and market application

DELIVER

The interpretation of the data and the formulation of a theory to be completed

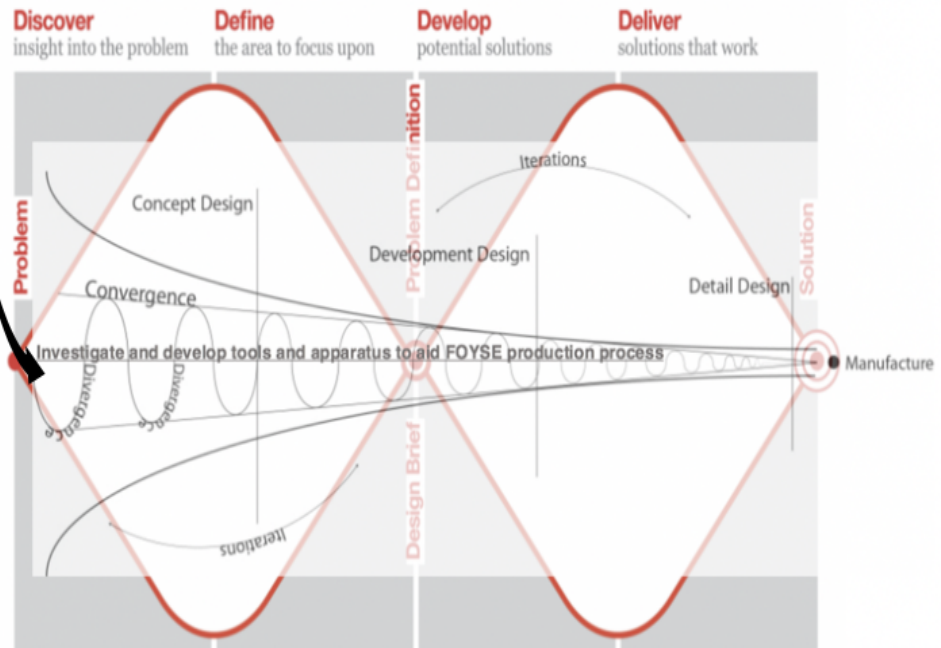
Engineering Design Model: Investigate and develop tools and apparatus to aid FOYSE production process

New apparatus to aid manufacturing process

Production process segmented into 5 sections

Raising fibre from yarn
 Tension feeding station
 Agitation/Entangling
 Drying/take up

Manual and semi-automated solutions



Experimentation tools for manufacture:

Use FOYSE manufacturing method to create samples via experiment and then observe results

Produce samples to demonstrate design and functional capabilities

Develop material into products for proof of concept for market application

Products create outside of the current three manufacturing classifications

Figure 3.26: Problem definition.

Two further research designs were considered but were deemed inappropriate due to the complexity of the research problem. The complexity arose due to the necessity of developing tools to assist in FOYSE manufacturing, concurrently with advancing the actual product and process.

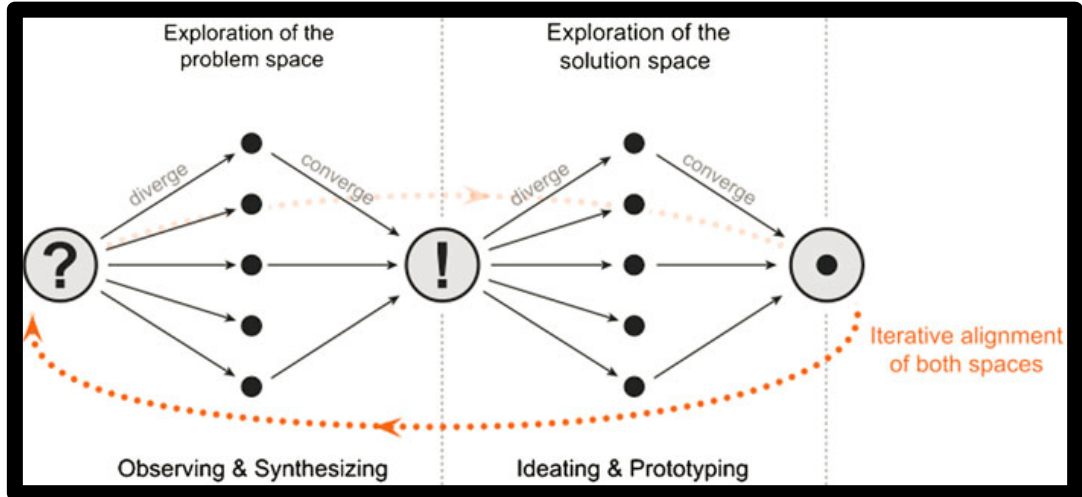


Figure 3.27: Basic Principles of Design Thinking Workflows (Lindberg et al., 2010).

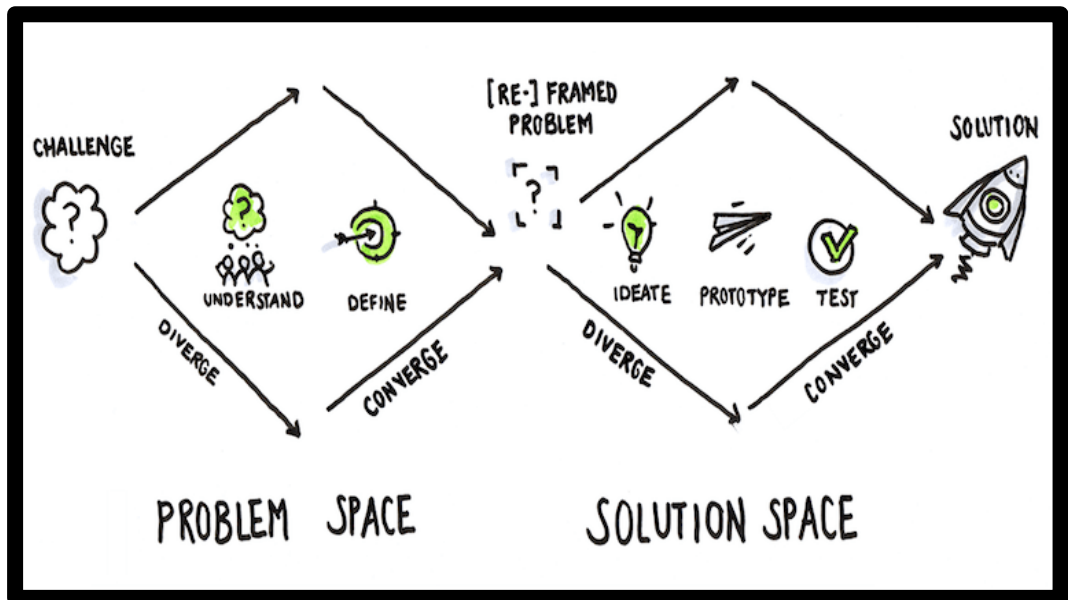


Figure 3.28: Design Thinking circular design (Zsakay 2018).

3.13 Framework Amalgamation Summary

The research question I am exploring is: Can the connection of fibre on yarn create a new fabric surface? This represents the starting point in all the three design thinking models presented. Understanding, observing, synthesising, and discovering are the headings assigned to this area. Out of the three research designs, discovery was the most appropriate as it best explained the approach to the design question. The second stage in each model is to investigate areas of the phenomenon most relevant to prove or disprove the hypothesis. Each of the design thinking models had different approaches. The Basic Principles of Design Thinking Workflows approach was observing and synthesising (Figure 3.27). The Design Thinking circular design was understanding and defining (Figure 3.28). Finally, the Double Diamond Model addressed the problem space with the headings for iteration, discover and design (Figure 3.24). The Lindberg design (Lindberg et al., 2010) has divergence and convergence in both problem and solution space of the design thinking process and the design feature of iteration for both spaces. Whereas the Design Thinking circular design does not have iteration and the design council model has iteration between problem, define, develop and deliver. Therefore, the design council model was used jointly with the Engineering Design Methods by Nigel Cross, see Figure 3.25.

The design models investigated were all part of fields that incorporated or could easily support innovation. The intertwining of four distinct processes within the research concluded that a single model would not be sufficient. This insight resulted in the research and final use of multiple models. The research concurrently experimented with product and process. This could not have been illustrated by simply placing the models next to each other. Therefore, placing one method on top of the other provided an accurate illustration of the process undertaken. The development also provided clarity and structure to both the product and development process.

3.14 Summary

Scientific instruments namely a microscope and tensile testing machine were used to analyse the samples created (research aims 1, 2 and 3). Observation of microscopic images was used to investigate relationships between the number of entangled fibres and material strength (research aims 1 and 3). A tensile testing machine was also used to test strength and tear resistance of samples in relation to British Test Standard ISO 2062 (research aims 1, 6 and 4). Data collection was continued to a greater extent by the collection of qualitative information. A structured questionnaire was used to identify distinct characteristics of the FOYSE fabric surface and diversion from the three known processes (research aim 6 and objectives A and B). The RepGrid was the tool used to carry out this process.

The data was collected and analysed using mixed methods. The inter-related concepts in Figure 3.26 were the organising model used to support my research study which was the development of a novel manufacturing process. It clearly defined my area of study by identifying what area of the phenomenon I will be investigating and how I will do it. Two forms of qualitative data are obtained in the research. An open-ended question was given to NTU students regarding their personal perception of fabrics created by FOYSE to address research aim 6. The second was an in-depth structure questionnaire which was completed via the repertory grid system which provided both qualitative and quantitative results to also address research aim 6. The knowledge gained from tensile testing results and microscopic observation identified that varying the density of fibre lifted from yarn surface, and then entangled, affected fabric strength and appearance which addressed research aims 1, 2A, 2B, 2C and 6. Chemical application and water temperature were also a factor that influenced strength and appearance. Research for developing samples used the systematic structure of differing the variables and constants listed in the following section experimental practice. This was conducted to address research aims 2C, 5, and objectives A and B. The next part of this thesis will detail the study of the FOYSE manufacturing process.

CHAPTER 4: A DETAILED STUDY OF THE FOYSE MANUFACTURING PROCESS

This chapter commences with an overview of the FOYSE process from conception to the argument for its position as a fourth class of textile. This proceeded to an analysis of the causes and parameters that influence appearance and strength of the fabric surface. This is undertaken through a detailed description of the FOYSE process including a chart detailing techniques and methods for fabric manufacture by known manufacturing and FOYSE. This is followed by an overview of the preliminary research undertaken incorporating both product and process; commencing by discussing the framework used in Chapter 3.

The chapter is then divided into sections, each focusing upon different fibre types, outlining the variables that describe their idiosyncratic appearance, functionality and the manual manufacturing process involved in developing these samples. I outline the methods developed for testing and recording as well as increasing the speed and scaling opportunities of the manufacturing process. Observations of fibre and yarn at a microscopic level are examined and documented both prior to and after chemical treatment. The chapter concludes with the results from the quantitative and qualitative data collection obtained from the manually manufactured samples.

4.1 Introduction to the FOYSE Manufacturing Process

FOYSE fabrics were birthed from my love for working with natural yarns and experimentation. As-long-as I can remember, I have been a creative always tinkering and investigating something new. Seeing yarns clumped together at the end of knitted panels I had put through a wash cycle just sparked a thought. Making the unsightly mess into something usable became my fixation. There began the journey of making material out of singular yarn ends without interlacing or interloping them. At that time, there was only one other textile manufacturing process which was nonwoven. Manufacturing fibres that are spun into yarn, and then into a fabric surface has been a mammoth task, which is justified due to the result regarding freedom of design expression and presenting a fourth class of textile to the world. The design consists of a vertical array of tensioned yarn which forms the fabric structure. The tensioned yarns must have a loose rather than rigid tension allowing retraction when the agitation process is taking place. Fibre retraction is a natural occurrence that takes place during water-based fibre entanglement, an action that bonds the fibres on the yarn together forming a fabric surface.



Figure 4.1: Schematic of Zephlinear.



Figure 4.2: Microscopic image of Zephlinear.

The array of yarns can be formed by the carrying of one continuous yarn as in the knit process. This method allows fabric lengths to be created in a batch system. Similarly, as in additive manufacturing (AM) commonly known as 3D Printing or Rapid Prototyping (Loh et al., 2021), one layer of yarn can be used to create irregular FOYSE fabric surfaces. This process can be built upon by precisely setting out a predetermined yarn foundation outside of a linear array and adding one layer at a time. The yarn can be positioned so that the yarn forms an end structure that has the character of a specific design structure. In general, the FOYSE process can present comparable benefits of AM including design freedom, low tooling start-up cost, rapid verification with reduced product development time (Loh et al., 2021). Alternatively, individual cones containing yarn can be placed onto a creel and used to feed each individual yarn in the array, similar to the laying of a warp in the woven process. This method allows the production of a continuous length of material rather than a batch process. This FOYSE unique manufacturing process adopts aspects from all three known methods of fabric construction.

1. An array of yarn is used like the warp of the weaving and warp knitting processes.
2. One feed to carry the yarn is best used for small batch production like the weft knitting process.
3. Fibre entanglement is used to entangle only the surface fibres of yarn to create a fabric surface like the felting process. However, the felting process creates fabric from fibre prior to being spun into yarn.

Incorporating different types of yarn, elements and embellishments can dramatically alter the fabrics' unique appearance and character. Assembling the fabric with thick and thin yarns or coloured yarn can create artistic designs. Insertion of differing components will further advance the practical and creative

process of fabric design. The current generation of textiles, including technical textiles, are passive (Dias and Arafa 2011).

It could be argued that varying design and enhancing the usage and efficiency of knit and weave could limit the advancement of current fabric manufacturing methods. Additionally, developments and demands for smart textiles and intelligent fibres are contributing factors to the lack of research into yarn manipulation of the fibre itself (Hearle 2005). Government bodies, Industry leaders, beneficiaries and researchers of the textile industry have focused on design styles and adaptation of current technology to accommodate advancing demands. An example of varying design style is a zig-zag pattern, using E-yarns containing LEDs, that was engineered to reduce breakage within the costume performance. Embroidery was the design style used to attach the yarn onto the costume (Hardy et al., 2018).

In addition, the insertion of active and reactive components into filaments and yarns for use within current industrial machines have also been the focus to accommodate the demand for E-textiles. A development of novel temperature sensing garments for health monitoring applications was investigated via 'new knitting techniques' (Lugoda et al., 2018). These demands are due to the continual increase of E-textile products being explored, from body motion capture to the prevention of diseases and side effects which is a multi-billion-pound industry (Hayward 2019). It appears apparent that the cost of making redundant ancient methods via current manufacturing machinery for advancing technology is too high a price to pay. However, historically and through scientific research, rarely have old methods been sufficient to contain new advancements. Very few adaptations have proven sufficient to become adopted into mainstream commercial use.

No man also seweth a piece of new cloth on an old garment: else the new piece that filled it up taketh away from the old, and the rent is made worse (Authorised King James Version 1611a).

The interpretation of new cloth according to the New International Version of the above text is unshrunk cloth. The ancient parable describes a problem of taking a new piece of textile fabric, possibly wool, and attaching it to an old piece of cloth. The result being a tear between the two materials during use or laundering. Breaking connector points is a common fault addressed when using E-yarns in current manufacturing processors and during wear (Hardy et al., 2018).

Thou shalt not wear a garment of divers' sorts, as of woollen and linen together (Authorised King James Version 1611b).

This text is a more specific account regarding the mixing of textile yarns made of incompatible fibre. Wool and linen have two very different properties, namely, uneven shrinkage. For this reason, manufacturers do not mix these materials together unless they have been chemically treated to react the same way during aftercare. Electrical circuits or components and E-yarn are a challenge to combine within textiles for many reasons, including uneven shrinkage. Additional problematic issues include the interlacing and interloping production processes as they incorporate bending, which can affect conductivity. Devices for detecting yarn breakage in a spinning or weaving machine such as a loom, knitting machine or warping machine are common. Yarn breakage during high-speed production processes occurs due to deficiencies in the yarn or a snag or knot due to tension (Makino et al., 1990). These points are also applicable to E-yarn as the embedded sensors if put under stress would affect conductivity. Despite the challenges, E-textile development continues to advance. Canadian engineer William Stephen George Mann is said to be the father of wearable technology. Mann is known for his work in augmented reality, computational photography, particularly wearable computing, and high dynamic range imaging. He states the following for the growth of the wearable technology sector.

This can be attributed to the decrease in size of electrical components and increase of personal portable electronics such as mobile phones. Early prototypes were quite obtrusive and often made people ill at ease, but more recently the apparatus has been gaining social acceptance. I attribute this partly to miniaturisation, which has allowed me to build much smaller units, and partly to dramatic changes in people's attitudes toward personal electronics (Mann 1997).

FOYSE manufacturing can complement structures that can sense the environmental conditions or stimuli, such as smart textiles. Also, FOYSE manufacturing can complement structures that not only sense, but react and respond to environmental conditions or stimuli too, such as intelligent yarns and components (Mohit 2011). The removal of interlooping and interlacing associated with yarn manufactured fabrics is replaced with a linear structure, an imperative characteristic of FOYSE manufacturing. In comparison, linear structures such as braiding, and warp knitting are two traditional but less widely known technologies (Ko 2014). These structures have been recently rediscovered and used in marine, automotive and aircraft applications where linear, tubular, and complex structural shapes are required. These structures also lend themselves for easy sensor incorporation, thus opening new design opportunities for multifunctional geotextiles (Ko 2014). E-yarns and conductive filaments can be easily incorporated within fabrics manufactured by FOYSE technology as the linear and tubular nature of E-yarn can be embedded within FOYSE without bending through interloping or interlacing. Also, computerised, and electrical components that cover a surface area larger than a typical yarn structure can benefit from the FOYSE process. This is due to fabric surfaces with large

areas of entangled fibre can be manufactured by FOYSE, providing capacity for embedding of such components.

FOYSE solves the problem of the limitation of having three classes of fabric manufacture. This is because nonwoven classification states the material is produced from fibre not passed through the spinning process. Therefore, FOYSE requires an independent classification as textile classification is dependent upon the technique used for its manufacture. When presented within a classification table FOYSE would be positioned as illustrated in table 4.3 with sub-classes.

Classification (structure)	Woven	Knit	Nonwoven	FOYSE
Sub-class (process)	Plain weave	Warp knit	Fibre entanglement	Zephlinear
Sub-class (process)	Twill weave	Weft knit	Fibre bonding	Hover- Tex

Table 4.3: Known fabric manufacture processes and structures with FOYSE.

The FOYSE process produces fabrics that have clear advantages over the limitations associated with current manufacturing processes. The result is a nonwoven that can function to a capacity like woven, knit, fibre bonded and entangled materials with added benefits. The additional characteristics of fabrics manufactured by FOYSE are present and in many cases matching the positive characteristics of the discussed fabric surfaces. The limitations that can be overcome, if desired, by the FOYSE manufacturing process are listed below. The original list was compiled by specialist retail buyer Angie Cox who studied fashion and psychology (Cox 2008). The strike through on the list indicates the limitation that can be overcome when using the FOYSE manufacturing process.

List of Limitations of the Three Known Manufacturing Processes

Limitations of woven:
<ul style="list-style-type: none">● Not as soft as knits
<ul style="list-style-type: none">● Don't always stretch and sometimes feel restrictive
<ul style="list-style-type: none">● Dirt can get trapped between a tightly interlaced fabric making it laborious to launder (dry clean and press)
<ul style="list-style-type: none">● Wrinkle quite easily
<ul style="list-style-type: none">● Relatively more expensive
Limitations of knits:
<ul style="list-style-type: none">● Lack a certain "crispness"
<ul style="list-style-type: none">● Never as dressy as a woven
<ul style="list-style-type: none">● Shrink and stretch out
<ul style="list-style-type: none">● Look shabby fast (less stable fabric composition)
<ul style="list-style-type: none">● Can cling in the wrong places thereby spotlighting muffin top
Limitations of nonwoven:
<ul style="list-style-type: none">● Little or no recovery if the fabric is stretched.
<ul style="list-style-type: none">● Structure sometimes feels restrictive
<ul style="list-style-type: none">● Too much stress fabric will pull apart and cannot be mended
<ul style="list-style-type: none">● Dense structure can appear unattractive

All textiles have both positive and negative characteristics (Hollen and Saddler 1968). However, due to the FOYSE process lending itself to all three processes, the negative characteristics can be addressed due to the nature of the manufacturing process. For example, yarns used to manufacture the FOYSE structure can be spaced to avoid dirt trapping within the fabric surface. A FOYSE structure with a woven appearance can be achieved without the process of the interlacing of yarns which allows the fabric to be constructed quicker. Using hairy yarn instead of loose fibres produces a fabric that can be mended as the yarns provide a structured surface that can be repaired.

4.2 Explanation of Manufacturing and Parameters that Influence FOYSE Appearance and Strength

A towelling cloth is laid flat on a tabletop to absorb water solution and provide tension so that the yarns stay in place. In Figure 4.4, individual woollen yarn, which can vary in thickness, are placed parallel on the flat towelling surface, and secured either end with masking or duct tape. In Figure 4.5, the yarns are brushed to loosen and uncurl the surface fibre on each woollen yarn; care is taken not to brush harshly which could cause yarn breakage. At this stage embellishments such as additional woollen yarns can be laid randomly or in a set shape or beads can be added to some of the woollen yarn in the parallel array. This can be accomplished by releasing from the tape the individual yarn required to accommodate the beading and then placed in the original position once beads have been added. Soap solution containing pH 9 value is lightly applied by hand to the woollen yarn. The straightened fibres are softly smoothed by hand in a rotation formation until they form an even surface by the entanglement and locking of the surface fibres. The towelling cloth and woollen yarns are then rolled tightly ensuring that the yarn and fibres stay as much as possible in the position they were placed. With this manual rolling process, it is impossible to guarantee the position of the parallel array of yarn; the nature of the rolling can allow some yarns in the array to move slightly. The towelling cloth is secured tightly and placed on a 30-minute wash cycle (minimum) of 40 degrees centigrade, ending in a spin that leaves the towelling cloth damp. When the wash process has ended, release and separate the newly formed woollen fabric, Zephlinear from the towelling cloth.

The manufacturing process may take a form different to that specifically described above to increase design capability, accommodate differing yarns or increase speed. Three instances of this are listed below:

1. Wash temperature and pH 9 value soap solution application can be on a varying scale depending on the original yarn thickness, the final weight and texture of fabric required.

2. Applying a second layer of yarn at a 90 degrees angle provides a stronger fabric with a unique characteristic which has been named 'Hover-TEX.'
3. The brushing process can be removed if using yarn with an already hairy surface.

The manufacturing process of Zephlinear has been documented and successfully replicated by NTU BSc Product Design students. It was imperative for the students to have a clear understanding of the systematic manual production process of Zephlinear prior to attempting to create workstations to automate the process. A selection of photographic images of the student's work are presented in my Transfer Report 2016 pages 35-38 (Appendix 1). Below are photographic images of the initial stages in the Zephlinear production process.



Figure 4.4: Photograph of yarn in parallel array secured with duct tape.



Figure 4.5: Photograph of yarn in parallel array having been brushed.



Figure 4.6: Zephlinear sample created by brushed fibre raised to 1-2 cm.

A chart detailing techniques and methods for fabric manufacture by known manufacturing and FOYSE is summarised in the following table (Table 4.7). The table illustrates that FOYSE is made from yarn yet incorporates the entangling of fibres. The combination of yarn and fibre entanglement is the novelty of the fabric surface. It is important to note that testing was carried out using a solvent to secure the entangled fibres. This proved successful but was not a part of the research. However, it established that through further research FOYSE could be secured by the wet finishing process and/or fibre bonding as in traditional nonwoven technology.

Techniques and Methods for Fabric Manufacture

Techniques

	WEAVE (INTERLACING)	KNITTING (INTERLOOPING)	NONWOVEN (FIBRE BONDING)	ZEPHLINEAR (FOYSE)
UNSPUN FIBRE			✓	
SPUN YARN	✓	✓		✓
INTERLOOPING OF SINGLE YARN		✓		
INTERLACING OF TWO YARNS	✓			
NO INTERLACING OR INTERLOOPING			✓	✓
APPLICATION OF WATER TO FORM FABRIC			✓	✓
BRUSHING PROCESS TO FORM FABRIC				✓
FIBRE BONDING			✓	✓
FOYSE (FIBRE ON YARN SURFACE ENTANGLEMENT)				✓

Table 4.7: Chart detailing fabric manufacture.

Zephlinear created by FOYSE can manufacture a variety of fabric surfaces. The addition of a second layer at varied angles increases the strength, appearance, and function capabilities of the fabric. Hover-Text created by FOYSE in addition to adding strength creates increased space available for embedding additional yarns and components. Adding layer upon layer multiple times widens design possibility and provides capability of raised areas within the material creation. Further modifications of FOYSE technology will be apparent without departing from the scope of wetting, agitating and drying yarn to create a fabric surface.

4.3 Product and Process

With reference to the Design Council's 'Double Diamond Model', as outlined in Chapter 3, I refer to the 'discover' aspect to develop 'insights into the problem'. These insights are needed to enable me to develop the FOYSE manufacturing method to create samples via a methodological and repeatable research process. Manufacture apparatus to aid in the FOYSE production process was embedded within the concept design space of the model. As was the premise of fibre being raised from the yarn surface using friction to then entangle and thus form the material structure. Being able to scale the process from the 'domestic' process, which I had initially identified prior to beginning this research, to a more industrial scale meant that developing a more efficient method of raising the fibre from the yarn surface was an important problem to solve.

Demonstration of the 'domestic' methods which were used to develop the early manual manufacturing process of FOYSE will now be detailed. To avoid repetition, the images focus on items used for the first two steps in the FOYSE manufacturing process which are to secure the yarn and raise fibre from the yarn surface via a brushing process. The tools and materials used in the process are listed below.

- Shetland wool oatmeal.
- A lid used as a surface to hold yarn in place.
- A brush to release yarn from fibre.



Figure 4.8: Yarn being tensioned ready for the bushing process.



Figure 4.9: Image of brush used to raise fibre from yarn.



Figure 4.10: Image of fibre being raised from yarn.



Figure 4.11: Fibre raised from yarn using a brush.

The method for FOYSE manufacture demonstrated in Figure 4.8 to 4.11 describes the production process in a one-off production process. There are four production methods used within the textile industry (Virtual Learning 2017) which are:

- One-off production – Where individual products are made, often from a prototype.

- Batch production - A small quantity of the product is made, and this could be from two up to one hundred.
- Mass production - Many products are made on a production line and is likely to include several hundreds. This is often called repetitive flow production.
- Continuous production - Many thousands of products are made.

The straightening (uncurling) of the fibres on the surface of yarn by each brush stroke would be enhanced by the area of the bristles and the density of the brush. Therefore, various brush types were tested to identify a method to increase performance in the scope of raising the fibre from the yarn surface. The first brush type utilised was a Boar Bristle Paddle Hairbrush, an 'off the shelf' product. The product was chosen due to its large surface area of the bristles, which is approximately 5cm x 7cm.

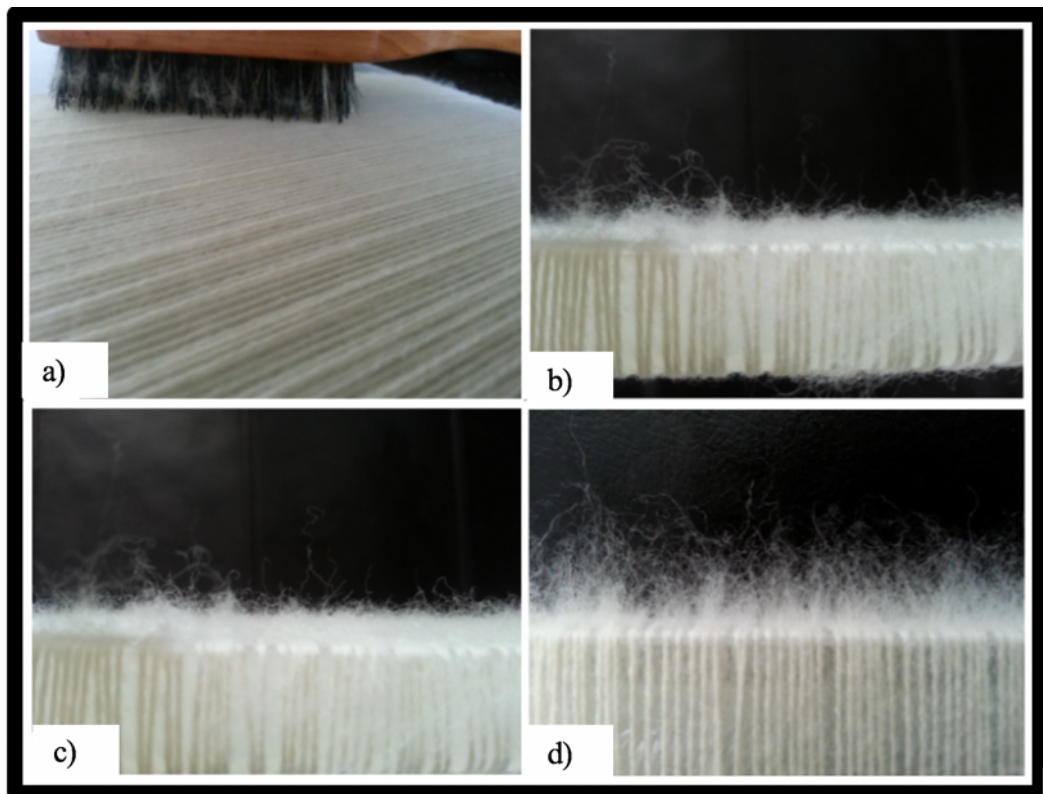


Figure 4.12: (a-d), a) Boar Paddle Hairbrush is placed on parallel array of yarn; b) Front perspective showing top and bottom of yarn with surface fibre raised and released; c) Fibre raised from yarn surface within two minutes of brushing; d) released from yarn surface with five minutes of brushing.

For comparison purposes several brush types were investigated to test their ability to raise the fibre from the yarn surface. This included a kit of three brushes all identical in size but containing varied bristle heads,

made from nylon, stainless steel and brass. The total length of the brush size was approximately 20 cm, the handle section 11.5cm and the brush bristle area approximately 1.5cm x 8 cm. An iterative testing process was completed to test the effects of applying these various brush heads to one type of yarn. Observation revealed the stainless steel and brass brushes pulled a larger portion of the fibre from the yarn structure. This indicates that rather than straightening the fibre on the yarn surface, these bristles would cause the fibre to break and weaken the yarn. However, the brush with the nylon bristles had to be applied with greater force by additional pressure against the yarn surface than in comparison to the brushes with stainless steel and brass bristles. Observation revealed that the flexibility of the nylon bristles resulted in the bristles slipping against the yarn surface rather than gripping the surface fibres on the yarn to cause them to rise. In comparison to the stainless steel and brass bristles, only small sections of fibre could be raised from the yarn surface at each brush stroke. None of the mentioned brushes were as effective as the Boar Bristle Paddle hairbrush. The large area of bristles on the boar hairbrush, and the fact that the bristles have tiny scales similar to wool, are contributing factors to its superiority over the other brushes.



Figure 4.13: Brush types tested nylon, stainless steel and brass.

The first step toward the development of an automated FOYSE manufacturing process is to mechanise the manual brushing of woollen yarns to straighten the surface fibres. Attaching a cylinder brush to a hand operated power drill to speed up the process was investigated. Brush types tested were made with plastic

bristles that are similar in performance to the Boar Bristle Paddle hairbrush I had used in the manual process. The result proved successful in straightening fibre from the yarn surface at a higher speed and more consistently than a manual-powered operation.



Figure 4.14: Cylinder hairbrush attached to a powered hand drill.

4.4 Variables and Influencing Factors

Yarn with a certain degree of 'hairiness'¹² is essential for the FOYSE process and is one of the key factors which influences the mechanical strength of the resultant fabric. Therefore, it is important to consider the length of fibres protruding out of the yarn surface and scales of the wool yarn. I therefore created several stages to test several variables in the process.

Stage 1 is to identify factors involved in developing a stable scaling up method.

- Creating a suitable workspace is the first consideration when seeking to scale production.
- Identify the size of fabric surface required.
- Investigate the production method i.e., batch or continuous flow, incorporating tools and apparatus development.

Stage 2 is to identify suitable yarns for the FOYSE process. The following yarns were proven to be successful for FOYSE manufacture.

- Hairy yarn.
- Yarn made of fibre that has scales.
- A mix of hairy and smooth yarn¹³.

Fibre webs used in nonwoven fabrics can be entangled and bonded via air, heat and solvents. Therefore, it was important to investigate if alternative methods would be available for bonding surface fibres that did not have scales. One sample constructed of 100% acrylic yarn was tested but deemed unsuitable for FOYSE due to the absence of scales on the fibre.

Stage 3 is to modify suitable yarns for improved appearance of FOYSE and function around stretch and retraction. This involves new apparatus design which would differ depending on the yarn choice.

¹² Yarn hairiness is a complex concept, which generally cannot be completely defined by a single Figure. Faults due to the hairiness of yarn have resulted in the introduction of measurement of hairiness. Especially weaving and knitting as this influences the characteristics of the product obtained.

¹³ Smooth yarn is yarn with undeveloped scales such as mohair or smooth surface such as silk.

- Brush yarn (manual/powered).
- Brush types tested (stainless steel, brass, nylon, plastic, hair).
- Created method/tool that secures yarn while undergoing brushing.

Stage 4 is to create a suitable surface and equipment for manufacture to include scale up and strength.

- Identify suitable apparatus to wrap yarn around and create appropriate tension (e.g., plastic container lids and table mats were tested),
- Flat surface (a table-top to provide a large surface to test scale up).

Stage 5 is to identify suitable surfaces when using a flat surface for manufacture. A flat surface was used to support the parallel array of yarn.

- Towel high fleece.
- Towel low fleece.
- No fleece surfaces.
- Mix bottom fleece top no fleece.

Stage 6 is to create tension when using a flat surface for manufacture.

- Knitting weight combs.
- Double sided tape.
- Knitting pins.

Stage 7 is to identify a method of creating parallel arrays of yarn.

- Manual
- Automated

Stage 8 is to identify methods for applying imagery or embellishments for fashion or function.

- Freehand
- Create imagery prior to application.

Stage 9 is to identify a method to classify visual design variations.

- Structured
- Semi-structured
- Free hand

Stage 10 is to identify yarn to enhance FOYSE appearance and functionality.

- Coloured yarn
- Textured yarns
- Smart yarn
- Intelligent yarn

Stage 11 is to test chemical and water application to control FOYSE appearance.

- Varying pH 9
- Water temperature
- Wash time

Stage 12 is to test the finishing process.

- Spin time
- Drying time

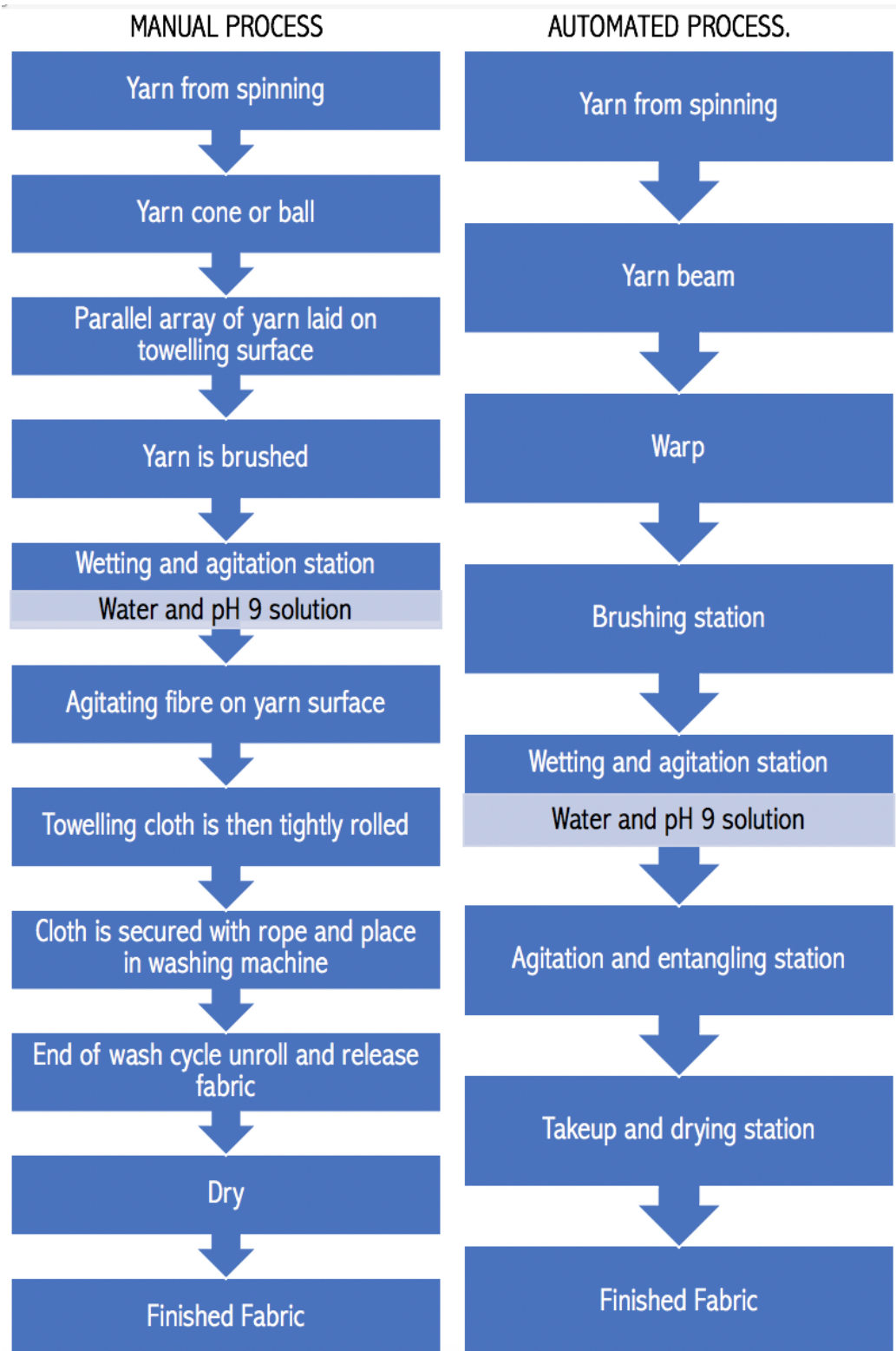


Figure 4.15: Flowchart of manual and automated process.

