Design and manufacturing of Screen and Inkjet printed e-textiles

A thesis submitted to The University of Manchester for the degree of Doctor of Philosophy in the Faculty of Science and Engineering

2021

Andrea Izquierdo Ruiz

Department of Materials

Contents

List of Figures

List of Tables

Abstract

Textile technology has opened the door to innovative and multidisciplinary research. A wide range of areas are approaching this sector to develop new products, taking advantage of textiles' physical and mechanical properties. There is no doubt that textiles can be used for everything, from products that improve medical care, such as protecting wounds to jackets with embedded controllers for Virtual Reality. However, there are still bridges to strengthen between disciplines. For example, Electrical Engineering and Fashion Design, where these two areas need to work even closer together to produce high-quality e-textiles.

Electronic Textiles (e-textiles) have been receiving much attention in the past two decades. But even though textiles offer an extensive range of advantages, their structure and fibre composition are also considered a big challenge as they are 3D porous materials, making it challenging to embed electronics. Literature has flagged different gaps that we should address as researchers to continue improving the manufacturing and testing of e-textiles. These include poor communication and linguistic barriers between disciplines, lack of production and performance testing standards, and limited end-user involvement in the design process.

This research uses experimental methods to determine the most suitable printing and materials for conductive track by exploring both Screen and Inkjet printing on different substrates (natural and synthetic) with two basic textile structures (plain weave and weft knit). It also highlights the importance of the materials' properties, their interaction and adaptability with other materials and their role in garment design. This multidisciplinary research involves chemistry, material science, product design, fashion design, and electrical engineering.

The present work's original contribution to knowledge is the development of a multidisciplinary methodology, replicable and easy to follow for different disciplines to manufacture and test functional printed e-textiles. Thus, guiding non-experts in the field through a step-by-step process to understand, characterise, print, test and replicate the manufacturing of printed e-textiles. The results presented in this research support the textile, fashion and engineering community to enhance the quality of new developments by building bridges between disciplines.

Declaration

No portion of this work referred to in this thesis has been submitted in support of another application for another degree or qualification of this or in any other university or other institute of learning.

Copyright Statement

Someone once told me..."Life is like Origami, it is full of folds".

Dedicated to the most beautiful, brilliant, loving, happy, creative person in the world, my mother, who also gave me the two best friends and amazing sisters I could ever have asked for. This thesis is one more fold to our lives, and I couldn't have done it without you all.

Acknowledgements

The path towards the completion of this thesis has been circuitous. Its completion is thanks in large part to all the incredibly patient and brilliant people who taught me new things, supported me and my research and stuck with me along this long journey. With boundless appreciation and admiration, I would like to express my gratitude to the following amazing group of people that helped me get here:

- My mother, Heyok, for teaching me to never give up and being next to me even when we are 5,418 miles apart.
- My two sisters, Mango and Firu, for their endless emotional, intelectual and economic support, I'm so grateful for having you both. Thanks for always, always, always taking care of me.
- My best friend Diego, for sharing all his endless knowledge, time, equipment, tools, plants and food to keep me going. Thank you for not giving up on me and encouraging me always to give the best of myself.
- My best friends and almost family, Choli, Candy, Montse, Ulises and Alex, for always being there to have a chat, make me smile and for not giving up in our long-distance friendship.
- My Mexican family and research fellows, David, Bart and Iñaki, for always helping me and being there to have a good laugh.
- My first PhD friend, Theo, for guiding me through all this long journey, always with a big smile on his face.
- My F5B and F10 girls, Courtney, Lou & Sharon, for calming me down every time I freaked out about my research, and for all the food and love you've shared with me.
- My happiest friends, Vas, Arsim and Lucie, for always offering your help, coffee, tacos, bubbles and hugs, especially during the writing period.
- My FOTENIX friends, for adopting me in their lab and for encouraging me to finish this Thesis!

To the fantastic team of experts in all the different Departments I worked in:
- Materials: Olwen, for all the guidance and patience since the first day I arrived to Manchester. Fiona, for all her support and for teaching me so many things during this period. Gill, for being the most efficient and always helping me order my strange materials. Rachel, for teaching me all about Inkjet printing but

especially for pushing me to finish this thesis. Jae, for all his hard work while helping analyse my materials. Dan, for all the help with my visual analysis, but mainly for being very supportive during my writing. Kathryn, for always looking after me and helping me when I most needed it. Hannah, for all her patience and help during my printing experimentation. Mark, Damindi, Adrian, David and Steve, for helping me with all my material and testing preparation. Helen for cheering me up and helping me with my layout.
- EEE: Dany, Alun and Morris the boys from the Mechanical workshop for always helping me with my prototyping. Derrick and Gary, for sharing the PCB tools with me. Simon, from the Electronics Club, for helping me with my testing and prototyping.
- Chemistry: Josh and his friends, for always helping me with my experiments and for always receiving me with a happy face.
- MACE: George, for helping me with my sample analysis and giving me gluten-free snacks when needed :)

To my advisory team, who guided me to achieve this:
- My Main Supervisor, Dr. Celina Jones, for the support and guidance during my research.
- My Co-supervisor, Dr. Simeon Gill, for making me believe in myself and for helping me structure all my crazy ideas.
- My Advisor, Dr. Joshua Moore, for all his endless help throughout my PhD, for sharing the excitement while performing testing and always having time for a chat.

To Lois and Zoe, for kindly reading and re-reading my thesis and helping me communicate my ideas.

To my sponsor, CONACYT, for believing that a Fashion Designer can also become a Scientist.

And lastly, I would like to re-dedicate this Thesis to two wonderful persons who could not read it (I'm sorry it took me so long), but I know they would be beyond proud of me for making it to the end. To my two infinite guardians, Pepe and Omar.

I'm tremendously fortunate for having you all in my life, Thank you.
#Modanoreprueba

01 Introduction

'We are in contact with textiles for 98% of our lives, and they are starting to become intelligent'. Hayward, 2020

There has always been interest in incorporating electronics into everyday products. According to Gasana et al. (2006), this dates from the fourth century AD with the use of manufacturing methods to produce metallised fibres; however, these were only used for aesthetic purposes. Later, the discovery of electricity opened the door to research and experimentation with fibres specifically designed to be conductive. In the late nineteenth century, the first combinations between electronics and textiles were explored, with an electric corset that was designed to cure ailments for ladies of all ages. Although, it was not until the nineteen-twenties that the creation of practical, electrical, and functional textiles began to be subject of focus. This started with research and patents for military products and electrically heated gloves for heavy goods vehicle drivers (Carron, 1911), and evolved to the production of multi-filament metal yarns, then conductive polymers, and all the way to illuminated clothing and reaching the integration of circuits on garments connected to electrical components (Everett, 2015) (Hughes-Riley et al., 2018) (Ghosh et al., 2006). The incorporation of electronics with textiles is what we now call electronic textiles (e-textiles), which Hayward, 2020 defines in the IDTechEx report as 'the combination of electronics and textiles to form "smart" textile products'.

Research into e-textiles plays an important role in the wearable technology industry and, more specifically, in promoting a higher quality of life due to their easy-to-use interfaces. Not only that, but they also have the fundamental properties of being flexible and comfortable to the human body thanks to the textile materials that are used (Carpi and De Rossi, 2005).

There is no doubt that electronic textiles these days are more versatile. Not only do they have the ability of heating or illuminating, but they can also measure body signs with the help of biosensors, transfer data and serve as preventive monitoring. Cicek (2015) and Tao(2001) mention in their research that the integration of technology into textiles enables a wide range of applications. From sensing and monitoring body functions, delivering communications and even controlling the environment. All of these applications can be integrated into textiles using different manufacturing techniques such as knitting, weaving, embroidery, or printing. The integration has reached the point where electronics can be miniaturised to fit the size of a thread and create digital fabrics. Like the fabric shown in fig 01.1, developed by Prof Yoel Fink from MIT. This fabric is produced with new fibres with multiple microscale digital chips. Giving it the freedom to store and process data while being thin and flexible. These fibres can go through a needle and be sewn just like any other fabric.

Figure 01.1 Digital Fabric - Prof. Yoel Fink, Credits:Image: Anna Gitelson-Kahn. Photo by Roni Cnaani.

Research has increased in this industry thanks to the non-obtrusive technology that can be embedded in our daily garments, and the importance of e-textiles is undeniable. However, (Emile Giles) finds most studies in the field have only focused on the engineering part of e-textiles, developing, and adapting electronics. These findings suggest the need for more research that is focused on the understanding of the end-user needs, not only caring about functionality but also comfort and aesthetic factors (Andrew, 2020) (Meng et al., 2020) (Pang et al., 2015).

"A successful fabric sensor design needs to draw on the expertise of professionals in many different fie ds, including textile scientists, polymer chemists, physicists, bioengineers, software engineers, and mechatronics engineers, among others"(Castano and Flatau, 2014) .

Up to now, far too little attention has been paid to the manufacturing methods and performance testing standards on e-textiles. The closest applicable standards in e-textiles are the ones that pertain to the safety and reliability of the wellness sector. Using IEC and ISO standards, among others. Some of the basic testing that any wearable needs to pass are in relation to: electrical safety, battery safety, electrical and motor systems, SAR testing, toxicology, cybersecurity, electromagnetic compatibility (EMC) and usability. Examples of standards for wearable technology are the *Wellness or Non-Medical Wearable: IEC/UL 62368-1*, *Medical Device Safety: IEC 60601-1-11* (UL- Wearable Technology Testing and Certification). Moreover, in research the state-of-the-art focus is on creating textile circuitry, but often neither the reliability of the process nor the lifetime of the device is explored. For instance, the standards used for testing the mechanical properties are based on textile British Standards (BS) or ISO. However, fabrics with electronics will not perform as normal fabrics. And in the opposite way, electrical standards are used to assess the electrical properties, but once again, the conductive materials have different properties. For example, a conductive thread will not have the same performance as a cable. These standards are required to make e-textiles; scalable, reproducible, durable, safe and reliable (physical and electrical performance). At the moment, everything is based on research; very few items (e-textiles) have been taken to the market and even these do not follow specific standards(Yang et al., 2019) (Castano and Flatau, 2014) (Gonçalves et al., 2018) (Li et al., 2020) (Elmogahzy, 2020).

In addition, few studies focus on end-user validation, leading to an absence of connection between technology and the user. This insufficiency of communication affects the wearability and performance of e-textiles directly. The feel and comfort of threads will never be compared to what rigid and bulky components can offer. And not only the comfort is affected, but these conductive materials and electrical components will be submitted to the same treatments (wear, washability, etc.) that any garment faces. Even though technology has advanced in such a way that we can barely notice the embedded electronics, the involvement of the end-user, together with the stakeholders, is essential throughout the research, design and manufacturing process (Yang et al., 2019).

It is now well established that multidisciplinary research is required to produce successful e-textiles. However, the mix of skills and expertise still remains unclear (Yang et al., 2019). This lack of multidisciplinary research is also related to the absence of a design methodology to produce e-textiles. E-textiles can be produced with different materials and techniques. However, an overall methodology could improve the connection between technology and user and could also help the understanding of materials and user needs (technical requirements, functionality, aesthetic, cultural requirements, anatomical and physiological characteristics) (Fernández-Caramés and Fraga-Lamas, 2018).

Undoubtedly, this area of research requires a multidisciplinary approach (Romero and Molina, 2016), (Hopper et al., 2016) (Yang et al., 2019), (Stoppa and Chiolerio, 2014), (Dunne, 2010). Due to the inherent complexity of combining electronics in textiles. For this reason, not only does collaboration between diverse areas need to be established, but also a shared methodology should be agreed upon, especially one that helps bridge the gaps between the different areas (McLaren et al., 2016).

1.1 Aim and Objectives

It is clear from analysis of the literature that most of the investigations that have been carried out in relation to screen and Inkjet printing with conductive ink have been performed on non-textile substrates, however there is a big interest and investment on printed textiles, (E-Textiles 2018-2028 (IDTechEx Research). Printing with conductive ink is highly effective on substrates with smooth surfaces such as films, papers or other materials like acrylic, however when it comes to textiles the results are not as positive. Due to the complex structure that textiles can have, woven knitted or non-woven, there is a lack of positive results on printed tracks and their conductance.

The biggest gap is how to achieve an even penetration of the ink through the fabric structure and natural fibres (Dumitrescu et al., 2014a). The integration of textiles and electronics is the base to produce a smart textile, the capability of being functional and smart and at the same time being flexible and comfortable, textiles also offer moisture absorption and wicking breathability, anti-bacterial and odor properties among other technical ones (McLaren et al., 2017).