4.5 Fibre to Yarn Manufacturing Process

The type of fibre used to manufacture yarn influences the entanglement process used in FOYSE manufacturing. In-depth research and testing of fibres was conducted for this investigation. The results from experimentation and testing with different types of fibres and yarns have shown that the process can successfully accommodate wool and wool blended yarn without use of chemical substances. However, the process is strongest when using 100% wool and a mixture of 5ml of pH value soap solution with a minimum of 500ml of water to aid the entanglement process. This is due to the natural ability of wool fibre to lock together when exposed to moisture, agitation, and heat (Rippon 2008). Wool has a unique surface structure as it is the only textile fibre with a layer of overlapping scales on the surface (Rippon 2008). This provides wool with the ability to entangle fibres with significant strength. Below are 3D microscopic images of animal fibre types used in sample creation and testing. The washing of the fleece experiments, which is detailed in section 4.3, also provided evidence in line with known knowledge that the scales on the surface of wool fibre are responsible for the entanglement process.



Figure 4.16: From left to right: Silk, Cashmere, Alpaca, Fine Wool, Coarse Wool (Hall 2016).

The British Wool Marketing Board has offered support to this research by providing wool from British Sheep. I requested samples of fleece prior to being spun into yarn to identify the yarn types suitable for

entanglement. Following the experiments on the wool fibre samples several experiments were completed on spun yarn. The varying processes produced yarn with differing properties and appearances, two of which are given below. Characteristically, woollen and worsted yarn have differences which are illustrated in the following images.

Worsted

Spun from wool fibres of:

- Length : longer than 3"
- Diameter: fine diameter

Fibres are washed, scoured, carded, combed and drawn

Process

Yarn

- Fine
- Smooth
- Even
- Tighter twist
- Higher tensile strength

Characteristics

- Less insulator
- Holds creases and shape
- More durable than woollens

Figure 4.17: Worsted yarn characteristics and image (Atalie 2017).

Woolen

Spun from wool fibres of:

- Length : spun from short fibres of 1-3"
- Diameter: medium or coarse

The fibres are washed, scoured and carded.

Yarn

- Bulky
- Uneven
- Low to medium slack twist
- Tensile strength lower than worsted

Characteristics

- Insulator due to trapped air
- Does not hold a crease well
- Less durable than worsted

Figure 4.18: Woollen yarn characteristics and image (Atalie 2017).

4.6 Novel Methodology to Measure Fibre Entanglement

I observed the six fibre samples provided by the British Wool Board using an Olympus Digital Microscope. Firstly, in their original state and then after undergoing a 40°C wash cycle with one 5ml of soap solution applied directly into the drum of the washing machine. The washing machine used is "Renlig " which has a wash-time of 90 minutes, the program's duration included a 1200 spin time. The six samples were all placed side by side onto a towel and rolled into a cylinder. The cylinder was secured by a nylon knitted tube and then placed into the washing machine drum. Once the 90-minute wash cycle was completed, the towel containing the fleece samples was removed from the drum of the washing machine, and the nylon tube was removed, releasing the towel, and revealing the washed fibres. The fibres were then left to dry naturally and when dry observed under the microscope. As expected of fibre agitated with pH and water solution, the fibres had entangled together. This testing of the six samples informed the decisions I made about the type of wool fibres which would entangle most effectively to create mechanically strong fabrics using the FOYSE process. Visual observation was used to investigate the assumption that the more intense the entanglement of the fibres the stronger the resultant fabric. This was determined from observing the level of fibre entanglement prior to fibre samples undergoing a 40°C wash cycle and the level of entanglement measured after fibre samples had undergone a 40°C wash cycle. From observation of microscopic images, it was clear in all six samples that after a 40°C wash cycle fibre entanglement occurred.

This process was also used to identify a method to measure the resistance level of entangled fibres, and this was completed by tugging strongly between the fingers and using embodied knowledge of the tension required. By observing microscopic images of the six fibre samples, they revealed that prior to undergoing a 40°C wash cycle, large areas of open space were clearly perceived. After undergoing a 40°C wash cycle less areas of open space were visible when viewed under the microscope. The area of fleece observed was 1280x960. Observing the decrease of open spaces proved a viable method for determining the level of entanglement. To demonstrate this, the spaces have been outlined with a white border on the microscopic images.

The higher the entanglement, the less visible open space was present on the microscopic images. To support the visual observation, the samples were handled to assess strength increase. The fibre samples prior to being washed had very little resilience when being pulled apart. The six fibre samples after undergoing a 40°C wash cycle increased in strength considerably to the extent that the fibres could not be pulled apart when strongly tugged. This validated the claim that the higher the fibre entanglement the

stronger the fabric surface. The results from testing different fibres are directly transferable when the fibres are spun into yarn. The results are transferable due to FOYSE manufacture creating textiles by entangling the fibre on the yarn surface. The following Figures 4.19 to 4.25 detail the fibre samples photographed at 1280 x 960, and they are annotated with white lines to indicate open space of fibre prior to going through a washing process. The green lines indicate the open space after fibres have gone through the washing process. By comparing the spaces with the white lines of the prewashed fibres and the spaces with the green line after washing the spaces decreased after the washing process.

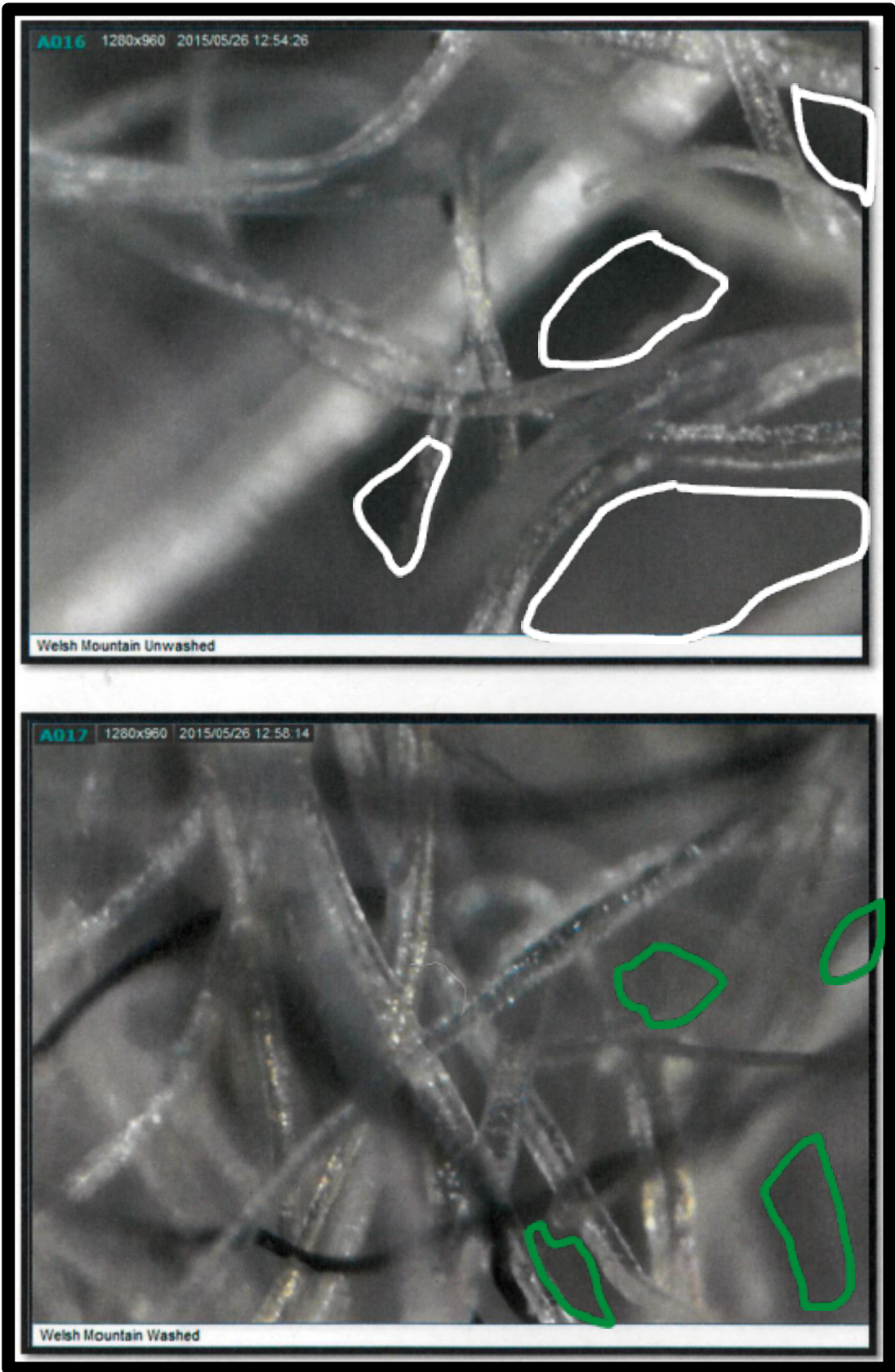


Figure 4.19: Welsh Mountain Wool unwashed and washed showing open space reduction.



Figure 4.20: Suffork Wool unwashed and washed showing open space reduction.

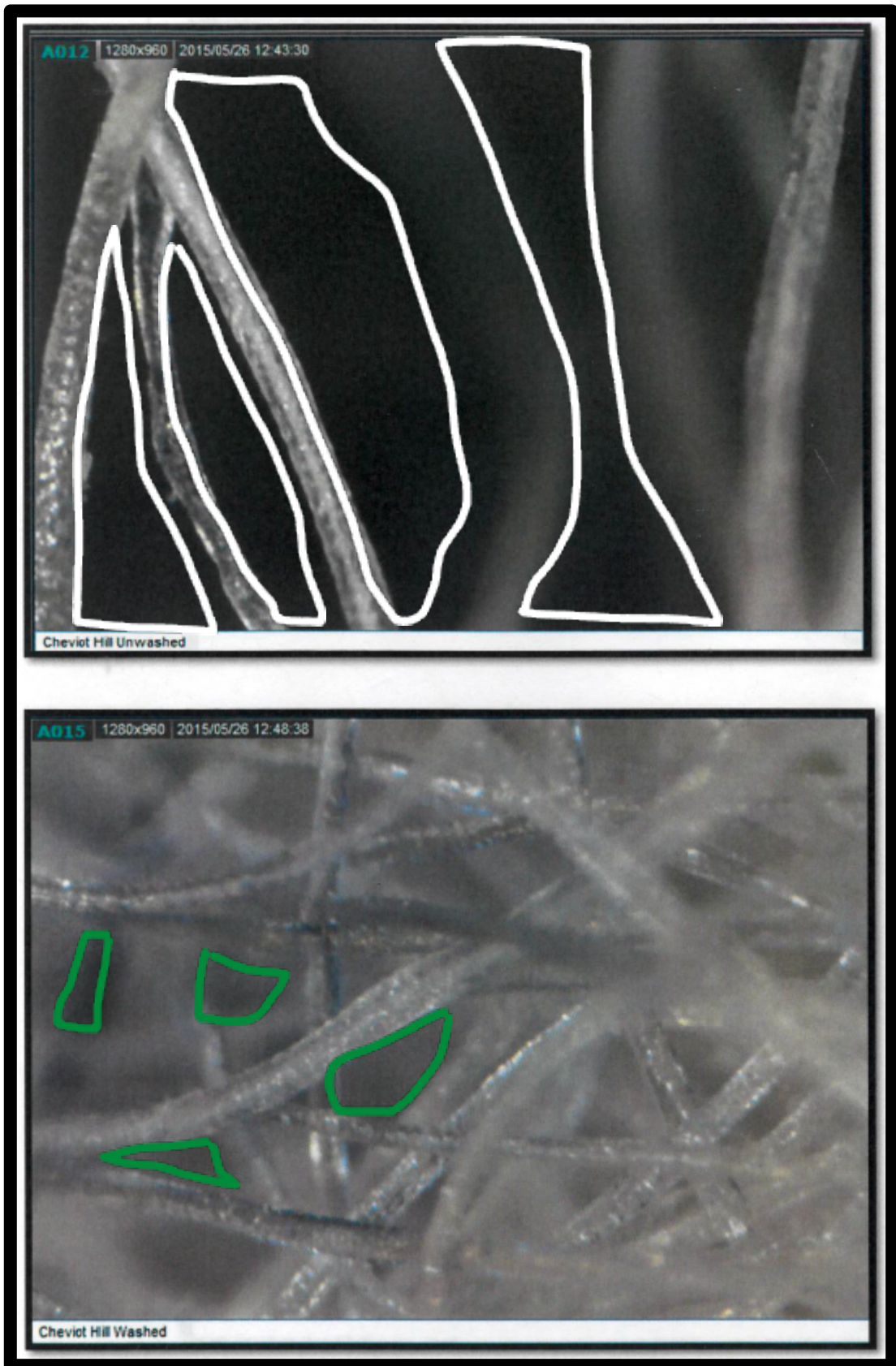


Figure 4.21: Cheviot Wool unwashed and washed showing open space reduction.



Figure 4.22: Mule North of England Wool unwashed and washed showing open space reduction.



Figure 4.23: Cheviot fleece on the left unwashed and on the right washed.

Figures 4.23 and 4.24 support the conclusions derived from the microscopic images as the fleeces on the left (unwashed) appear fluffy and on the right (the 40-degree washed samples) appear dense and matted. There are seven British wool types reared in the UK and these are listed in Figure 4.25. All the fibres from these sheep underwent wash tests except for Lustre Bluefaced Leicester fleece which was unavailable for testing at the time of the experiment. The images of the seven types of fleece samples in Figure 4.25 appear fluffy and without entanglement. This further illustrates those fibres prior to going through the washing process seemingly have no natural entanglement.

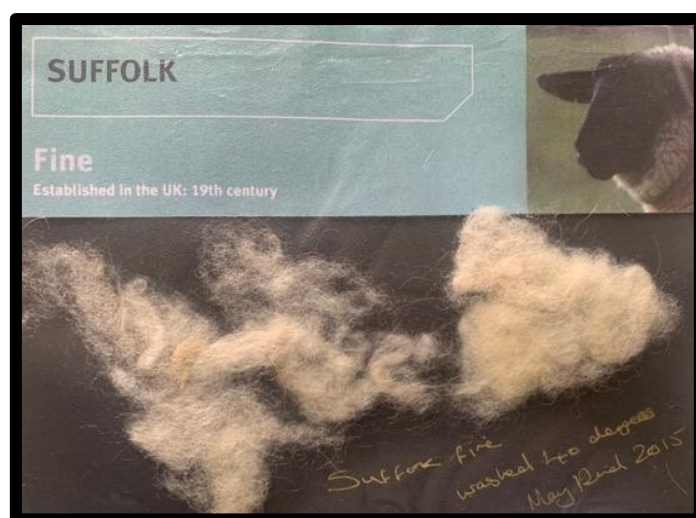


Figure 4.24: Suffolk fleece on the left unwashed and on the right washed.















Fine	Medium	Cross	Lustre	Hill	Mountain	Naturally Coloured
Suffolk	Welsh Halfbred	North of England Mule	Bluefaced Leicester	Cheviot	Welsh Mountain	Jacob
						
29 - 35	31 - 35	29 - 35	26 - 35+	30 - 33	35+	30 - 35+
						
Woven apparel, futons & hand knitting.	Woven apparel, hand knitting & carpets.	Knitwear & carpets.	Lustrous yarn, knitwear & woven apparel.	Woven apparel, knitwear & carpets.	Carpets.	Woven fabrics, knitwear & carpets.

Figure 4.25: Image and descriptions of 7 British wool types.

4.7 Suitable pH Conditions for Entangling Wool Fibre

The soap solution used to entangle the fibres on the surface of yarn is a product called fairy liquid which is level pH 9 (Procter and Gamble 2016). Water temperature will determine how quickly the fibre will felt. In practical terms, one should use hot water between 40-50°C. Some felt makers shock the fibre by alternating it between warm and cold water (Nancy 1988). This allows the scales to open out on the fibres making them coarse. This technique produces a fabric acceptable for carpets but not suited for next to skin garments.

Agitation is the final ingredient. Pressure forces the air out of the fleece so the [fibres] can come in contact with one another. Beginning with careful massage and circular motions this allows the [fibres] to slowly migrate to produce a thin stretchable felt. This is a slow process and can't be rushed (Nancy 1988).

Using both woollen and worsted spun yarn samples I conducted some testing by varying water temperature, wash time and pH 9 solution. Lowering the temperature in the entanglement of the yarn process to 40°C from 60°C has proven to be significant regarding the strength of the entanglement.



Figure 4.26: Unwashed samples.



Figure 4.27: Sample washed for five minutes showing 15 mm length reduction.



Figure 4.28: Sample washed for ten minutes showing 27mm length reduction.

The higher the water temperature the greater the fibre entanglement which is clearly visible by the evidence of yarn shrinkage. This is evident in Figures 4.26-4.28, therefore removing the pH 9 conditions has proven again to have significance in the entanglement of fibre spun yarn. The greater the presence of soapy solution, then, the greater the fibre entanglement that again is visible by the yarn shrinkage. However, increasing the end washing time, which affects the level of agitation, appears to compensate for the lowering of water temperature and absence of soapy solution. It should be noted that the entanglement process and yarn shrinkage that occurs in the wool samples are irreversible. Again, a random approach was taken for the sole purpose of identifying yarn ideal for the FOYSE manufacturing process.

4.8 Results of Experiments to Test Impact of Variables on Fabrics Created by FOYSE

Detailed experiments have been completed on a variety of FOYSE structures varying water temperature, agitation, and pH solution. Altering water temperature, lowering soapy solution, changing times of agitation and wash cycle has proven that regardless of the variance FOYSE materials can still be manufactured. The photo and microscopic images are evidence of the creation of stable FOYSE structures which related to research aims 1, 2A and 2B. The layering of the yarn and raising of fibre from yarn is consistent regardless of temperature used to entangle the surface fibres. However, increasing the end washing time, which affects the level of agitation, appears to compensate for the lower level of soap. I will outline the results of the eight samples, detailing the process and variabilities from start to finish: yarn type, brushing process, pH solution, tension, wetting, wash cycle and dry/spin time. Lowering the temperature in the production process to 40°C from 60°C has proven to be insignificant regarding how yarns are positioned in the fabric construction process. This is important to note due to some fabric designs using the FOYSE process may require multiple layers of yarn.


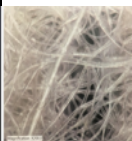



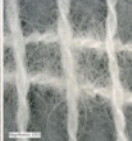


Yarn	Brushing	pH/Water solution	Tension	Wetting agitation hand	Wash Cycle Machine	Drying/Spin	Photo	Microscope Image
100% Lambswool 2/15 NM	1 cm (50-70 strokes average)	1 teaspoon. to 500ml	0	Lightly wet and create surface skin	40 degrees centigrade	1200 RPM spin dry temperature 60		
100% Lambswool 2/15 NM	1 cm (50-70 strokes average)	1 teaspoon. to 500ml	Yes	Lightly wet and create surface skin	40 degrees centigrade	1200 RPM spin dry temperature 60		
100% Lambswool 2/15 NM	1 cm (50-70 strokes average)	1 teaspoon. to 500ml	Yes	0	40 degrees centigrade	1200 RPM spin dry temperature 60		
70% Mohair 30% Silk Silver thread	0	1 teaspoon. to 500ml	Yes/loose	0	60 degrees centigrade	1200 RPM spin dry temperature 60		

Table 4.29: The results of eight samples detailing the FOYSE process they underwent (1/2).


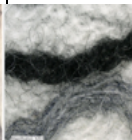





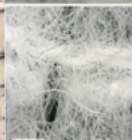
Yarn	Brushing	Ph/Water solution	Tension	Wetting agitation hand	Wash Cycle Machine	Drying/Spin	Photo	Microscope Image
100% Lambswool 2/15 NM	1 cm (50-70 strokes average)	1 teaspoon. to 500ml	Yes/Loose	Lightly wet and create surface skin	40 degrees centigrade	1200 RPM spin dry temperature 60		
100% Lambswool 2/15 NM	1-1.5 cm (120 strokes average)	1 teaspoon. to 500ml + teaspoon	Yes/Secure	Lightly wet and create surface skin	2x40 degrees centigrade	1200 RPM spin dry temperature 60		
100% Lambswool 2/15 NM + Elastic	1 cm (50-70 strokes average)	1 teaspoon. to 500ml	Yes/Secure	0	40 degrees centigrade	1200 RPM spin dry temperature 60		
100% Lambswool 2/15 NM + Rubber	1 cm (50-70 strokes average)	1 teaspoon. to 500ml	Yes/Secure	0	60 degrees centigrade	1200 RPM spin dry temperature 60		

Table 4.30: The results of eight samples detailing the FOYSE process they underwent (2/2).

4.9 Summary

As a result, from the sampling methods, experiments, fibre and yarn tests it is concluded that the type of fibre used to manufacture yarn influences the entanglement process used in the FOYSE production process. Varying water temperature and pH solution also has a different effect on the process and fabric surfaces manufactured by FOYSE. The microscopic data results from the six fibre samples that underwent a wash test all revealed that the washing process reduced open areas (Figure 4.19-4.22). In addition, they also confirmed that the open spaces varied from sheep breed (Figure 4.23-4.25). To obtain an understanding on the reason for this occurrence I recommend further research regarding wool fibre properties. The three points below were also proven to have significant influences in the structure and strength of samples created by the FOYSE process (Figure 4.12).

- Yarn with a certain degree of hairiness due to fibres on the yarn surface is essential for the FOYSE process.
- Height of yarn raised from the surface of fibre.
- Water temperature and solution.

These findings have significant implications for understanding how fabrics manufactured by the FOYSE process can be manipulated, to alter the fabric appearance. The eight samples in Table 4.29 illustrate that non-textile embellishments can be embedded between the fibre on yarn to enhance fabrics manufactured by the FOYSE process. Applied together, the findings of this chapter suggest multiple fabric surfaces can be created by slight alteration in the brushing and washing process to create FOYSE products. The following section of this thesis will investigate the material properties of fabric surfaces manufactured by the FOYSE process.

CHAPTER 5: A DETAILED STUDY OF MATERIAL PROPERTIES OF TEXTILES MANUFACTURED BY FOYSE

BY FOYSE

The fabrics created by the FOYSE manufacturing method have a distinctive visual appearance in comparison to other known methods of textile manufacture - weaving and knitting. Unlike weaving and knitting, fabrics produced by FOYSE do not have a point at which yarn is interlaced or interlooped.

5.1 Fabric Structures

Woven fabric is manufactured by a process that visually has yarn crossing over and under (interlacing). This method removes the fluency of the yarn which creates its own visual distinction. Within the plain weave structure shown in Figure 5.1, the weft yarn crosses over a warp yarn, then disappears under the next warp yarn, then reappears again, and this interlacing is constant. Another example is presented in the twill weave structure, Figure 5.2. Rather than the interlacing crossing over one yarn the crossing takes place over two yarns. In Figures 5.1 and 5.2 the structures are presented with a red arrow to identify the direction of the warp yarn within the fabric. The arrowhead points directly to the warp yarn meeting the weft yarn.

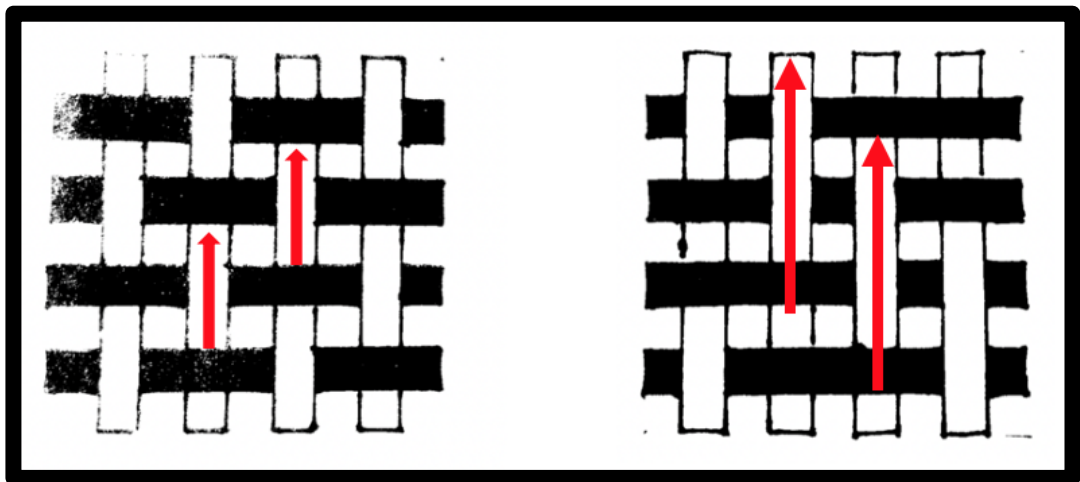


Figure 5.1: Plain Weave Structure.

Figure 5.2: Twill Weave Structure.

The visual distinction in knit fabric can be viewed in this illustration of the front and back of an inter-looping structure. Rather than the interlacing of two yarns taking place vertically and horizontally as in the woven structure, within the plain knit structure a single yarn is inter-looped horizontally. As the yarn interloops to create a new row of stitches the knit creates its own visual distinction shown by the red arrow in Figures 5.3 and 5.4. Another contrast between woven and knit structures is that, while the weave structure has a similar appearance on both the front and reverse side, the plain knit structure has evident visual differences.

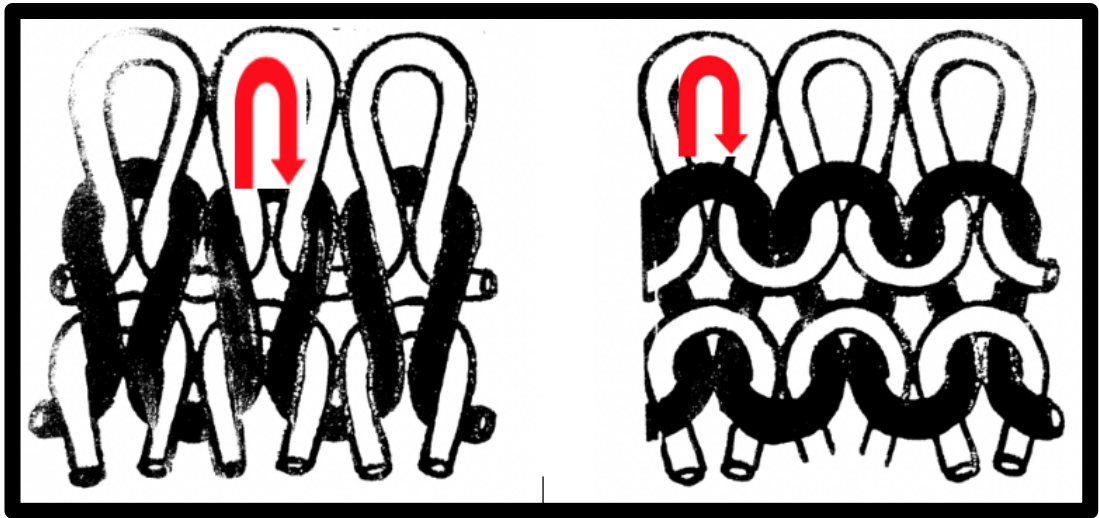


Figure 5.3: Plain knit technical front.

Figure 5.4: Plain knit technical reverse.

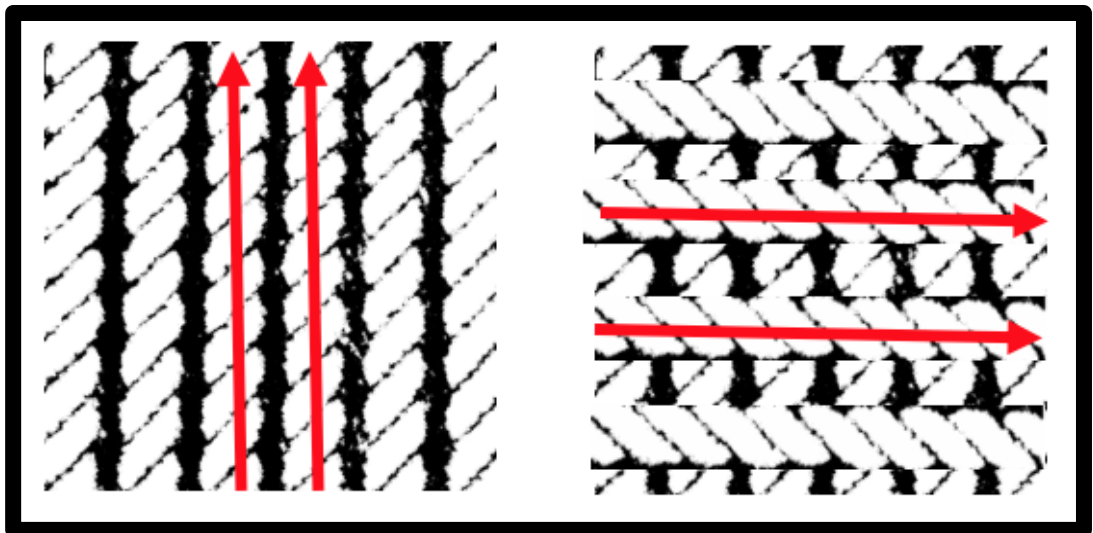


Figure 5.5: Zephlinear by FOYSE.

Figure 5.6: Hover-Tex by FOYSE.

The nonwoven structure does not have a systematic, regular appearance which can be identified in weave and knit textile samples. FOYSE fabrics have their own, idiosyncratic visual appearance which is the result of agitating continuous lengths of yarn. Zephlinear in Figure 5.5 demonstrates the yarn connected parallel by fibres raised from the yarn surface and then entangled. Hover-Tex is an advancement of Zephlinear and adopts an additive approach to fabric manufacturing. Additive manufacturing (AM) is the term used for 3D Printing or Rapid Prototyping. Hover-Tex holds similar advantages to additive manufacturing such as products that are created one layer at a time in position within a design domain. In general, the benefits of AM include design freedom, low tooling start-up cost, rapid verification with reduced time to market in

product development, service, and increased R&D efficiency (Loh et al., 2021). Placing an additional parallel array of yarn at a 90-degree angle also adds the capacity to embed large components between the two layers. This transforms the visual appearance and enhances the strength of the end material due to the doubling of the yarn layer.

5.2 Aesthetics of FOYSE Fabrics

5.2.1 Tactile Characteristics

Whereas aesthetic concerns visual sensation, tactile characteristic concerns perception by touch. Whether a fabric is experienced as soft, coarse, hard, or smooth they all have impact upon the end use applications of the fabric. The tactile characteristic of FOYSE is dependent upon the manufacturing process and yarns used in the product manufacture. The placement of the yarns is a secondary factor to the material's tactile characteristics and influences, particularly the surface structure of the material's utility. For example, if a design has large uneven sections on the surface, it can then have the tactile characteristic of being bumpy and uneven rather than smooth. Also, the density of the yarn has a contributing factor to the materials performance in this area. If the fabric is dense then it can be perceived as being a hard structure rather than soft. The sample below is created using 100% worsted spun yarn count 2/17NM whereby the yarns are positioned near each other. The final fabric is smooth and dense providing a structure that would be suitable for formal and outerwear such as suiting or coats.

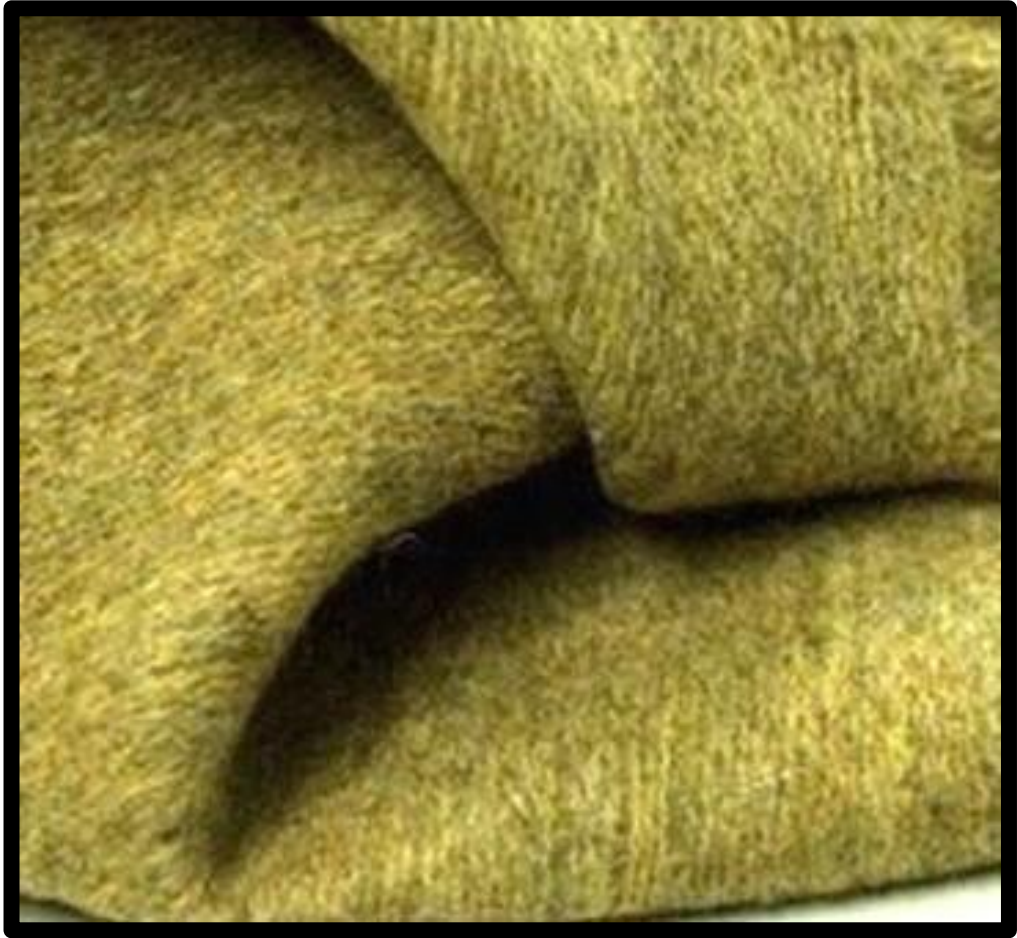


Figure 5.7: Zephlinear created with high quality finish determined by smooth surface.

5.2.2 Visual Aesthetics

Aesthetics comfort is the subjective perception of clothing by visual sensation (Brand 2004). In addition, these characteristics have direct influence with tactile sensation such as how the material feels on the surface of the skin. Aesthetic qualities are defined as a relationship among a minimum of six concepts, seven are listed below that are an important consideration in the development of a new fabric (Brand 2004):

- Style - related to colour, fabric application.
- Body – fabric structure.
- Cover – finish i.e., visual appeal.
- Surface – effects – print, embellishment, yarn qualities.
- Texture – of yarn and resulting fabric.
- Drape – weight of fabric, application to other fabrics i.e., lining fabric and product application.
- Resilience - abrasion resistance which influences fabric performance.

The aesthetic characteristic of FOYSE fabrics is dependent on both the manufacturing process and the choice of fibre used to create the yarn. However, the FOYSE manufacturing process can be adapted and manipulated through creative exploration and design knowledge to influence and effect the visual aesthetics and tactile characteristics. For example, the fibres used to manufacture the yarn can be modified to alter lustre which affects the brightness of the resulting fibre, and this in turn affects the intensity of dyeability which influences the depth of colour. The result of such modifications can make nylon look like a natural fibre such as silk, illustrated in Figures 5.8 and 5.9.