Addressing the gap in literature, the thesis aims to explore and develop a novel method to produce and test printed electronic textiles. Adopting the product development methodology of designing, prototyping, testing and improving. In being able to achieve the aim, the objectives are as follows:

Objective 1

Determine the challenges of existing methodologies to print and connect conductive inks to electronics in the creation of e-textiles.
-Conduct literature review explaining, classifying and defining e-textiles, reviewing and comparing current print methodologies, material selection and connections to sensors and microcontrollers.
-Define e-texiles and its classification related to usage and materials
-Review and compare printing methods, including the materials that are used for each method and their characteristics.
-Research how e-textiles can be connected to sensors and microcontrollers

Objective 2

Characterise the textile and ink samples and examine the impact of fabric and ink properties on printing processes, to identify and determine process requirements when applying conductive inks on porous materials. To achieve this, a set of objectives was created:
-Provide an overview of the different textile structures (woven and knitted) and fibres chosen for this project (cotton, bamboo, polyester).
-Determine the most suitable ink vs solvent ratio for printing.
-Examine the textile surface tension in relation with the conductive inks, using the contact angle, sessile drop method.
-Analyse and compare the properties of each textile sample, according to their structure and interaction with the conductive ink.

Objective 3
Inkjet printing evaluation will examine and determine the most suitable design specifications and printing parameters to produce a homogenous conductive printed track.
Further details will be given on how the objective will be achieved:
- Create several track designs, similar to the ones presented in the screen printing chapter, to evaluate the printing process.
- Analyse the impact that each printing parameter has on the final print.
- Analyse print homogeneity using Digital Optical Microscope technique.
- Analyse the electrical performance of the print by measuring the electrical resistance of the printed samples.

Objective 4
Screen printing evaluation will examine and determine the most suitable combination of design specifications and printing parameters to produce a homogenous conductive printed track in Screen Printing.
Further details will be given on how the objective will be achieved:
- Design of printed tracks with different widths to understand the limitations of the printing method.
- Asses the weight of each printing variable by printing multiple tracks using different line widths and multiple number of strokes on each textile substrate.
- Analyse the print homogeneity by examining the ink distribution and particle interaction under SEM and Digital Optical Microscope.
- Evaluate the conductance of printed tracks by using a Digital Multimeter (DMM).

Objective 5
Evaluation of the electrical performance and conductance quality of each print. This will advise if the printing methodology was successful enough to produce reliable printed e-textiles.
To achieve the performance testing, the prints were tested using Electrical Impedance Spectroscopy (EIS) principles under the following scenarios:
- Testing of printed samples using three different textile material and each pertaining to two different type of textile structure were characterised through EIS profiling.
- Testing of bending performance, characterised through EIS profiling using the previously mentioned samples bent on top of a mannequin arm body, average size 12.

Objective 6
The embedded electronics experimentation aims to integrate electronic components from the LilyPad collection into the textile substrates using the conductive ink as electrical solder.
Further details will be given on how the objective will be achieved:
-Incorporation of LilyPad electrical components into the existing printed samples using the same conductive ink.
-Testing and analysis of the electrical performance of the printed track once connected to the components.

The overall structure of the study takes the form of nine chapters, including:

- **Chapter 1**
Introduction, Research outline and motivation, presenting an overview of e-textiles and research gaps.

- **Chapter 2**
Literature Review, Overview of e-textiles research, how are they made and where are they going.

- **Chapter 3**
Methodology Describes different methodologies and how they were adapted to create a new approach to design and manufacture e-texties.

- **Chapter 4**
Material Characterisation, Illustrates the different materials used for this research and the material characterisation each one went through to understand the interaction between conductive ink and textiles.

- **Chapter 5**
Inkjet Printing Outlines the Inkjet printing process that was followed, presenting limitations and challenges of the inkjet printing. This chapter suggests different solutions to improve the printing process, print quality and electric performance.

- **Chapter 6**
Screen Printing Describes the Screen printing process that was followed, presenting limitations and challenges of the technique. This chapter also suggests and address different solutions to improve the printing process, print quality and electric performance.

- **Chapter 7**
Electric Performance
Demonstrates the electric performance of the prints using the Electrical Impedance approach to test the resistance and reactance of every print.

- **Chapter 8**
Embedded Electronics
Demonstrates the possibilities for conductive printing and electronics integration into a textile substrate.

- **Chapter 9**
Results, contributions and limitations
Describes the overall findings, comparing the printing methods. Describes the limitations of the research and advice for further work.

Literature Review 02

'Wearable technology (WT, or wearable computing) encapsulates a plethora of devices worn directly on or loosely attached to a person.' **(Godfrey et al., 2018)**

The past decade has seen the rapid development of wearable technology in many different sectors. A wide variety of products ranging from medical devices to fashion accessories and garments. This development has pushed manufacturers to combine electronics with materials that weren't used as frequently in the past. Not only that, but the need also to design and create electronics that can be embedded with other materials an increasingly important area in electronics.

Big brands such as Apple, Samsung and Google have introduced us to a new era of portable electronics. Interactive eyeglasses, intelligent watches, and even smart keychains. However, there is an undeniable potential for improving manufacturing and user experience of wearables. And while these wearables are empowering the industry, what a person wears is directly related to the material properties, comfort, feel and look of the product.*'As humans, we prefer to wear woven cloth against our bodies' (Kholiya, 2011)* The idea of having hard plastic components and wires attach to the body is not that appealing.

That's why in the wide range of wearable technology there is space for e-textiles. A combination of rigid and bulky materials that belong to the electronics sector.

With soft, porous, flexible materials from the textile industry. Textiles not only provide comfort and aesthetics, but they also offer a wide range of manufacturing techniques such as printing, knitting sewing woven...etc. Making them a highly adaptable material to electronics.

2.1 Wearable technology

Wearable technology (WT) can be defined as a smart devices integrated to different types of accessories such as wristband, wristwatches, eyeglasses and smartphones, clothing, and many other objects in our daily lives. All smart devices have the same property of connectivity, however they may not share the same technology. They are all connected to measure, analyse, send or receive information that is being recorded by de device (Aileni et al., 2019).

Wearable technology gives us the opportunity to have a computerised device which accepts and processes inputs. This device could either work independently or be tethered to a computer or another device which can receive and read these data, providing a good interaction between product-user. These wearable devices can be attached to the body (like smart patches), around the body (like wristbands, headbands, watches, pendants or smart clothing), or in the body (like embedded sensors under the skin) (Cicek, 2015). The market of wearable technology is has a wide range and each year it is growing and expanding to different applications. According to IDTechEX. There were 5 main trends on 2015 on the wearables market fig.02.1; showing that advanced infotainment has the biggest sales. Infotainment is when users expect some kind of interaction with the information they receive from their devices whilst keeping them entertained.

The most popular wearable technologies, according to Forbes and CCS are; wristbands, watches, eyewear, wearable cameras, hearables, tokens and jewellery among other products that still produce a couple of billions. Without doubt, WT is a big thing on the market and it has great opportunity to grow and create products that help improve peoples life.

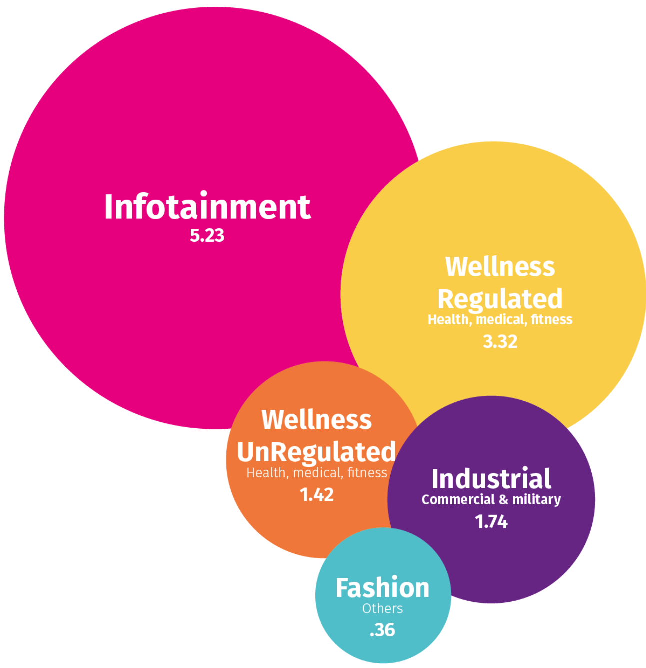


Figure 02.1 Wearable Technology Market $Bn, 2015 (IDTechEX, 2018)

Wearable technology has become ever-more present, adopted and accepted by a high number of people for daily life use, according to Business Wire and IDTechEx. Their, data study on the wearables market (worldwide) fig 02.2, claimed that shipments reached a new high score of 33.9 million units sold by the end of 2016 with the wearables market is growing 16.9% year over year. They predicted that by 2020 the shipment amount will be around the 50 million; (Business Wire ,2017) (IDTechEx, 2016) . Wearable technologies such as smartwatches, activity trackers and smartphones are used to track, record and quantify our daily lives and activities, with the aim of promoting better health and well-being. As technology has

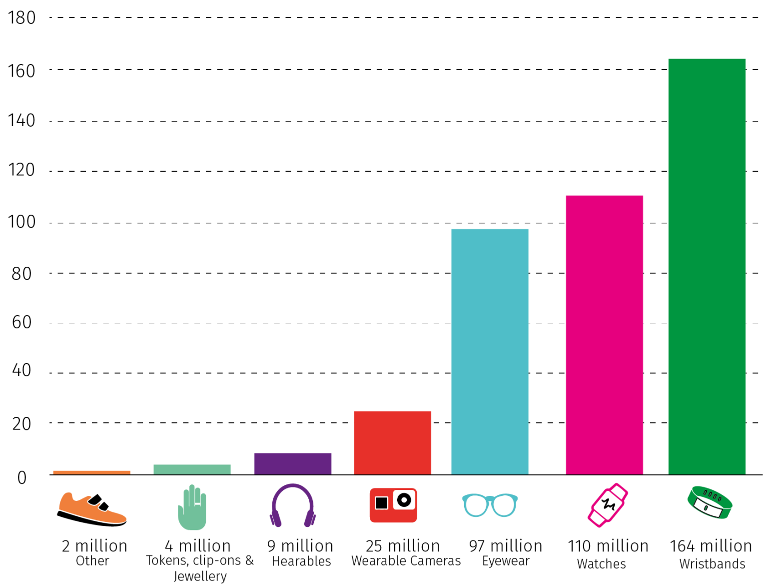


Figure 02.2 Global Wearables Forecast 2016-2020 (CCS Insight, 2016)(Forbes, 2016)

progressed and allowed for the improvement in performance and miniaturization of sensors and batteries, it has become easier to embed them within our objects and environment. This need for a soft and flexible solution for embedded electronics is being research and developed with the use of electronic textiles (e-textiles). The integration of conductive materials such as silver, copper or graphene on porous materials has become a great challenge. The development of conductive inks, conductive threads and conductive fabrics is getting more attention. However, there is still a need to understand the challenges of using porous, flexible and stretchable materials.

2.1.1 Who is adopting wearable technology?

Healthcare

The idea of embedding sensors that can monitor a person's health without being obtrusive has gained a lot of attention. Sensors such as temperature, Electrocardiogram (ECG), strain, moisture among others are the most popular sensors being used. Not only these sensors can be embedded in clothing, but they can also send this information within milliseconds to a Dr, nurse, carer or even the user. In this way e-textiles can and are being used as preventive technology fig.02.3 , (Hughes-Riley et al., 2018), (Zhang et al., 2008), (Pentland (Sandy), 2004), (Bonato, 2010).

Some examples of the products that are in the market are shown in figure 02.3: Image **a**, The Supersapiens continuous glucose monitoring device in action. It is a continuous glucose monitoring technology designed specifically for non-diabetic athletes to maximize high intensity training. Image **b**, The Vital Patch is a health monitoring device in the growing field of TeleHealth that has proven to be useful for diabetic people detecting low blood glucose through heart rate variability. Image **c**, Fitbit Smartwatch to improve health, sleep and fitness of users. It has Amazon's Alexa integrated.

a b c

Figure 02.3 Medical wearables, application examples. **a** Supersapiens glucose sensor, **b** Vitalpatch, **c** Fitbit Versa2Fitbit

Fashion

Wearables can also be a fashionable product. The idea of integrating electronics in a more discrete and comfortable way to our day life products has attracted the attention of big brands like Google and Levi's. Integrating mobile controllers to jackets in ways that only the user knows how to control is one of the examples. Not only that, these new materials that are being introduced to the fashion world can also change the colour, pattern and sometimes texture of a garment. A big range of wearable sensors has been developed to make them easier to integrate as well as resistant to water (Seymour, 2008); (Mondal, 2018) . There is still research to be developed, therefore, these electrical components are completely embedded and one of the major limitants is the power supply fig.02.4.