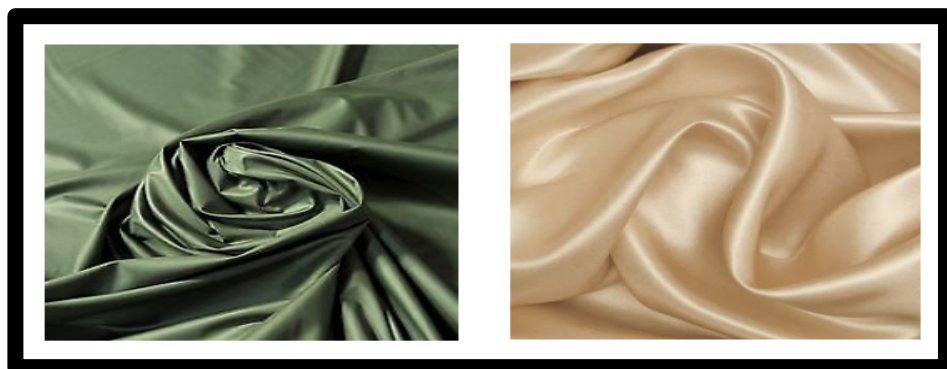


Figure 5.8: Nylon Satin Source: Pinterest.

Figure 5.9: 100% Silk Satin Source: Pinterest.

Theoretically, it could be argued that the FOYSE process can produce a fabric surface that can be modified to an extent that it does not look or perform like typical wool, but a cotton fabric as in Figure 5.10. Therefore,

increasing functionality and the potential end use for FOYSE manufactured fabrics. The image in Figure 5.10 is a handmade fabric created using the FOYSE process, made from 100% merino wool inlay with a mohair and silk outer layer, it creates a fabric surface comparable to 100% cotton handmade Edwardian lace (Figure 5.11).



Figure 5.10: Zephlinear Floral Cobweb Source: Library Artstor.

Figure 5.11: 100% Silk Satin Source: Pinterest.

The illustration below shows at least three layers of yarn. The first and third layer are horizontally or vertically placed depending on how the sample is positioned. The embedded yarn is composed of red, blue, and gold yarn. The process of FOYSE entangles these layers together forming a unified fabric manufactured using a mohair and silk mixed yarn for the main structure. The structure is embedded with a metallic lurex, fine wool and luxury yarns cashmere and angora. The yarn for the main structure is placed 8 to 10mm apart and embellished with the yarns previously mentioned, resulting in a fabric surface that has the tactile characteristics of a soft and highly flexible open structure. This would be suitable for fabrics with high breathability often worn to keep an individual cool such as lace garments.



Figure 5.12: Sample created using FOYSE process.

5.2.3 Density

The density of fabrics manufactured by FOYSE determine the materials performance capabilities, and this is influenced by the production process itself and the characteristic of the yarn used. Area-density of structures created from woven fabric is determined by the number of warp yarns and weft yarns within a selected area. However, FOYSE can be manufactured with just a warp or a weft in isolation as in the woven structure. The higher the number of yarns in this design within a selected area, the higher density. Several experiments were completed on spun yarn, by using varying water temperatures, wash time and removal of pH 9 concentration. Increasing the temperature in the entanglement of the yarn process to 40°C degrees

to 60°C degrees has proven to be significant regarding the strength of the entanglement. In a surface width of 10 mm, 4 yarn ends are visible when the sample is washed at 40°C degrees (Figure 5.13). After a 60°C degrees wash, although hard to visualise due to the density of the material, over 6 yarn ends are evident (Figure 5.14).

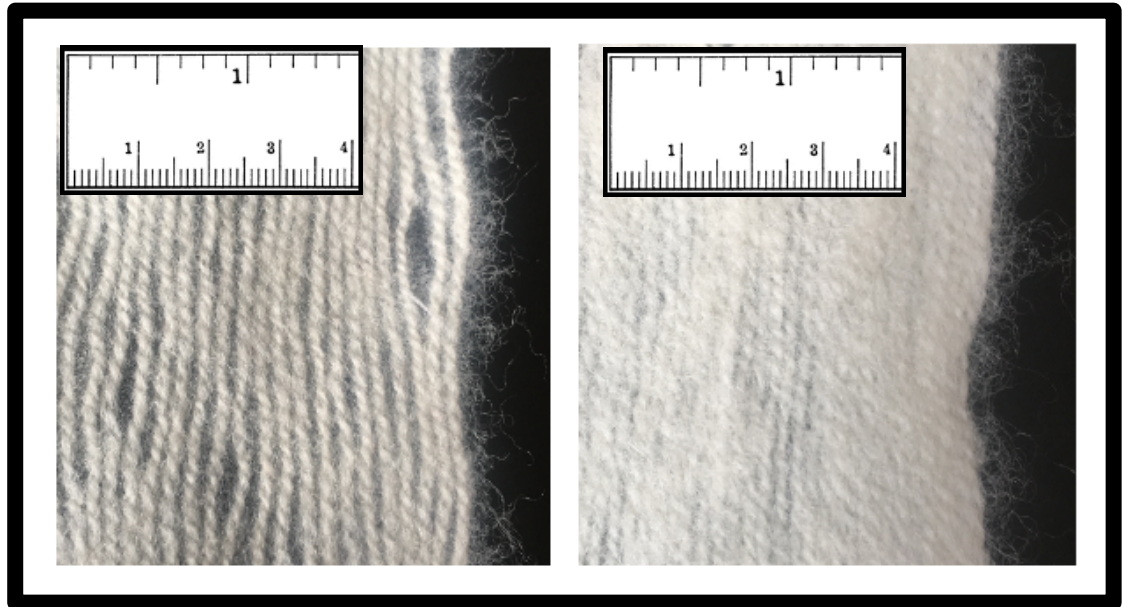


Figure 5.13: Sample washed 40°C degrees.

Figure 5.14: Sample washed 60°C degrees.

The higher the water temperature the greater the fibre entanglement; this is clearly visible by the evidence of yarn shrinkage. Also, removing the soapy solution has proven to have significance in the entanglement of the yarn process. The presence of soapy solution causes greater fibre entanglement that again is visible by the yarn shrinkage. Samples of the yarns used in the experiments for yarn shrinkage are presented below.



Figure 5.15: Unwashed wool yarn.



Figure 5.16: Washed 60°C minus soap solution.

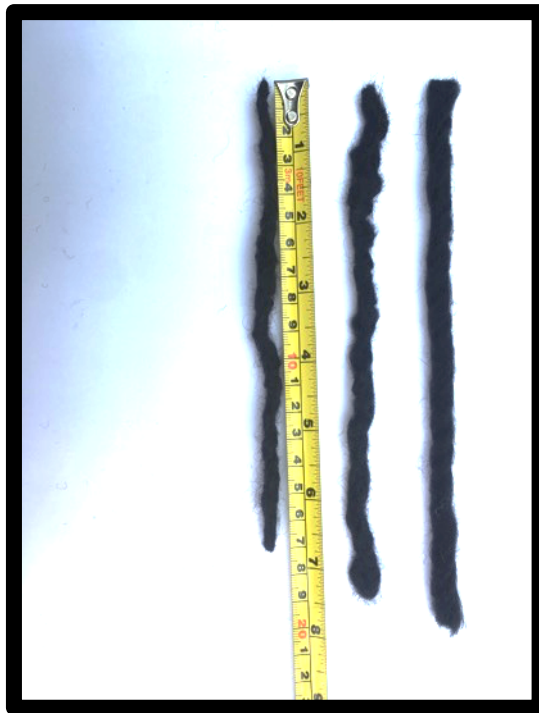


Figure 5.17: Washed 60°C with soap solution.

5.2.4 Elasticity and Stretch

When developing a FOYSE fabric, yarns can be embedded in between the vertically and horizontally placed yarns creating a multi-layered fabric surface that is unique in its structure. Placement of the embedded yarn influences the elongation and flexibility of the material's utility; and by introducing elasticated yarn there is an enhancement and elongation. As identified when considering the aesthetic characteristics of FOYSE fabrics, the elongation capacity is also dependent on both the manufacturing process and the yarns used in the fabric production process. Depending upon the distance of the parallel yarns, FOYSE fabrics can elongate up to 40% with full retraction: 200mm without stretch, 270mm with stretch as in Figures 5.20 and 5.21. In addition, FOYSE fabrics have been tested to elongate from 145 mm to 230 mm as in Figure 5.23. The wider the parallel yarn is placed apart, then, the greater the elongation. The details of the yarns used in the samples are the Mohair & Silk Mix yarn specifications (Figure 5.18) and the Falkland wool yarn specifications (Figure 5.19).


Product specifications	
Blend	Mohair & Silk Mix
Brand	Rowan
Length	210m
Material	70% mohair, 30% silk
Needle Size	3.25-5mm
Ply	Fine
Tension	18-25sts and 23-34 rows
Washing Instructions	Hand wash
Weight	 25g

Figure 5.18: Mohair & Silk Mix yarn specifications.

Description	Specification
Yarn Details	
Count	1/5 Nm
Composition	100% Falkland Wool
Shade	Undyed
Yarn Style	Single
Hand Knitting Range	4 Ply
Suggested End Uses	Hand Dyeing, Hand Knitting, Machine Knitting, Hand Felting
Package Details	
Hank Weight	100g
Metres / Hank	Approx 495 m
Sales Unit	
Hank	5 x 100g Hanks per pack

Figure 5.19: Falkland wool yarn specifications.

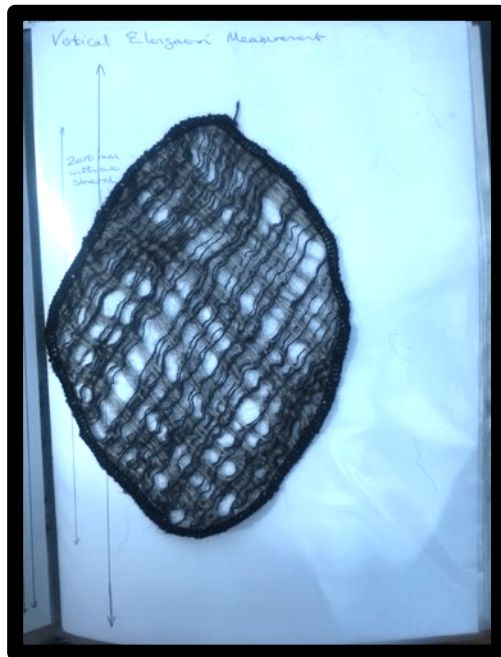


Figure 5.20: Sample 200mm unstretched.



Figure 5.21: Sample 270mm when stretched.

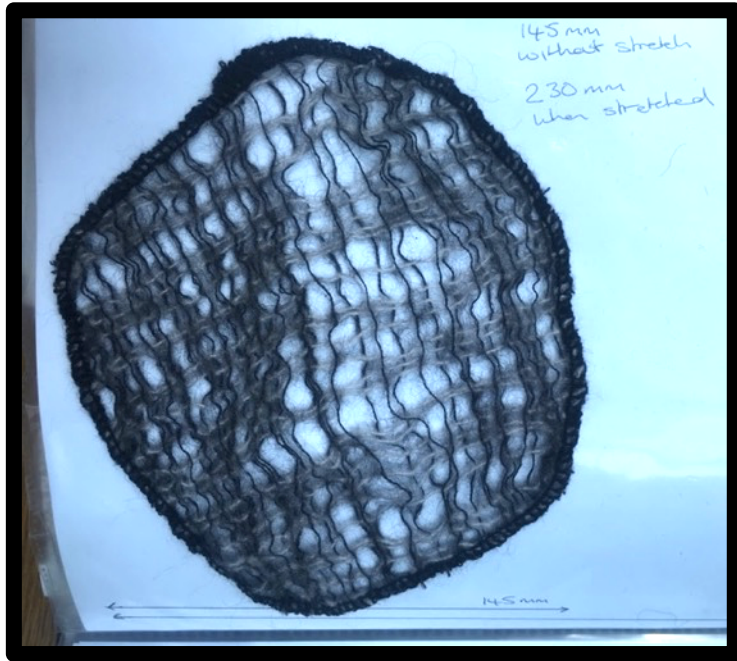


Figure 5.22: Sample 145mm unstretched.

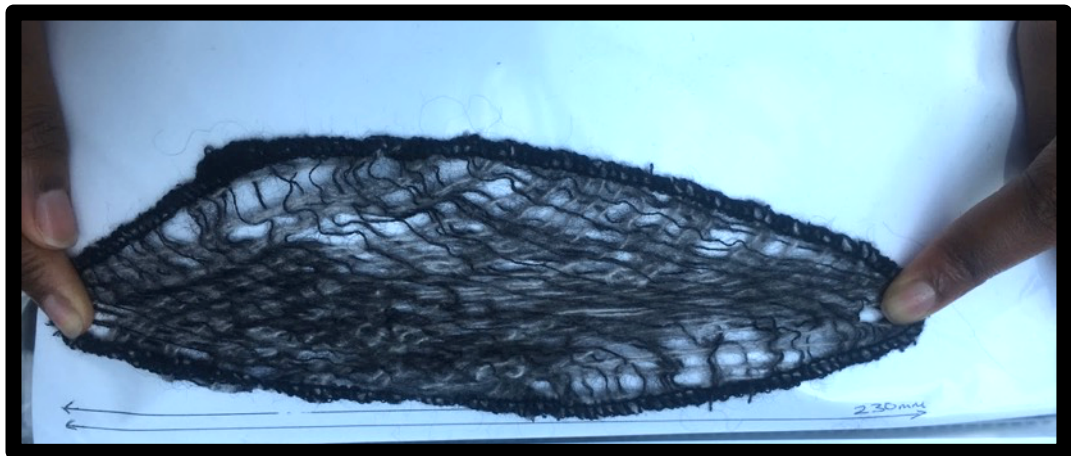


Figure 5.23: Sample 230mm when stretched.

5.3 Durability Characteristic via Tensile Strength

Tensile testing¹⁴ have been completed on Zephlinear fabrics and Hover-TEX fabrics. Six samples of Zephlinear fabrics were tested in the first batch of tests with a basic summary. Two samples of Hover-TEX were in a second batch of tensile tests with an in-depth summary. Each of the Zephlinear samples in the first batch underwent tensile tests in the weft direction. One sample, in the first batch was named stripe lambswool and was manufactured with low fibre entanglement. Another sample, in the first batch was named lambswool and was manufactured with high fibre entanglement. The stripe lambswool sample was divided into two sections for each one to undergo tensile testing for comparison. The results of these two samples are presented in Figure 5.25 and the results are defined as follows. The lines on the graph represent the stress-strain curve which is a graphical way to present the reaction of the sample when load is applied. The green line in the series graph section is defined as the first stripe lambswool sample that underwent tensile testing. The dark red line in the series graph section is defined as the second stripe lambswool sample in the first batch that underwent the tensile testing. A further sample named as lambswool was divided into four equal sections for each sample to undergo tensile testing. An image of one of these samples is presented in Figure 5.28. The four curves represented in Figure 5.26 are defined as each of the four lambswool samples which underwent tensile testing in the first batch of tensile tests.

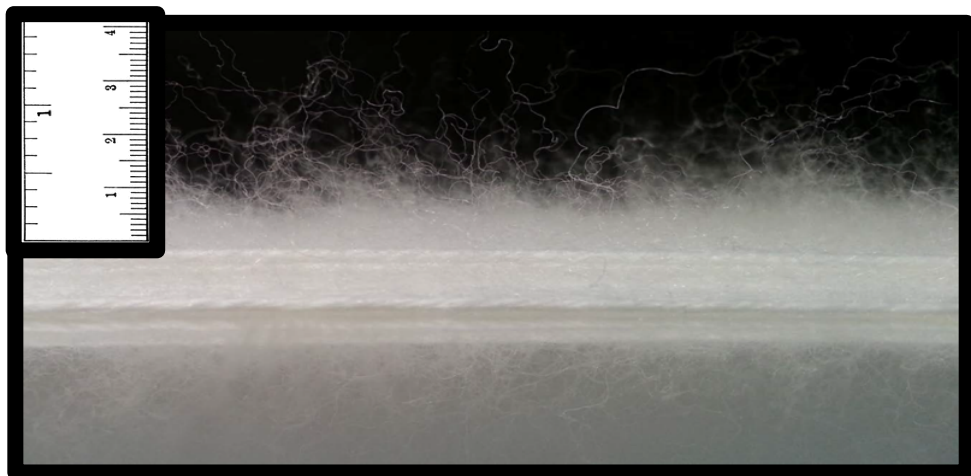


Figure 5.24: Side view image of a parallel array of yarn 10cm by 10 cm brushed for 100 strokes creating raised fibre on yarn averaging to 2 cm.

¹⁴ Tensile Testing of fabric is a destructive test process that provides information about the breaking strength of material. It is an industry standard of mechanical testing of textile resistance against force.

The test results of the stripe lambswool sample provide data that reveal one sample registering a high fibre breaking strength and breaking force of 600 cN. The second sample of the stripe lambswool provides data that shows one sample registering a high fibre breaking strength and breaking force of 450 cN. The results from the further four lambswool samples are given in Figure 5.26. The test results of these four lambswool samples provide data that shows two samples registering a high fibre breaking strength and breaking force in the region of 2000 cN. The two remaining samples registered a high fibre breaking strength and breaking force in the region of 4000 cN. All Zephlinear samples in the first batch of testing have a strength suitable for textile material according to British Test Standard ISO 2062. In comparison, the tensile strength of a single jersey made from 100% cotton has the maximum breaking force between 211 N and 235 N with an average 220.8 N along the length of the fabric and between 149 N and 166 N with an average of 159 N across the width of the fabric (Sitotaw and Adamu 2017). The Zephlinear and Hover-TEX samples were all brushed until they had raised fibre on average of 1-2 cm as in Figure 9. The varied height of surface fibre is due to the brushed yarns having irregular raised points when raised from the yarn. Brushing a sample 10 cm by 10 cm for 100 strokes is adequate for producing a nap of surface fibres which will entangle allowing a fabric strength and breaking force of 600 cN as in Figures 5.27. Brushing a sample 10 cm by 10 cm for 150 strokes is adequate for producing a nap of surface fibres which will entangle allowing a fabric strength and breaking force of in the region of 2000 cN as in Figure 5.28. Varied chemical application and water temperature are also factors that affect the fabrics end strength. Sampling at this stage is limited due to the fabric currently being manufactured manually.

Test report

Customer : NTU
 Test standard : ISO 2062:2009
 Test device : Zwick Tensile Tester
 Supply identifier : Statex

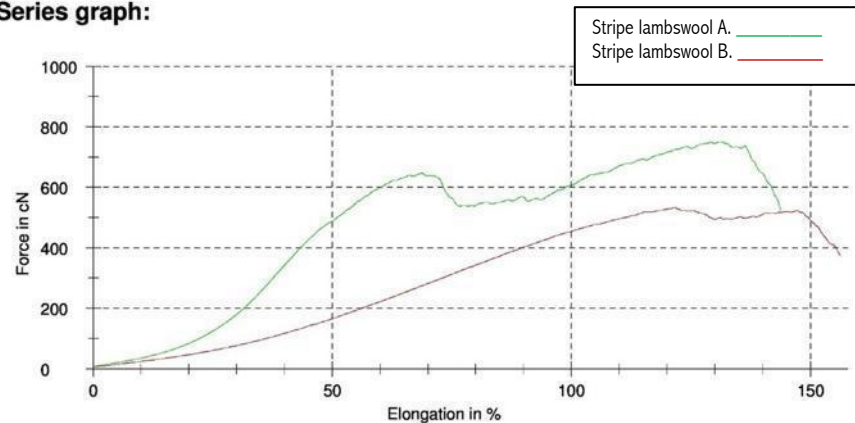
Specimen type : Stripe lambswool .zs2
 Tester : Colin Cork
 Note : Test to ISO2062:2009

Test speed : 250 mm/min
 Grip to grip separation at the start position : 80.00 mm
 Travel preselection x% : 1.00 %
 Force preselection : 100.00 cN

Test results:

Nr	J ₀ cN/tex	J _{ch} cN/tex	F _x cN	B _x cN/tex	ε _x %	F _H cN	B _H cN/tex	ε _H %	W _H mJ	T _u J/g	F _B cN	R _B cN/tex	ε _B %	W _B mJ
1	1.40	1.01	7.63	0.0325	36.2	533	2.27	120	238.42	12.7	373	1.59	156	376
2	2.16	1.48	9.99	0.0425	22.3	751	3.20	130	461.81	24.6	525	2.23	144	542

Series graph:



Statistics:

Series	L	J ₀	J _{ch}	F _x	B _x	ε _x	F _H	B _H	ε _H	W _H	T _u	F _B	R _B
n = 2	mm	cN/tex	cN/tex	cN	cN/tex	%	cN	cN/tex	%	mJ	J/g	cN	cN/tex
x	80.00	1.78	1.25	8.81	0.0375	29.2	642	2.73	130	350.11	18.6	449	1.91
s	0.00	0.538	0.328	1.67	0.00712	9.87	154	0.655	5.4	157.96	8.40	107	0.456
v	0.00	30.21	26.34	18.98	18.98	33.77	23.99	23.99	4.29	45.12	45.12	23.85	23.85

Figure 5.25: Image of tensile tests showing two curves relating to stripe lambswool samples as in Figure 5.27.

Curve graph:

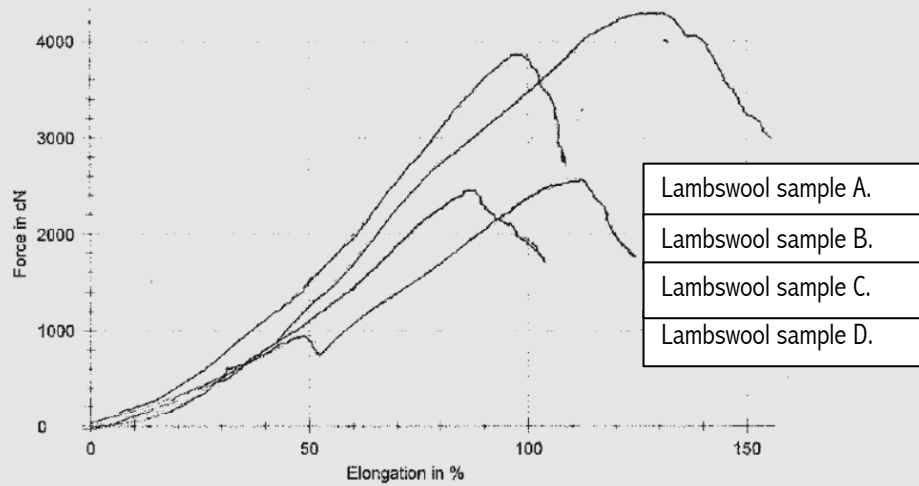


Figure 5.26: Image of tensile test results lambswool as in Figure 5.28. Identified as A to D from end point, ascending order.

The Zephlinear samples were placed horizontally in the grips of the Zwicki tensile testing machine allowing only the entangled fibres to receive stress. Therefore, the breaking point measurement is formed when the entangled fibres on the yarn are breaking apart. The results show visually a bending of the linear line which indicates the fibre on the yarn is breaking at a steady rate. This demonstrates that a consistent tearing action is occurring when the grips on the Zwicki tensile tester are moving apart. This is significant as it demonstrates that the fibres within the Zephlinear samples are responsible for the tensile strength.



Figure 5.27: Stripe lambswool.



Figure 5.28: Plain lambswool.

Two samples of FOYSE manufactured material were tensile tested and the results from each test are below in Figure 5.29 and 5.30. Each of the samples were tested 4 times in the warp and weft direction resulting in the testing of 8 samples in total for each design. The nature of Hover-Tex is to have yarn laid horizontally and vertically. The result of this is that the breaking point of the material is mainly subject to the strength of the yarn rather than the fibre entanglement. Unlike the Zephlinear tensile results, the Hover-Tex results show abrupt changes giving a zig zag visual appearance. This visual effect is contributed to the yarn snapping at breaking point when the sample has stress applied such as in the nature of the tensile testing process.

Hover-Tex Tensile Testing

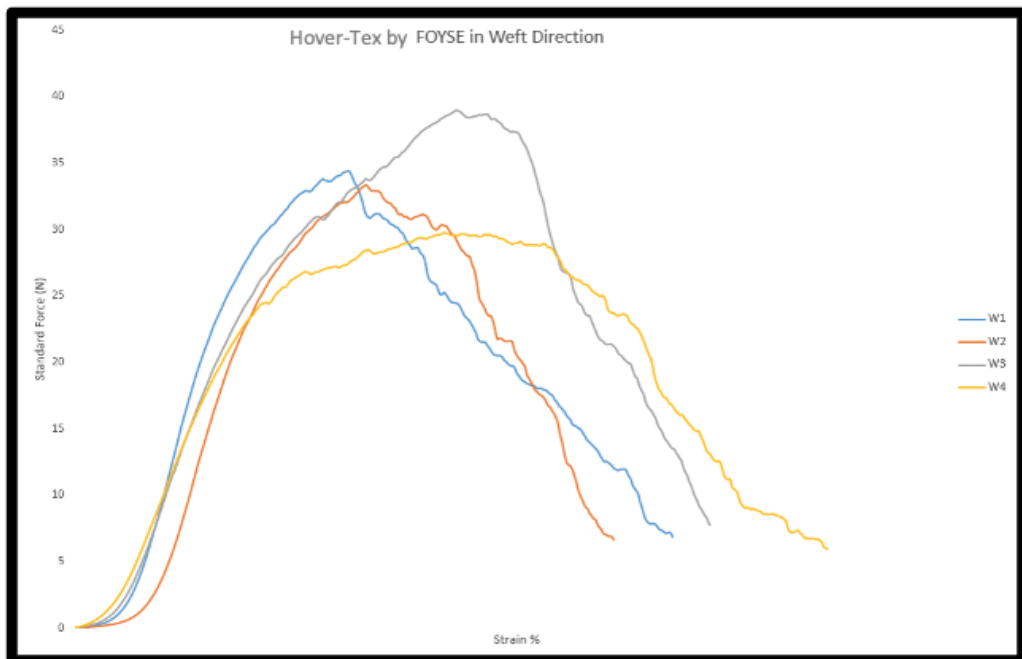


Figure 5.29: Tensile test in Weft direction. W1 is sample 1, W2 is sample 2, W3 is sample 3, W4 is sample 4.

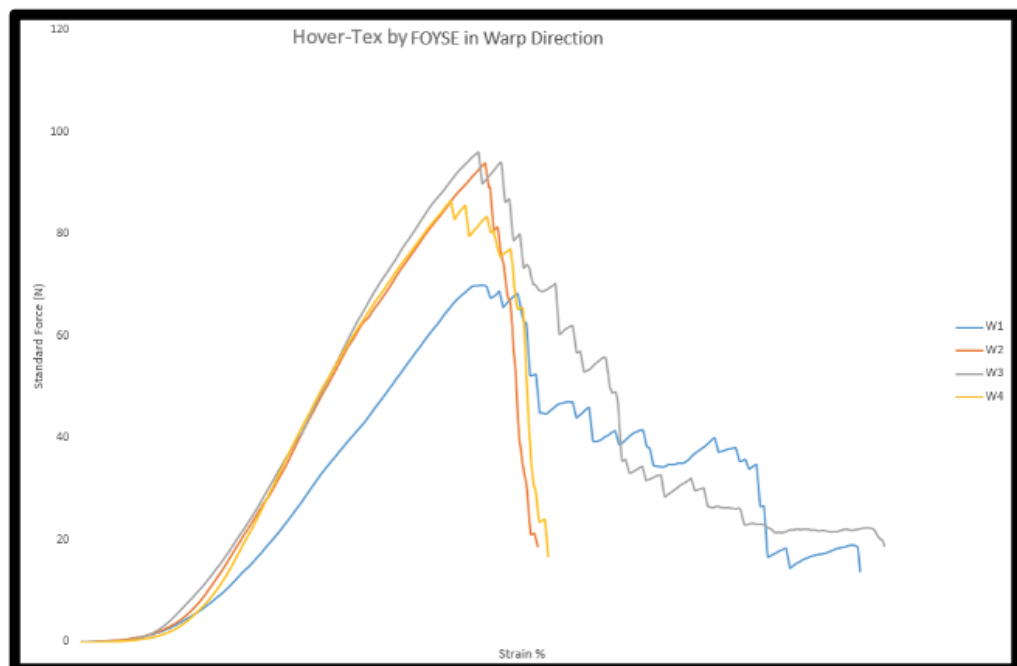


Figure 5.30: Tensile test in Warp direction. W1 is sample 1, W2 is sample 2, W3 is sample 3, W4 is sample 4.

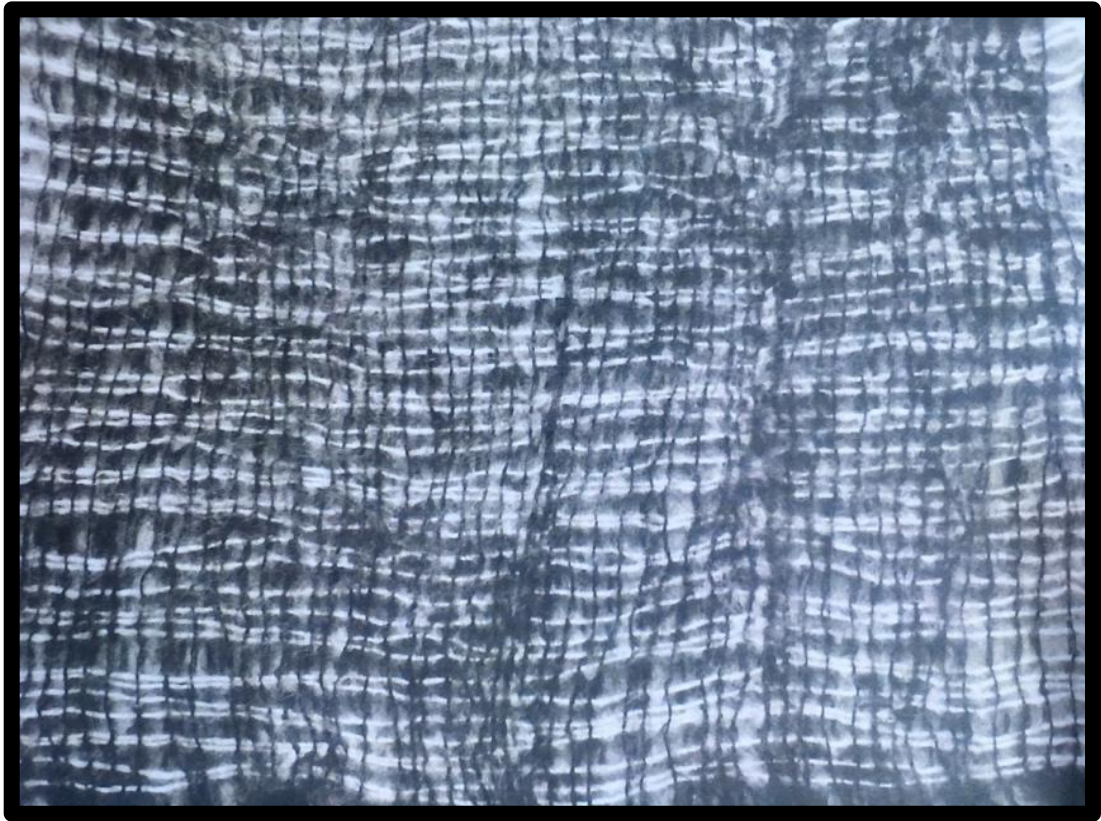


Figure 5.31: Image of FOYSE manufactured fabric prior to tensile testing.

The above sample was manufactured using 100% Falkland wool detailed in Figure 5.31 which is placed in the weft direction. The mohair and silk mix yarn were used for the warp direction of the sample. The sample original size was 8x8 inches made up of 60 mohair yarn ends and on average 48 merino wool. Each sample was divided into 8:1x4 inch samples which were then individually tested.

The tensile test in the weft direction presents a smooth curve which indicates that the Falkland wool fibres were breaking in a tearing process. The tensile test in the warp direction presents a jagged zig zag pattern. This indicates that the mohair and silk mix yarn fibres break at the same time presenting a snapping pattern causing the zig zag.

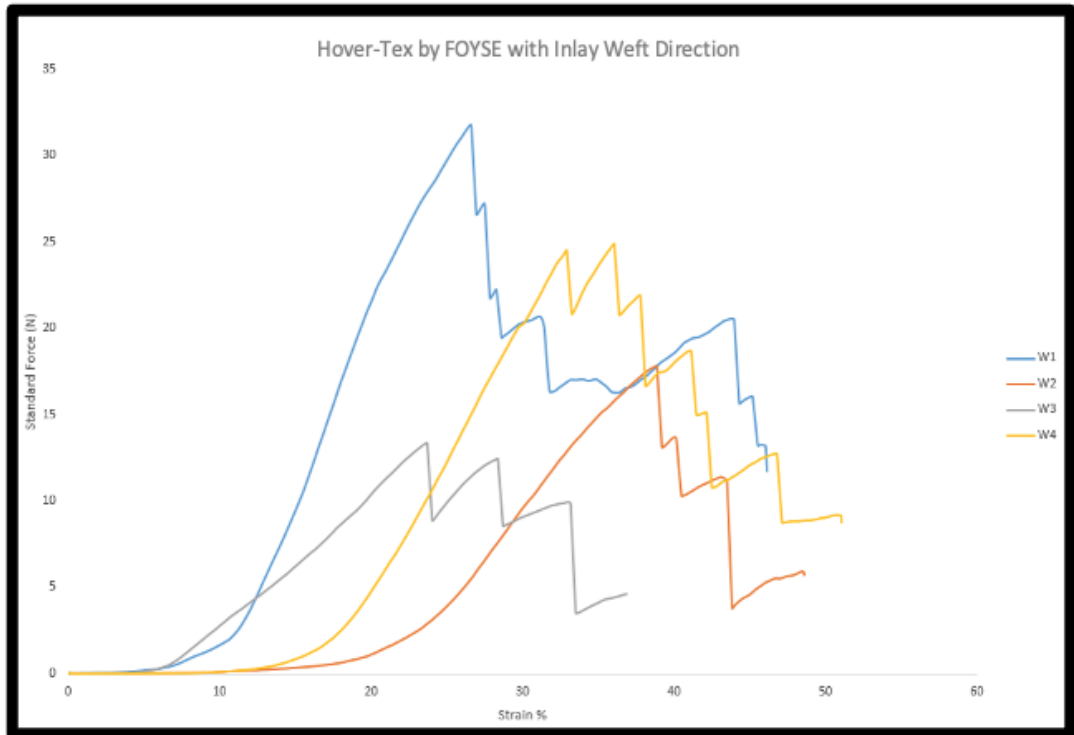


Figure 5.32: Tensile test in Weft direction. W1 is sample 1, W2 is sample 2, W3 is sample 3, W4 is sample 4.

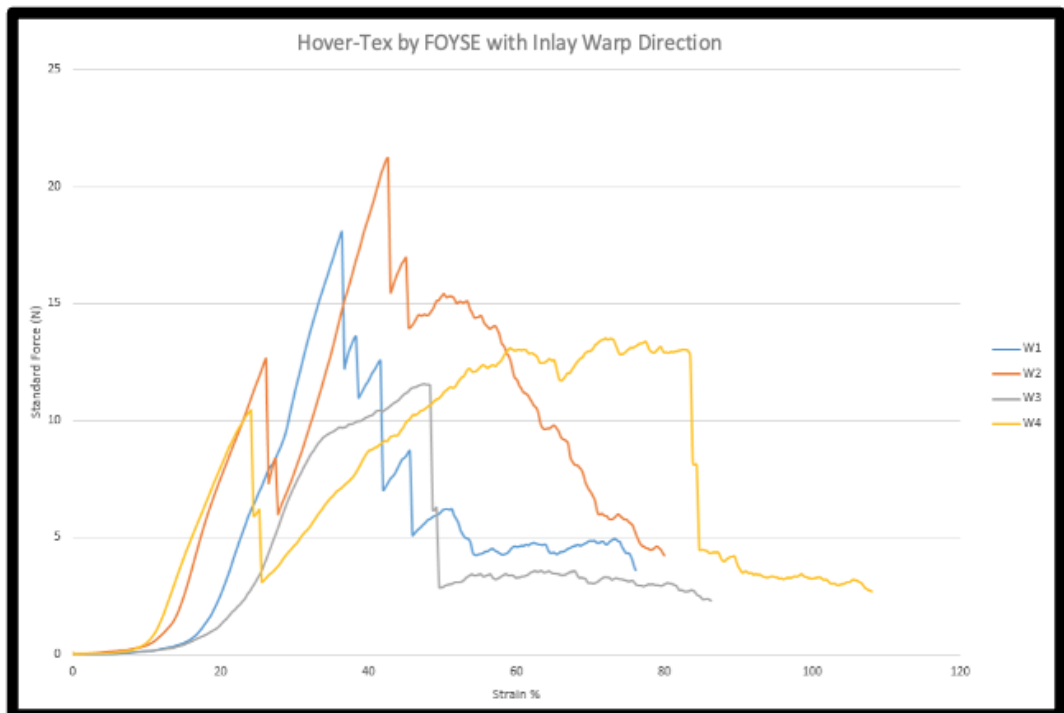


Figure 5.33: Tensile test in Warp direction. W1 is sample 1, W2 is sample 2, W3 is sample 3, W4 is sample 4.

The mohair and silk mix yarn specified in Figure 5.32 and 5.33 was used for both the warp and weft direction of the sample. The tensile test in the warp and weft direction presents a jagged zig zag pattern. This indicates that the mohair and silk mix yarn fibres break at the same time presenting a snapping pattern. Therefore, irrespective of being placed in a weft or warp position the mohair and silk mix yarn break in a snap motion.