Tha fashion sector is not only integrating electronics to change the colour of the clothes but also to make them intelligent but at the same time stylish and comfortable. Some examples of this integration is shown in fig. 02.4 Image **a**, Intelligent Levi's + Jacquard Jacket, the iconic Levi's® Trucker jacket merged style with innovative Jacquard technology allowing users to answer calls, play music, and take photos right from the sleeve of the jacket. Image **b**, xo Backpack, it is an app-connected backpack with fiber optic fabric that allows users to change its colour and visualize sound and music. Image **c**, MIDI controller jacket DK1 is the first jacket that allows users to create music through body movements and body sensors. It includes: an accelerometer, a gyroscope, with two push buttons and one piezoelectric.

a b c

Figure 02.4 **a** Intelligent Levi's + Jacquard Jacket, **b** xo Backpack, **c** MIDI controller jacket DK1

Military

The development of wearable technology commenced primarily to cater the military field, and it continues to be its main application (Scataglini et al., 2018). In field, soldiers are exposed to unpredictable conditions in which their health and safety could be compromised. Wearable technology offers unique solutions for health monitoring and stress management of soldiers, environmental safety monitoring and also empowering human functions (Scataglini et al., 2015). Wearable systems, technology as well as smart textiles can provide a 'second skin' for soldiers which can have physiological, psychological, biomechanical and ergonomical benefits (Scataglini et al., 2018). These new technologies present a wide scope for future growth and potential for application in other fields. Nonetheless, financial resources continue to be a barrier towards greater proliferation of wearable technology on the market (Sahin et al., 2005); (Lim et al., 2010).

a, Microsoft augmented reality headsets used by the US army, these augmented reality headsets allow soldiers to conduct combat, exercises and training in one system. Image **b**, Wrist-mounted computer for military, a wrist computer with OLED curved displays that give soldiers strategic information, live UAV video streams and battlefield maps. Image **c**, Soft Exosuit from Harvard Biodesign Lab, prototype of a soft wearable robot that use innovative textiles to provide a more conformal, unobtrusive and compliant means to interface to the human body.

a b c

Figure 02.5 Military wearables application examples, **a** Microsoft augmented reality headsets used by the US army, **b** Wrist-mounted computer for military ,**c** Soft Exosuit from Harvard Biodesign Lab

2.1.2 Wearable Technology and Healthcare Monitoring

Wearable sensors are technology and a totally unobtrusive small device that can provide information when a patient needs to be monitored over weeks or even months, this technology allows doctors and caregivers to overcome the limitations of manual monitoring and can provide accurate and immediate information. interventions (Bonato, 2005).

These sensors are usually wireless coefficient and work thanks to batteries that are integrated into the devices and in the case of textiles is woven or embedded in some part of the textile where they are not very noticeable or annoying. These sensors receive information, be it movement, temperature, light, etc and this information must be extracted from them in some way, either by sending the information to an electronic device; an app for cell phone, tablet, computer, or even a clock.

Sensors detect signals, therefore the existence of sensors is essential to design and produce smart textiles. Fabric-based sensing has been a large field of research in the biomedical and healthcare sector (Custodio et al., 2012). Some of the most common sensors used for this interest are the electrocardiogram (ECG) (Schneegass and Amft, 2017), electromyography (EMG) (Locher and Tröster, 2007), and electroencephalography (EEG) (Schneegass and Amft, 2017) . However those are not the only sensors that can be used, sensing temperature and movement has become very popular, as well as sensors that can measure oxygen, glucose, salinity, and moisture (Schneegass and Amft, 2017) (Stoppa and Chiolerio, 2014). The most common Sensors incorporated on e-textiles can be found in Table 02.1 , these sensors already exist for commercial use, therefor some products need to adapt their designs so these sensors can fit on them.

Vital physical signs	Sensors
Electrocardiograph (ECG)	Skin electrodes
Electroencephalogram (EEG)	Scalp-placed electrodes
Electromyography (EMG)	Skin electrodes
Blood Pressure	Cuff pressure sensor
Blood glucose	Glucose meter
Galvanic skin response	Woven metal electrodes
Respiration	Piezoelectric sensor
Activity, mobility and fall	Accelerometer

Table 02.1 Examples of wearable sensors and how they can be applied.

One of the biggest challenges while working with electronic textiles is the incorporation of these sensors to flexible substrates such as textiles, companies such as Arduino have created specific sensors and microcontrollers that are completely wearable, meaning that they are waterproof, can be easily attached to a flexible substrate and are not as bulky as a normal electronic microcontroller or in this case as an Arduino board.

The miniaturization of sensing equipment has allowed for the development of wearable/portable diagnostic and monitoring applications, capable of long-term day-to-day use by patients outside of clinical environments. By allowing remote monitoring, wearable applications allow healthcare practitioners to extend their impact outside of the lab, and more importantly, provide instant, cheap and reliable data without barriers such as geographic location. However, these systems are still in their infancy and are subject to limitations that prevent them from being ubiquitous, such as battery technology (Kekade et al., 2018), and how to analyse the massive amounts of data that would be generated from a practical point of view; but also from a more human aspect, the stress patients suffer from the stigmas associated with wearing conspicuous medical devices. As textile technology progresses the ability to embed such conspicuous components into clothing presents a fascinating dimension for overcoming such barriers, however, designers of such systems are now tasked with new challenges of how to not only improve the efficacy of a system but also how to improve its usability and overall patients' self-perception and independence (Basadur et al., 2014).

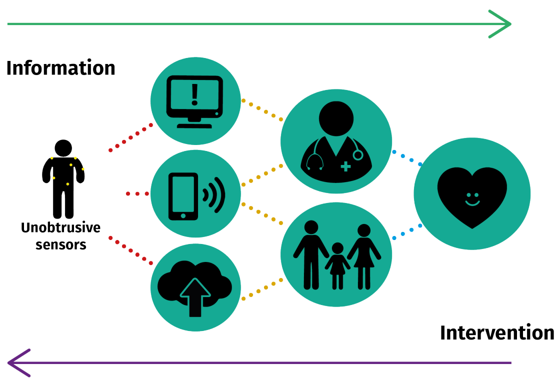


Figure 02.6 Remote Healthcare monitoring system, information being send by unobtrusive sensors places on garments, stored and analysed and processed in the cloud and providing useful information and send feedback to doctors, carers and family.

2.2 Electronic Textiles (e-textiles)

The elementary purpose of electronics is to interconnect multiple devices that talk to each other, and the key elements leading this interconnection are wires. The ideal behavior of such wires is to connect elements without any losses in signal strength or the introduction of unwanted elements like electromagnetic noise. Therefore, a wire must behave like a perfect conductor of electricity. One that does not impose any resistance to the flux of electrical current. However, in reality, this is often the case. Electronics, in general, rely upon the use of copper as this is considered a good electrical conductor that is easy to work with, cheap, and vastly available around the world. Copper can be used either as wires or as deposits in PCB. For this reason, one of the key elements that are often looked at is its electrical conductivity characteristics.

In textiles this does not apply 100%, textiles are porous, not uniform 3D materials. Therefore one of the biggest gaps in the literature is the lack of material understanding and characterisation of such complex materials since it is often overlooked. Therefore, there is a gap in our knowledge regarding the adequate behavior of conductive inks in textiles.

Reviewing the state of the art in this area can be challenging, since there is a lack of common agreement in the terminology. Commonly, smart and e-textiles are often confused, however these two are highly different to each other. Smart textiles are materials that can react or adapt themselves according to the environment or the interaction with other materials or even the user or the environment that these might have (Godfrey et al., 2018) and are therefore an important part of wearable technology. In the other hand, e-textiles refer to the integration of textiles and electronics02.8.

Figure 02.7 Google and Levi's Project Jaquard

They have the capability of being functional and smart and at the same time being flexible and comfortable, textiles also offer moisture absorption and wicking breathability, anti-bacterial and odour properties among other technical ones (McLaren et al., 2017). Therefor due to the wide range of possibilities that textiles give to the wearable market. According to the review of (Stoppa and Chiolerio, 2014) on wearable electronics and smart textiles, it is important to classify and understand the type of e-textiles that can be or are already produced.

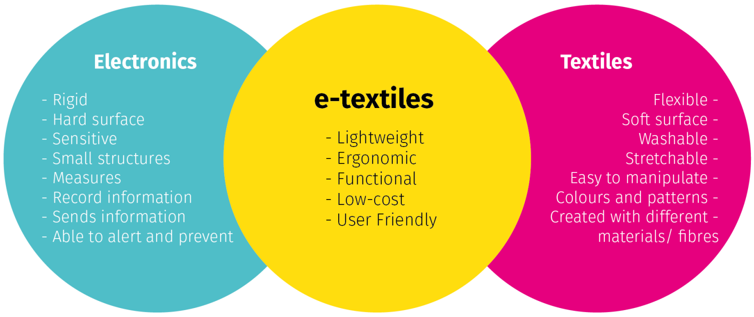


Figure 02.8 e-textiles,

Textile technology has become a very important economic sector, since wearable technology has begun to expand its market; textiles have become a very important material. Conductive thread, conductive ink, embroidery, knitting weaving and printing are just some examples of the techniques and materials that are being tested and used to produce e-textiles 02.9. Products like smart watches, activity trackers, smart t-shirts are the most common products related to smart and functional products, they can be used to record and quantify our daily lives and activities, with the aim of promoting better health and wellbeing, or even sometimes their main purpose is entertaining and interactive purpose, such as artistic or musical performances. However,

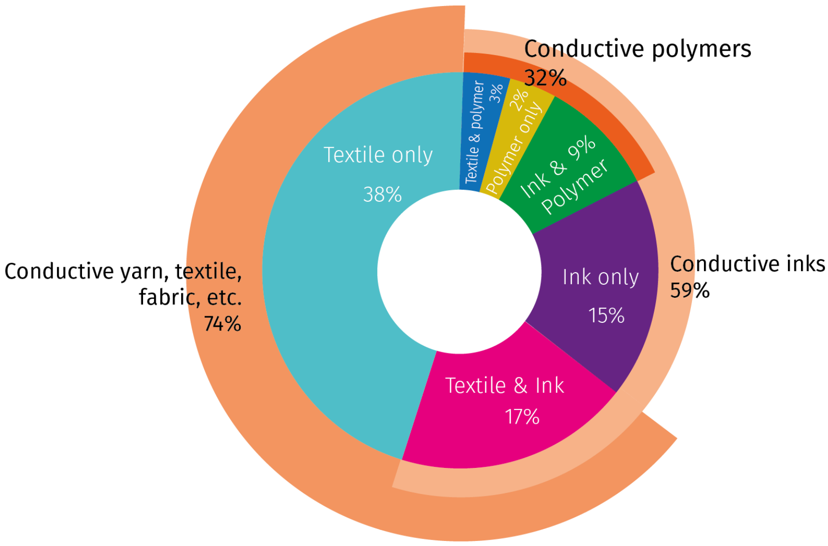


Figure 02.9 Percentage of interest in different conductive materials

despite their popularity, these devices are still in their infancy and have not yet fully developed into the life changing solutions and designs most manufacturers proclaim to have achieved (Levine et al., 2016). Smart textiles are defined as textile products that may include fibres or filaments, yarns, knitted, woven or non-woven structures. Today's aims on smart functional e-textiles are to produce garments that are comfortable, stylish, and functional. As Seymour (2008, p. 15) puts it : 'Technology and fashion are not as distant from each other as it might first seem, The thread-up and tread-down of the weaving process corresponds to the 0 and 1 binary logic of computer circuit' (Seymour, 2008).

Passive smart textiles are only able to sense the environment/user, based on sensors. There is a wide variety of sensors and with the rapid evolution in technology Ariyatum et al., 2005 , some can be made smaller and easier to adapt to textiles, however in the case wearable sensors the most important to detect vital signs and physical activity are: Temperature, heart rate, pressure, strain, position, glucose, moisture, location (GPS), force, motion and proximity. Active smart textiles: reactive sensing to stimuli from the environment, use of a sensing device; **Very smart textiles** are able to sense, react and adapt their behaviour to the given circumstances and environment Ariyatum et al., 2005.

Electronic Textiles can be used for almost everything, from fashion to military use and from medical to recreative use, it all depends on the sensors and the textiles that are being used. One sector where wearable technologies are gaining popularity is the healthcare sector, wearables related to monitoring activity, such as fitness trackers, and devices that record the daily activities of the user and keeps the data to provide an analysis of the user health.

They can also be designed to be interconnected with the cloud and can measure, record and react to real-time measurements of their physiological functions. Such applications of this technology include assistive garments that react to emotional and stress states and respond to provide comfort; or applications such as sensing garments that measure biometric data of particular activities to relate level of performance to the user, such as the Underarmour smart shoes that track a users' activity to promote better fitness and performance.

E-textiles are a promising sector, brands like Quicksilver, Nike and Adidas have been trying to integrate technology on their products. Some examples of the products currently in the market are shown in fig.02.10.

- Nadi X yoga pants allow users to improve their yoga practice. These pants have integrated sensors and haptic feedback (vibration) to let users know when their yoga posture needs to be corrected or refined. The haptic feedback creates small vibrations on the body part that needs to be adjusted. The Nadi X pants are connected to an iOS app that offers instructions on how to optimize each pose, in addition to proper yoga flows. The pants are washable and are available in various sizes for men and women in a variety of sizes and are completely machine washable (Wearablex, 2021) .

-Under Armour's "Athlete Recovery" clothing line is made with a mineral-infused textile that absorb the heat from the human body and then reflects it back onto the wearer's skin as infrared light. The infrared light eases fatigue, enhances relaxation and helps muscles recover faster. There are also pillowcases and sheets fabricated with the same technology (Under Armour, 2021).

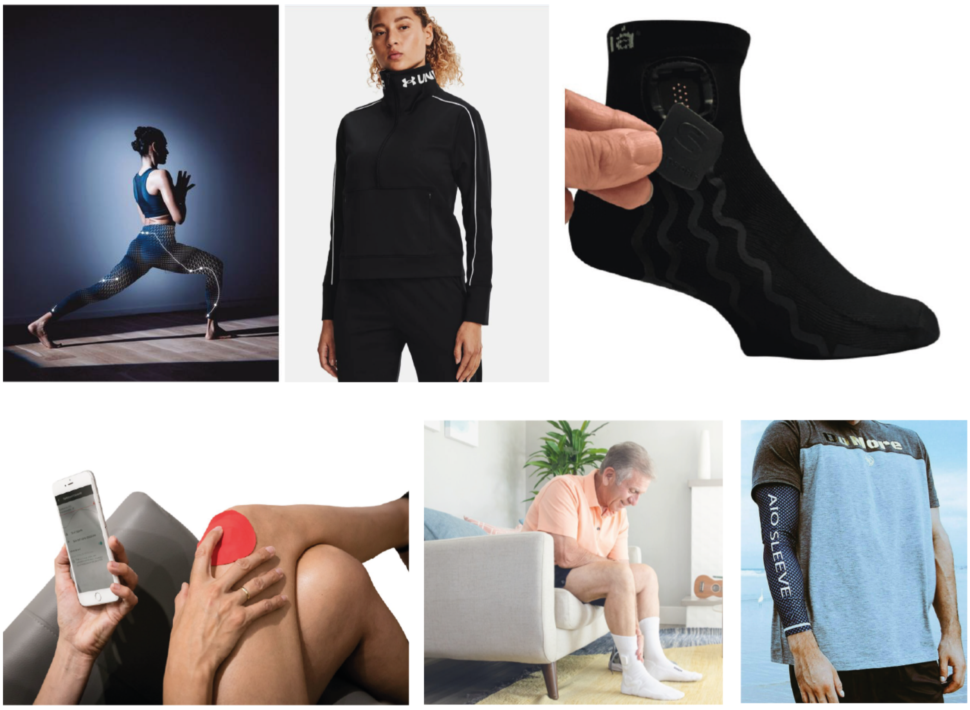
-Sensoria socks use built-in advanced textile sensors. The objective is to let the user know how the foot lands and tracks other environmental and performance variables while walking or running. The socks are paired with a Bluetooth smart and detachable core that delivers superior accuracy in step counting, speed, calories, altitude and distance tracking, as well as track cadence, foot landing technique and the impact score generated while walking or running.The socks can identify injury-prone running styles (heel striking, ball striking, etc.) and coaches the user in real-time via audio cues. The socks also integrate an odometer feature that can let know users when it might be time to invest in a new pair of shoes. The product includes:
- One pair of smart sock v2.0 made from high-tech running friendly fabric (only one sock instrumented with textile sensors).
- One Sensoria Core microelectronics that snaps into the dock attached to the sock.
- One USB charger.
- A dedicated mobile application that monitors and guides you through real-time audio cues while you run (Sensoria, 2021) .

-Spinali smart bandages are connected bandages to ensure continuous monitoring of scarring over a wound or a cut. They use antimicrobial and data textiles. The bandages can inform medical staff or a patient about the beginning of infection, allowing it to tackle it fast and have a better recovery rate. These bandages are also intended to reduce the waste of bandages by knowing exactly when the bandage needs to be replaced. They can be used for chronic wounds care (patients with diabetes, immunosuppressed or those who are under chemotherapy), monitoring of wounds in crisis contexts (army, natural disasters), and for prevention. The bandage contains an agent that will emit a warning light when pathogen bacteria appear. This signal is detected by a sensor, which delivers this information to the user (patient or medical staff). The bandage also contains an antimicrobial agent anchored on the textile that releases when the pathogen is detected (Spinali Design, 2021).

-Siren Socks are smart socks using small sensors placed throughout the socks' fabric to measure the foot's temperature at six different points. They are officially referred to as Siren's Diabetic Socks and Foot Monitoring System. The socks continuously measure foot temperature; this data can be an early indicator of injury that may lead to ulcers in order to prevent or treat them. The Siren Socks can also help nurses and doctors to monitor the patient's foot health and look for signs of inflammation and schedule a check-up appointment (Siren Care, 2021).

-The AIO Smart Sleeve is a piece of smart clothing that uses electrocardiogram (ECG) technology to monitor heart rate activity, monitor body temperature, air quality, UV rays, sleep and workout intensity. This piece of smart clothing is not only intended for fitness but also to measure stress levels, detect heart inflammation and prevent coronary heart disease (Technologies, 2021).

a b c



d e f

Figure 02.10 **a** Nadi X yoga pants,**b** Under Armours' Athlete Recovery, **c** Sensoria socks ,**d** Spinali smart bandages, **e** Siren socks, **f** AIO Smart sleeve. (Wearablex, 2021); (Under Armour, 2021); (Sensoria, 2021); (Spinali Design, 2021); (Siren Care, 2021); (Technologies, 2021)

2.2.1 e-textiles, what are they made of?

Electronic textiles can be manufactured with different conductive materials that can be mixed with fibres, threads or can even be dyed or printed. These materials are usually made from metals such as silver, copper, gold, steel and nowadays, even graphene is being used due to its conductive properties. When these conductive materials are mixed with other textile materials, they can produce e-textiles. The next section gives an overview of the most common textile conductive materials.

Textiles

Fabric selection is the most important decision that designers and manufacturers have to make. It is not only comfort or colour that matters, but the resistance and mechanical properties need to be considered. In recent years, the environmental impact has been added to the list of things to consider since it is well known that synthetic fibres are extremely difficult to recycle, however, due to the finishing all fabrics go through, the recycling process is very complex. Most of the finishing include chemicals which makes it difficult to separate the fibres from.

Garments made from natural fibres tend to be more breathable and tend to stay cool and more comfortable than those made from synthetic textiles, making them a very popular material. As mentioned before, these natural fabrics are increasing in popularity due to the awareness of carbon emission produced by synthetic materials. Although they tend to be better for dealing with weather sweat and sensitive skins, natural fibres are less durable than synthetic fabrics and can be destroyed by staining and by insects who feed on animal- and plant-based materials. This is something that synthetic garments can easily cope with; not only that, they are also stronger and more resistant to stretching and their production process is less resource-intensive than the natural fibres.

Textile Structures

Textile structures are important to analise and understand before printing due to their complex and uneven surface. There are three main textile structures, woven, knitted and non-woven (Gong and Ozgen, 2018), however, the most popular structures for garment producing are woven and knitted. **Woven structure** fig.02.12(a) consists of two sets of yarns that are positioned in perpendicular directions, the lengthwise yarn is called warp and crosswise comes the weft fig.02.11. Warp yarns are held stationary in tension while the weft runs transversally and inserted over-and-under the Warp yarns. Depending on the use of the fabric the weave design can change and each design determines the properties of the fabric such as moisture permeability, transparency, air permeability, UV protection, drape, and so on (Kumar and Hu, 2017).

Knitted structure fig.02.12(b) consists of yarn inter-looping. Due to this technique, it is possible to achieve garment formation while knitting in contrast with weave structures, were a cloth needs to be produced before creating a garment with it. Knitted structure is the second most popular technique of producing fabric garment formation (Gong and Ozgen, 2018) . Similar the woven structure, the design of the knitted fabric can change and this will give the fabric different properties (Miao et al., 2018) however, the knitted structure has a high percentage on accessible extension. In comparison to the woven structure where the percentage is less than 10%, knitted structures can have 100% extension (Gong and Ozgen, 2018). Knitted structures in comparison to

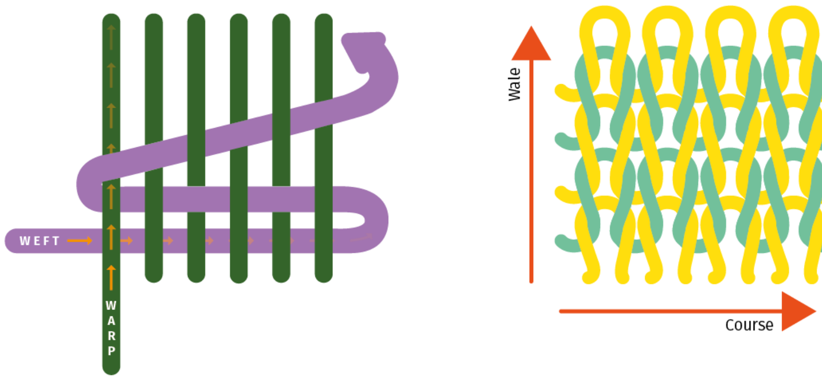


Figure 02.11 Woven structure and Knit structure construction

woven structures do not have a warp or weft defined, however due to the structure of interl-oopinng they have Wales and Courses 02.11.

Textile fabrics are not perfectly smooth substrates and that is what makes them such a complex material to be printed on; they inherently possess some surface roughness due to the different structures (knitting or weaving)as shown in figures 02.13, 02.14, 02.15 and 02.16, that may influence the wettability, adhesion, and uniformity of a printing. Furthermore, textile fabrics are porous, which can lead to capillary action or wicking. For printing, capillary action can affect the resolution of line width and design of the printed design (Kelvin Fu et al., 2018).

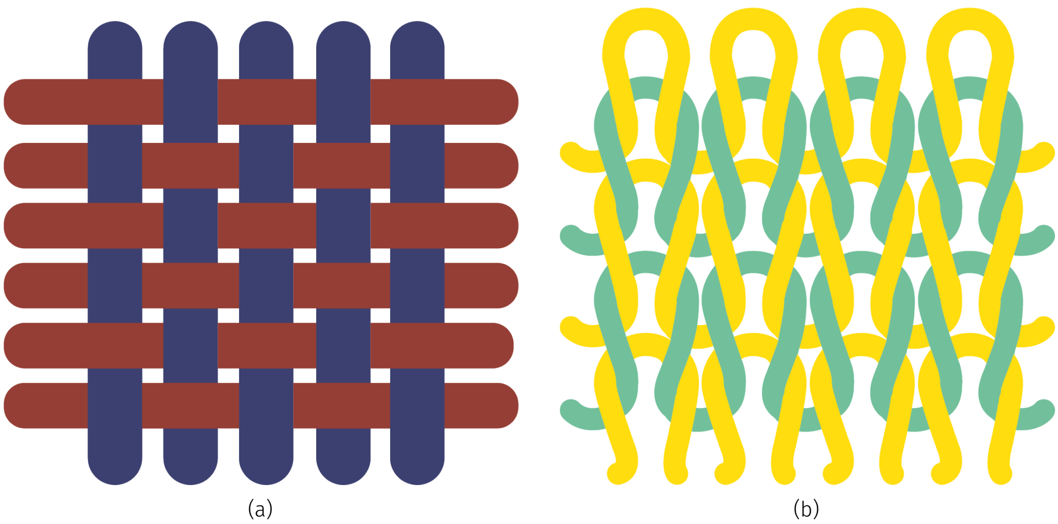


Figure 02.12 Main textile structures **(a)** Plain Weave structure, **(b)** Weft Knit structure

Conductive Threads

Conductive threads work just like cables in electronics, however instead of attaching of attaching electronics to textile substrates, the threads of the textile can provide the same properties and functions. Conductive threads can be produced by mixing fibres such as polyester or acrylic fibres with metal fibres to create a mix of conductive and non-conductive materials. These threads can also be produced by coating the fibres with metals, galvanic substances or metallic salts (Castano and Flatau, 2014).