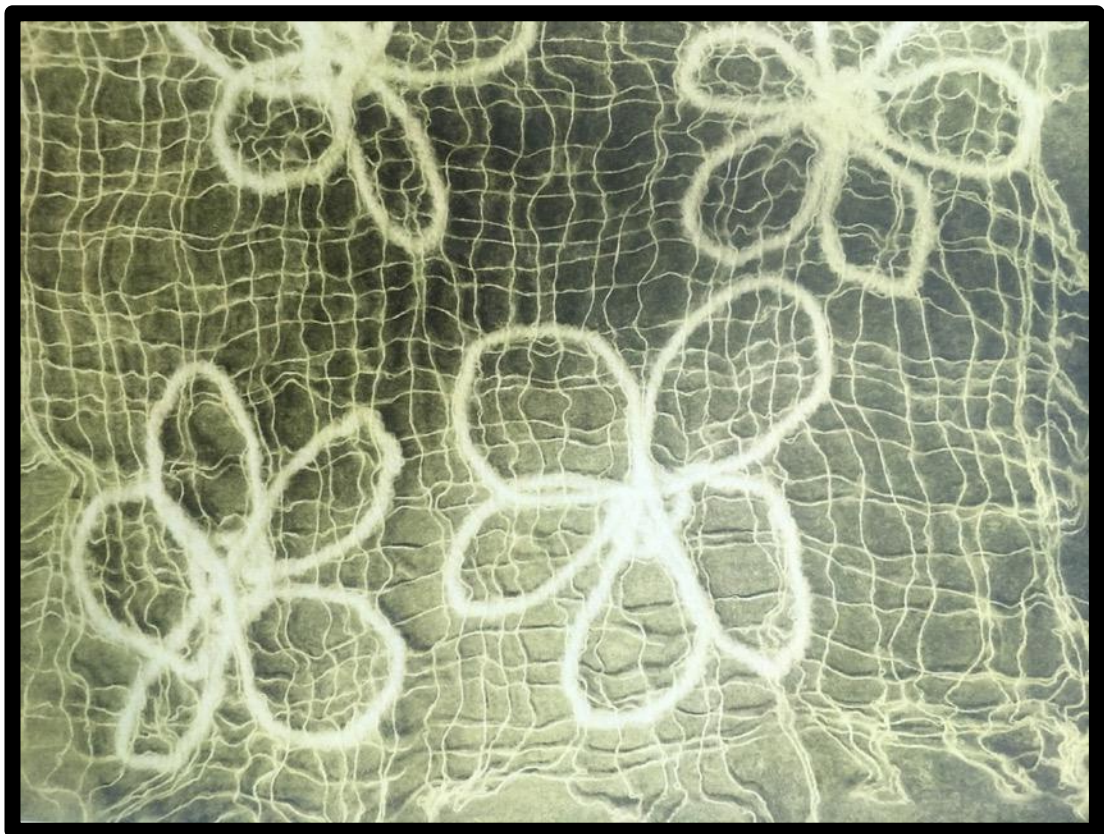


Figure 5.34: Image of FOYSE manufactured fabric with inlay prior to tensile testing.

The sample contained Falkland wool fibres placed in a floral shape between the weft and warp of the sample, see Figure 5.34. This seemingly had the effect of slowing down the snap motion of the mohair and silk mix yarn in the warp direction. All four test samples in the warp direction show that the jagged zig zag pattern turns into a tearing pattern after being exposed to strain at 50%.

5.4 Variance of FOYSE Fabric

In addition to the qualitative previous data collection, which was derived from an open-ended questionnaire, the repertory grid technique was used to gather qualitative data that could be interpreted into quantitative ratings. The *triadic method* was used in this research as collecting data on the same topic from two different data points was thought to enhance the validity of the research. The purpose of the triangulation was not to cross-validate the data but to capture the differing dimensions of the same phenomenon. The initial qualitative questionnaire identifies fabrics manufactured by FOYSE being associated with terms such as novel and unique. The second qualitative data collection via the RepGrid identified how participants personally perceived FOYSE fabrics in relation to materials created by the three known textile construction methods.

Interviews were conducted to gather additional data relating to how individuals understand FOYSE fabrics and to aid in the classification of FOYSE within textile processes. The participants in this study did not require any specific technical ability or knowledge regarding textile manufacturing. However, they would need some knowledge regarding the visual and performance differences of the three known construction methods knitting, weaving and non-woven. As a result, the interviewees were students with an interest or career aspiration in the field of design. The interviewees were asked to compare a total of four images (elements) displaying fabric surfaces. The purpose of this was to gather their individual perception of how fabric made by FOYSE differed from the other known fabric surfaces.

The document titled 'Structured Questionnaire Results' (Appendix 2) is the data collected using the RepGrid. This data collection technique is used to elicit qualitative data in the form of attributes as well as quantitative data as mentioned. All the interviewees were familiar with all four construction methods to the degree that they provided visual variation. Zephlinear by FOYSE is the focus fabric for the structured interviews. The questionnaires were successful in the elicitation of personal constructs about FOYSE fabric. Each participant was able to provide a sentence on why they thought Zephlinear created by FOYSE was different from woven and non-woven structures. The two sentences below provide data given by the interviewees. One participant responded to the question 'What makes it different?' by writing: 'It isn't non-woven but is a type of weave & felting technique'. While the other participant responded: 'It looks sort of like a mixture of the two'; the two referring to the other two materials non-woven and woven. The statements are termed in totally different ways but result in the same meaning. Zephlinear created by FOYSE looks like both woven and non-woven material mixed together. The data is the result of a structured questionnaire that allowed participants to describe the difference of the elements in a way that gave meaning to them. The results provided evidence

that firstly, participants experienced the material in slightly different ways. Secondly, the results provided evidence of Zephlinear having notable difference in comparison to the provided classes of textiles. Regarding quantitative results, 5 out of 6 participants gave Zephlinear by FOYSE a 3, regarding the visual appearance of Zephlinear, being visually both structured and unstructured. The remaining participant gave Zephlinear a 4 stating that the material had both structured and unstructured characteristics. The structure questionnaire results showed data that the numbers given by participants differed by one or two points.

To bring greater focus the data analysis chart below (figure 5.35) are the results regarding how the participants understood Zephlinear in isolation from woven, knit and nonwoven. Again, the data results presented reveal participants differed by one or two points in the 5-point scale in relation to the seven constructs. This area and the data collected is recommended for further research and analysis.


1							5
Distinct structure	3	3	3	4	3	3	Unstructured
Some structure	3	3	3	4	3	2	No structure
Loose	3	2	4	3	2	4	Stiff
Unstructured and structured combination	1	1	1	1	2	2	One structure no combination
Vertical structure mixed with entanglement	1	1	3	1	1	1	No vertical structure mixed with entanglement
More moveable	2	1	1	2	2	2	Less moveable
Durable	2	3	4	2	3	2	Un-durable
PARTICIPANT	1	2	3	4	4	4	

Figure 5.35: Data analysis chart of structured questionnaire results.

The focus of the research regarding FOYSE development investigated both the production process and product development which determined the motive for the data collection. The empirical research is conducted to assess acceptability of FOYSE fabrics for design practice. This is [achieved] by identifying material advantage to present the process as a viable fabric surface (Cooper and Kleinschmidt 1987). Obtaining data on interviewees' perceptions will provide information that can be used in future research and gather options for possible end uses for FOYSE fabrics. In addition, variance from known methods is assumed as being an advantage point. Structured interviews supported by the Repertory Grid Technique (RepGrid) is used to reflect the views of the interviewees regarding the perceptual features and divergence of Zephlinear from known fabric surfaces. The results from the RepGrid are based on George Kelly's Personal Construct Theory first published in 1955 and provided both qualitative and quantitative data for evaluation (Bryman 2006).

5.5 Summary

This chapter has described the methods used in this investigation to study properties of textiles manufactured by FOYSE. There are eight properties discussed under the headings and subheadings which are: Fabric Structures, Aesthetics of FOYSE Fabrics presented under four subheadings, Visual Aesthetics; Tactile Characteristics; Elasticity and Stretch; and Area-density. The list concludes with Durability Characteristic of Materials created by FOYSE via Tensile Strength and finally Variance of FOYSE Manufactured Fabric. The data collection process to identify variance of FOYSE manufactured fabric were structured interviews supported by the Repertory Grid Technique (RepGrid). Structured questionnaires were presented to the interviewees for them to reflect their individual views on Zephlinear fabric. The participants were interviewed to collect information regarding the perceptual features and divergence of Zephlinear from known fabric surfaces. The RepGrid data results provided evidence that in comparison to woven, knitted and non-woven material, Zephlinear created by FOYSE manufacture visually appeared different to the interviewees. In addition to this, Zephlinear created by FOYSE, provided data revealing that words used by the participants to describe Zephlinear appeared to interchange with the words used across the three known classes of textile materials.

It is therefore concluded that the results obtained by the investigation in this chapter supported the hypothesis. Namely that fabric surfaces created by FOYSE manufacturing, via strain tests, demonstrate that it has strength to be classified as a textile fabric. This was determined firstly, by the data results that measured the breaking point resistance via tensile tests. Secondly, the results regarding the properties pertaining to the visual appearance of FOYSE manufactured fabric suggested significant visual variance from the currently known methods of fabric construction. Thirdly, data collected from the structured interviews concluded that the interviewees identified Zephlinear created by FOYSE, as having visual difference from the three known methods of manufacture.

The next chapter describes the procedures and methods used in this investigation in relation to proof of concept for scale of manufacture. Manual and powered tools to aid in the manufacture of FOYSE fabrics by semi-automation is the basis of initial experimentation. Each stage of the production process is independently explored. Inquiry is then conducted into the possibility of full automation of the FOYSE manufacturing process.

CHAPTER 6

PROOF OF CONCEPT FOR SCALE OF MANUFACTURE

6.1 Introduction

Within the textile industry the speed and efficiency in which materials are manufactured affect cost. This is due to the influence between labour costs and time to manufacture. For example, hand knitted apparel is more expensive than a machine knitted garment, simply due to the additional manual labour. Many textile advancements, for example the development of E-textiles, are likely to be limited in part by cost (Hardy et al., 2018). Limits of material innovations include the surface sizes which can be created and timely methods of incorporating complementary devices such as functional yarn and electronics. These factors are determining factors for the products created by FOYSE position in the marketplace. The scale and to some extent, the speed of manufacture has been paramount in establishing the viability of FOYSE fabrics in identifying whether it will be considered for craft, industrial use, or both. As discussed in Chapter 3.1.2, the research aims to assess how the scale and speed of production in which the FOYSE fabrics are manufactured influences the end use. Therefore, the development of the processes to both aid manufacture as well as developing technology to automate manufacture were investigated. Domestic tools and functioning toy replicas of textile manufacturing equipment were a part of the testing for proof of concept. Various adaptations were created for experimentation to speed up and automate the FOYSE process. Aim 2c of this project is to transition the hand production of FOYSE fabrics to part or completely mechanical means, and therefore, extend its potential value to a wider range of commercial production. The purpose of mechanical investigation is to identify if fabrics created by FOYSE can be scaled in terms of the size, width and length with increased speed and less labour. To enable this to be addressed two concepts were investigated:

- Batch production using single feed¹⁵

A single feed is the term used to describe the process of a single yarn being passed back and forth to create a parallel array of yarn. This is illustrated in Figure 6.12 whereby a robot is used to carry a single yarn to create a parallel set of yarns such as the warp in weaving and warp knitting.

- Continuous production using multiple yarns; investigating connecting the stages in the process.

¹⁵ Batch production is a method of manufacturing where identical or similar items are produced for small runs.

Continuous production using multiple yarns is whereby several yarn ends are used to create a warp. Multiple yarn feed is the term used to describe the process whereby individual yarns are positioned parallel to each other to create a warp structure.

6.1.1 Stages in the Development of Manual and Powered Tools to Aid Manufacture

Several stages were investigated to explore the potential for automation of the FOYSE process. These stages included consideration of methods: to feed the yarn from various yarn holding sources such as a ball, cone, or hank to keep yarns stable and to test yarn for manufacture suitability; to identify suitable yarn coverings; to analyse tension; creating parallel array of yarn; applying imagery or embellishments; speeding up the process; and the application of chemicals and water to agitate the yarn to increase fibre entanglement.

Stage 1: Identification of Yarn Type

Yarn type affects the manufacturing process of FOYSE as identified earlier in chapter 4.1.6. Experiments to test the impact of variables resulted in the following yarns demonstrating their abilities for FOYSE manufacture. Chapter 2.3 outlined the research which identified that the type of yarn selected determined the type of tool needed to raise the fibres on the yarn surface. The research established that yarn made of fibres with scales, a mix of hairy and smooth yarn and woollen spun yarns were the most effective when using the FOYSE method. If yarn without scales is used it must be able to be embedded between the entangled fibre on yarn. This is accomplished by the fibres that have been raised from the yarn surface entangling around the fibre without scales. Allowing the unscaled yarn to be held in a secure position by the support of the entangled surface fibre.

When considering the scalability of the manufacturing additional factors needed to be considered:

- What form is the yarn prior to manufacture: ball, cone, or hank?
- How will yarns of a different count perform when seeking to speed up or automate?
- How will yarn of different physical makeup react, such as wool fancy yarn or metallic yarn?

When producing manual manufacture of small samples these questions do not create the challenges that they do when automated. Whether the yarn is in the form of a ball, cone or hank is irrelevant as the hand is able to ensure a smooth flow of yarn with little disruption. This can be also said for working with yarn of different counts as alternating between thickness of yarn can be managed through the manual process.

Finally, the same can be said for yarns used for embellishment for function and appearance. One example is that woollen yarn and metal wires can function differently, and this would be an issue. Many fine metal yarns are wound onto spools for transportation and therefore, have the characteristic of spring back due to the wire remaining slightly coiled when released from the spool. This is due to wire typically being rigid in comparison to yarn, for example wire can be manufactured to be an unbendable rod but yarn cannot as one characteristic of yarn is to be flexible to move with the body. When incorporating these types of yarns in FOYSE manufacture, the issue is addressed by releasing small sections of the coiled yarn, then securing it within the parallel array of yarn which act as a tension. An example is in Figure 6.14 which is an example of how the parallel array of yarn can be passed over a yarn to keep it in place.

Stage 2: Methods to adapt yarns to increase surface fibre entanglement.

Once yarn is tensioned any treatment to the yarn to enhance its ability to entangle is then applied. There are multiple types of wool and wool mix yarns, therefore, depending on the yarn choice it may be that a modification to its character is needed. For example, Rowan baby silk mohair described in chapter 4 is spun with a hairy surface, therefore, little brushing is required to lift fibre from the surface of the yarn. Whereas a worsted-spun wool yarn would need the raising of fibre to enable the yarn to obtain a surface that would enhance suitability for fibre entanglement. Uncurling fibre on the yarn surface is termed as 'raising the nap'¹⁶ which describes the releasing of the fibre from yarn after it has been manufactured into fabric. In contrast with 'raising the nap', within the FOYSE process the term is used to describe the raising of fibre from the yarn surface prior to being manufactured into fabric. Through experimenting and testing outlined in chapter 4, it was concluded that the uncurling of the fibre from the yarn surface was a time-consuming and laborious process. Research of current industry machinery revealed that no technology is available to complete this process. The testing of a variety of manual tools were explored including placing a hairbrush onto a large single bolt (Figure 6.1). The bolt was 6 inches in length which allowed the end of it to be placed into a hand-held powered drill/driver. This created a tool that could assist in speeding up the raising of the fibre from the yarn surface. The FOYSE process used a brush with soft bristles to delicately lift fine fibre from spun yarn. Through visual observation care was taken to ensure the number of fibres uncurred did not break the yarn. Manual brushing to lift fibre from the yarn would be inconsistent due to human inability to produce identical brush strokes. Therefore, the powered option overcame this problem by providing consistency regarding the rotation of the brush resulting from the motor-powered drill. This is

¹⁶ Raising the nap is the name given to the raising process, which draws out the ends of the fibres on both woollen and cotton fabric.

just one example of how current methods can be adapted to support the innovative development of the FOYSE production process.



Figure 6.1: Hairbrush attached to powered driver.

Stage 3: Create a method/tool that takes yarn from a ball, cone or hank and places it in a parallel array for FOYSE manufacture for multiple lengths.

Within the batch production of FOYSE yarn is held in place through being positioned between comb teeth attached to a board as in Figure 6.1. In contrast, for continuous lengths a large flat surface is required as stated in chapter 2. For this method, a flatbed knitting machine tension arm with springs and a mast was attached to the side of a table. In single feed FOYSE manufacture the yarn is passed back and forth to create the parallel array of yarn on the tabletop, excess yarn is released. Similarly, in flat bed knitting a tension arm is used to take back excess yarn length during the reversing of the carriage, which was the reasoning for its use in this part of the process. The tension arm was suitable for applying yarn from a cone or ball but not a hank. With further development, this would reduce the time in single yarn application. An

alternative method was explored in the form of a strip of wood attached to the side of a table, but this was unsuccessful due to lack of flexibility.

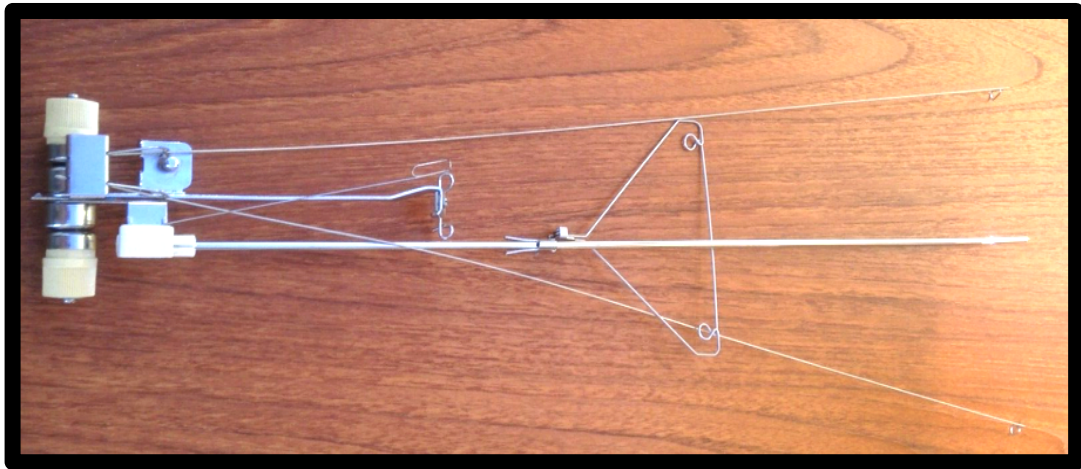


Figure 6.2: Flatbed knitting machine tension arm with springs and mast.

Stage 4: Create a suitable surface for handheld and flat surface batch manufacture.

Both the knit and woven processes have options for manufacturing on a small-scale basis (through domestic knitting machines and table-top looms). Having the ability to manufacture material with limited equipment and space is advantageous within the creative craft and hobby industry. Creating a suitable tool for handheld and small batch manufactured FOYSE fabrics was explored. Two options have been investigated and proven successful, a basic flat surface, such as a tabletop, is ideal for laying out the parallel array of yarn needed for the FOYSE manufacturing process. Alternatively, a rectangular board with fine teeth combs attached either side, as in chapter 2, is ideal for handheld FOYSE manufacture without the use of a tabletop or stationary flat surface.

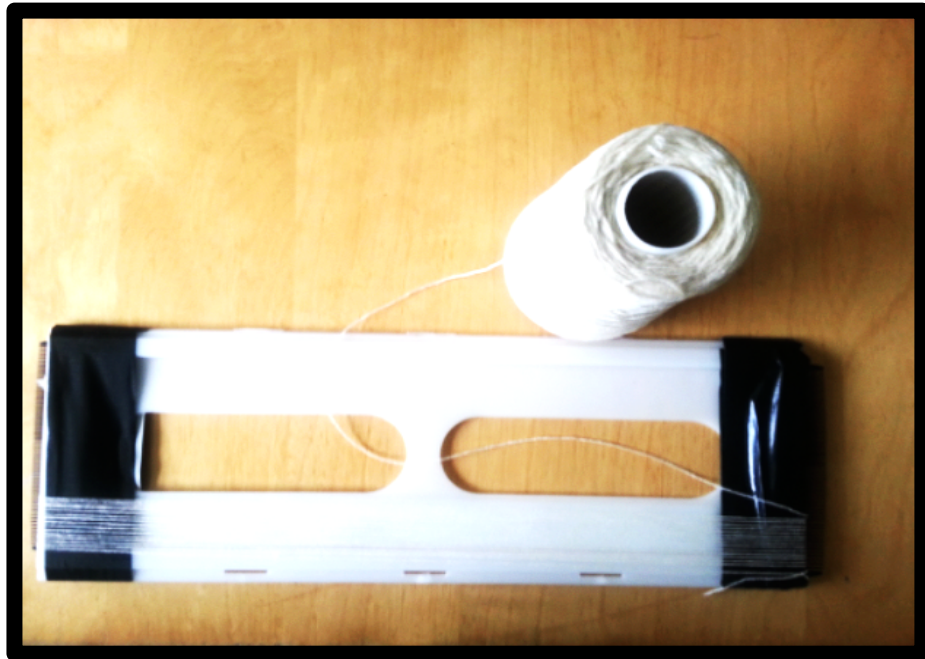


Figure 6.3: Plastic board with fine tooth combs attached either side with duct tape.

Stage 5: Identify suitable surface covering when using a tabletop to create a surface for FOYSE manufacture.

When yarns are placed directly onto a smooth flat surface, such as a table-top, they have no boundary. Therefore, the yarns slide across the flat surface from side to side. This movement would increase depending on the amount of application of the fluid solution used to manufacture FOYSE. I explored the potential to create a fixed position with a flexible absorbent material that had the capacity to retain the yarns position when laid out. A towel and fleece fabric were investigated due to both materials possessing a surface with uneven areas and the capacity to absorb water. Thus, providing support for the yarn when going through the wetting stages of FOYSE manufacture. Listed below are the materials used to investigate the most suitable surface for this stage of FOYSE manufacture:

- Towel high fleece such as 4mm material pile height
- Towel low fleece such as 3 mm material pile height
- No fleece surfaces such as flat woven surface
- Mix bottom/ No fleece such as yarn placed between a 3mm towel and a flat woven surface.

Using a towel with low fleece of approximately 3 mm in height to secure the yarn while undergoing the washing process proved the most successful. A towel with fleece above this height (on average 4mm) would become entangled with the fibres lifted from the yarn surface when undergoing the wash process.



Figure 6.4: Parallel array of yarn after under-going wash process wrapped within a towel.

Stage 6: Create tension for holding yarns in place when using a flat surface for FOYSE manufacture.

In contrast to the method described in stage 4 (plastic board with fine tooth combs), using a flat surface to manufacture FOYSE required a different process. Using a flat surface on one side provides availability to tension the yarn on one side in comparison to the wrapping process when using the handheld tool. Three options to hold the parallel yarns in place were explored: knit weight combs, double sided sticky tape and a loom knitting tool. The most successful was the loom knitting tool as it held the yarn securely. This was due to each peg on the knitting loom having a rounded head larger than the actual peg. This prevented the yarn that was placed on it from slipping off when tension was applied. Loom knitting rods are a craft tool used to create a knitted structure manually and without needles. This apparatus was purchased from Hobby Craft and redesigned so that the loom pegs used to hold a knit stitch could act as a tension rod when creating the parallel array of yarns. Loom knitting has been around for hundreds of years, the first industrial method documented as being the stocking frame by the Rev Lee in Nottinghamshire in 1589. Knitting looms are made in various shapes, sizes, materials, and are often called by different names such as knitting board, frame, rake, and the classic loom (Johanson 2020). The loom knitting rods were

separated and placed on opposite sides of a table to produce tension that holds the parallel array of yarns in place. Knit weight combs were experimented with but the fine teeth proved it was only adequate for fine yarn. Double sided tape was tested, although the distance between each yarn could not be made consistent due to the manual application. This method would be appropriate when consistency of space between parallel yarns is not required.

- Knit weight combs.
- Double sided tape.
- Loom knitting tool.

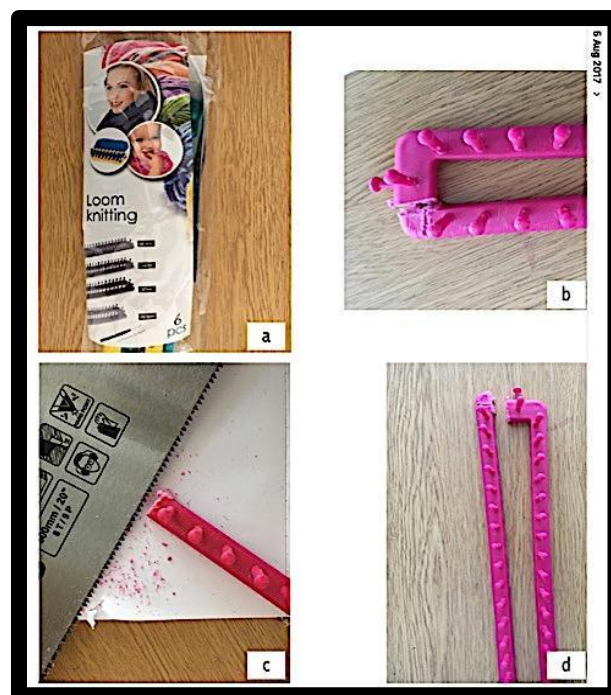


Figure 6.5: a. Loom knitting kit.¹⁷ b. Manual knit looms out of packaging.¹⁸ c. Manual knit loom cut in half to create two single rows. d. Manual knit loom cut in two halves to accommodate the FOYSE manufacturing process.

Loom knitting kits are produced in two shapes as in fig 6.6. The loom knitting tools can create hollow knitted tubes manually and were traditionally used to teach the principles in knitting within early education. The process used a thread spool with four or five pins and was called a French knitting spool. This process is

¹⁷ Knitting on a loom can produce the same types of traditional knitting including intricate designs like cables.

¹⁸ The benefit to making these on a loom is that it is often easier on your hands, and it usually works up faster. To accommodate the FOYSE process the loom is cut in half.

still in use today and is continually being developed as in a registered patent in 2012 (Yasuhiro 2012) and presented in Figure 6.7.

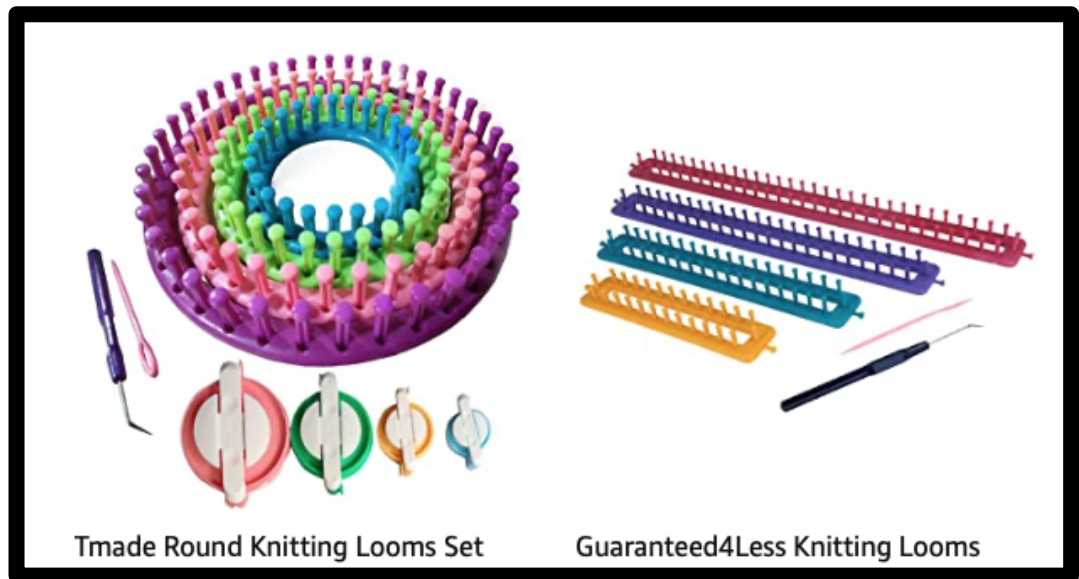


Figure 6.6: Image of circular and rectangular knitting looms. Image source: Amazon.co.uk.

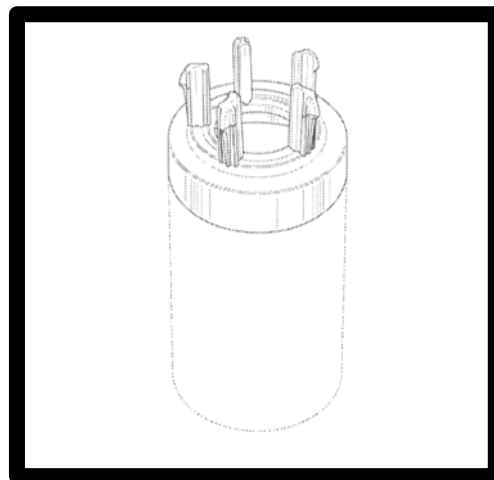


Figure 6.7: Image ornamental design for a French knitting spool (Yasuhiro 2012).

The manual loom knitting rods and knit weight comb proved successful to create tension. The knit loom had to be cut in half to create a single row of pegs to accommodate the FOYSE manufacturing process.

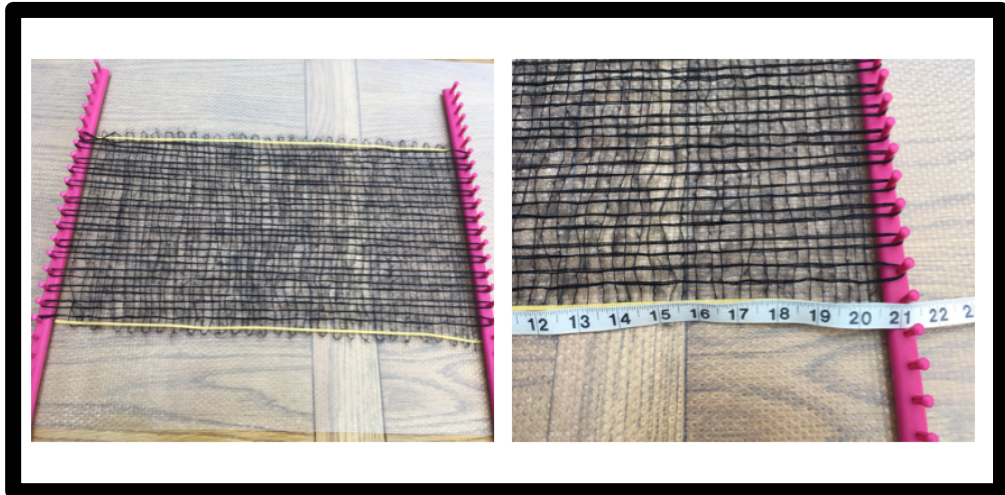


Figure 6.8: Loom knitting rods holding yarn at an appropriate tension level for FOYSE manufacturing process.



Figure 6.9: Knit weight comb holding yarn at an appropriate tension level for FOYSE manufacturing process.

Stage 7: Identify method of creating parallel array of yarn.

I began the exploration of manual and powered tools to enable me to identify potential solutions in creating parallel arrays of yarn. This began with experimentation using a 'toy knitting machine' with the intention to

find a method for the manual process of laying out the yarn for FOYSE production.¹⁹ The decision to utilise a toy knitting machine was that it is less laborious to dismantle and adapt due to being predominantly plastic.²⁰ However, the concept was proven without the need to alter parts of the knitting machine. Placing most needles in the non-working position except for one needle on either end of the knitting bed creates large floats. These floats are replicated when the knitting carriage is moved left to right. This motion enables the creation of the parallel array of yarn required for the development of FOYSE fabric. However, this method produced a single bulky loop either side of the array of yarn which in the normal knitting process is called a selvedge stitch. However, due to not having another stitch in proximity, it was weak and loose, unlike a selvedge stitch which is used to secure the end of knitted panels. Further development to address this resulted in a suitable method to increase the speed in laying out the yarn with a single feed. The images in fig 6.10 below show the toy knitting machine, a close up of large floats created on the toy knitting machine and the 'array of yarn' which I was able to produce by hand to illustrate similarity to floats produced on the knitting machine.

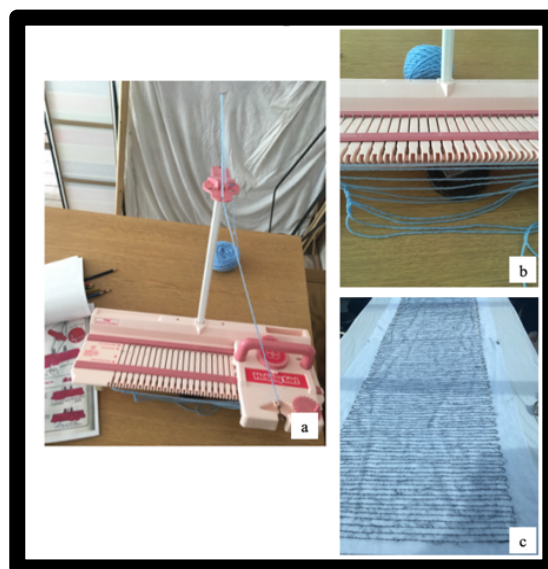


Figure 6.10: a. Toy knitting machine set up. b. Toy knitting machine in the process of laying out large floats. c. Example of parallel array of yarn required for the manufacture of FOYSE fabric.

Automated parallel yarn layout was also investigated by using a small robotic device called an Ozobot. The Ozobot is a small robot designed to follow user-created paths (Lovett 2017). Manufactured by the company brand of the same name the Ozobot offers a screen free way to code. This robot is an award-winning device

¹⁹ VTG Boxed Tomy Real Knitting Machine #2708 Age 8+ Hobby Girl c.1984, made in Japan.

²⁰ These machines are no longer in production, a second-hand version manufactured in the 1970s was purchased through private sale.

that operates by using a line-following sensor whose behaviour one can customise. This is completed by using different coloured pens to draw lines. Varying the colour of the pens alters the operation of the Ozobot. The colour code chart in Figure 6.11 is an example of the Ozobot code structure.

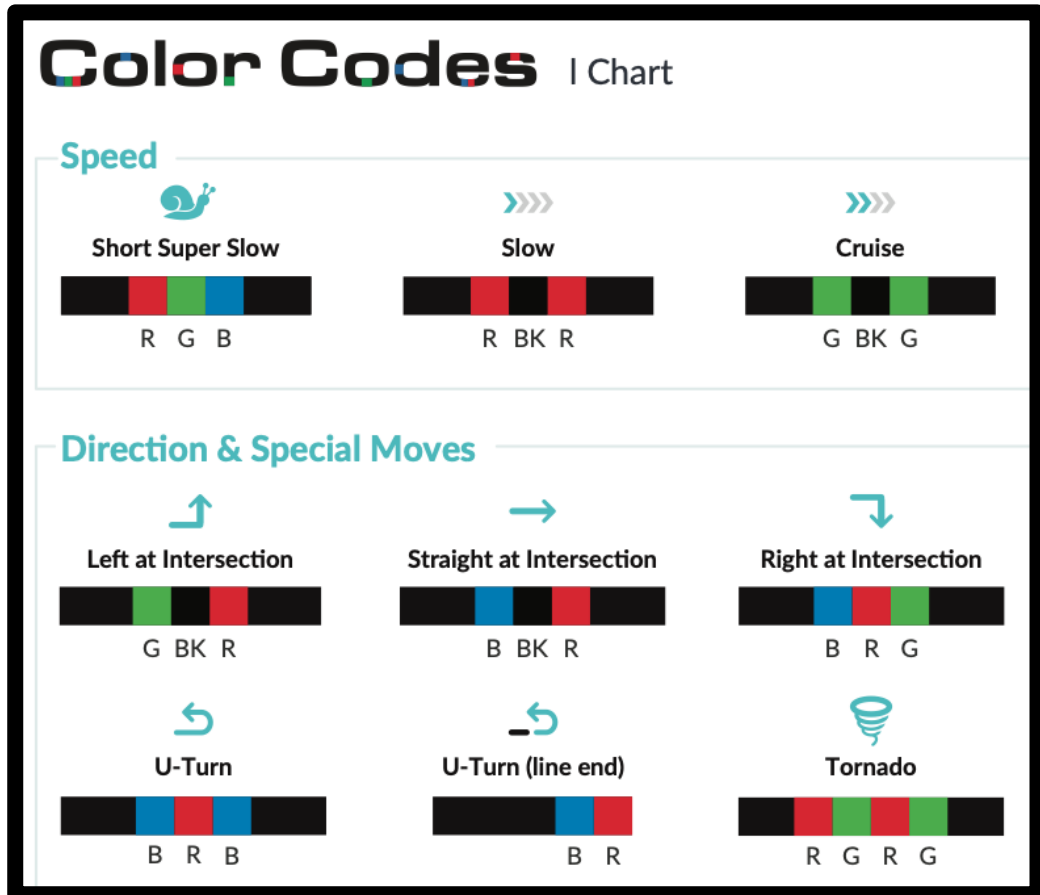


Figure 6.11: Ozobot speed and direction codes.

A large eye needle was attached to the Ozobot with sticky tape and then threaded with double knit spun yarn. It is assumed that various yarn counts can be used depending on using a needle with the appropriate size eye for the yarn to be threaded through. Lines replicating a parallel array of yarn were drawn onto a piece of paper. High performance Fruity Skittle Magnets available from Amazon.com were placed at each end of the parallel lines so that when the Ozobot turned to go in the opposite direction, the yarn was held in position. This would create an automated array of parallel yarn. The process was successful, but the Ozobot moved slowly in comparison to the speed in which the toy knitting machine performed. The toy knitting machine is attached to a guide which allows the user to apply force, allowing the carriage to move quickly. The Ozobot is guided by a colour line and a small computer that does not have the capacity of the

force of a human arm. However, the experiment did offer proof of concept for automated yarn layout and if a more powerful device was created then further experimentation would potentially be fruitful.



Figure 6.12: Ozobot in the process of laying out the yarn for FOYSE production.

Stage 8: Identify a method for applying imagery or embellishments and speeding up the process.

During this project, further creative possibilities in terms of how to embellish the surface were considered, and therefore, explorations on how to create imagery were considered.

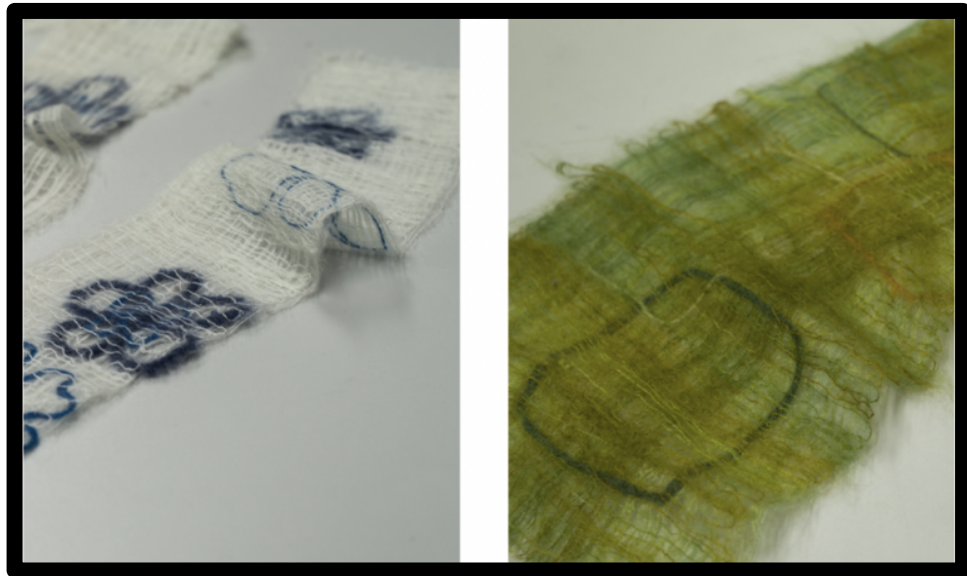


Figure 6.13: (left to right) Hover-Text floral scarf, Hover-Text cube scarf.

The samples in Figure 6.13 were created using free-hand imagery positioned on a layer of parallel yarn. A final layer of yarn was then placed at a 90-degree angle to the first layer. Two methods of applying the free-hand imagery to the parallel array of yarn were conducted. The decorative shapes in Figure 6.13 (right) were individually crafted as they were positioned on the yarn. Once the second layer of parallel yarn was applied the imagery became embedded within the FOYSE structure. Figure 6.13 (left) shows various sized floral forms which were made in batches and then laid near one another and then placed onto the FOYSE structure. This method of applying imagery by creating a batch of similar designs and then placing them onto the parallel array of yarn decreased the production time.

Stage 9: The application of a chemical mix of water and pH solution.

In the production of FOYSE fabric, an important part of the process relates to the application of a chemical mix of water and pH solution. It was therefore important that methods for this application were explored. Three methods of applying the solution to the yarn were attempted: application by sponge, application by spraying and pouring the solution onto the yarn. These methods were added prior to the FOYSE sample being rolled and placed into a washing machine. The pouring option was not suitable due to limited control concerning even application, furthermore, usage of a sponge was not successful as the sponge disrupted the yarn layout. Spraying was the most effective method as the spray bottles provided even coverage without disturbing the yarn position in comparison to pouring the solution which moved the layout.



Figure 6.14: (left to right) Yarn prepared for FOYSE production. Solution applied to yarn to accommodate FOYSE production.

Stage 10: A method to be created to agitate further the entangled fibres.

The process also required a method to be created to agitate the entangled fibres further. Experimentation was completed by replacing the use of a conventional front load washing machine with one that was top loading. The benefit of this was that the sample was both visible and accessible throughout the agitation process. The twin tub washing machine also had a timer that allowed regulation of the spinning process, which can be programmed to a 15-minute spin time. The water is added manually, and as there is not a heating function, water is added to the machine at the desired temperature of 40 degrees centigrade.



Figure 6.15: Top loading washing machine. Image source: (Ebay 2018).

So far, this chapter has described the methods used to investigate ten stages of the FOYSE manufacturing process by using both powered and manual 'off-the-shelf' technologies. These methods have given insight into numerous possibilities to advance FOYSE manufacture regarding speed and automation. All the methods investigated were proven to be adequate and supports the understanding that FOYSE manufacture can be conducted in a variety of innovative ways. However, I was keen to explore the possibility of how to fully automate this process.

6.2 Development of Technology to Automate Manufacture

Full automation of the FOYSE process would be a very advantageous development in this research. Therefore, investigating the concept for semi and possible full automation of the FOYSE process will now be discussed. Several prototypes were created to demonstrate possible advancements at different stages of the process. It was necessary to investigate each step and therefore, required individual mini projects to examine the functionality for improved performance. These involved ideas obtained by observing historical machinery and those in current use within the textile industry, as well as the machinery used for laundry due to the FOYSE process involving practices used to clean textiles: washing, agitation and drying. Several drawings and mock-ups of a range of methods to automate the FOYSE process were created and the apparatus in Figure 6.16 is the first prototype created to illustrate a vision of scalability.

The focus on scalability was to identify methods that would support creating larger lengths and widths of fabric at an increased speed and ideally including a level of automation. The example below shows the yarn securely in place for fibre entanglement and the brushing station at optimal functionality as the yarn brush can glide seamlessly over the yarn to lift fibre hairs.



Figure 6.16: First prototype of apparatus to scale FOYSE and speed up the manufacturing process.

See below description for how the initial mock-up operated.

The process begins (right to left) with parallel yarn being separated by a black comb. The lengths of yarn likening a warp were manually passed through the black comb and secured by duct tape. The parallel array of yarn then passes over a small roller sleeve, normally used for applying emulsion paint to keep tension. In production, this first sleeve would move left to right and aid in adding moisture to the brushed yarn. After the first roller sleeve, the image has a round hairbrush which illustrates the process for raising the fibre from the yarn surface. The next step is again a roller sleeve but this time with a sponge paint sleeve used for gloss or satin paint. The purpose of this was to provide tension and add chemical lubrication. The yarns would then pass down into a shallow water bath suspended between two tension holders created from paint sleeves with padding removed. On the suspended parallel yarn is the frame of a sponge hair roller without the sponge. This is clipped onto the parallel yarn and would pass from left to right to illustrate the agitation process used to entangle the yarns. Below this section is a green lid to represent the shallow bath which would contain a chemical mix of water and pH 9 solution. The final naked roller sleeve is used to represent the take up section of the apparatus. Between these two points would be a drying system but this and the feeding station are not included in this initial mock-up of scalability.

6.3 Full Automation Implementation

In contemplation of creating a working life-sized apparatus to investigate the concept of FOYSE full automation, I purchased an Ashford rigid weaving loom and stand (Ashford 2020). This loom and stand were chosen as they were able to accommodate a weft of 48 inches in width, while providing sections that could be adapted to operate as the individual workstations.

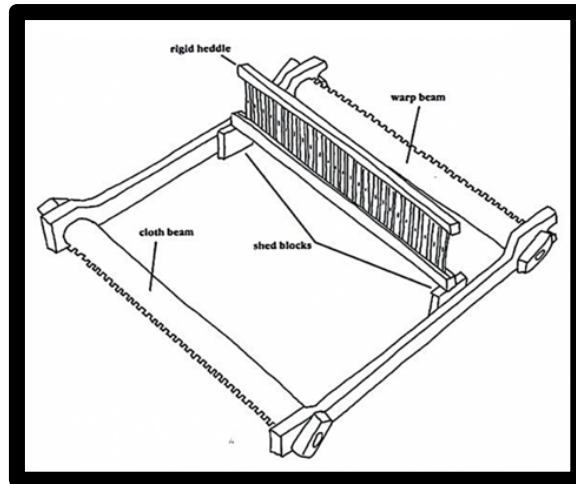


Figure 6.17: Birds-eye view of Ashford rigid loom (Ashford 2020).

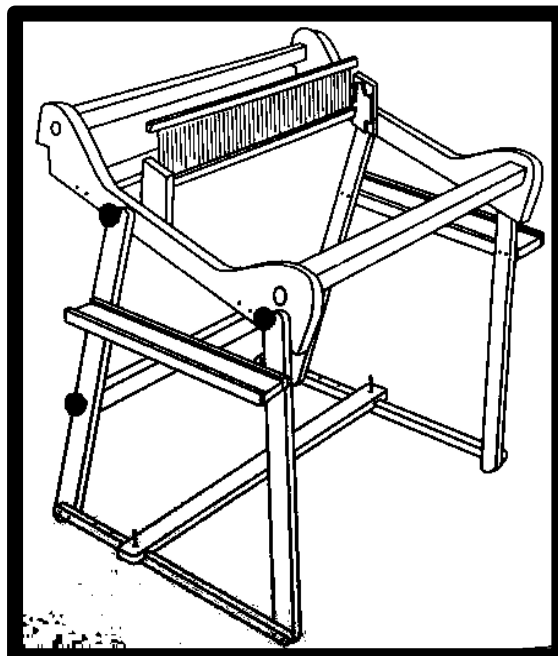


Figure 6.18: Diagram of Ashford rigid loom placed on loom stand (Ashford 2020).

Once the loom was set onto the stand, experimentation was conducted and several attempts to find a solution to create FOYSE were made. A major problem within the experimentation was the lack of surface area within the loom to accommodate all 5 stages of the manufacturing process. Having both wet and dry processes meant that the same space could not be used for multiple purposes. The idea came to incorporate the stand with the actual weaving loom to create a larger surface area for the manufacturing process of FOYSE. Rather than seeing the loom and loom stand as two isolated entities, I envisioned the loom and stand as one apparatus. The full apparatus was then visually sectioned into five parts to accommodate the identified workstations and these realisations are significant to the progression of this project.

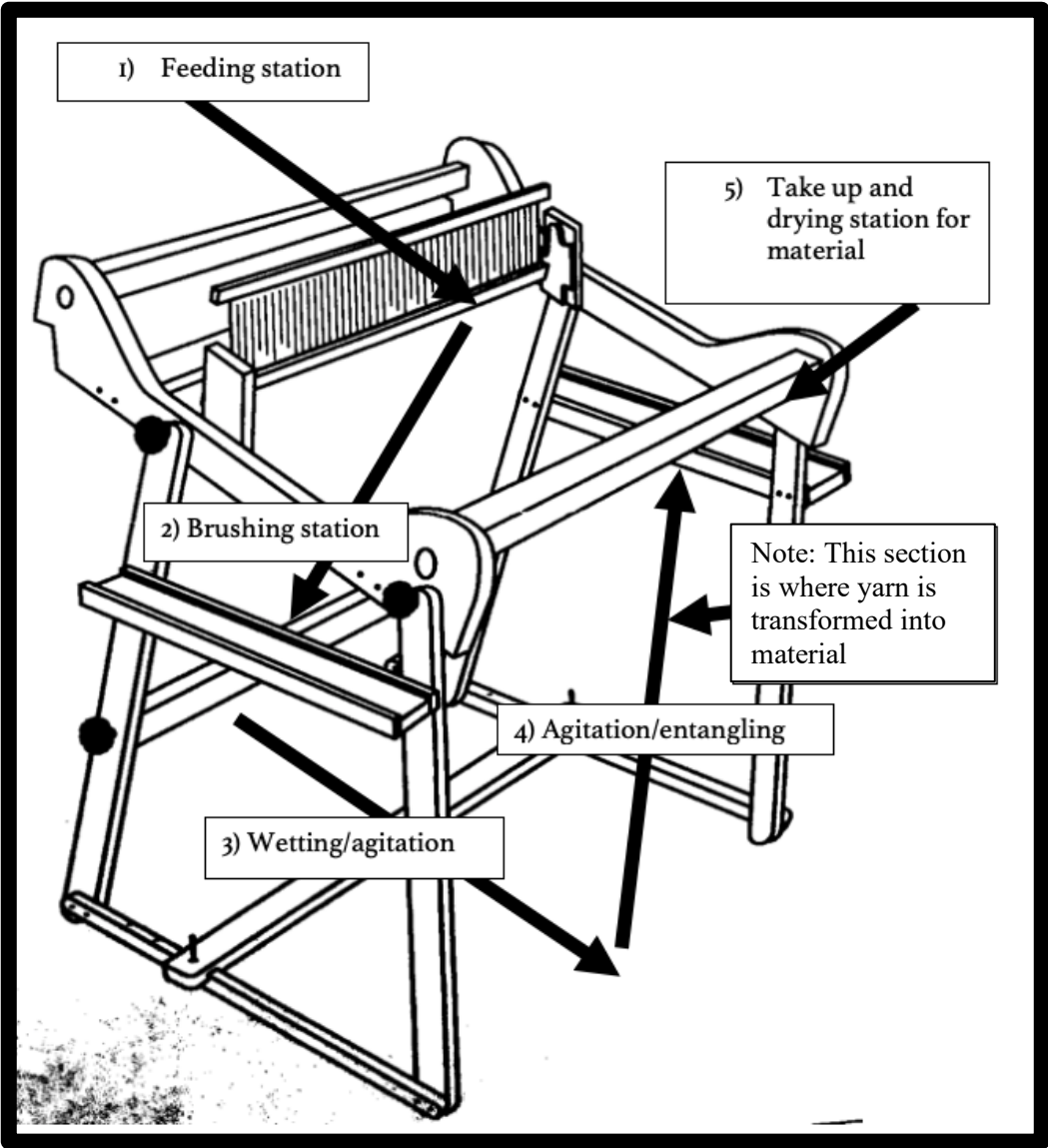


Figure 6.19: Diagram of loom and stand sectioned into FOYSE workstations (Ashford 2020).

The following adaptations were made to the loom and stand to accommodate the FOYSE production process.



Figure 6.20: Image of fine teeth combs attached to the heddle.

1. Several fine teeth combs are attached to the heddle to bring the yarns into closer proximity.
2. Two circular rollers are connected by ties allowing a 1-millimetre gap for yarn to pass through. The small gap is to act as additional tension for the yarn and the circular rollers to redirect the yarn.
3. The supporting post below the heddle is covered with a foam pipe insulation tube to add tension to the yarn and redirect the yarn onto a facing, newly placed roller added to the bottom stand.
4. The newly placed roller is covered with a foam pipe insulation tube to add tension to the yarn and redirect the yarn onto the loom beam used to take up the fabric.

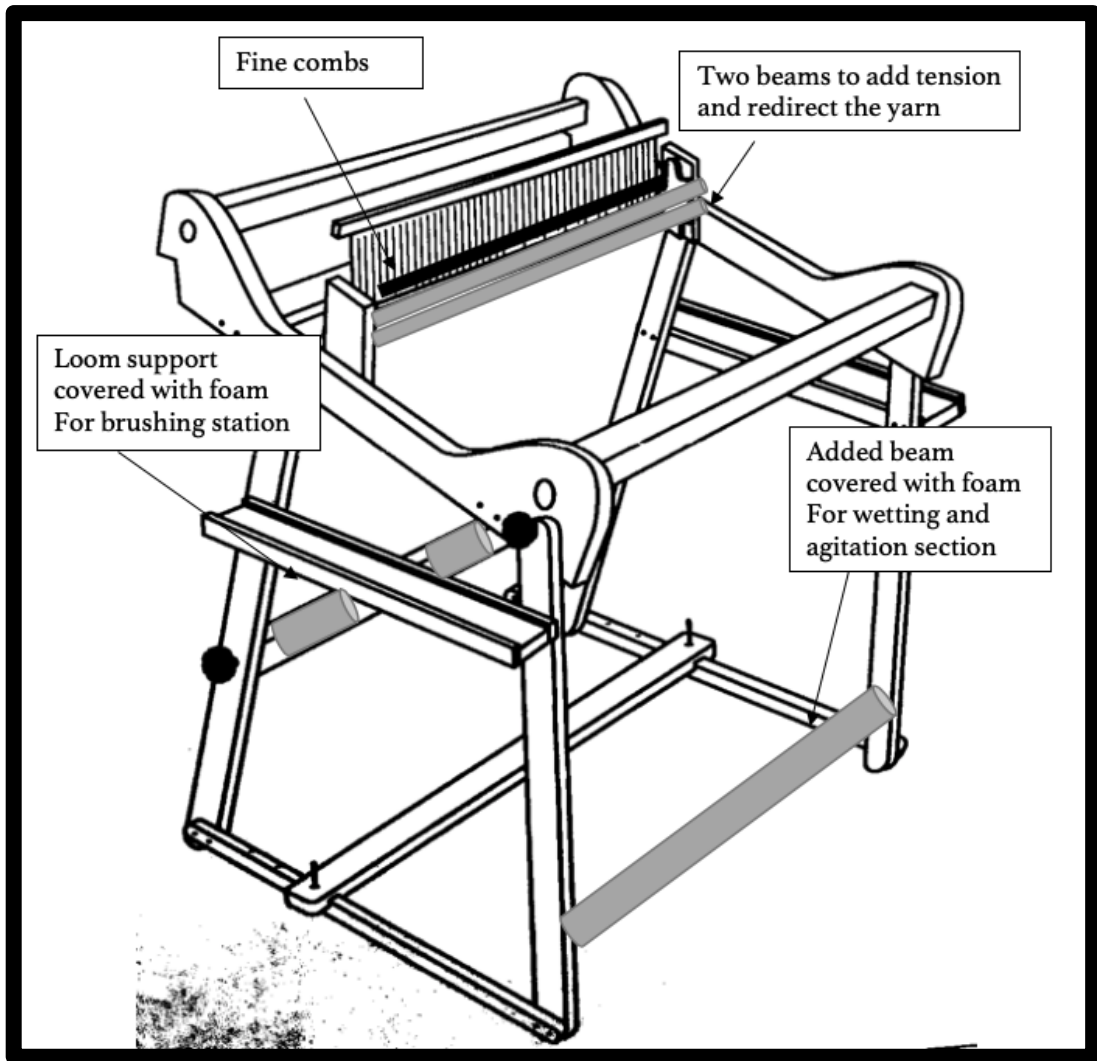


Figure 6.21: Diagram of loom and stand with added components.



Figure 6.22: Image of Ashford ridged loom set up.

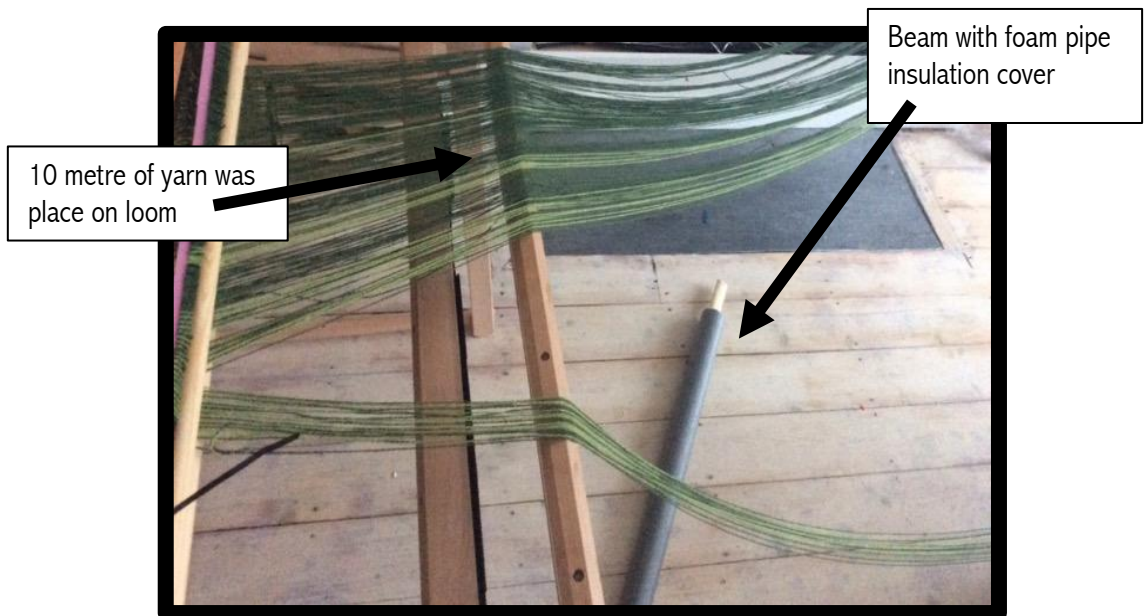


Figure 6.23: Image of Ashford rigid loom and yarn in place.

Three external apparatus were created to aid in FOYSE manufacture on the newly devised combination of the loom and stand.

1. 40 mm pipe covered with Velcro to raise fibre from yarn.
2. Wooden rod covered in bamboo mat to aid in entangling fibre on yarn as bamboo is commonly used to entangle natural fibre in the fibre art sector.
3. Combs placed in a slider paper holder to act as a yarn separator.

Both apparatuses are designed to operate in an up and down motion:



Figure 6.24: (from left to right) 40 mm pipe covered with Velcro to raise fibre from yarn and wooden rod covered in bamboo mat to aid in entangling fibre on yarn.



Figure 6.25: Combs placed in slider paper holder to act as yarn separator.

On testing of the newly invented method, the yarns attached to the take-up beam moved. The movement was due to the vibration caused as the yarns were being entangled by the up and down movement of the bamboo rod. The movement was slight, although it affected the final material due to causing the yarn to overlap. Therefore, additional combs were added to keep the yarns parallel and reduce the risk of overlap. The first set of combs attached to the beams on the heddle were attached horizontally. Once the yarns were exposed to the chemical solution (soap solution) they would cling together, therefore, reducing in width. To address this, the combs used to keep the yarns in place during the entangling process were set at an angle. This positioning proved to be adequate in keeping the yarns in proximity and in the same position once made wet in preparation for the agitation process. The moveable spacer proved to be an ideal solution for this problem.



Figure 6.26: Combs placed in slider paper holder to act as yarn separator in action.

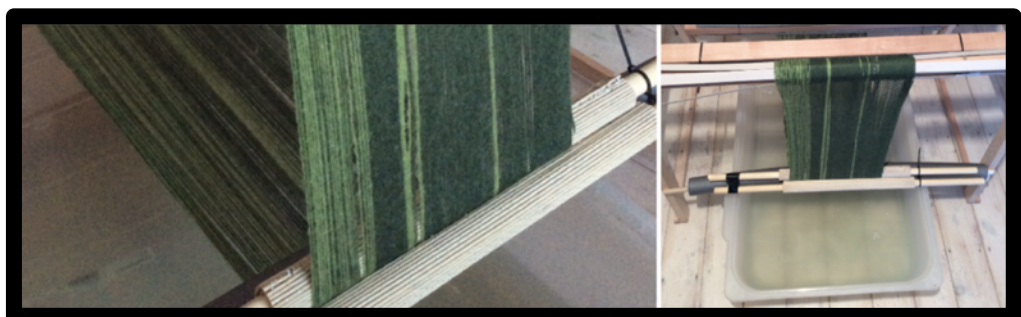


Figure 6.27: Wooden rod covered in bamboo matt to aid in entangling fibre on yarn in action.

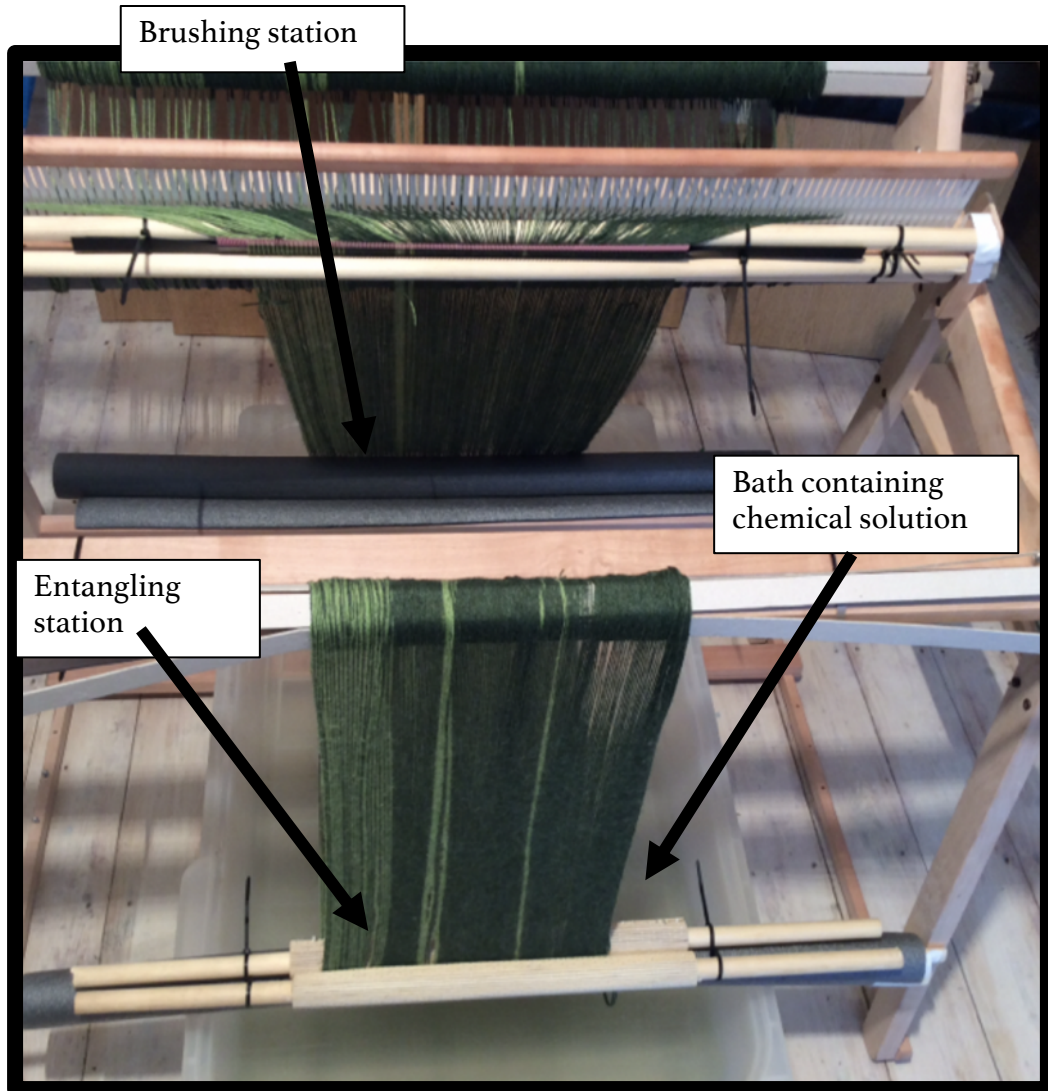


Figure 6.28: Entangling station attached to Ashford rigid loom.

Combining the loom with the stand and creating apparatus to use in the manufacturing proved conclusively that the FOYSE process could be automated in a continuous process.

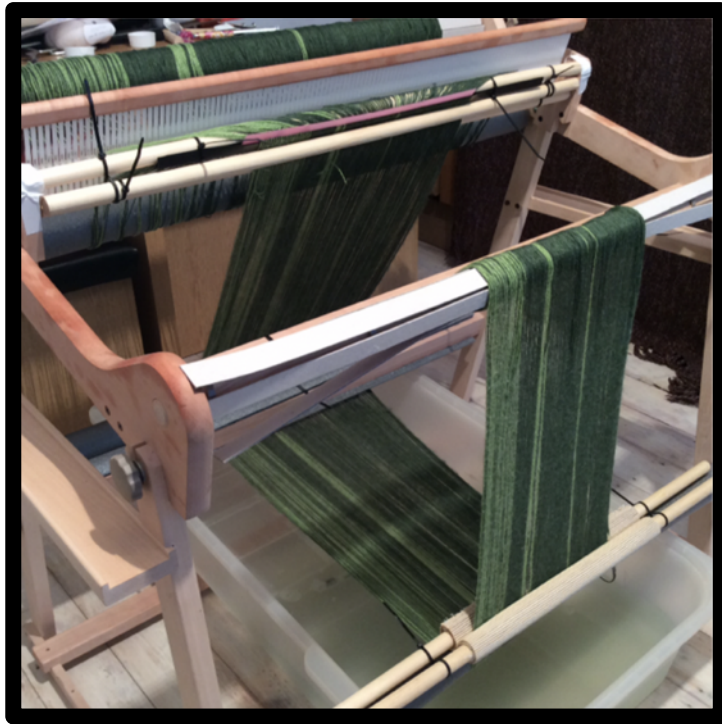


Figure 6.29: Ashford rigid loom adapted into FOYSE frame side view.



Figure 6.30: Ashford rigid loom prior to adaptation to FOYSE frame (Ashford 2020).

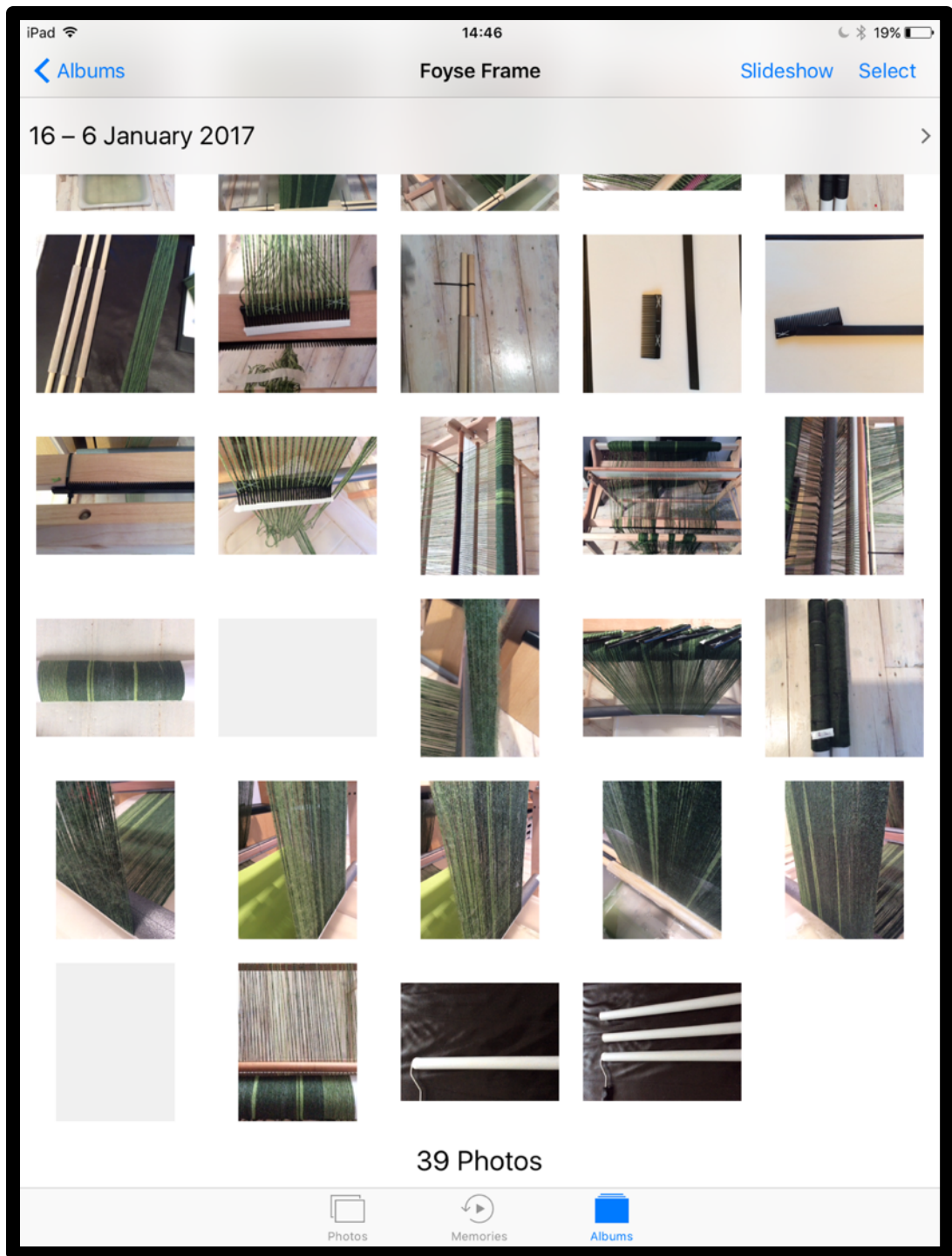


Figure 6.31: Images of Ashford rigid loom adaption development stages.



Figure 6.32: Image of tensioned yarn on the FOYSE frame.

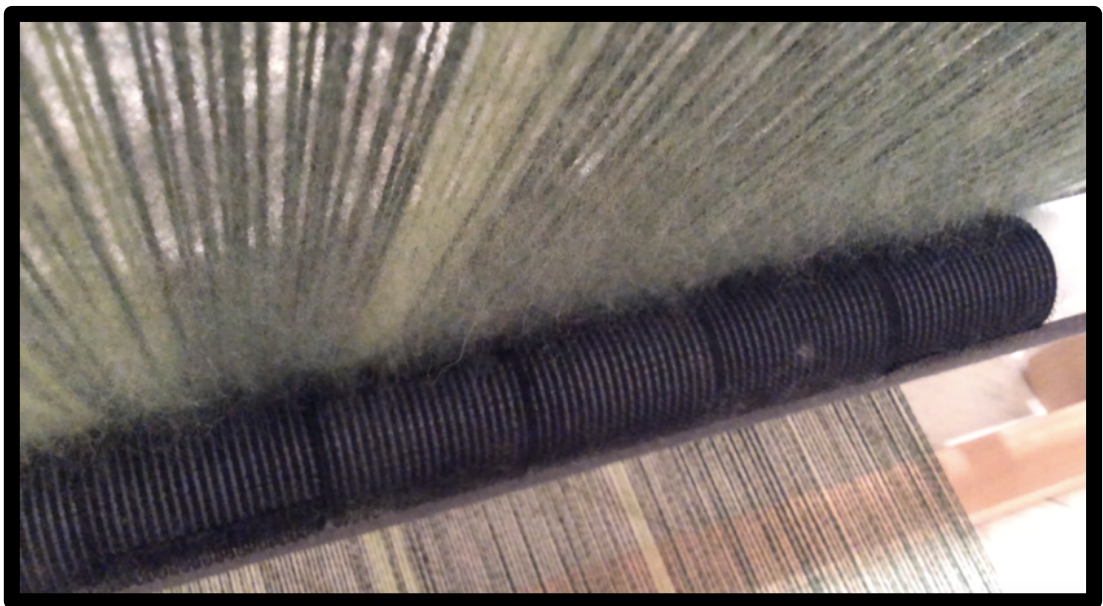


Figure 6.33: Image of brushing process on the FOYSE frame.

Powered automation

The next stage of investigation was to identify methods to have the apparatus powered. I identified that the method of attaching two circular rods for yarn to pass through resembled the rollers on a mangle²¹. While the appliance was originally used to wring water from wet laundry, today mangles are used to press or flatten. The mangle is within the laundry process of garment care and not garment manufacture. The five stations identified within FOYSE manufacture were broadly identified as part of the laundry process.

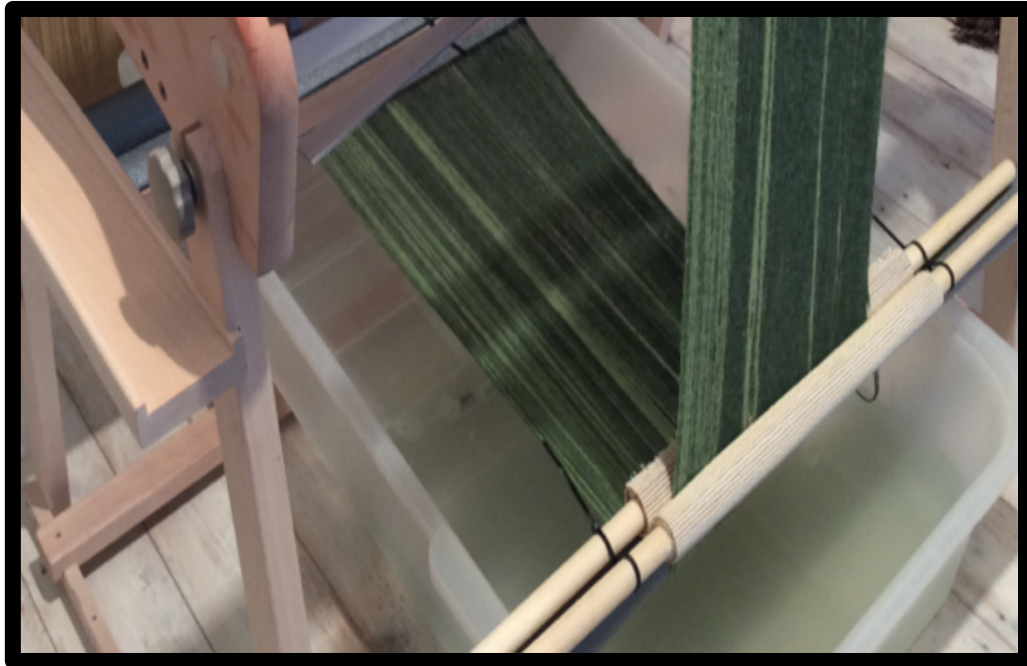


Figure 6.34: Image of yarn between agitation rods on FOYSE frame.