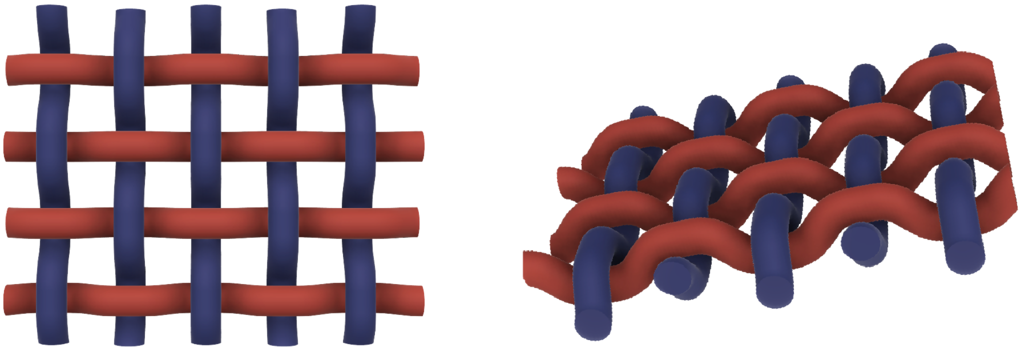


Figure 02.13 Plain Weave, front and 45 angle 3D view

Figure 02.14 Plain Weave side cross-section

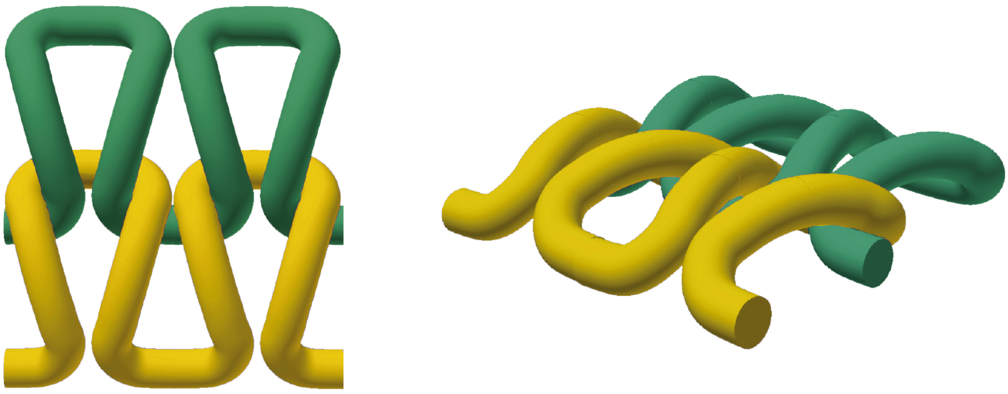


Figure 02.15 Knit, front and 45 angle 3D view

Figure 02.16 Knit cross section

Conductive Inks

E -textiles can also be produced by using conductive inks. These inks must contain a high percentage of a highly conductive material precursor such as Graphene, Copper and Silver (Stoppa and Chiolerio, 2014). These inks can be used to print on different substrates such as films, paper and textiles. However, because of the nature of textiles and the structure it has and the ink formulation, it is important to analyse and choose the most suitable ink to each substrate. There are several manufacturing techniques to print with conductive inks, screen printing and inkjet printing are the most popular on the market, especially because they offer high-precision results (Stoppa and Chiolerio, 2014).

Sensors

A crucial aspect of electronic textiles is the integration of sensors. These have always been perceived as hard and obtrusive components. However, thanks to nanotechnology and Micro-Elecro-Mechanical Systems (MEMS), sensors have successfully been able to reduce their shape (Sazonov and Neuman, 2014). Not only that, they can be manufactured with flexible materials such as polymer films. Unfortunately, these sensors are not completely adapted to be embedded in textiles fig. 02.17. However, there are manufacturing techniques under research that have been working hard on improving this (Wang et al., 2020).

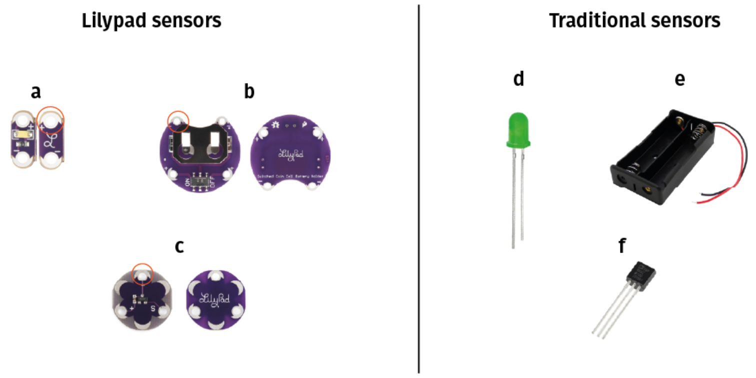


Figure 02.17 Differences between traditional electronic components Vs Lilypad components with special features to be embedded into textiles. **a** LED, **b** Battery holder, **c** Temperature sensor, **d** LED, **e** Battery holder, **f** Temperature sensor

These sensors allow us to enable communications between electronic devices and humans, optimizing the interaction between humans and technology (Sazonov and Neuman, 2014). There are numerous sensors that can measure a wide range of variables and vital signs. Some of these can measure temperature, heart rate, pulse oximetry, global positioning system (GPS) pressure sensors, accelerometers. They can be captured from or around the human body, storage and shared in communication different ways.

Wearable sensors need to be positioned in specific parts of the body to get the necessary information from the sensors fig. 02.18, especially if they're sensing vital signs. The human body can influence the performance of the sensors. It can also block signals between the sensor and an anchor, which directly affects the accuracy of the information (Otim et al., 2019).

Electrical Circuits

Electric circuits are important concepts that have many practical applications in today's technology; they are closed paths in which electrons move to produce electric currents. In other words, they are paths for transmitting electric current. Ohm's law and Kirchhoff's rules are two basic laws that describe mathematically the performance of electric circuits. An electric circuit incorporates three different components: a source of electrical energy, a device, and a closed-loop of conducting material (Hazen, 2021) .

The Source of Electrical Energy. This is the first component in an electric circuit that allows electrons to move. This source has a positive and a negative terminal from where the charge can flow to one another. Examples of sources of electrical energy include batteries, solar cells and hydroelectric plants. This push of electric charge is called voltage and is measured in volts. Device in the Electric Circuit. It is the second component, which responds to the current passing through the circuit. A device today is most commonly plugged into a

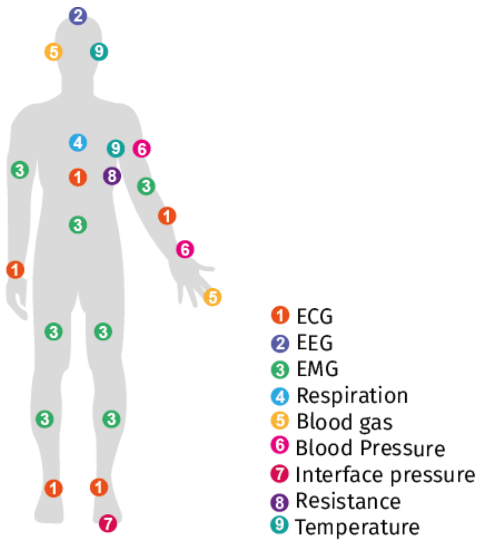


Figure 02.18 Body positioning for sensors.

wall, but a device can also work with batteries (closing the loop). The device closes the electric circuit (Wang, 2010). Resistance of the Electric Circuit. This is the third component of an electric circuit, which, as the name points out, provides resistance to the flow of electrons. Resistance is necessary because electrons collide with each other and with atoms of the conductive materials converting some of the energy to heat (Brookes, 1975) (Khukharev, 2016).

Electric circuits have additional components to the three main ones already explained. These additional components are a switch and a fuse or circuit breaker. A switch is simply a device that helps to break or interrupt the continuous loop of the conducting material. Hence, when the switch is open, there is no current flow and vice versa. The fuse or circuit breaker is used to prevent fires due to electric overloads burning up when the electric current gets too high (Gregersen, 2018).

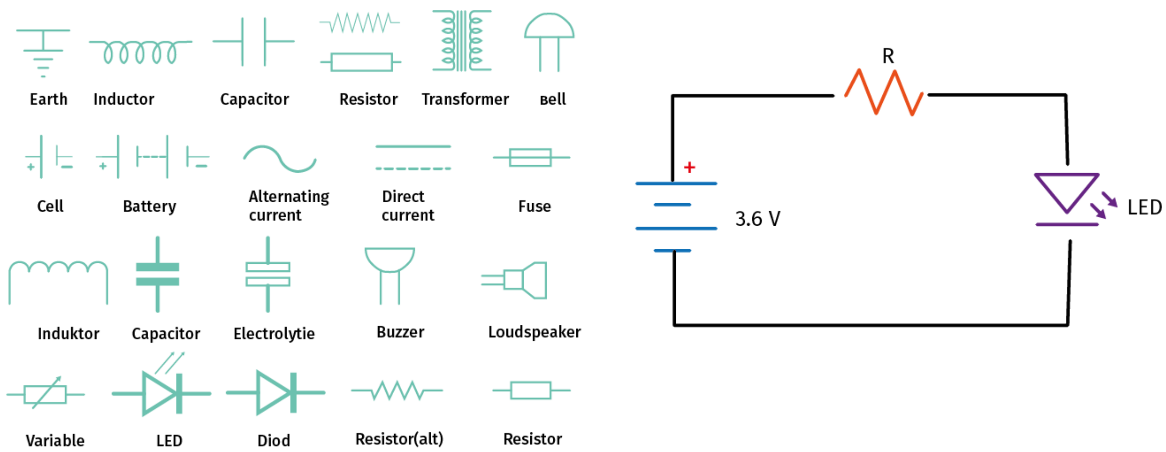


Figure 02.19 Basic circuit symbols and basic circuit design

Types and design of electric circuits

Electric circuits can be classified in different ways. One way is in direct-current circuits and alternating-current circuits. In a direct-current circuit, current flows only in one direction; this is the case of a circuit being feed by a battery. In an alternating-current circuit, current pulsates back and forth many times each second; this is the case of most household circuits (Khukharev, 2016).

Another way of classifying electric circuits is by their design in series circuits and parallel circuits. Series circuits consist of several devices linked in a single large group one after another. In a series circuit, there can be different devices with different voltages, but the same current is flowing through each one of them. If any device in a series circuit is broken, it causes the whole circuit to fail. In parallel circuits, the different devices are arranged in a way that a single source supplies voltage to separate loops of wire. Therefore, the voltage in every device of the circuit will be the same, but the current will be different for each device, allowing them to work even if another device from the circuit fails. One common example of a parallel circuit is modern Christmas lights allowing the little light bulbs to work even if one fails; however, Christmas series were initially designed as series circuits, making all the bulbs fail if one failed (Hazen, 2021).

2.2.2 LilyPad

The Lilypad wearable e-textile technology started as a research project focused on sewable electronics; then, it was developed into a ready-to-use sellable product (AMX, 2021).

With sewable electronics, it is possible to create wearable e-textiles (electronic textiles) because they combine traditional craft processes (sewing, fashion design and textile design) with electrical engineering, computer science and hardware skills. Thus, sewable electronic projects are a way in which technology can be used in a more flexible and non-traditional way, merging both the knowledge and experience of sciences with those of arts and crafts. Today, many e-textile projects use flexible conductive materials such as conductive thread and fabric to replace wiring (Spark Fun, 2018).

Over the past years, electronic textiles, or e-textiles, have become an increasingly important part of wearable computing. The objective of e-textiles is to provide useful functionalities while appearing "invisible" in the garments where they are installed. E-textiles provide fashion and textile designers, artists, and manufacturers with new expressive materials full of possibilities. Electronic textiles appeal to many people from various research areas and with different interests because they integrate computer science, electrical engineering, textile design, and fashion design and provide new experimental and creative opportunities in engineering and design. They also progressively enable people to develop their imagination in unusual yet useful ways. The LilyPad research and development was, therefore, focused on exploring and exploiting these features of e-textiles. The solution provided was a toolkit aimed to empower newcomers to design, engineer and build their own e-textiles in a motivating, flexible and "soft" way (Buechley and Eisenberg, 2008).

2.2.3 The LilyPad circuit and pieces

Independently of the complexity of each LilyPad circuit, all of them have three basic parts, fig. 02.20:
- A power source
- Conductive Paths (conductive thread stitching) between electronic components
- The LilyPad pieces (or modules) that will perform the function of each project and that are connected together to light up, make sound or perform other behaviours (Spark Fun, 2018).

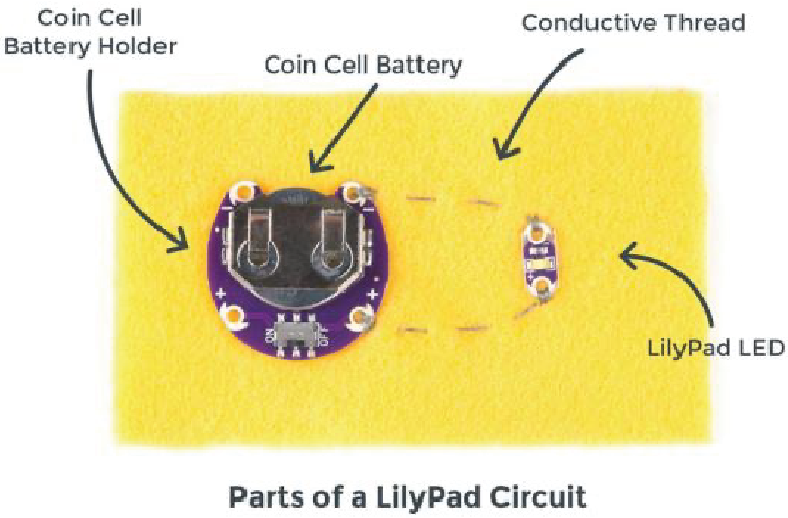


Figure 02.20 Parts of a Lilypad Circuit, (Spark Fun, 2018)

The LilyPad pieces, as fig. 02.21 2 shows, include a variety of components that can be sewn to create various electronic textile garments. There are LEDs in a variety of colours, buttons, switches, sensors, buzzers and controller (Arduino) boards. The pieces are selected depending on the individual vision and goals of each project (Spark Fun, 2018) . Each LilyPad piece has large connecting pads to allow them to be sewn into clothing, and they are washable (AMX, 2021). Specifically, the Lilypad Arduino construction kit enables researchers,

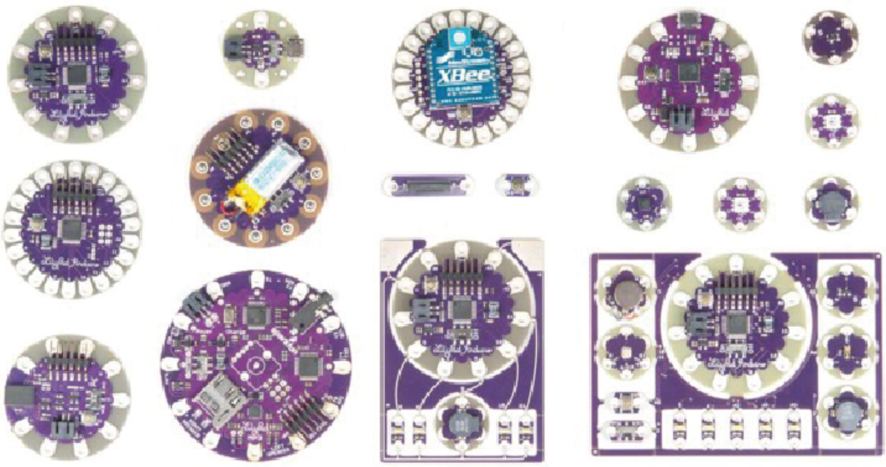


Figure 02.21 Diffeent type of LilyPad components, (Spark Fun, 2018)

designers, engineers, students, teachers, and hobbyists to build wearable, soft computers. The most recent version of this kit, which is commercially available from SparkFun Electronics, contains:

- Mainboard, which runs on 2.7-5.5 V and comprises an ATmega168V microcontroller, a reset switch, an indicator LED, 16 Kbytes of program memory, an 8-MHz processor, a 10-bit analogue-to-digital converter, and 20 I/O pins, including six analogue inputs and six pulse-width modulation (PWM) outputs;

- 5 V power supply—with one AAA battery, an on/off switch, an indicator LED, and an NCP 1400 DC-DC step-up

converter, capable of supplying a maximum of 100 mA;
- Speaker;
- Vibrating coin-cell pager motor; an accelerometer with an ADXL330 3-axis acceleration sensor, +/-3 g in each direction, and an analogue output of 0-3 V;
- Ambient light sensor, with analogue output of 0-5 V; and an RGB LED (Buechley and Eisenberg, 2008) .

To build an e-textile using the LilyPad, the user has to sew the pieces together using the conductive thread. The "petals" on each flower-like piece then create a physical and an electrical connection once they have joined with the conductive thread. The user can then program the micro-controller in C with the Arduino programming environment, which is free and quite user-friendly (Buechley, 2010).

Figure 02.22 4 shows a close-up of an early prototype of a LilyPad microcontroller module sewn into a dance costume to test it. In this prototype, the stitching went directly through the PCB's conductive fabric, and embedded sensors controlled computer-generated lighting and music. However, the commercial version has holes in the petals allowing for a similar kind of sewing but in a more practical and straightforward way (Buechley and Eisenberg, 2008).

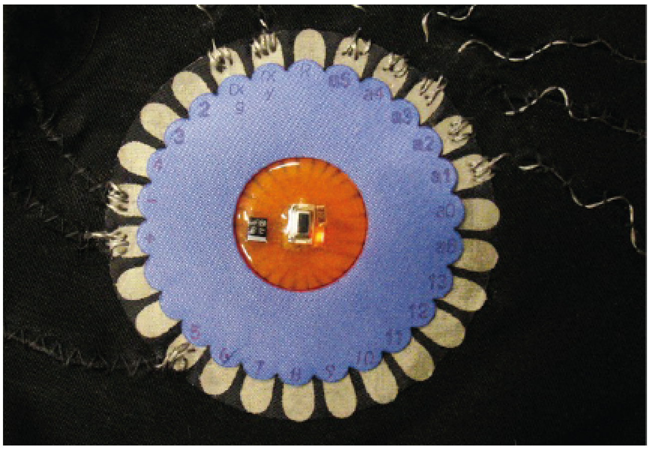


Figure 02.22 Lylipad prototype, (Buechley and Eisenberg, 2008)

2.2.4 Rethinking educational technologies with Lilypad

As mentioned before, the LilyPad is a construction kit that enables people to construct and program tangible interactive devices (Buechley, 2010). The developers of the LilyPad point out that one of the main motivations behind the LilyPad research was to build an accessible and powerful open-ended toolkit that could contribute to making e-textile design a means through which adults and children, in general, can become technologically fluent and at the same time express themselves creatively (Buechley, 2010). Therefore, one key aspect was to test the Lilypad with potential users.

During the research and development of LilyPad, six user studies were conducted with people of various ages and backgrounds to teach them how to build their own electronic fashion using the LilyPad. During the studies, one key aspect to observe and record was the motivational and affective issues of participants: who chose to participate and why, whether they became engaged and lasting impacts (if any) had on them. Overall, from the studies, positive feedback was gathered, suggesting that e-textiles might serve as a playful and motivating introduction to computing and engineering for future students of such disciplines. LilyPad proved to create great interest among women (who usually shun computing classes); thus, it could be especially useful to promote their involvement in these study areas (Buechley et al., 2008).

The LilyPad is a medium that promotes creative experimentation and engagement of people with computing and electronics while they learn basic skills in these areas (Buechley and Eisenberg, 2008). Therefore, it can also be suitable to enable Bifocal Modelling in science classrooms and laboratories, which currently are not well suited to support learning experience based on true scientific inquiry, meaning the students do not often develop and test their own hypothesis. Bifocal Modelling is an educational framework aiming to link the theoretical and empirical aspects of learning, which in most current educational systems are disconnected (Buechley, 2010). Experiences in which students work from beginning to end in a project which they define, investigate and execute provides continuity between what was read or heard (theory) and what is being observed and physically constructed (empirical experience) .

The ideas presented by the developers and researchers of LilyPad are in line with Csikszentmihalyi's research, who, through his flow theory proposing how humans can achieve optimal experiences, demonstrates that personal motivation and enjoyment are highly predictive of achievement. However, today most educational systems neglect this crucial aspect of the learning process and overall experience of people (Buechley et al., 2008); (Csikszentmihalyi, 1990). Therefore, a technology such as the LilyPad not only opened the door to a more accessible and playful way to design and create e-textiles, but also to a new kind of hands-on technology-based educational tools aiming not only to teach how something is done, but in the best possible way for students and teaches, promoting an optimal experience for both.

2.2.5 Current and future research on the LilyPad

After being developed and launched to the market, the distribution, adoption, and evolution of the LilyPad was tracked for two years. The tracking was done using sales data, publicly available project documentation and surveys. An investigation on the community of developers who adopted the LilyPad kit was done, paying special attention to gender. This investigation corroborated what current research in diversity in STEM has been pointing out: that *"Women and other minorities don't join STEM communities not because they are intimidated or unqualifi d but rather because they're simply uninterested in these disciplines"* (Buechley and Hill, 2010). Furthermore, the experience with the LilyPad suggests that one useful and more constructive approach to building engineering culture could be to build new clubhouses that are culturally and intellectually broad instead of trying to fit people into existing engineering cultures (Buechley and Hill, 2010).

Therefore, one of the current goals of research on the LilyPad is to question traditional disciplinary boundaries and to expand disciplines making room for the interest and passions of diverse people (Buechley and Hill, 2010). The future research on the LilyPad includes an investigation to develop specifically geared software platforms to program e-textiles (Buechley et al., 2008).

The LilyPad is a clear example that it is possible to build complex yet innovative technological artefacts in a colourful and beautiful way, enabling technologies to grow both technically and culturally when they are re-envisioned and re-contextualized (Buechley and Hill, 2010).

2.3 e-textiles manufacturing techniques

It has been defined that e-textiles are a combination between textiles and electronics. Therefore there are multiple manufacturing techniques to produce electronic textiles such as weaving, knitting, embroidery, printing and sewing (Kuroda et al., 2021), (Mondal, 2018) (Chen and Kong, 2020). However, most of them involve using conductive materials such as conductive ink, conductive thread, conductive fabrics, and these conductive materials have specific properties that have to been considered while manufacturing. For example, a conductive thread can be used in a sewing machine instead of a normal thread. However, some conductive threads are made with short fibre staples (Lund et al., 2018). Thus, they are prone to break easier while going through the machine due to the friction between thread and needle. Although, these conductive materials have some considerations to be aware of since they have not been adapted 100% to be used on textiles. The manufacturing processes to produce e-textiles are much more complex than the normal processes for conventional fabrics (Kuroda et al., 2021). By using conductive materials, all of these manufacturing can be applied. Plenty of research has been applied in developing threads, inks and conductive fibres. This research focuses on the printing technique, exploring Screen Printing and Inkjet Printing.