From observing the mangle, the idea came that, rather than having a roller that moves vertically back and forth, the yarn could pass through several rollers. This could then eliminate the time-consuming process of the repetitious occurrence used by the two-roller process. Below in Figure 6.35 is an illustration to demonstrate the adding of additional rollers and which position on the apparatus they would be placed. Figures 6.36-6.38 are images of laundry equipment that were observed in the research regarding full automation of the FOYSE process.

²¹ A mangle or wringer is a mechanical laundry aid consisting of two rollers in a sturdy frame connected by cogs and, in its home version, powered by a hand crank or electricity. The apparatus was invented by Ellen F. Eglin in the 1800s.

Apparatus to Automate Manufacture of Zephlinear

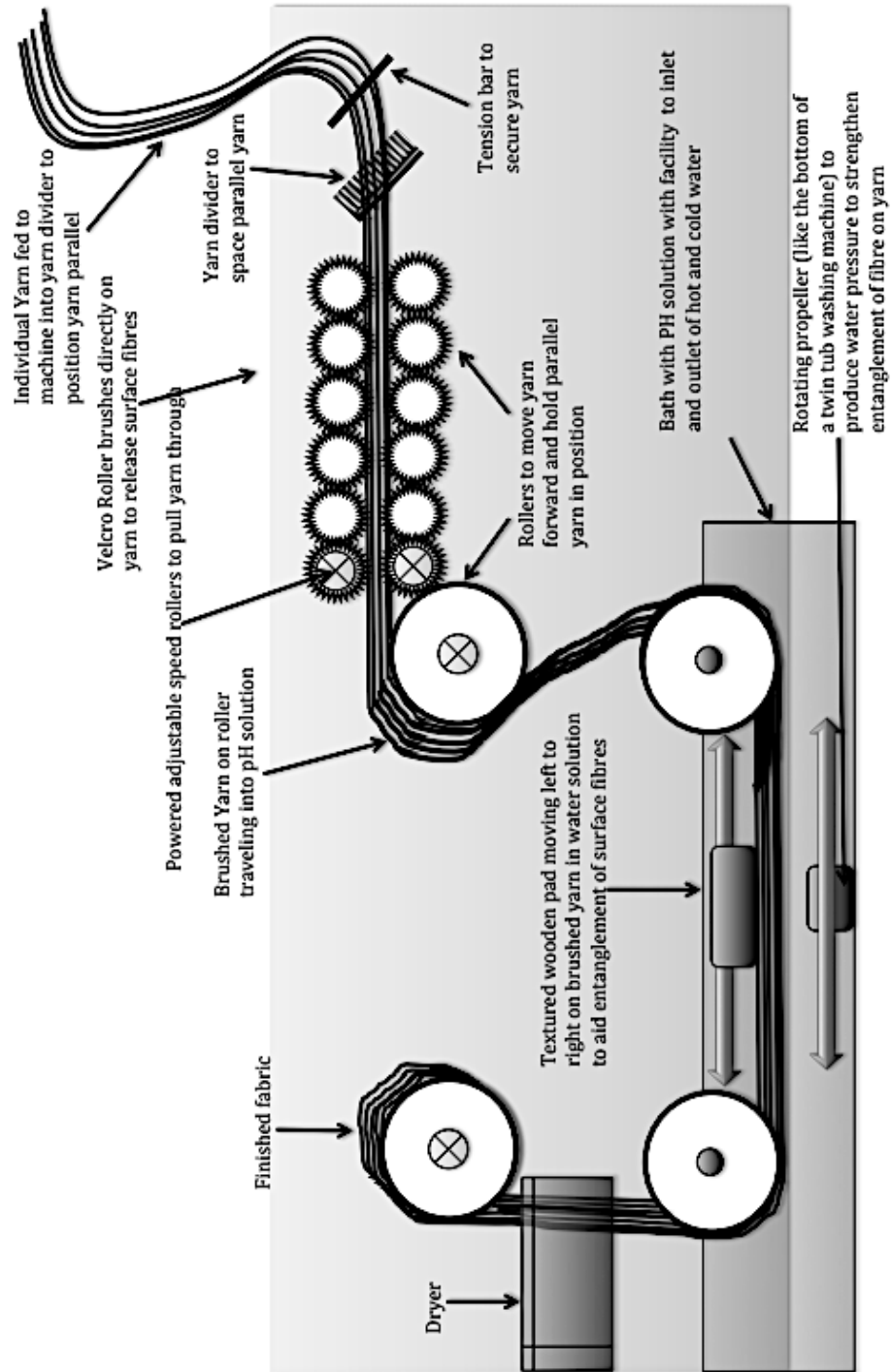


Figure 6.35: Image of FOYSE apparatus with additional rollers.



Figure 6.36: Mangle washing antique laundry (Pixabay 2017).



Figure 6.37: Woman's Friend washing machine (Daderot 2011).



Figure 6.38: Box Mangle (Antonsson 2011).

6.4 Industrial First Stage Design of Zephlinear Machine

This design along with the loom and frame was then passed onto the product design company G2 Innovation who further developed the process by focusing on how to manufacture FOYSE in large quantities. The capability of mass production will be required for industrial adaption of any textile (Nashed et al., 2019). The company could see how the process could be adapted for mainstream industrial production. This was a major step, as it was evidence from an independent industrial source confirming the process as viable. Rather than placing each of the stations in a U-shape, figurations as in the adaption of the loom and frame were made and the company developed an s-shaped formation.



Figure 6.39: Mock-up of FOYSE machine.



Figure 6.40: FOYSE frame brushing station showing top rollers.



Figure 6.41: FOYSE frame brushing station showing bottom rollers.



Figure 6.42: Spaces attached to FOYSE frame for dividing yarns.



Figure 6.43: Top view of agitation and entangling process (rotating bamboo sheet).



Figure 6.44: Bottom view of agitation and entangling process (rotating bamboo sheet).



Figure 6.45: Rinsing station (central black box), drying (hot air) and take-up station (rollers on right).

6.5 Fabric Finishing Options

It is also vital to acknowledge that transforming fabrics created by the FOYSE process into usable products is essential for adoption in the textile industry. Therefore, traditional garment make-up methods were investigated, and several stitch methods were tested which included overlocking, cover stitching, flat stitch and linking. All the processes were successful proving that fabrics created by FOYSE can undergo typical garment make-up methods.



Figure 6.46: Images of FOYSE manufactured fabric undergoing garment makeup manufacture on linker; and close-up views of overlock and cover stitch.

6.6 Summary

The research outlined in this chapter led by my findings and research, supported by two live student projects and an industry partner has provided a prototype machine, proving that this is an effective, scalable, process capable of automation.

The students' varied interpretation of the brief was extremely interesting. Moreover, the preliminary work carried out by the students provided evidence that the FOYSE manufacturing process could be fully automated. In addition, automation was achievable using a variety of methods, which highlights that the FOYSE manufacturing process lends itself to the three known methods of manufacture. My experiment of adapting a weaving loom provides evidence that the FOYSE process can be automated in a domestic setting, and this is of interest to the home craft industry. Investigation and testing of novel tools and processes by an industry partner has also demonstrated that the FOYSE manufacturing process can not only be fully automated but scaled up. These three factors are a clear indication that the FOYSE manufacturing process is suitable for commercialisation in different contexts.

This chapter illustrated the transition of the hand production of FOYSE fabrics to mechanical means. FOYSE fabrics being identified as craft or commercial is a determining factor as to where it would be positioned in the marketplace. The prototype completed by G2 Innovation was a major step in the development process as the designers developed a compacted version of all 10 workstations. A feed station, a brushing station, a wetting station, a station to add optional chemicals, an agitation station, a water temperature control station, a station to deliver spun yarns through the apparatus, a feed station, a drying station, and a final station that holds the finished fabric. This chapter concludes with the testing of cut and sew make-up options for FOYSE fabrics created with similar characteristics to woven fabrics. In comparison, make-up options using a traditional linking machine were undertaken for fabrics created by FOYSE with characteristics of knitted fabrics.

The conclusion of this chapter is that proof of concept for scale of manufacture in the textile craft sector and for an industrial concept has been proven. All factors are a clear indication that the FOYSE manufacturing process is suitable for commercialisation. In addition to the woven, knitting, and non-woven industry sector, FOYSE has the potential to deliver a whole new industry by introducing what could be described as the first non-woven textile created by yarn, a hybrid textile.

CHAPTER 7: MARKET EXPLORATION

7.1 Introduction

The FOYSE process aims to contribute a new approach, method, and fabric to the current range of fabrics available within manufacturing. This thesis has aimed to provide a proof of concept regarding the scalability of the process. Chapter 6 opens with a discussion on other aspects of textile design practice. One of which is control over quality for FOYSE products and related services including how the new knowledge is transferred.

7.2 Results of the Project

Zephlinear textiles, the FOYSE process and associated tools have resulted from this project. The craft guild model is currently under investigation as one possible method of delivering and sustaining the FOYSE process and associated products within the textile industry. Craft guilds date back to mediaeval times and prior to the industrial revolution craft guilds were utilised as a platform to regulate the production, price, quality and distribution of a particular product and process (Cummings and McMasters 2005). The expertise involved in FOYSE manufacture will require a similar platform to create a skilled craft community and workforce for this novel process to survive in the textile industry. Craft guilds were in fact created to protect the skills and knowledge that would ensure the continuance of a specific craft which further supports this route to establish Zephlinear textiles and FOYSE technology. The guild concept has had centuries of influence on how people in certain trades are trained. The guild concept of master; experienced; apprentices, operates widely today (Cummings and McMasters 2005). A recent search in google of the word apprenticeships generates about 76,600,000 results in 0.58 seconds which gives evidence to this. Typical characteristics of craft guilds include compulsory membership of artisans practising and official approval and regulation of apprenticeships (Epstein and Prak 2008) which is another significant aspect imperative for the effective delivery of FOYSE manufacture within the textile community.

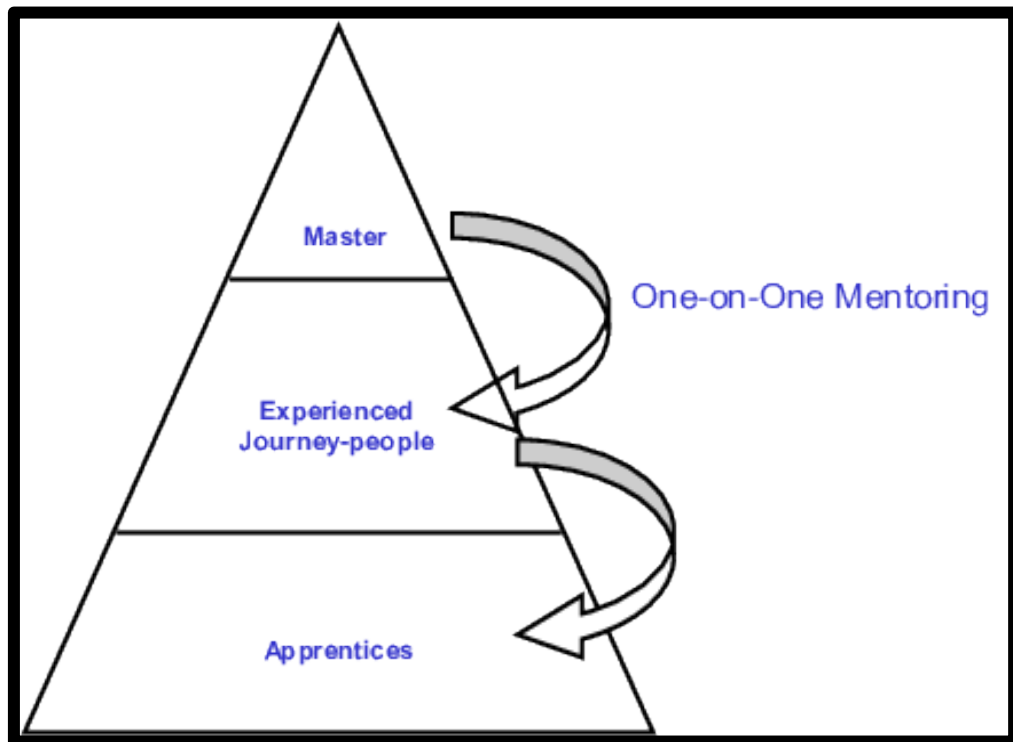


Figure 7.1: The Craft Guild Concept (Cummings and McMasters 2005).

All three known methods of fabric manufacturing have guilds or groups which are still an important contribution to society today. Pendleton stated of herself that ‘Community [fibre] guilds still allow me to participate and conjoin within ongoing artistic traditions’ (Pendleton 2007). The literature review of this thesis stated the secondary research would cover four specific areas. The four specific topic areas are:

1. Literature relating to the development of the three known manufacturing techniques.
2. Advancements of textile fabrics relating to tools utilised for manufacture.
3. Social context.
4. Economic context.

As stated in the literature review, these four topics are important to the research as they hold a fundamental position regarding how and at what speed FOYSE manufactured textiles are developed within the textile industry. The guild concept has proven to be a system in society that has the power to influence the growth or stagnation of new products within the textile industry. Figure 2.1 in chapter 2 presented a model of textile and textile production as interaction between resources, technology, and society (Strand et al., 2010). All four

areas in the list above not only interact but are closely entwined as presented in the introduction of chapter 2 and reiterated in the following extract:

Handmade clothing and environmental textile products with their aesthetical and social meanings represent the oldest forms of human culture. The development of mass-produced textiles has, on the other hand, posed an increasingly important economic and consumer issue in relation to large-scale industrial production, along with the commercial business of mass-produced textiles. In contrast, handmade, self-directed, creative activity with manually operated tools has gained more psychological significance and value in the life of the common and modern individual. As well as an educational factor for children, textile crafts can be divided into a science including investigating, designing and making-up processes, with which economic, technological, historical, and aesthetic factors can also be taken into consideration (Kaukinen 2009).

This implies that applying the traditional concepts for introducing and sustaining new textile developments, such as FOYSE, is still relevant today.

7.3 What Can FOYSE Fabrics and the Process Be Used For

FOYSE technology encapsulates three textile techniques into one, uniting the three technologies. In line with fabrics produced by woven, knit and traditional nonwoven, FOYSE manufactured fabrics can also be used across a variety of sectors within the textile industry.

E-Textiles – Safety

I embarked on this research due to my belief that the FOYSE process could answer the limitations currently within textiles. Namely, current applications of E-yarn have been incorporated within textiles that are woven or knitted. In some literature, E-yarn has been stitched as a method of attachment to a fabric surface (Hardy et al., 2018). E-yarn breaking or bending due to pressure and tension is named as an issue of concern.

A challenge is incorporating non-stretch E-yarns with stretch fabric that is desirable for some applications. To address this challenge, E-yarns containing LEDs were embroidered onto the stretch fabric of a unitard used as part of a carnival costume. A zig-zag pattern of attachment of E-yarns was developed (Hardy et al., 2018).

The FOYSE process provides areas of entangled fibres that offer support to sensitive E-yarns. In addition, the FOYSE process removes the labour-intensive method of embroidering a zig zag pattern onto a fabric structure to accommodate LEDs. The entangled fibres within the FOYSE process aid in limiting the issue of 'weakness' in the junctions between E-yarns. The problem with connector points was observed by the researcher and noted as requiring further design work and reinforcement (Hardy et al., 2018).

The images from Figure 7.2 to Figure 7.4 are a selection of two Zephlinear scarves embedded with a power source and E-yarn containing 10 LEDs programmed with 3 settings. When the LEDs are not switched on, they are totally concealed as in Figure 7.2. These LEDs can quite easily be replaced by electronics that hold information and/or sense and respond to environmental changes.



Figure 7.2: Zephlinear by FOYSE scarf with embedded 3-way programmed LED lights switched off.



Figure 7.3: Zephlinear by FOYSE scarf with embedded 3-way programmed LED lights switched on in a light environment.

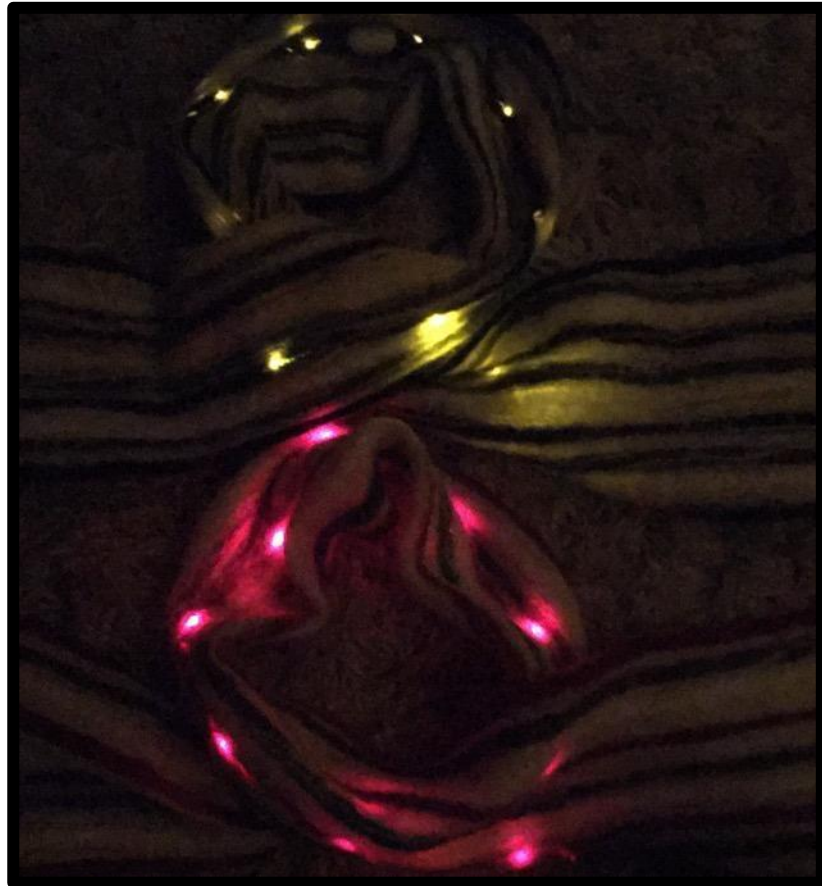


Figure 7.4: Zephlinear by FOYSE scarf with embedded 3 way programmed LED lights switched on in a dark environment.

FOYSE manufactured fabrics, in addition to images in Figures 7.3 and 7.4, can be constructed with large open spaces and fine heat conductive yarn. Figure 7.5 is a prototype of a variation of Hover-Tex created with a 70% mohair and 30% silk mixed yarn with conductive silver thread yarn. It demonstrates the level of heat that can be released from an open structured material. The large spaces result in the fabric having high breathability and extremely lightweight. Theoretically, FOYSE smart materials are an ideal structure to be lined within military apparel for heat distribution capability with minimal additional weight. Further research in this area is recommended.

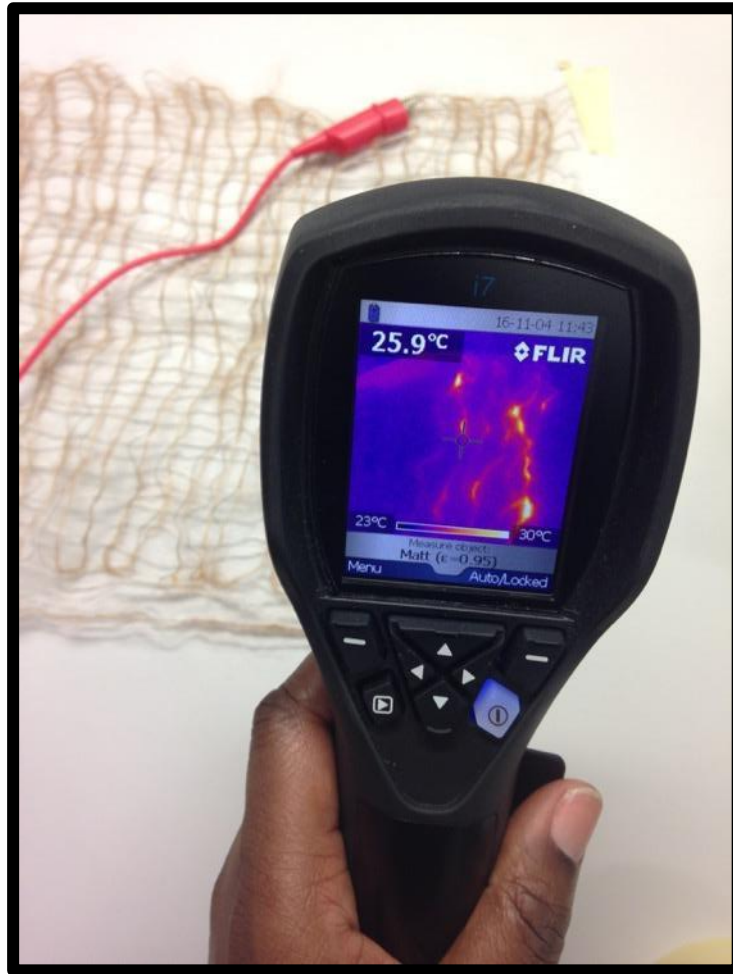


Figure 7.5: Device showing temperature of heated Hover-Tex created by FOYSE sample.

E-Textiles – Healthcare

Current developments within the area of personalised medicine have further advanced the need for wearable electronics. E-textiles have the capacity to monitor an individual's state of health in a continuous, real-time, and non-invasive manner (Fan et al., 2020). Woven and knitted textiles are the two methods used to create smart material within the health environment. An article published in 2020 announced a new development in the form of a knitted sensor. The article commences: In this study, we introduce a triboelectric all-textile sensor array (TATSA) with high sensitivity for epidermal subtle pressure capturing, knitted with conductive and nylon yarns (Fan et al., 2020). The process is used to create a fabrication and structure of all-textile pressure sensors which is then integrated into a shirt for the monitoring of pulse and respiratory signals in real time (Fan et al., 2020). This integration is completed by stitching the patches onto the shirt as shown in Figure 7.6: G.

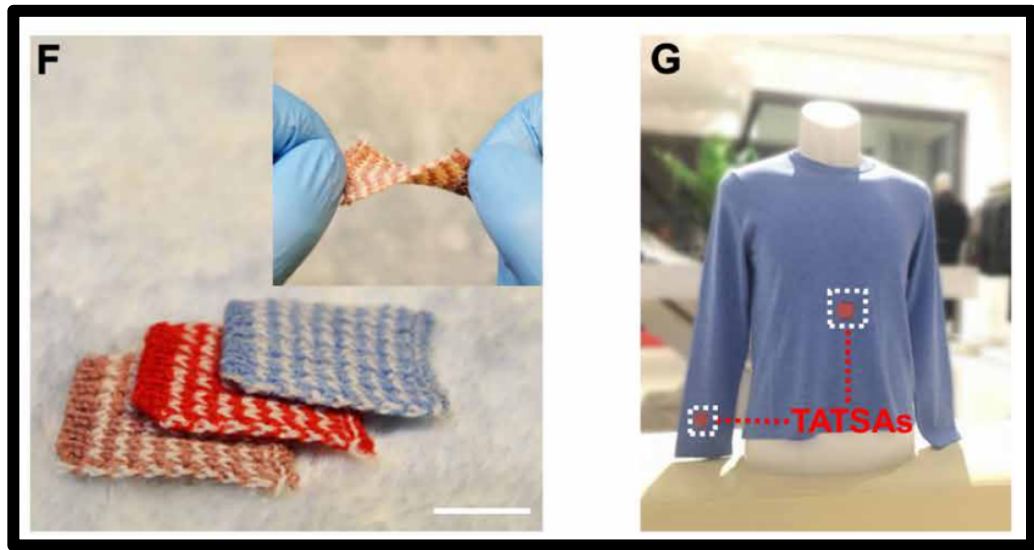


Figure 7.6: F: TATSA sample patch; G: TATSA patches sew into garment (Fan et al., 2020).

This is a convoluted procedure of incorporating E-yarn within a textile structure in comparison to the FOYSE process. FOYSE fabrics can incorporate E-yarn without stitching, which also provides the opportunity for sensors to be placed irregularly within a textile. This is advantageous as the capability of irregular placement of sensors would accommodate varied physical body shapes.

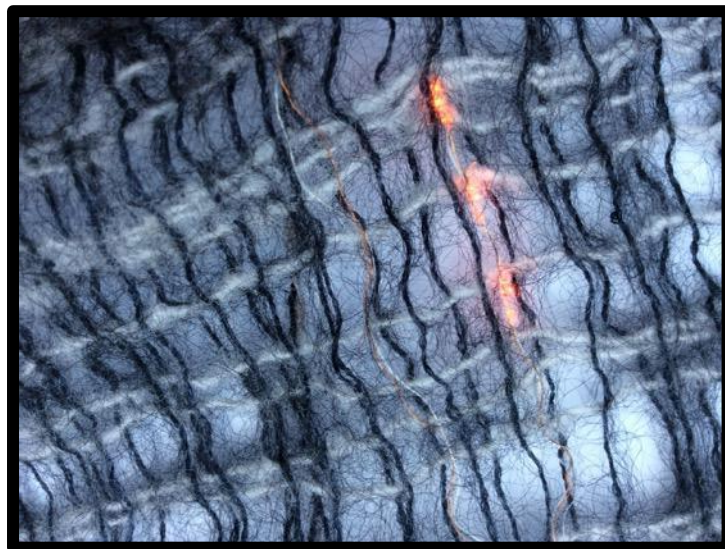


Figure 7.7: Sample created by FOYSE manufacture with embedded E-filament.

Fitness

There has been a big drive to limit waste within the textile industry in which sports brands have previously been named as a large contributor to landfills. Polyester mesh has been used within sport garments for decades and major brands such as Nike have sought alternative manufacturing methods and materials to address this problem. Recycling plastic bottles to make a fabric called Grind materials is one of Nikes innovations. Nike Grind materials are used in 71% of Nike footwear and apparel products, apparel trims, soccer kits and Fly knit yarns (Moorhouse and Moorhouse 2017). According to Nike.com, between 2012 to 2016 the technology has reduced nearly 3.5 million pounds of waste (Moorhouse and Moorhouse 2017).

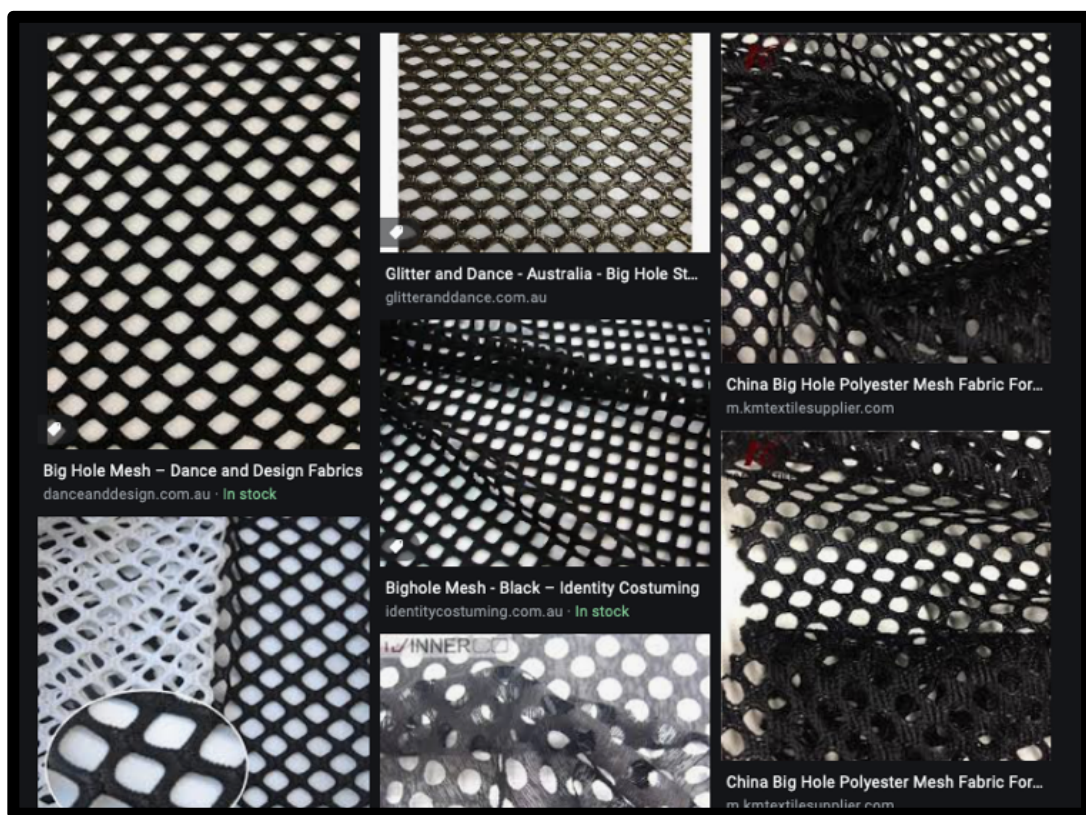


Figure 7.8: Polyester mesh samples, open source Google.com.

The two images below illustrate structures that could replace polyester mesh that is used within the sports and fitness industry. The samples were created by request for a project conducted by consultants for a major wool company. The aim of the study was to create a natural fibre t-shirt containing wool that could be used for high-intensive indoor sports such as squash, in the summer. The combination of natural fibre used to spin the yarn coupled with open mesh construction provides an appealing alternative material for the sports and fitness industry. A merino wool t-shirt was sectioned with a FOYSE panel and over a period of three weeks was used

for indoor training sessions. Due to the scope of this research feedback was limited to observing the difference between the original t-shirt and the FOYSE panel section. The consultant reported the following:

The panel helped to increase the breathability of the shirt, as the shirt became saturated around the panel. It was also observed that the gaps within the panel moved slightly, which was a nice feature. For our purpose a wool shirt for indoor sports in the summer would need lots of open sections throughout the panels. Perhaps an array of small open and closed sections throughout. And not just large open section panels situated under the arms.

Creating large pieces of FOYSE fabrics with the addition of high speed was also requested by Amir Morgan, innovation specialist at Nike. As stated in the research aims and objectives scalability and speed of manufacture would be a factor of commercialisation of the FOYSE process.

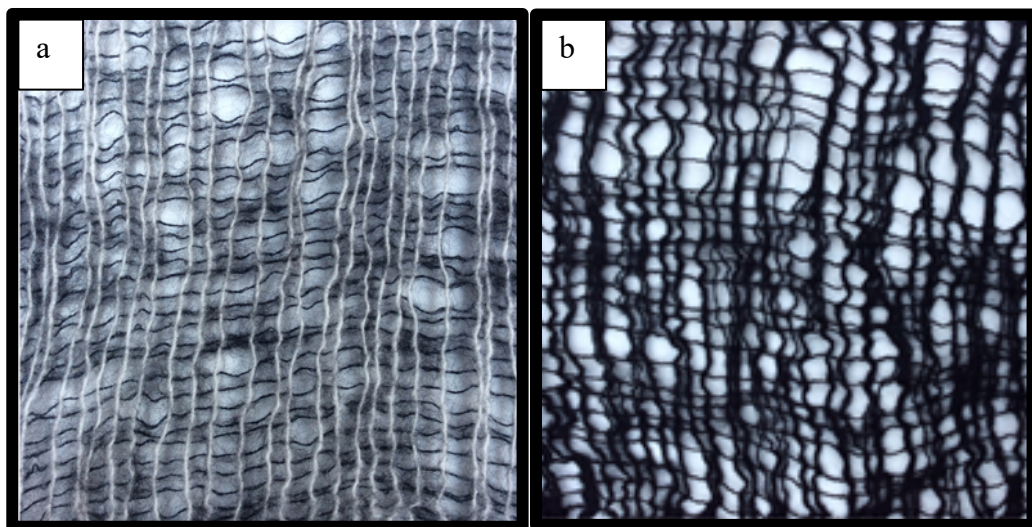


Figure 7.9: a) Cream 100% Merino Wool and 70% Mohair, 30% silk

b) 100% Wool and 85% Wool, 15% Elastane.

Samples manufactured by the FOYSE process (Figure 7.9) can provide Polyester mesh alternatives to create a breathable fabric suitable for sporting activities.

Casual Wear Accessories

In addition to functional and technical textiles FOYSE can be used to create textiles for day-wear accessories as in Figure 7.10 and 7.11.



Figure 7.10: Hover-Tex design created by FOYSE manufacture.



Figure 7.11: Zephlinear design with embedded floral imagery created by FOYSE manufacture.

Bridal and Occasional Wear

An alternative to day-wear accessories, FOYSE manufacturing can be used for bridal, occasional accessories and full garments as in Figure 7.12 and 7.13.



Figure 7.12: Exhibition of FOYSE apparel displayed at the White Gallery, ExCel London.



Figure 7.13: Exhibition of FOYSE apparel displayed at the White Gallery, ExCel London.

FOYSE Fabrics and Garments Created Outside of Traditional Make Up Methods

Garments have been constructed using the FOYSE process outside of the traditional make-up methods. Beading without stitch as in Figure 7.16 and a dress produced without interloping, interlacing and stitch as in Figure 7.17. In addition, this dress is also created without the use of the cut and sew production method, therefore, producing minimal waste. These advancements will contribute to the zero-waste design-thinking that is much needed within the fashion and textile industry. Whilst zero-waste fashion design has been a niche market for many years, new demands for more sustainable practices in the fashion industry and low waste production pushes this to the forefront of new design innovation (Moorhouse and Moorhouse 2017). The approach of integrating the beading into the manufacturing process as in Figure 7.16 reduces the cost of manufacturing as the need to stitch them on separately is removed. Reduction of cost is also applicable to the dress in Figure 7.17 as the fully fashioned process allows a garment to be constructed with limited waste.



Figure 7.14: Fabric beaded without stitching.



Figure 7.15: Fabric beaded without stitching.

FOYSE Process for Education

The FOYSE process will also be used for educational purposes. Providing the opportunity at the earliest age for students to experiment with new ways of producing and designing is necessary for children to compete in the advancing world. One ongoing project is to provide all UK junior schools with an affordable e-textile kit that utilises design registered tools and E-yarn developed through this research. This kit has been tested by Cape View Elementary School in Florida, USA. The request came from the Arts teacher, Marguerite King Goswick who wanted to introduce textiles into her classroom.



Figure 7.16: Children experimenting with FOYSE manufacture and LED filament in the UK.

Textiles for Interiors



Figure 7.17: Cushion produced with FOYSE manufactured fabric.

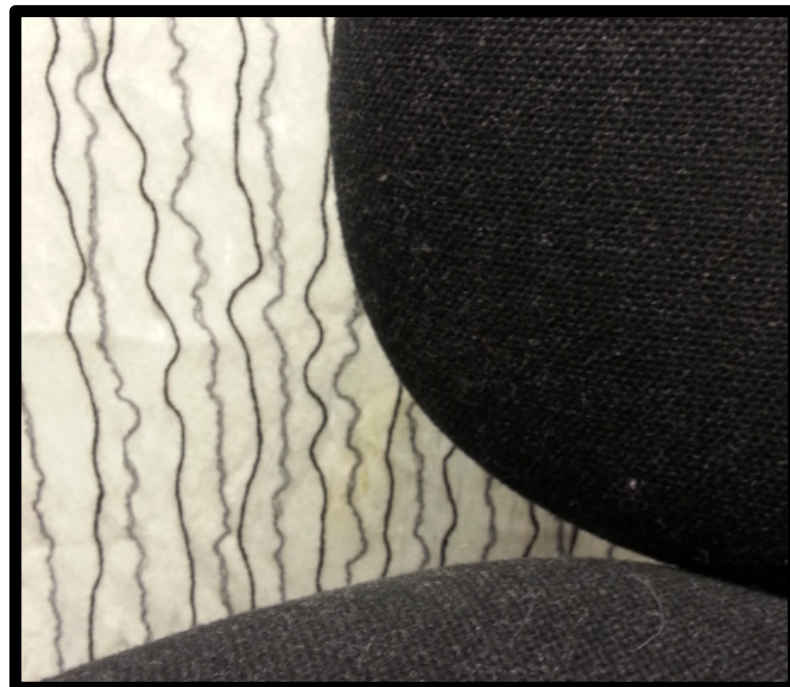


Figure 7.18: Wall Covering produced with FOYSE manufactured fabrics.

Wall Art Abstract Line Drawing Created by FOYSE



Figure 7.19: Abstract line drawing created by FOYSE.