2.3.1 Manual Screen Printing

Manual Screen printing is a process of transferring a design onto a flat surface. It can be made by hand or in automatized machines (for mass production). It also can be used on any fibre/ material, and it is a cheap process compared with other printing techniques (Prudenziati and Hormadaly, 2012). The most basic technique is manual silk screen printing. It is called silk screen because the screen or mesh that is used to transfer the design was made of silk, however to lower costs and to have a better performance for a longer period of time, the mesh can vary in thread spacing and this will impact the quality of the print. If the space is small, then less ink will be able to go through it therefore a lighter layer of ink will be deposited, preventing any bleeding and achieving a crisp print. However, in some cases like in textiles it is required to have a mesh with larger spacing therefore the ink can go through and be absorbed by the textile. Silk was replaced with polyester . This screen is mounted on a wood or metal frame fig. 02.23.

Afterwards, a positive image of the design that is going to be transferred into a material/product is printed on a special film which then will be taken to a dark room and with the help of a light sensitive emulsion the print will be transferred to the screen creating a 'stencil' (Szentgyörgyvölgyi et al., 2018). The following step is to place a flat substrate, as it was mentioned before, it can be any flat surface, the important thing is to choose the correct ink for each substrate, it all depends on the material and use.

Once the ink is adequately chosen the silk screen frame needs to be placed on top of the substrate and on top of it goes the ink on one side of the design (it usually goes on the top side of the design, however this can vary depending on the size and the design) (Prudenziati and Hormadaly, 2012). With help of a tool call Squeegee (rubber blade with sharp edges and a wood or metal handle), the ink is pulled along the frame, with a 45° angle, this will make the ink to go through the areas that are not covered with emulsion (the design or positive). It is necessary to do several strokes to have a clear and bright design, however the pressure that is being used can make a substantial difference in terms of how neat the design appears. Once the design is transferred the frame can be removed, leaving the substrate with a fresh print that then needs to be cured or dried, again, it all depends on the type of ink that is being used (Bralla, 2007). After setting the design, the print is ready to use/ wear.

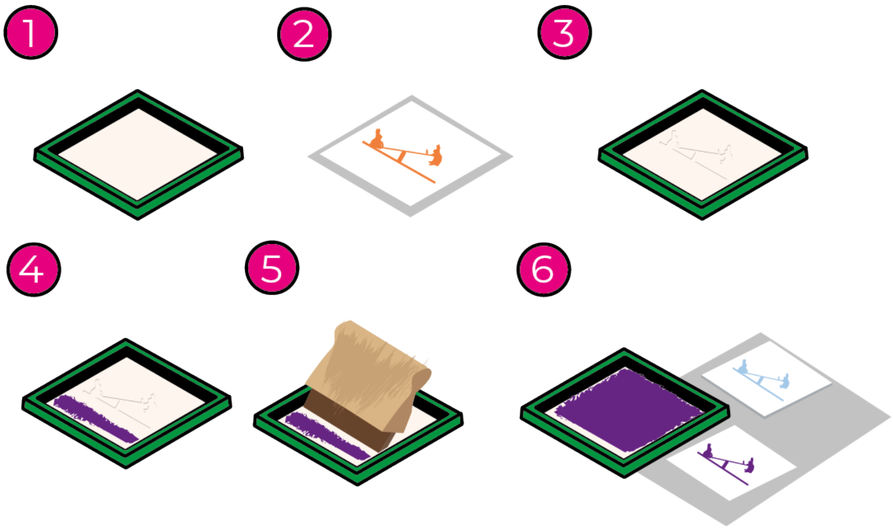


Figure 02.23 Manual screen printing process
1 Frame with clean screen, **2** Image of the design that will be printed, **3** Image is transferred to the screen, **4** Printing paste is placed on the screen, **5** With help of a squeegee the paste is pushed through the mesh, transferring the design to the selected substrate, **6** Transfered design that should be either baked, cured or dried.

Even though screen printing can be a manual manufacturing technique, there are still parameters to follow to achieve a neat print. When producing e-textiles, these parameters are highly important to achieve a successful pattern with a positive electrical performance. These parameters include: mesh size, squeegee material, angle and size, mesh size and thread count, number of printed layers, and curing process (Fasolt et al., 2017), (Pan et al., 1999).

The screen printing mesh can be created with different materials like cotton, silk, nylon, polyester or metal. These fabrics have different thread counts, which influences the quality of the print (Novikov and Novikov, 2013). The count corresponds to threads/cm. The higher the count, the higher the quality print is achieved. However, this also depends on the thickness of the paste or ink. The most common mesh size are shown in fig. 02.24 (Novikov and Novikov, 2013).

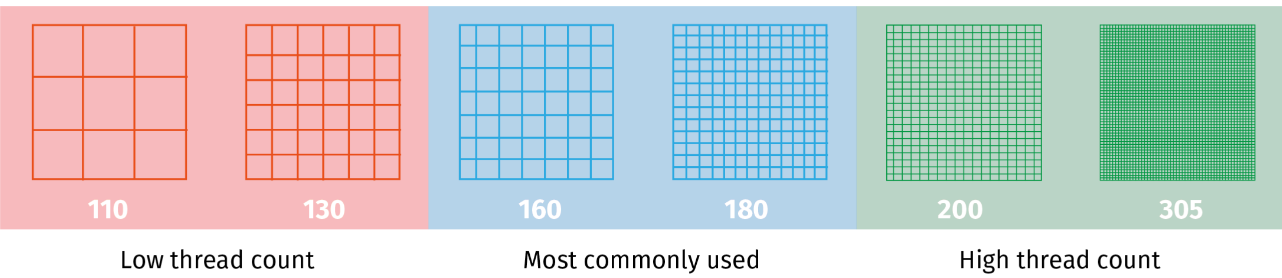


Figure 02.24 Different type of mesh counts

For conductive printing ink, choosing the most suitable mesh is imperative (Izdebska, 2015). Conductive ink, as previously mentioned, is comprised of metallic conductive particles or flakes and solvent agents to keep the particles in place, creating highly dense inks.

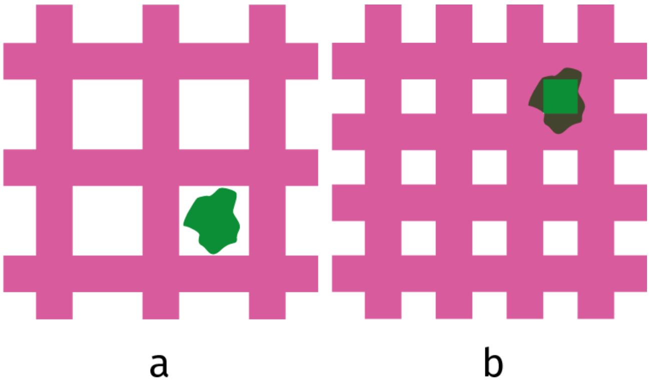


Figure 02.25 **a** Example of a wide mesh thread count, facilitating the printing of big particle size, **b** Thight mesh thread count, particles could be trapped and this can cause clogs on the mesh.

These particles or flakes from the ink need to be able to go through the mesh to stick on the substrate surface, and not only that, but the mesh also needs to be wide enough to avoid any clogging that could affect the print (Novikov and Novikov, 2013). These cloggings are usually presented when the ink or paste is too thick/dense to be printed, and the mesh count is very high, fig. 02.25 (Jamale et al., 2016).

2.3.2 Inkjet Printing

Ink-jet printing is a non-impact printing method (H Ujiie and Ujiie, 2006), meaning that this manufacturing technique works and provide a printing method without the need of intermediate tools, it has direct contact with the substrate (Perelaer and Schubert, 2012). Inkjet printing works with three basic components, the print head the ink and the substrate as shown in fig 02.26.

There are two classes of inkjet printing: Continuous Ink Jet (CIJ) and Drop-on-Demand Ink jet (DOD). CIJ is when the ink is pushed through nozzles applying constant speed and pressure, this type of ink-jet printing is created with droplets fig 02.26, there is no control on the size of the drops (H Ujiie and Ujiie, 2006). However, this can be controlled with the jet velocity, this type of printing is usually used for marking and coding packages. On the other side DOD can control everything that happens with the ink and the droplet, nozzles, temperature, drop size, drop spacing fig 02.27 (H Ujiie and Ujiie, 2006). By having the control of all these elements the print with conductive ink can have better electrical performance. The conductance depends on the interaction of the particles between each other as it was discussed in the previous chapter.

During this process the substrate is placed on a plate and with a program the user can control every variable, as it was mentioned before, drop spacing, contact angle, cartridge temperature, layers, plate temperature, cartridge angle and many other presets that can improve the quality of the printing (Rida et al., 2009). Once this process is completed the next step would be to print and this is where the machine printing head has no other intermediate, and it prints directly to the substrate, in this case textiles. Afterwards the substrate may be removed and taken to the oven to be cured. Curing times depend on the ink that is being used, in terms of this project, nano-silver-particles conductive ink was used and the curing time and temperature was 150C for 35 min (Chen et al., 2015).

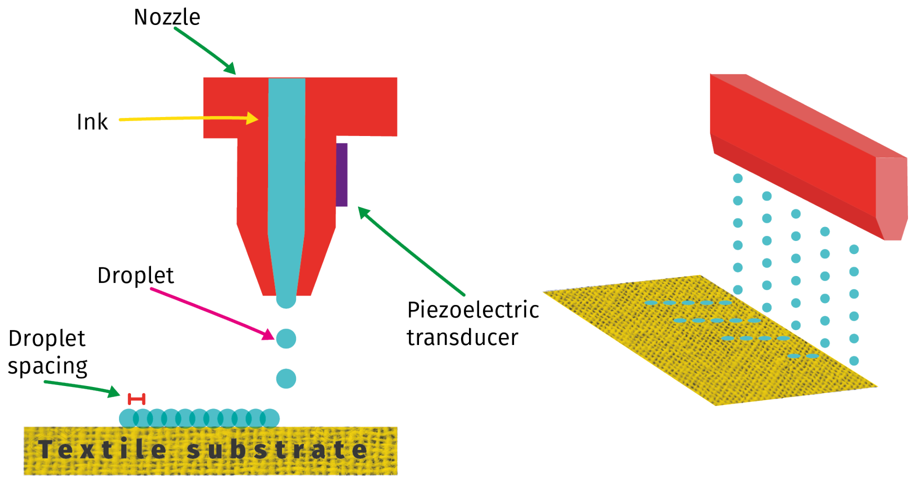


Figure 02.26 Inkjet Printing Process
Inkjet printing parts and drops coming out from the nozzles representation.

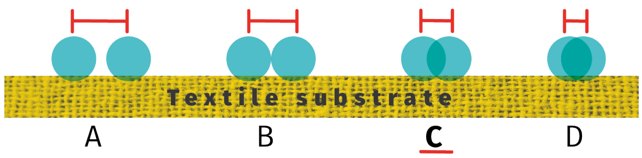


Figure 02.27 Droplet Spacing
The drop interaction is essential to achieve proper conductance **A** Droplets too sparsely, **B** Droplets still not interacting with each other, this affects the conductance and the quality of the print design, **C Optimal spacing where the drops interact and can create a crisp print**, **D** Excessive interaction can cause bleeding on the print.

2.4 Research on printed e-textiles

Electronic textiles have gained a lot of interest in recent years; research has been carried out in different disciplines such as Textiles, Electronics (Kim et al., 2010), Chemistry (Stringer et al., 2004), Materials (Vervust et al., 2012), Fashion Design, Biotechnology and Medicine. However, all these disciplines focus only on their expertise; for example, Chemistry researchers tend to analyse conductive inks and their performance with different printing methods (Urbaniak-Domagala et al., 2016). Unfortunately, they test these inks on substrates that can not be used to create garments (Wang et al., 2020) (Komolafe et al., 2020). On the other hand, Fashion Designers are looking into ways to incorporate electronics into textiles, but again, the lack of multidisciplinary research prevents the creation of functional and replicable products.

Even though this lack of collaboration is still evident, the contributions of each discipline have not been in vain. For example, the information regarding ink characterisation, connecting electric components, or even using flexible polymers to coat textiles is very important (Rida et al., 2009) (Perinka et al., 2013) (Younes, 2017) (Rizwan et al., 2017) .

To produce printed electronic textiles, it is not only essential to understand the ink or the textile but also the interaction between materials or how these materials will react to the human body (sweat, and movement can affect the conductance). Several authors have mainly explored printing on synthetic fibres, and even though these prints have positive results, these fabrics are not the best for garment production (Abu-Rous et al., 2018) (Singh et al., 2010). Also, PU coated fabrics are quite popular, but again, these can not be used for a fitted garment (Izdebska, 2015). This research aims to use the information published by the different disciplines and integrate methods and materials to develop a printing methodology that any field can follow and replicate.