7.4 Summary

To enable me to explore the potential applications of the FOYSE fabric, I have considered a range of possible market solutions. Some of these possibilities require minimal development of the fabric, particularly in the context of aesthetic and fashion led outcomes such as apparel and home furnishings. In these contexts, using trends to develop colour, shape, pattern, and image in a designer context would lead to resolved 'ready to market' solutions. The feedback from requested testing of a t-shirt with FOYSE panels (Figure 7.9) informs of a functional difference. The totally concealed E-yarn applied to wearable clothing without the need for stitching in Figure 7.2 informs of a manufacturing difference. This process was investigated after a request from the global company Venture Heat who spoke of the high costs of having heated wires hand sewn into garments. Each sample product and service outlined in this chapter provide proof of concept. However, some of the technical textiles' manufacturing require further development to be commercially viable regarding speed of production. This is discussed in section 3.1.1 Experimental Testing to Speed Up the Manufacturing Process and Chapter 6 Proof of Concept for Scale of Manufacture. Also, Chapter 6 investigated using a microrobot to lay out yarn which would be a solution for the issue regarding speed. The following chapter details the academic and industry outputs the project has been involved with including collaborations.

CHAPTER 8: PROJECT OUTPUTS AND DISSEMINATION

8.1 Introduction

As a result of the research, namely products and tools described in chapters 6 and 7, several patents have been filed. Government funding for further development and commercialisation of Zephlinear by FOYSE has been secured. A Limited company has been established and via the trademark Zephlinear, a family of brands have been created. Each brand gives direction and clarity regarding the delivery of the new technology, tools, and associated products to targeted textile sectors. Zephlinear Couture for delivery of high end FOYSE manufactured apparel; FOYSE Technology for delivery of teaching the FOYSE process; Fabtangle a device for crafters and hobbyists designed to entangle fibre fast; and Zephlinear Education, a teaching programme designed for sharing next generation textiles and tools.

8.2 Project Outputs and Dissemination

In 2021, a collection of samples manufactured by the FOYSE process was requested by Material ConneXion®. This company is a private global library with locations in New York, Bangkok, Bilbao, Daegu, Milan, Skövde and Tokyo. A paper on the FOYSE process was accepted for the Seventh International SPWID²² conference 2021 and published in conference proceedings. The paper titled 'E-textiles the Need to Breath: A Novel Manufacturing Process and Textile for Lightweight Transparent Sustainable E-textiles and Wearables' went on to be awarded 'best paper' by the conference hosts. In addition, one of eight Ivy League Universities in the US, the University of Pennsylvania Fisher Fine Arts Library Material Collection, requested to document samples manufactured by the FOYSE process. Furthermore, they requested to exhibit physical samples in the renowned Fisher Arts Gallery. The eight samples sent and documented are in Figures 8.1 to 8.8 The following link connects to all eight samples <http://bit.ly/ZephlinearUPENN>.

²² SPWID: Smart Portable, Wearable, Implantable and Disability-oriented Devices and Systems conference.

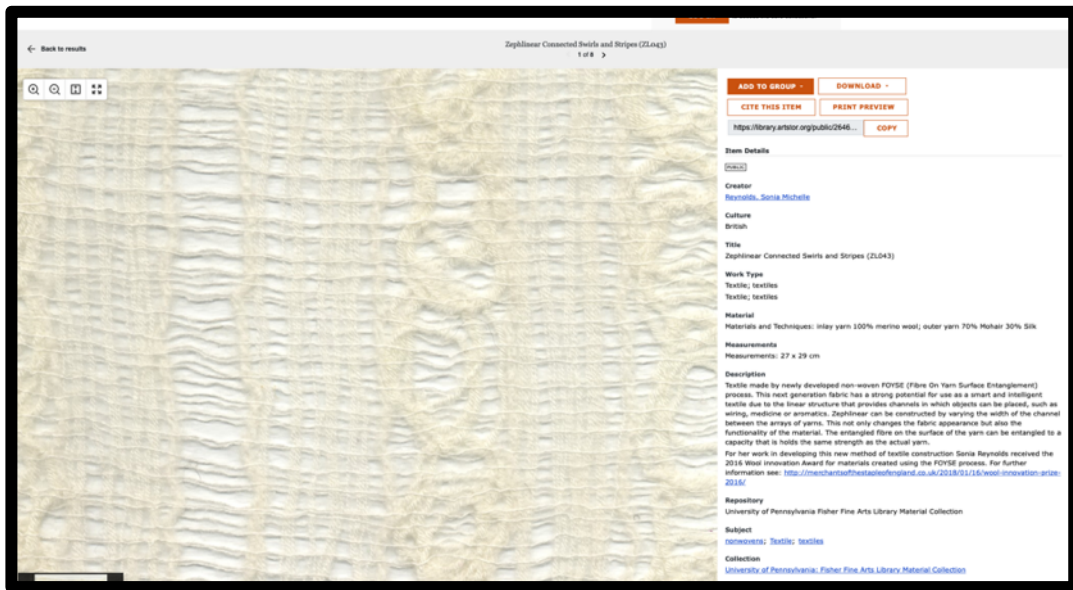


Figure 8.1: A sample of Zephlinear exhibited at University of Pennsylvania Fisher Fine Arts Library Material Collection.

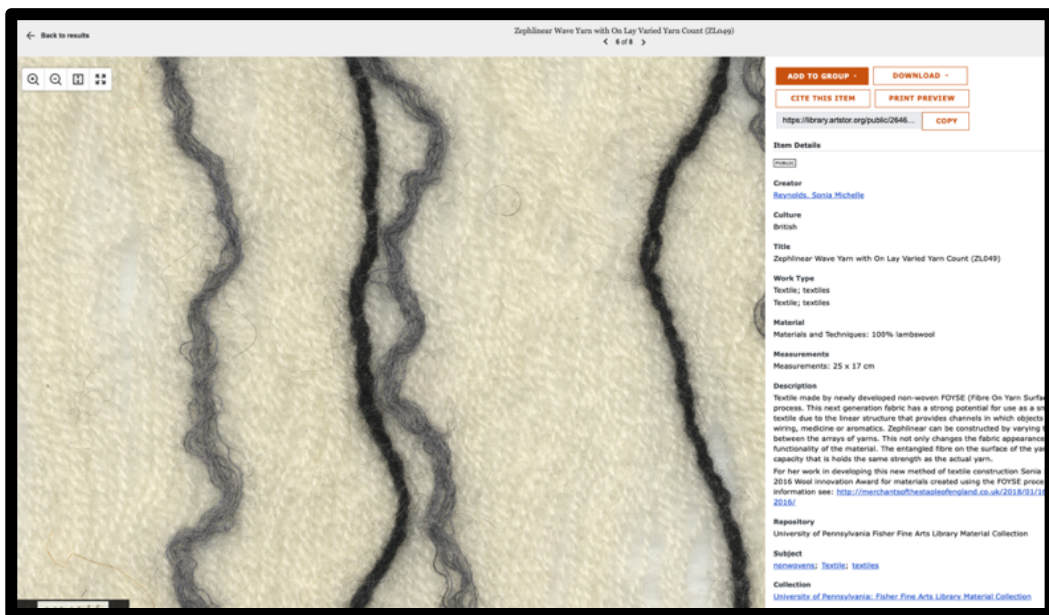


Figure 8.2: A sample of Zephlinear exhibited at University of Pennsylvania Fisher Fine Arts Library Material Collection.

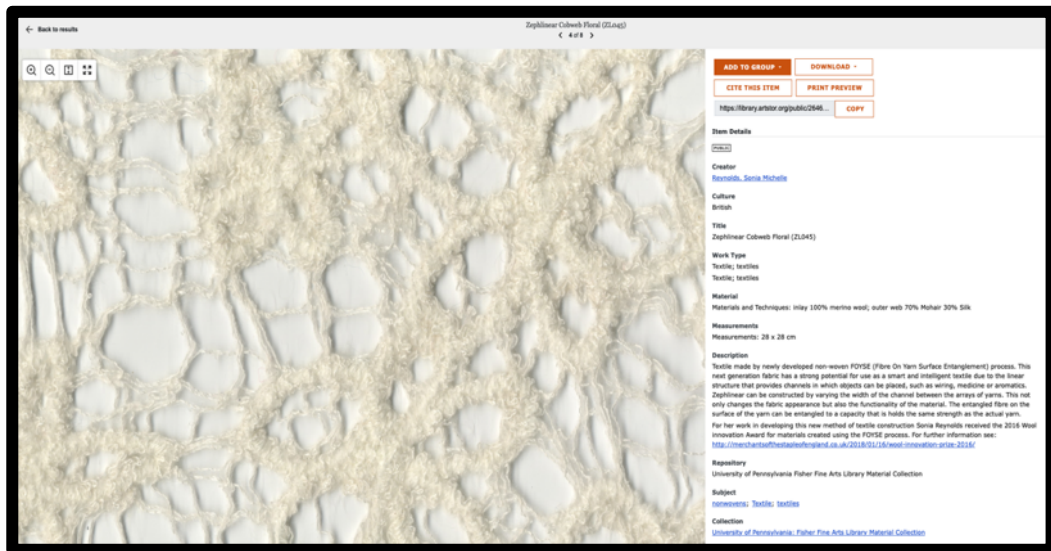


Figure 8.3: A sample of Zephlinear exhibited at University of Pennsylvania Fisher Fine Arts Library Material Collection.

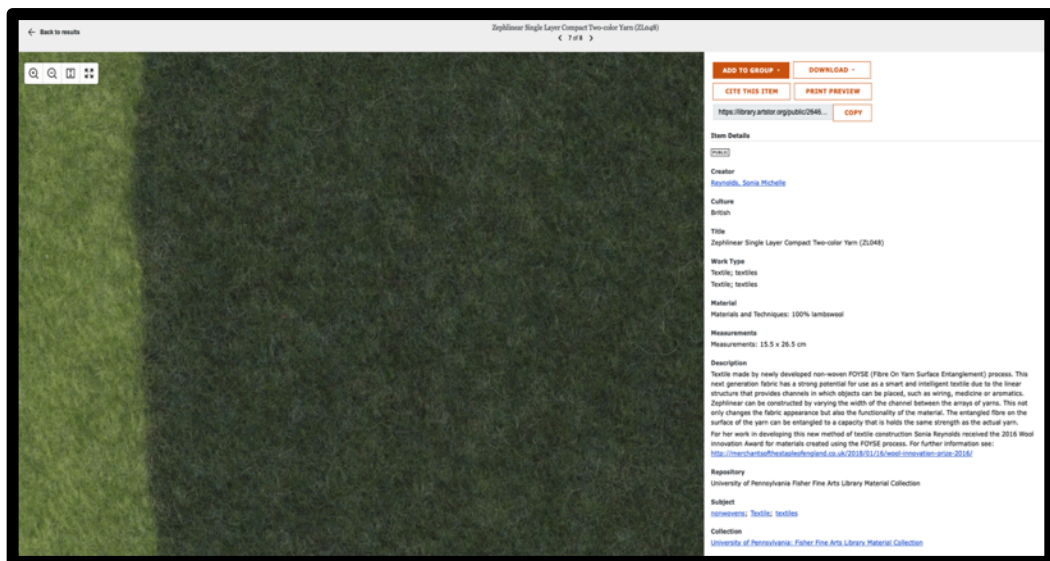


Figure 8.4: A sample of Zephlinear exhibited at University of Pennsylvania Fisher Fine Arts Library Material Collection.

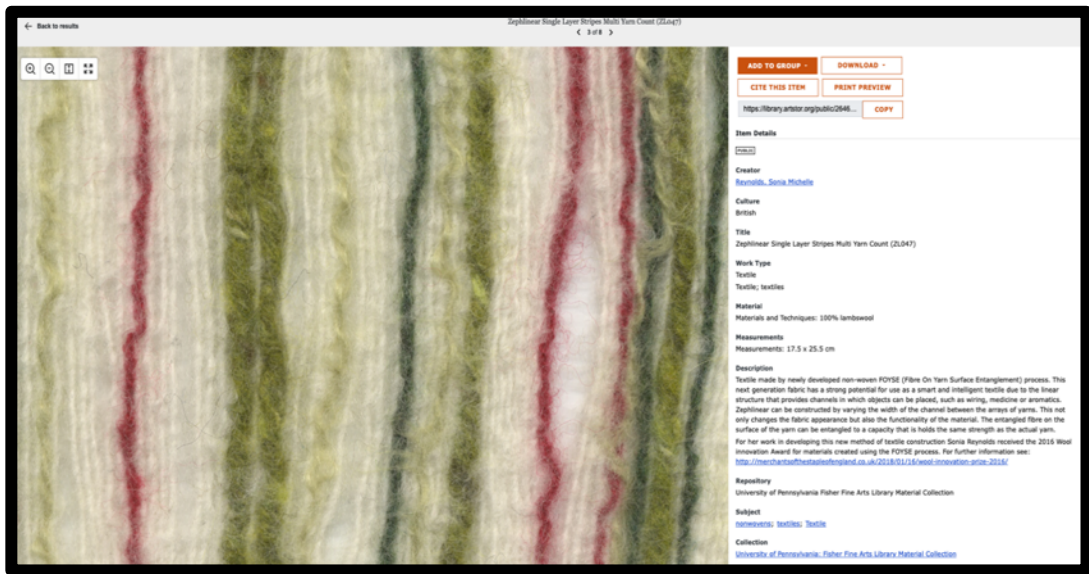


Figure 8.5: A sample of Zephlinear exhibited at University of Pennsylvania Fisher Fine Arts Library Material Collection.

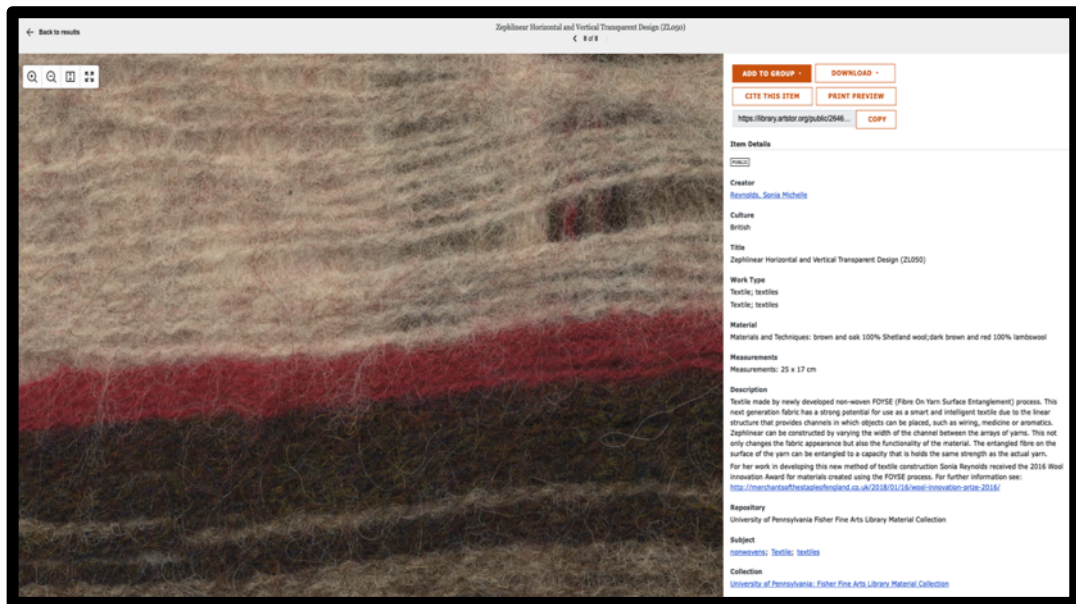


Figure 8.6: A sample of Zephlinear exhibited at University of Pennsylvania Fisher Fine Arts Library Material Collection.

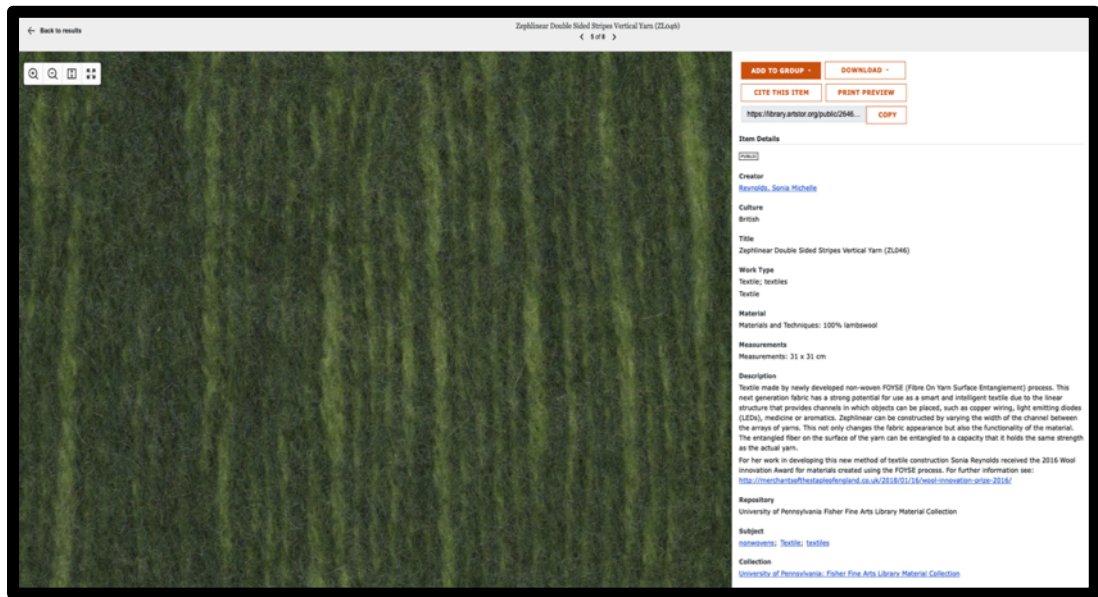


Figure 8.7: A sample of Zephlinear exhibited at University of Pennsylvania Fisher Fine Arts Library Material Collection.

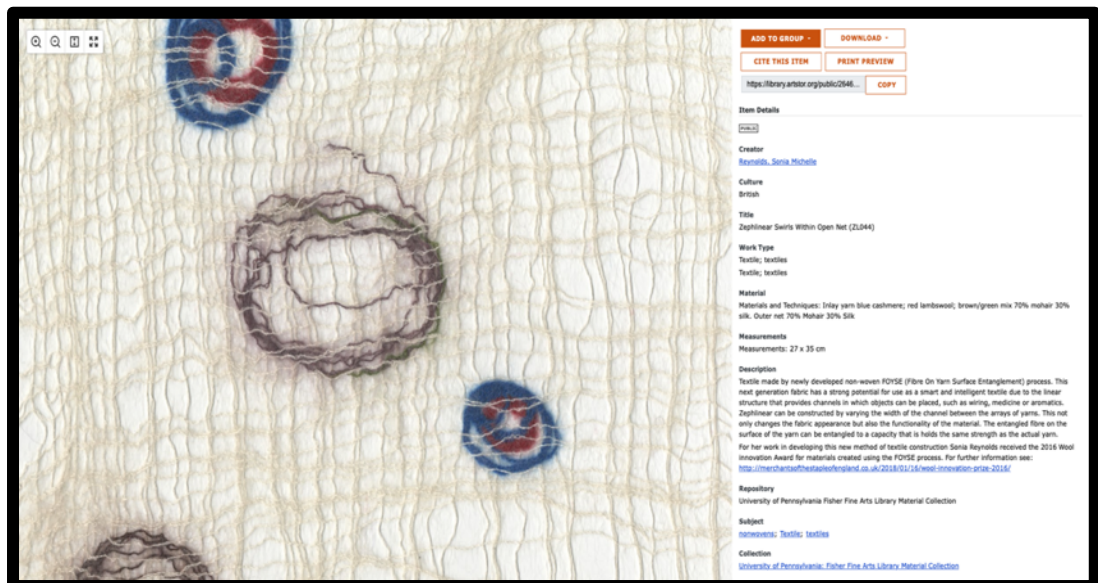


Figure 8.8: A sample of Zephlinear exhibited at University of Pennsylvania Fisher Fine Arts Library Material Collection.

NTU marketing team issued a press release on my research to the textile trade media. It has been well received and to date Zephlinear has received coverage in over twenty-five global online news websites. In addition, industry leaders interested in the project updates and collaboration have made contact.

8.3 Summary

This chapter has presented outputs of the research. Significant interest has been generated from established bodies within industry and academia. This attention was obtained from a press release, the Zephlinear website, exhibitions, and the Wearable Technology Show Silicon Valley. Having received awards such as the National Wool Innovation Prize Award and the Santander Innovation Grant, FOYSE products have received significant exposure. The Material ConneXion® Library is a private commercial library that is accessed by members from design studios, engineering firms, universities, and Fortune 500 companies around the world. Therefore, having a collection of fabrics created by the FOYSE process located there, offers further possible opportunities for future outputs. The ability to create large runs of FOYSE manufactured fabrics at a lower cost and shorter timescale than traditional hand-woven fabrics will also enhance the appeal of the FOYSE process. This will be of particular interest to designers desiring small runs of textile fabrics. The following chapter discusses future works.



Figure 8.9: Top and trousers produced by FOYSE manufactured fabric.

CHAPTER 9: SUMMARY, CONCLUSIONS AND FUTURE WORK

9.1 Thesis Summary

This thesis was undertaken to develop a novel method of fabric manufacture and introduce a fourth class of fabric construction for design practice. The technology for this manufacturing process is named FOYSE as presented in the introduction of this research. Every innovation produces associated products and services. Subsequently, the necessity to create and experiment with novel tools and techniques to support the unique technology was a natural output of the research. From initial experimentation and sampling of the FOYSE process, two very distinct fabric surfaces were created named Zephlinear and Hover-*Tex*. These materials are also presented within the introduction of the thesis which includes the research context. This investigation identified the current state-of-the-art-of fabric manufacture and outlines the current limitation within the textile industry due to having three fabric manufacturing methods: interlacing of at least two sets of yarns, inter-looping of yarns of one set and bonding of fibres of a web.

The interweaving of the tasks of inventorship, in addition to the confinement of the systematic approach needed for my PhD research, proved to be a challenging journey. My research could identify with one item of literature which was by Christine Padesky; she took a similar role to my position in the research of a scientist-practitioner-entrepreneur. The term is used in the article 'The Road Less Traveled' (Padesky 2004). I similarly identified myself (in chapter 3) as a researcher-inventor-designer-entrepreneur. My journey through the actual research process led me to produce a concept that combined the Double Diamond Model from the Design Council and the Engineering Design Model from Engineering Design Methods by Nigel Cross. This combination (in chapter 3) supported in clarifying and formalising the inventive steps embedded in this investigation. The vision for this research is that it would be used for design practice as stated in the title of the research.

Experimenting and testing new methods to test the strength of FOYSE fabrics was undertaken. In addition to tensile testing a novel approach of visual observation under a microscope was developed. The purpose was to investigate the assumption that the more intense the entanglement of surface fibres of yarn the less open space would be visible. From six samples tested (in chapter 4) it was identified that when less open space was visible the surface fibre appeared to have entangled to a greater extent. This entanglement was assessed by placing the samples between fingers with an attempt to separate the fibres. More research in this area is suggested as, theoretically, an image analysis technique could be used to determine the strength of fibre entanglement. In addition to identifying FOYSE fabric strength, a novel process to automate the laying of yarn was developed and detailed (see chapter 5). Yarn was attached to a miniature robot and programmed to travel

along a designed shape to create a parallel array of yarn for FOYSE manufacture. The use of miniature robots could transition the way not only for FOYSE but for all manufacturing processes that use yarn.

Much iteration of the entire FOYSE process, which included the development of handmade tools, was undertaken. A project that looked at individual powered workstations completed by NTU students proved the automation concept. A domestic weaving loom was the final apparatus used to complete a FOYSE fabric, all combined workstations are presented in chapter 6. A collection of samples and garments have been created to showcase the versatility of FOYSE fabrics. Current applications of E-yarn incorporated within textiles are tightly woven or knitted to allow it to be stitched or firmly supported. Unlike these smart textiles, as presented in chapter 7, FOYSE provides a structure whereby E-yarn can be used as part of an open mesh structure. This is a major advancement and building block for the advancement of e-textiles. Chapter 7 also includes novel concepts such as creating garments and adding embellishment such as beading without the cut- sew and stitch process. A selection of FOYSE fabrics is currently available to view online and physical samples on request at the Fisher Arts Gallery situated at the Ivy League University of Pennsylvania. Images of these samples are in chapter 8. Data to understand how individuals view fabrics created by FOYSE and for classification has also been collected. A collection of further outputs and dissemination outlets of this project have also been documented (appendix 3).

9.2 Conclusion

The FOYSE process has been proven to create a stable fabric surface to a scale and strength suitable to be classified as a textile according to the British Test Standard ISO 2062 (research aim 1- 3). The qualitative and quantitative data results from this research have proven FOYSE technology is suitable for manufacturing textiles (research aims 1 - 6). Data collected from open and closed questionnaires confirmed that fabric surfaces created by FOYSE were understood to have design and performance variance from known methods of textile manufacturing (research aims 4, 5 and objective A). Handheld tools and apparatus to aid the manufacturing process of FOYSE were also created and used to manufacture a portfolio of samples (research aims 2A, 2B, 5 and objective B). Therefore, the aims and objectives in this research have been answered and a fourth class of textile suitable for design practice developed.

One of the findings to emerge from the literature review is that the three known methods of textile manufactured fabrics evolved over time. Textiles created from yarn, which developed from string, indirect evidence in the form of perforated beads, fishing net weights and cord-impressed pottery occurs worldwide (Hardy 2008). This supports the theory that no one individual or community created the process of creating textiles using the interlacing or interloping process. The consequent revelation supports that, until this study there has not been a new textile manufacturing process invented but rather the further development of interlacing, interlooping and fibre bonding methods. The recorded invention from Nottingham that revolutionised the textile industry globally was the invention of the knitting machine by William Lee in 1589. This not only transformed the knitting industry but was the catalyst of the industrial revolution. This mechanised knitting machine, with many innovations, was misunderstood and not welcomed by the hand-knitting industry but viewed as a threat to the status quo of the industry at that time.

During the period of this research, substantial financial funding from industry and governments was provided for research and development within the area of creativity and innovation, sustainability, and E-textiles. Even though I believe this ground-breaking research is advantageous to these sectors this research did not attract funding and is self-funded. In reflection, lack of finance provided the opportunity for me to become more resourceful. I personally worked through the design process required to create novel tools and an apparatus to aid in the FOYSE process. The research journey at times led me to feel isolated, although, awareness of the challenges pioneers before me faced gave me the understanding that this experience was normal. Establishing this new technology FOYSE, which is also confirmed by a patent granted, makes the barriers I faced worthwhile. FOYSE is a convergent technology in that it lends itself to the known three textile manufacturing processes,

which within themselves are unrelated. I therefore predict it will have similar market value as woven, knit and nonwoven textile processes.

9.3 Contribution to Knowledge

The FOYSE process provides advancement to knowledge regarding how fabric from yarn can be created by entangling surface fibres of yarn (hairiness). In addition, how a fabric surface can be created by the wetting and drying of yarn. A further contribution is how a fabric surface can be created by an additive process of layering yarn upon yarn. This knowledge will advance education by the teaching of a new construction method which will open new channels for creative thinking. For example, incorporating different types of yarn, elements and embellishments can dramatically alter the fabrics' unique appearance and character. Crafting a fabric with thick and thin yarns or coloured yarn can create artistic designs currently unavailable via known manufacturing processes; an example is given in Figure 9.1.

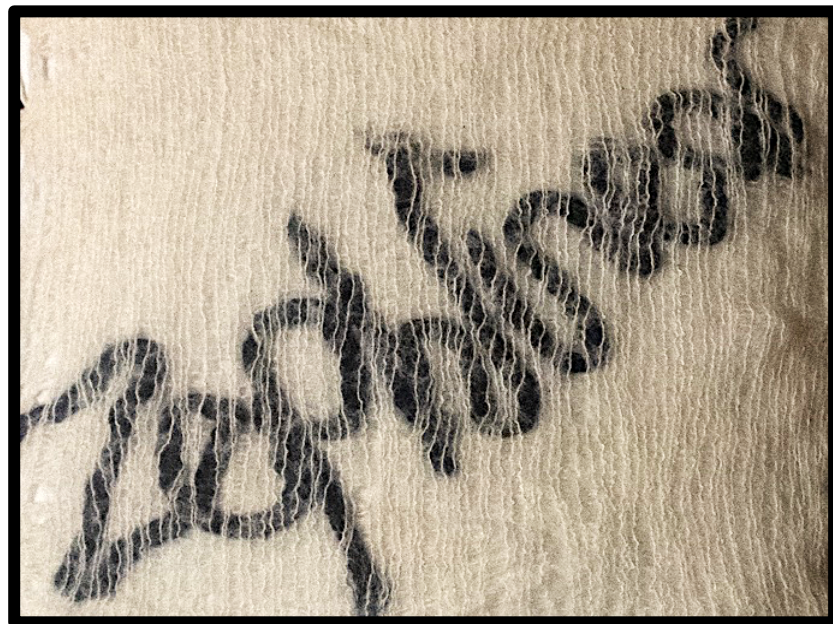


Figure 9.1: Image of fabric created by FOYSE technology.

The FOYSE process also offers an alternative solution to create e-textiles outside of the known manufacturing processes. This will further advance the function of the material and contribute to the advancement of e-textiles. An example of this is that the FOYSE manufacturing process can produce e-textiles with large open areas for increased breathability, transparency, and lightweight fabric surfaces. Moreover, removing the need to weave, knit, stitch, or embroider e-yarn or electronics onto or within fabrics. The FOYSE manufacturing process rather embeds textiles within the yarn or between the fibre on the surface of yarn, entangling layers as seen in Figure 10.1.

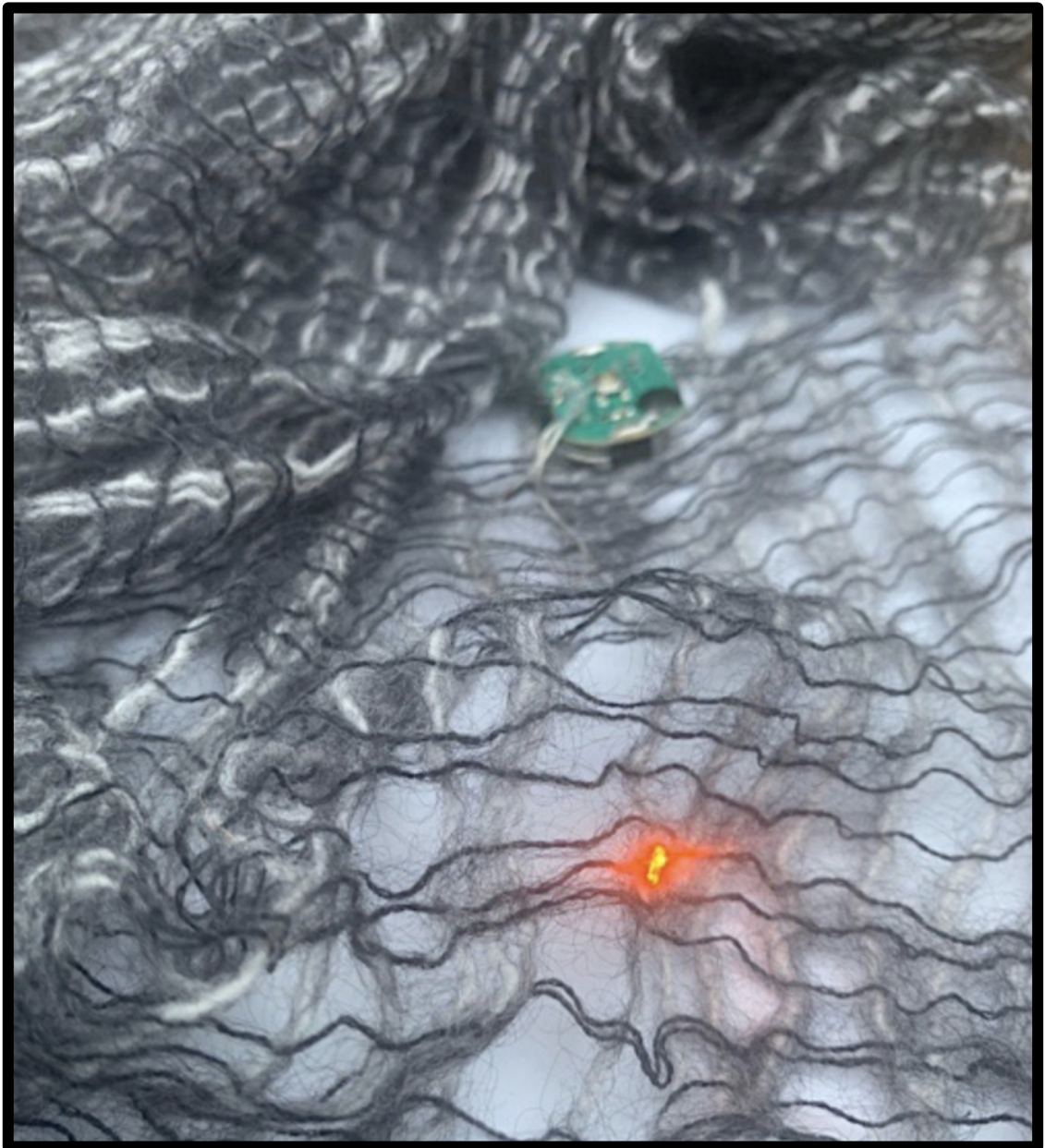


Figure 9.2. Hover-Tex 2 sqm sample with a 3mm programmable light-emitting device to power and control embedded devices.

In addition, new knowledge has been created by:

1. Historical analysis of textile manufacturing and its impact across four sectors from the first recorded discovery of textiles to present day (see chapter two, literature review).
2. Novel tool for uncurling surface fibre on yarn.
3. Development of apparatus to prove the concept of full automation.
4. Identifying via microscopic images the relationship between open space and strength of fabric entangled fibre.
5. Collection of textile apparel created outside of the three known textile manufacture processes.
6. Garments using yarn made without stitch, weave and knit.
7. Mini robots used to lay a parallel array of yarn for FOYSE manufacture.

9.4 Future Work

Funding and support have been provided for the advancement of Zephlinear, Hover-Tex by FOYSE and resulting outcomes from this research. The eight areas of new knowledge previously listed will each require independent investigation. Exhibitions, lectures, and online workshops will be conducted for further dissemination of FOYSE technology and products. Also, publishing research within academic publications will be undertaken.

An advancement of the FOYSE process is also part of my future work. Using the FOYSE process with spun yarn containing fibres without scales and various filaments underwent preliminary experimentation. A novel manufacturing process using one layer of hairy yarn and one layer of flexible 3D printer filament is the new investigation. This novel process is currently patent pending, application number GB2110410.4. Included in the patent is a hybrid filament of improved functionality resulting from combining the filament and loose fibre or fibre spun yarn. This novel product provides a filament and fibre mix that can be simplistically embedded with microelectronics and has characteristics ideal for next to skin textile products. In addition, the process can rapidly create textiles and e-textiles by utilising an adapted 3D printer. This advancement is ideal for rapid prototyping and small textile production manufacturers. Businesses that require fast-paced textile design and manufacturing capacity will also benefit from this novel textile manufacturing process.

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Appendix 1: Transfer Report 2016 pages 35-38

Development of Technology to Automate Manufacture

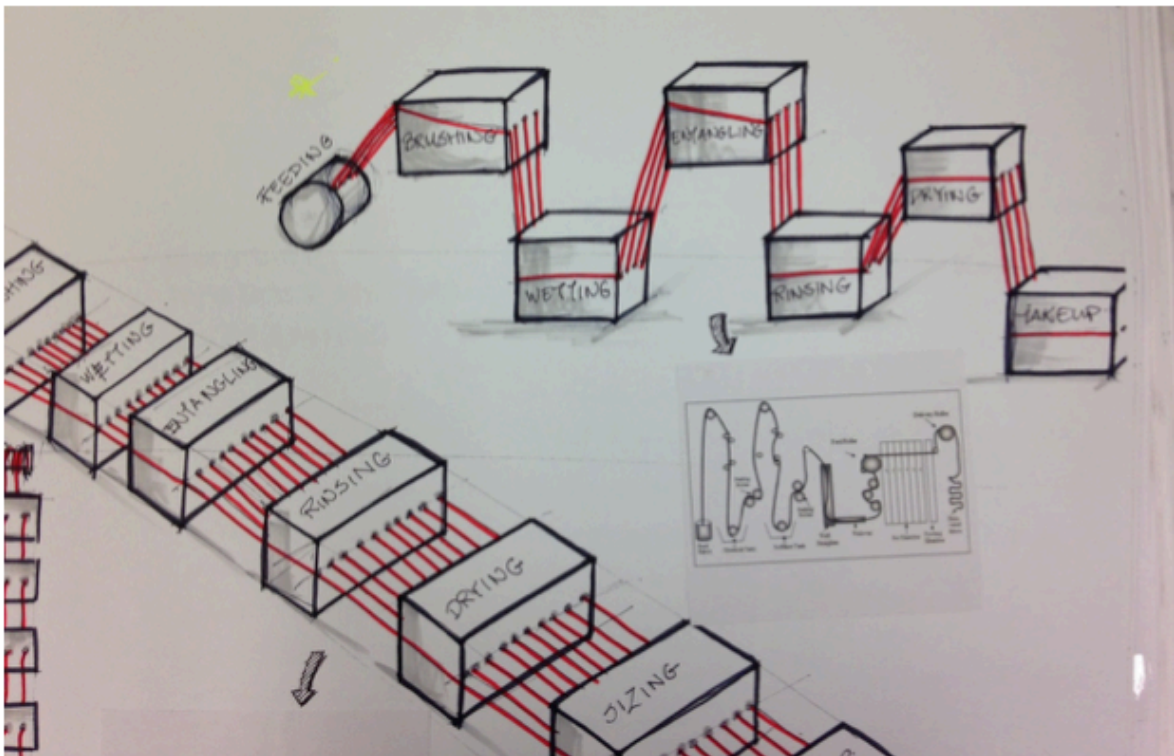


Figure 21: Sketch of process layout by BSc Student

BSc Product Design students at NTU were given a Mechatronics Project to create 5 workstations. An in-depth Investigation into the construction and process development of the fabric has been conducted.

Components:

- Yarn feed station
- Brushing station
- Wetting/agitation station
- Drying station
- Roller to collate material

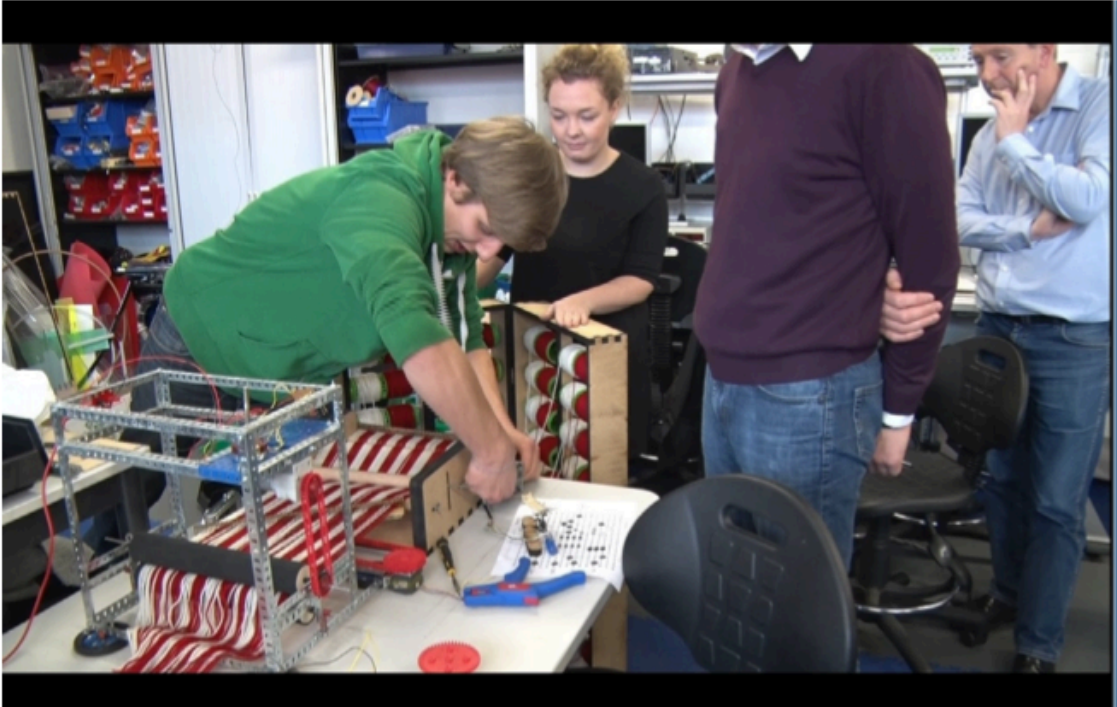


Figure 22: Students working on the feeding station for Zephlinear



Figure 23: Students working on the brushing station for Zephlinear



Figure 24: Students working on wetting and agitation station for Zephlinear

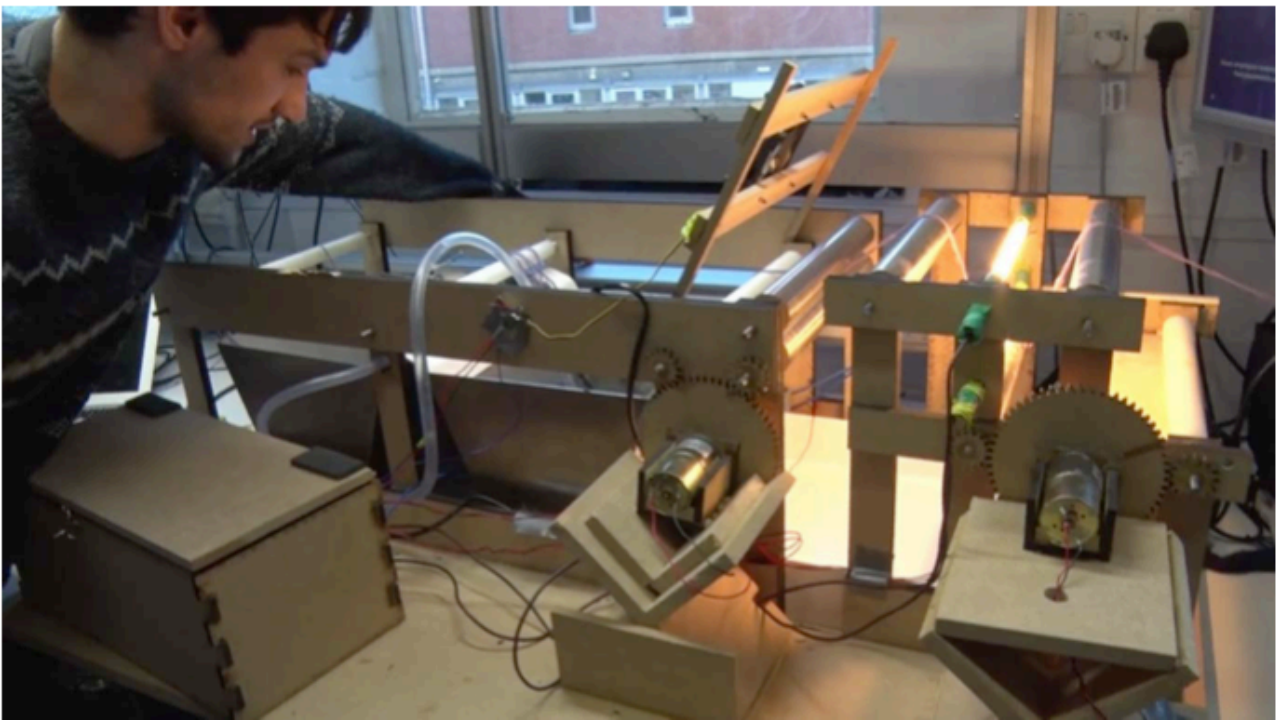


Figure 25: Students working on the Drying station for Zephlinear

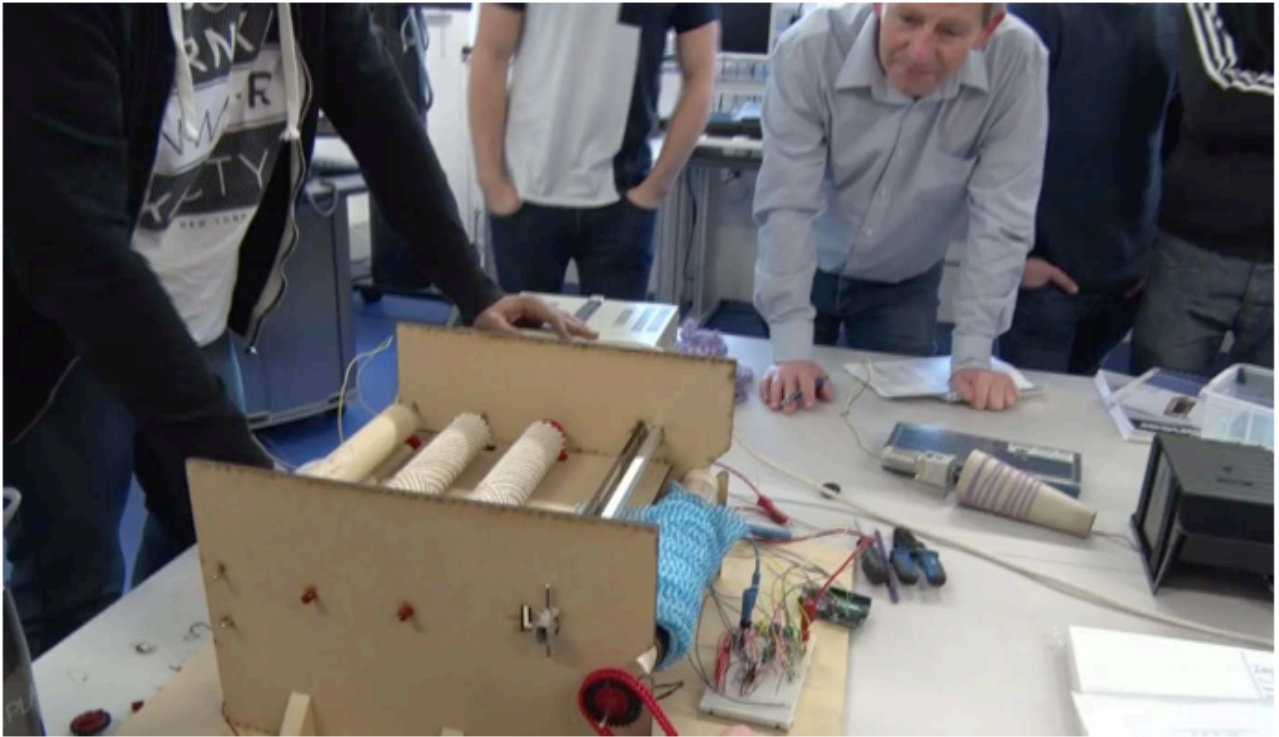


Figure 26: Students working on the take up station for Zephlinear

Appendix 2: Structured Questionnaires Results

Element elicitation

NON-WOVEN WOVEN KNIT



Q1: Which of these things is not like the others? *Non-woven*

Q2: What makes it different from the other two? *Made from non woven yarns*

Q3: As opposed to? *Woven yarns.*

NON-WOVEN WOVEN ZEPHLINEAR



Q1: Which of these things

Q2: What makes it differ

Q3: As opposed to? *N*

*linear
like a mixture of*

WOVEN KNIT



Q1: Which of these things is not like the others? *zephlinear*

Q2: What makes it different? *looks like a mixture of non woven*




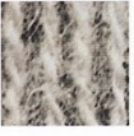
Q3: As opposed to? *full structure? But with a structure*

TOPIC: FABRIC CONSTRUCTION

ELEMENTS: 4 PERCEPTUALLY DIFFERENT FABRIC SURFACES

CONSTRUCTS: 7 CONSTRUCTS ELICITED FROM INTERVIEWED PEOPLE

RATINGS: ON A 5-POINT SCALE

	NON - WOVEN (FELT) FIBRE BONDING OR INTERLOCKING OF SCALES	WOVEN (INTERLACING OF TWO YARN ENDS)	KNIT (INTERLOPING OF A SINGLE YARN END)	ZEPHLINEAR (FOYSE) FIBRE ON YARN SURFACE ENTANGLEMENT	
1					5
Distinct structure	5 5	1	1	3	Unstructured
Some structure	5	1	1	3	No structure
Loose	1	4	4	3	Stiff
Unstructured and structured combination	5	5	5	1	One structure no combination
Vertical structure mixed with entanglement	5	1	1	1	No vertical structure mixed with entanglement
More moveable	1	3	3	2	Less moveable
Durable	3	2	2	2	Un-durable

RepGrid constructs results participant 1.

Element elicitation

NON-WOVEN WOVEN KNIT



Q1: Which of these things is not like the others? *Non-woven*

Q2: What makes it different from the other two? *It has no pattern, no interlocking.*

Q3: As opposed to? *looping and crossing over of yarns*

NON-WOVEN WOVEN ZEPHLINEAR



Q1: Which of these things is not like the others? *Non-woven*

Q2: What makes it different? *It has no definite lines structure.*

Q3: As opposed to? *the yarn in the others has straight lines vertical and/or horizontal.*

NON-WOVEN KNIT ZEPHLINEAR



Q1: Which of these things is not like the others? *Zephlinear*

Q2: What makes it different? *It is looser and less structured*

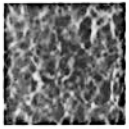


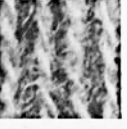
Q3: As opposed to? *Zephlinear just has vertical lines, with any other fibres.*

TOPIC: FABRIC CONSTRUCTION

ELEMENTS: 4 PECEPTURALLY DIFFERENT FABRIC SURFACES

CONSTRUCTS: 7 CONSTRUCTS ELICITED FROM INTERVIEWED PEOPLE

RATINGS: ON A 5-POINT SCALE

	NON-WOVEN (FELT) FIBRE BONDING OR INTERLOCKING OF SCALES	WOVEN (INTERLACING OF TWO YARN ENDS)	KNIT (INTERLOPING OF A SINGLE YARN END)	ZEPHILINEAR (FOYSE) FIBRE ON YARN SURFACE ENTANGLEMENT	
1					5
Distinct structure	5	2	2 1	3	Unstructured
Some structure	5	1	2	1 3	No structure
Loose	5	3 4	3	2	Stiff
Unstructured and structured combination	5	5	5	1	One structure no combination
Vertical structure mixed with entanglement	5	3	2	1	No vertical structure mixed with entanglement
More moveable	5	3	2	1	Less moveable
Durable	3	2	1	3	Un-durable

RepGrid constructs results participant 2.

Element elicitation

NON-WOVEN WOVEN KNIT

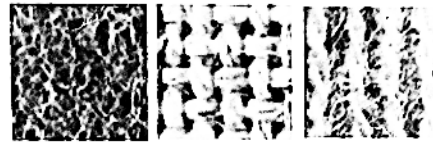


Q1: Which of these things is not like the others? non-woven

Q2: What makes it different from the other two? it doesn't have a clear

Q3: As opposed to? knit & woven woven structure

NON-WOVEN WOVEN ZEPHLINEAR

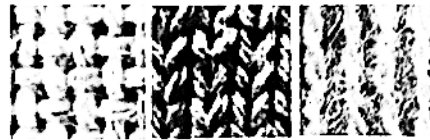


Q1: Which of these things is not like the others? zephlinear

Q2: What makes it different? it isn't non-woven but is a type of

Q3: As opposed to? weave & felting technique.
woven & non-woven

NON-WOVEN KNIT ZEPHLINEAR



Q1: Which of these things is not like the others? non woven

Q2: What makes it different? it is a type of weave instead of

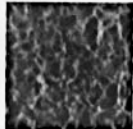


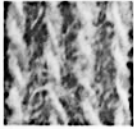
Q3: As opposed to? knit technique.
knit &
zephlinear.

TOPIC: FABRIC CONSTRUCTION

ELEMENTS: 4 PERCEPTUALLY DIFFERENT FABRIC SURFACES

CONSTRUCTS: 7 CONSTRUCTS ELICITED FROM INTERVIEWED PEOPLE

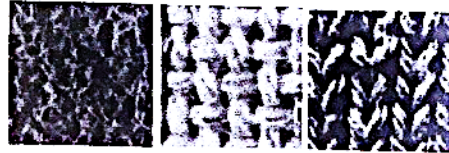
RATINGS: ON A 5-POINT SCALE

	NON - WOVEN (FELT) FIBRE BONDING OR INTERLOCKING OF SCALES	WOVEN (INTERLACING OF TWO YARN ENDS)	KNIT (INTERLOPING OF A SINGLE YARN END)	ZEPHILINEAR (FOYSE) FIBRE ON YARN SURFACE ENTANGLEMENT	
1					5
Distinct structure	5	2	1	3	Unstructured
Some structure	4.5	4.1	1	3	No structure
Loose	5	1	3.5	4	Stiff
Unstructured and structured combination	3	5	2	1	One structure no combination
Vertical structure mixed with entanglement	5	2	1	3	No vertical structure mixed with entanglement
More moveable	3	1	2	1	Less moveable
Durable	4	3	2	4	Un-durable

RepGrid constructs results participant 3.

Element elicitation

NON-WOVEN WOVEN KNIT

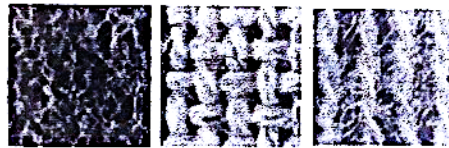


Q1: Which of these things is not like the others? *Non-woven*

Q2: What makes it different from the other two? *Its stuck together*

Q3: As opposed to? *intertwined*

NON-WOVEN WOVEN ZEPHLINEAR

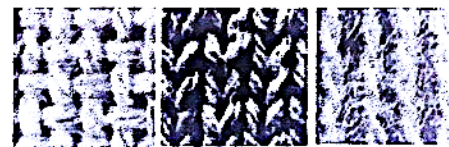


Q1: Which of these things is not like the others? *woven*

Q2: What makes it different? *its interlocking*

Q3: As opposed to? *stuck together*

~~NON-WOVEN~~ KNIT ZEPHLINEAR



Q1: Which of these things is not like the others? *Zephlinear*

Q2: What makes it different? *stuck together*




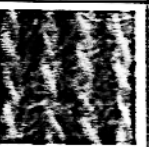
Q3: As opposed to? *interlocking*

TOPIC: FABRIC CONSTRUCTION

ELEMENTS: 4 PERCEPTUALLY DIFFERENT FABRIC SURFACES

CONSTRUCTS: 7 CONSTRUCTS ELICITED FROM INTERVIEWED PEOPLE

RATINGS: ON A 5-POINT SCALE

	NON - WOVEN (FELT) FIBRE BONDING OR INTERLOCKING OF SCALES	WOVEN (INTERLACING OF TWO YARN ENDS)	KNIT (INTERLOPING OF A SINGLE YARN END)	ZEPHILINEAR (FOYSE) FIBRE ON YARN SURFACE ENTANGLEMENT	
1					5
Distinct structure	5	1	1	4	Unstructured
Some structure	5	1	1	4	No structure
Loose	1	4	5	3	Stiff
Unstructured and structured combination	5	3	4	1	One structure no combination
Vertical structure mixed with entanglement	5	1	2	1	No vertical structure mixed with entanglement
More moveable	1	3	5	2	Less moveable
Durable	5	2	1	2	Undurable

RepGrid constructs results participant 4.

Element elicitation

NON-WOVEN WOVEN KNIT



- Q1: Which of these things is not like the others? *Non woven*
Q2: What makes it different from the other two? *its not interlocking kind of*
Q3: As opposed to? *The others look like they go in and out (interlocking)*

NON-WOVEN WOVEN ZEPHLINEAR



- Q1: Which of these things is not like the others? *non woven*
Q2: What makes it different? *Its not interlocking*
Q3: As opposed to? *The others look like interlocking*

NON-WOVEN KNIT ZEPHLINEAR



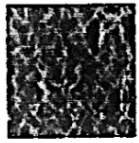


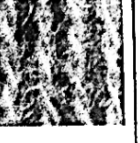
- Q1: Which of these things is not like the others? *Zephlinear*
Q2: What makes it different? *It looks distressed and stuck together by some*
Q3: As opposed to? *The others look interlocking*

TOPIC: FABRIC CONSTRUCTION

ELEMENTS: 4 PECEPTURALLY DIFFERENT FABRIC SURFACES

CONSTRUCTS: 7 CONSTRUCTS ELICITED FROM INTERVIEWED PEOPLE

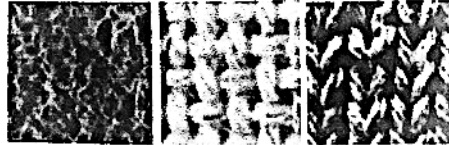
RATINGS: ON A 5-POINT SCALE

	NON - WOVEN (FELT) FIBRE BONDING OR INTERLOCKING OF SCALES	WOVEN (INTERLACING OF TWO YARN ENDS)	KNIT (INTERLOPING OF A SINGLE YARN END)	ZEPHLINEAR (FOYSE) FIBRE ON YARN, SURFACE ENTANGLEMENT	
1					5
Distinct structure	5	1	2	3	Unstructured
Some structure	4	1	2	3	No structure
Loose	1	5	4	2	Stiff
Unstructured and structured combination	2	5	4	2	One structure no combination
Vertical structure mixed with entanglement	5	5	5	1	No vertical structure mixed with entanglement
More moveable	1	5	3	2	Less moveable
Durable	5	1	2	3	Un-durable

RepGrid constructs results participant 5.

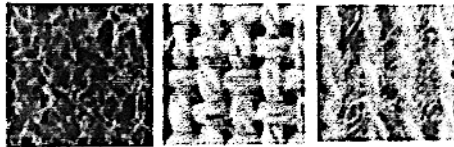
Element elicitation

NON-WOVEN WOVEN KNIT



- Q1: Which of these things is not like the others? *Non-woven*
Q2: What makes it different from the other two? *No clear structure*
Q3: As opposed to? *Clear structure*

NON-WOVEN WOVEN ZEPHLINEAR



- Q1: Which of these things is not like the others? *Woven*
Q2: What makes it different? *Clear structure cross pattern*
Q3: As opposed to? *No clear pattern*

~~NON-WOVEN~~ KNIT ZEPHLINEAR



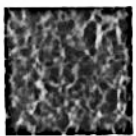


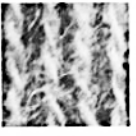
- Q1: Which of these things is not like the others? *Zephlinear*
Q2: What makes it different? *Mixed entanglement*
Q3: As opposed to? *No entanglement*

TOPIC: FABRIC CONSTRUCTION

ELEMENTS: 4 PERCEPTUALLY DIFFERENT FABRIC SURFACES

CONSTRUCTS: 7 CONSTRUCTS ELICITED FROM INTERVIEWED PEOPLE

RATINGS: ON A 5-POINT SCALE

	NON - WOVEN (FELT) FIBRE BONDING OR INTERLOCKING OF SCALES	WOVEN (INTERLACING OF TWO YARN ENDS)	KNIT (INTERLOPING OF A SINGLE YARN END)	ZEPHLINEAR (FOYSE) FIBRE ON YARN SURFACE ENTANGLEMENT	
1					5
Distinct structure	4	1	2	3	Unstructured
Some structure	1	3	2	2	No structure
Loose	5	4	2	4	Stiff
Unstructured and structured combination	5	3	1	2	One structure no combination
Vertical structure mixed with entanglement	5	3	2	1	No vertical structure mixed with entanglement
More moveable	5	4	2	2	Less moveable
Durable	3	2	2	2	Un-durable

RepGrid constructs results participant 6.

Appendix 3: A collection of Outputs and Dissemination Outlets

Zephlinear Global Media Links

<https://phys.org/news/2016-09-space-revolutionise-textiles-industry.html>

<https://www.theengineer.co.uk/non-woven-material-shows-potential-as-e-textile/>

<https://www.tevonews.com/functional-apparel-news/495-new-space-cloth-nonwoven-yarn-targets-smart-textiles>

https://www.just-style.com/news/space-cloth-is-first-non-woven-material-made-from-yarn_id128897.aspx

<https://www.fashionatingworld.com/new1-2/zephlinear-the-innovative-smart-textile>

<https://www.ideaconnection.com/new-inventions/zephlinear-fabric-could-lead-to-smart-clothing-11197.html>

<https://www.eastmidlandsbusinesslink.co.uk/mag/manufacturing/space-cloth-revolutionise-textiles-industry/>

<https://edgy.app/4-incredible-smart-textiles>

<https://www.frogheart.ca/?tag=zephlinear>

<https://www.nonwovensnews.com/209-newsletters/september/13254--sp-1122256592>

<https://electronics360.globalspec.com/article/7365/new-space-cloth-material-could-be-ideal-for-embedded-electronics>

<https://www.ntu.ac.uk/about-us/news/news-articles/2016/09/space-cloth-to-revolutionise-textiles-industry>

<http://merchantsofthestapleofengland.co.uk/2018/01/16/wool-innovation-prize-2016/>

Portuguese Media

<https://www.portugaltextil.com/zephlinear-revoluciona-texteis/>

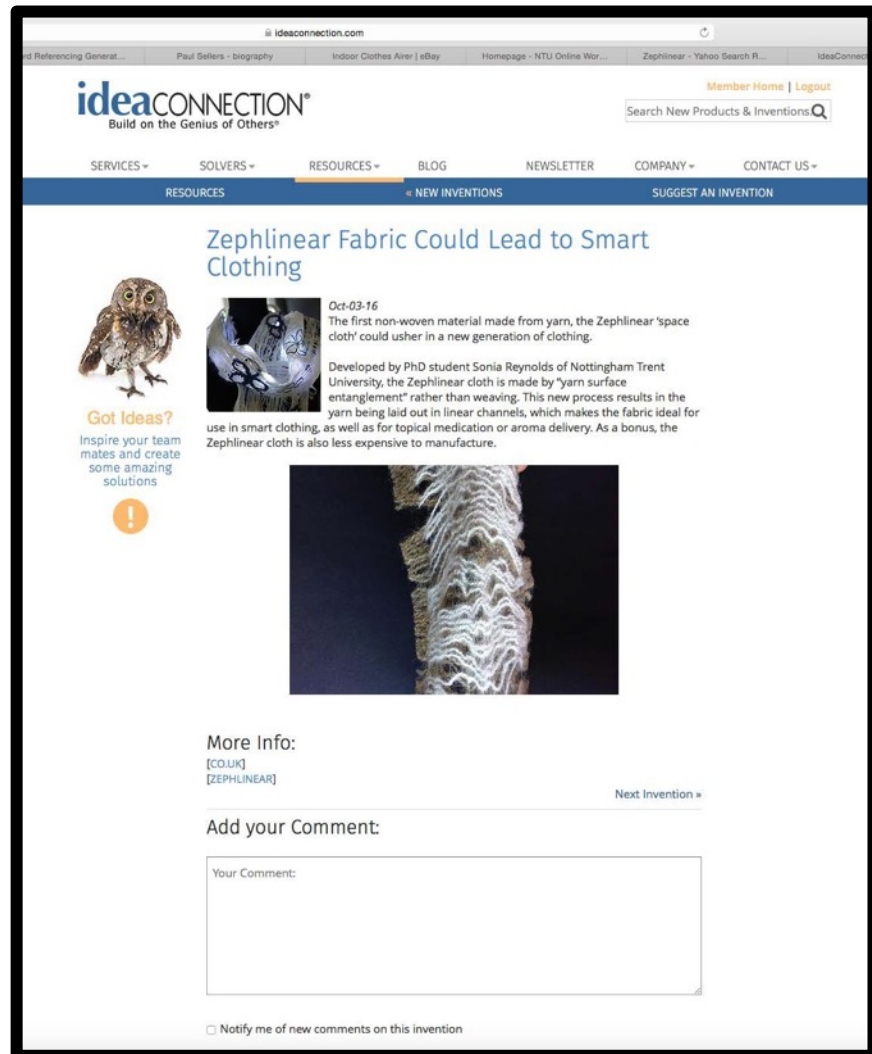
Chinese Media

<https://translate.google.co.uk/translate?hl=en&sl=zh-CN&u=https://www.since-expo.com/media/264.html&prev=search&pto=aue>

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The screenshot displays the Idea Connection website interface. At the top, the logo "ideaCONNECTION®" is visible with the tagline "Build on the Genius of Others®". A navigation menu includes "SERVICES", "SOLVERS", "RESOURCES", "BLOG", "NEWSLETTER", "COMPANY", and "CONTACT US". A search bar for "New Products & Inventions" is located in the top right. The main content area features a blog post titled "Zephlinear Fabric Could Lead to Smart Clothing". The post includes an owl icon, a date of "Oct-03-16", and a short paragraph describing the fabric as a first non-woven material made from yarn. A larger image shows a close-up of the fabric's texture. Below the post, there is a "More Info" section with links to "[CO.UK]" and "[ZEPHLINEAR]", a "Next Invention" link, and a "Add your Comment" section with a text input field and a "Notify me of new comments on this invention" checkbox.

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RESOURCES « NEW INVENTIONS SUGGEST AN INVENTION

Zephlinear Fabric Could Lead to Smart Clothing

Oct-03-16
The first non-woven material made from yarn, the Zephlinear 'space cloth' could usher in a new generation of clothing.

Developed by PhD student Sonia Reynolds of Nottingham Trent University, the Zephlinear cloth is made by "yarn surface entanglement" rather than weaving. This new process results in the yarn being laid out in linear channels, which makes the fabric ideal for use in smart clothing, as well as for topical medication or aroma delivery. As a bonus, the Zephlinear cloth is also less expensive to manufacture.

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Space cloth boasts strong e-textile capability

Scientifically named Zephlinear, the fabric features a unique structure that comes with space for encasing copper wiring, LEDs and other nano-enabled sensors.

October 05, 2016

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Zephlinear fabric made of Rowan Baby mohair, embedded with angora and British wool
Image source: Zephlinear

A UK-based designer and researcher has developed a new form of nonwoven material with a strong potential for use as a smart textile.

Sonia Reynolds, who is currently taking a PhD in the subject at the Nottingham Trent University, has created the so-called "space cloth", which features a unique structure that comes with space for encasing copper wiring, LEDs and other nano-enabled sensors.

The fabric is scientifically named Zephlinear and unlike conventional woven or knitted materials, which are made by interloping or interlacing of fibers, the textile is fabricated using an innovative technique called yarn surface entanglement. It was nicknamed space cloth because of its appearance and e-textile capability.

According to Reynolds, her researched showed that the fabric is strongest and most efficient when created from natural yarns such as pure wool, hair and wool-silk combination. Synthetic fibers, however, can also be adopted.

"This is a real breakthrough for the textiles industry. It's the first nonwoven material made from yarn and promises major benefits for the future of clothing, and more," Reynolds commented.

"Because of the material's linear channels of yarn, it has great potential to be used as a smart textile. In particular, we believe it lends itself well to being embedded with microcapsules containing medication or scent, to either help deliver drugs to specific parts of the body or to create antibacterial and aromatic clothing," she added.

Reynolds introduced the material, which is patent-pending, at the recently concluded Wearable Technology

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Home Technology Engineering September 21, 2016

'Space cloth' to revolutionise textiles industry

September 21, 2016



A lightweight zephlinear scarf with LEDs. Credit: Nottingham Trent University

A designer and researcher has pioneered a new form of fabric which promises to revolutionise the textiles industry.

Sonia Reynolds invented 'space cloth' – the first non-woven material made from yarn. It has a strong potential for use as a smart textile due to its unique structure with space to encase copper wiring, light emitting diodes (LEDs) and more.

Ms Reynolds brought the idea to Nottingham Trent University's Advanced Textile Research Group and is now undertaking a PhD in the subject to further develop the fabric's novel manufacturing process under the direction of Professor Tiaak Dias and Dr Amanda Briggs-Goodie, of the School of Art and Design.

Scientifically named Zephlinear, unlike traditional woven or knitted materials which are made by the interlocking or interlacing of yarns, it is made by a newly established technique known as yarn surface entanglement.

Ms Reynolds said: "This is a real breakthrough for the textiles industry. It's the first non-woven material made from yarn and promises major benefits for the future of clothing, and more.

"Because of the material's linear channels of yarn, it has great potential to be used as a smart textile. In particular, we believe it lends itself well to being embedded with microcapsules containing medication or scent, to either help deliver drugs to specific parts of the body or to create antibacterial and aromatic clothing.

"As the material is visually different, it has potential to be used for other applications as well, such as wall coverings, in addition to clothing.

"And because it's much less labour intensive to make than knit or weave fabrics, it's a more environmentally friendly material to produce as well."

The name, Zephlinear, derives from the merger of two words, zephyr and linear. It was given the nickname 'space cloth' due to its appearance and its e-textile capabilities.

The material – which is patent pending – was recently presented at the Wearable Technology Show, USA, by Ms Reynolds.

Research shows that it is strongest and most efficient when created from natural yarns such as one hundred per cent wool hair and silk, although it can also be made from synthetic yarns.

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Space cloth is first non-woven material made from yarn

By Beth Wright | 23 September 2016

UK researchers are developing a new form of sustainable fabric, claimed to be the first non-woven material made from yarn, which they say could be incorporated into antibacterial and aromatic clothing.

According to a team at Nottingham Trent University, the 'space cloth' has strong potential for use as a smart textile due to its unique structure with space to encase copper wiring and light emitting diodes (LEDs). Scientifically named Zephlinear, the new fabric is made by a newly-established technique known as yarn surface entanglement. Traditionally, woven or knitted materials are made by the interlocking or interlacing of yarns.

While the exact process is under wraps for IP purposes, the team explained to just-style how the finest hair or fibre can entangle to a capacity that it locks together to an irreversible extent. The manufacturing process to create Zephlinear uses this characteristic to entangle only the yarn surface fibre. The extent of the entanglement is only visible under a microscope but can produce a fabric structure of incredible strength in contradiction to what is visible to the naked eye.

Invented by UK designer and researcher Sonia Reynolds, the fabric is currently in the hands of the university's Advanced Textile Research Group who are working with Reynolds on her PhD in the subject to further develop the fabric's novel manufacturing process.

"This is a real breakthrough for the textiles industry," says Reynolds. "Because of the material's linear channels of yarn, it has great potential to be used as a smart textile. In particular, we believe it lends itself well to being embedded with microcapsules containing medication or scent, to either help deliver drugs to specific parts of the body or to create antibacterial and aromatic clothing."

In addition Reynolds adds Zephlinear, which derives from the merger of two words, zephyr and linear, has the potential to be used for other applications such as wall coverings, in addition to clothing.

"And because it's much less labour intensive to make than knit or weave fabrics, it's a more environmentally friendly material to produce as well," she explains.

According to the researchers, Zephlinear is strongest and most efficient when created from natural yarns such as 100% wool, hair and wool/silk mixtures, although it can also be made from synthetic yarns.

Professor Tiaak Dias, who leads the university's Advanced Textiles Research Group, adds Zephlinear has huge potential for textiles and combines well with e-textile technologies such as heated textiles or textiles with embedded LEDs.

"Zephlinear is a remarkable development in an industry which is advancing at an incredible pace," explains Dias. "As a fabric it is very lightweight and flexible, and it retracts back to its original shape well after it has been stretched. We're very much looking forward to developing the material further and feel certain that it will help provide people with smarter and more environmentally friendly clothing in the future."

The material, which is patent pending, was recently presented at the Wearable Technology Show in the US.

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Zephlinear is the first non-woven material made from yarn

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5 WAYS TO GUARANTEE QUALITY IN YOUR MANUFACTURING SUPPLY CHAIN

Kristin Mitrowell, CMO of supply chain clarity software company Segura hosts this webinar that is intended to provide practical advice to those responsible for ethical trade, sourcing, quality and product compliance.

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New 'space cloth' nonwoven fabric targets smart textiles

Published: 15 September 2016 Written by Tommy Lee 



Credit: Nottingham Trent University

NOTTINGHAM – A textile designer in the UK has developed a new type of fabric called the 'space cloth' which, as the first ever type of nonwoven material made entirely from yarn, is claimed to have the potential to revolutionise the textile industry – particularly in the field of smart textiles and wearable electronics.

Working alongside the Nottingham Trent University's Advanced Textile Research Group, student Sonia Reynolds says the development is unlike traditional woven or knitted fabrics which are made by the interloping or interlacing of yarns.

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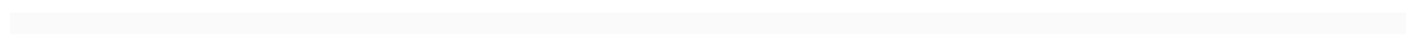
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Media coverage on Textile Evolution.

Appendix 4: Patents Act 1977: Intention to Grant under Section 18(4)





Sonia Michelle Reynolds
c/o Adamson Jones
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NOTTINGHAM
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Patents Directorate

Concept House
Cardiff Road
Newport
South Wales
NP10 8QQ

Direct Line: 01633 814616
E-Mail: Gareth.Stephens@ipo.gov.uk
Switchboard: 0300 300 2000

Your Reference: 9240/6368PGB
Application No: GB1706938.6

1 April 2022

Dear Sirs

Compliance date under section 20: 20 October 2022

Patents Act 1977: Intention to Grant under Section 18(4)

Intention to grant: shortly after

3 May 2022

I confirm that the examination of your application has been completed. The examiner has found that it complies with the requirements of the Patents Act.

Basis of the examination

The examination has taken account of the amendments filed with your letter of 18 February 2022.

As no grant fee is required, your application will be forwarded for grant shortly after the date given above. No further action is required by you prior to grant, but if you do wish to take any further action with regards to this application, you will need to do so by this date.

Please let me know if you would like me to forward the application for grant sooner than the date given above. **Please note it is not possible to request a delay to grant.**

Further Information and enquiries



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Further information on patents is available at: www.gov.uk/patent-your-invention

You are strongly advised to direct any further questions that you may have to a patent attorney or other professional adviser (please see above). However we may be able to assist with general enquiries about the processing of your application. You can contact us by email at patentprocess@ipo.gov.uk or by telephone on 0300 300 2000.

Yours faithfully

Gareth Stephens

Gareth Stephens
Examiner Assistant