The table below, table. 02.2, is a summary of the most relevant publications related to printed electronic textiles. These publications are from different disciplines, and they all use different inks (silver and graphene), and various textiles (PU coated, polyester, polyester and cotton blend, paper and flexible films).

Method	Year	Publication	Authors
Screen printing	2020	Screen Printed Flexible Water Activated Battery on Woven Cotton Textile as a Power Supply for E-Textile Applications	Li et al., 2020
	2018	Determining and Selecting Screen Printing Form Parameters for Printing on Paper and Textile	Szentgyörgyvölgyi et al., 2018
	2017	A novel and simple method of printing flexible conductive circuits on PET fabrics	Wang et al., 2017
	2016	Screen-Printing Fabrication and Characterization of Stretchable Electronics	Suikkola et al., 2016
	2014	The development of screen printed conductive networks on textiles for biopotential monitoring applications	Paul et al., 2014
	2014	The influence of the textile materials structure on the screen printed circuits' characteristics	Dumitrescu et al., 2014b
	2013	Screen printing of a capacitive cantilever-based motion sensor on fabric using a novel sacrificial layer process for smart fabric applications	Wei et al., 2013
	2012	Electrical conductive textiles obtained by screen printing	Kazani et al., 2012
	2010	Electrical Characterization of Screen-Printed Circuits on the Fabric	Kim et al., 2010
	2021	Evaluating the Effect of Textile Material and Structure for Printable and Wearable e-Textiles	Komolafe et al., 2021
	2011	Printable low-cost sensor systems for healthcare smart textiles	Rai et al., 2011
	2019	UV Curable Conductive Ink for the Fabrication of Textile-Based Conductive Circuits and Wearable UHF RFID Tags	Hong et al., 2019
Inkjet printing	2020	Silver nanoparticle conductive inks: synthesis, characterization, and fabrication of inkjet-printed flexible electrodes	Fernandes et al., 2020
	2017	A wearable tracking device inkjet-printed on textile	Krykpayev et al., 2017
	2017	Silver-based reactive ink for inkjet-printing of conductive lines on textiles	Kastner et al., 2017
	2015	Inkjet Printed Conductive Tracks for Printed Electronics	Chen et al., 2015
	2013	All-inkjet printed strain sensors	Ando and Baglio, 2013
	2012	Humidity Sensor Printed on Textile with Use of Ink-Jet Technology	Weremczuk et al., 2012
	2010	Progress towards the first wireless sensor networks consisting of inkjet-printed, paper-based RFID-enabled sensor tags	Lakafosis et al., 2010
	2005	Inkjet printing of conductive patterns on textile fabrics	Bidoki et al., 2005
	2015	Capacitive Strain Sensors Inkjet-printed on PET Fibers for Integration in Industrial Textile	Quintero et al., 2015
	2019	Inkjet-printed silver films on textiles for wearable electronics applications	Kao et al., 2019
	2012	Humidity Sensor Printed on Textile with Use of Ink-Jet Technology	Weremczuk et al., 2012
	2017	All inkjet-printed graphene-based conductive patterns for wearable e-textile applications	Karim et al., 2017

Table 02.2 Most relevant research publications regarding Screen and Inkjet printed electronic textiles.

2.5 Garment design and manufacturing

The garment or apparel-manufacturing process has evolved from a manual art to an industrial activity due to technological advancements, including the use of computerised equipment (for the design, pattern-making and cutting), 3D scanning technologies, automation, and material transport, all of which have improved production efficiency. Therefore, modern clothing and fashion have been deeply influenced by these technological advancements. (Watkins and Dunne, 2015); (Nayak and Padhye, 2015) These advancements have brought progress and optimisation but also have created problems. This is why it is fundamental to understand the garment-manufacturing process to establish operating new rules aiming to minimise material waste, select materials responsibly, and establish a more fair production process not only focusing on the materials for garment production but also on the humans that produce them (Tyler, 2008) .

Garment-manufacturing of ready to wear apparel or garments involve the sequential processing of various steps, which begin with a need or an idea and end with a finished product. (Gersak, 2013) Therefore, the garment manufacturing process involves the design of the product, its production and all the activities to deliver it to users. Garment ideation and manufacturing steps can be divided generally as follows:

- Identification of need or idea: identification of user's need or idea for a new garment.
- Garment design: The process of ideating the garment to respond to the needs of the client's brief. This step includes both the definition of the final design (appearance, measurement and fitting) and the creation of the cutting and laying patterns for each of the different required sizes in which the garment will be manufactured.
- Fabric selection and purchase: Selecting the correct fabric for the type of garment is crucial for the successful outcome of the process.
- Receiving the fabric and fabric relaxing: the fabric relaxing process can be performed manually or mechanically. This process allows the fabric to relax and contract prior to its manufacturing, avoiding shrinkage issues further in the process that may affect the end product.
- Spreading, form layout, and first cutting: The fabric is first spread to identify fabric defects, control tension and slack during cutting and ensure the alignment of each ply on top of others. Then textile spread and then cut into uniform plies. Spreading and cutting can be done using an automated system or manually, depending on the units to produce and the technology available.
- Laying of paper patterns: this step helps to plan and order the placement of the different pieces of a garment. Marking: this step involves the arrangement of the full-size patterns in the most optimal manner over the uniform plaids of fabric.
- Cutting: all the pieces of the patterns, manually or mechanically.
- Details: includes embroidery, screen printing. Sewing: First, the cut pieces are bundled depending on their size, colour, quantities etc., then they are sewn using the most appropriate stitches and threads for each type of fabric and desired finished.
- Finishing steps: including checking, spot cleaning, laundry, fusing and pressing. Packaging and shipping: to send them to the end-user or the point where the garment will be purchased from (Textile School, 2019); (Cooklin et al., 2011) .

When creating a garment, there are many things to consider. Apart from the main physical and mechanical characteristics of the fabrics, the direction of how the pieces need to be cut when they are lying down in the fabric is also fundamental (Vilumsone-Nemes, 2015). This is known as grainline, it refers to the direction of the yarns along the warp threads perpendicular to the weft. Respecting the grainline is essential since the fabric can perform differently; draping, stretching, print, endurance and flexibility are some of the characteristics that can be affected or, in the opposite way, can be achieved while positioning the patterns in different ways under the fabric (Behera, 2015). In industry, following the grainline is the most common way to cut pattern pieces (Orzada, 2001).

2.6 Material Characterisation

A selection of different scanning and performance equipment where selected to assess the produced samples of this research. This selection is based on imaging technology such as Microscopes and tomography equipment. Textile testing equipment to assess the performance of the selected materials and electrical testing using equipment to measure the conductance performance of the printed samples.

2.6.1 Contact Angle **(CA)**

Contact angle or Wetting angle fig.02.28 refers to the angle of contact between a drop of liquid resting in contact with a surface or a textile substrate, the drop of liquid being in a stable state, and the tangent to that surface(Report, 2016). The contact angle is determined by the resultant between adhesive and cohesive forces (Rouette, 2001).

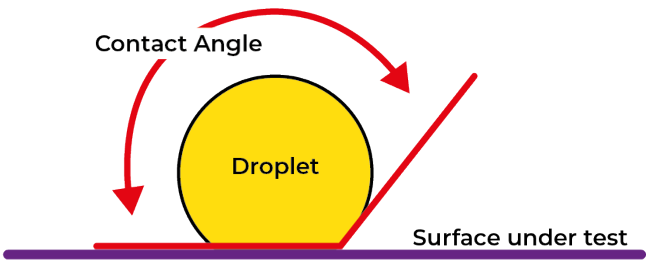


Figure 02.28 Contact Angle Principle

As shown in fig. 02.29 hydrophilic materials have a wetting angle of 0–90°(low contact angle) (Report, 2016). These materials are the ones that can absorb water. Materials which tend to be water repellent have a wetting angle greater than 90°, therefore, they are considered hydrophobic (Good, 1992) (Rouette, 2001).

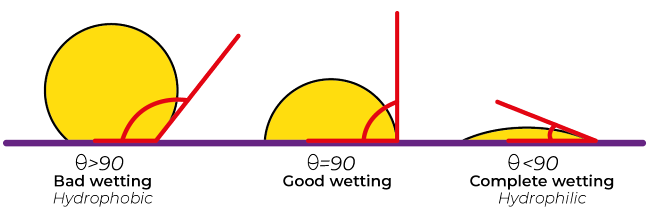
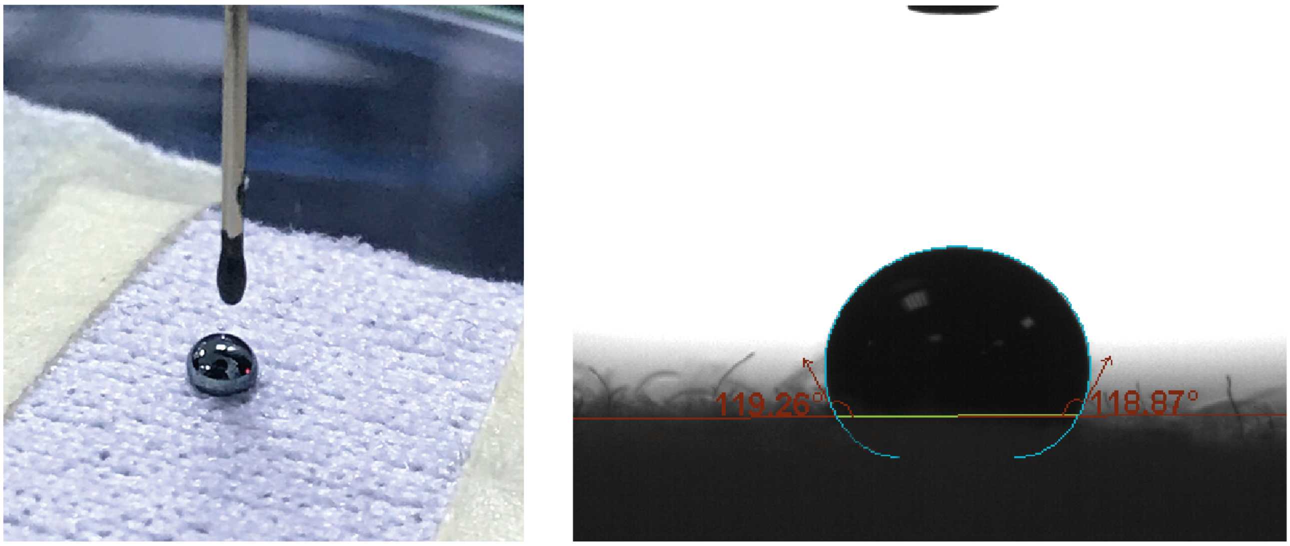


Figure 02.29 Contact angle wetting

The advantage of this method is that it is straight forward; the test only needs the liquid that is going to be tested, and the substrate (Oura et al., 2003). Multiple droplets can be deposited in various locations on the sample to determine heterogeneity and absorbance of the substrate. In the case of textiles, this is a very important fact because textiles are made of fibres and threads, meaning that the surface is not plain and even like other surfaces such as paper or plastic films. When using textiles, the contact angle may vary because of this structural property or if the fabric has any finish or coating (Atae-Allah et al., 2001). The contact angle is determined by a Goniometer and using the sessile drop technique, which is described in the next section.

In fig. 02.31 the trajectory of the drop is explained from when it comes out of the syringe until the ink is absorbed by the substrate(textile). As previously mentioned, the drops can have different contact angles depending on the liquid and the substrate. They might be fully absorbed, or they can stay in any other of the stages, where the drop is only making contact but nor being absorbed.



A B

Figure 02.30 **A** Drop on textile, image captured with mobile phone camera. **B** Example of real Contact Angle being measured in the camera of the Goniometer kit, this camera records the impact of the drop to the substrate and automatically calculates the right and left angle as it is shown in the image. The camera is calibrated before starting the experiment so the drop is in focus

Sessile Drop Goniometer

The Sessile drop method is used for surface-tension measurement. This method requires only small quantities of liquid, can be applied to liquid-vapour and liquid-liquid interfaces, and can be used in extreme conditions of temperature and pressure (Atae-Allah et al., 2001). The main premise of the method is that by placing a droplet of liquid (in case of this research, silver nano-particle ink) supplying it using a syringe as shown in fig. 02.32 to a known surface(different textile substrates) (Kwok et al., 1997). The shape of the drop, the contact angle, time of absorption and the known surface energy of the liquid are the parameters that are used to calculate the surface energy of the substrate sample.

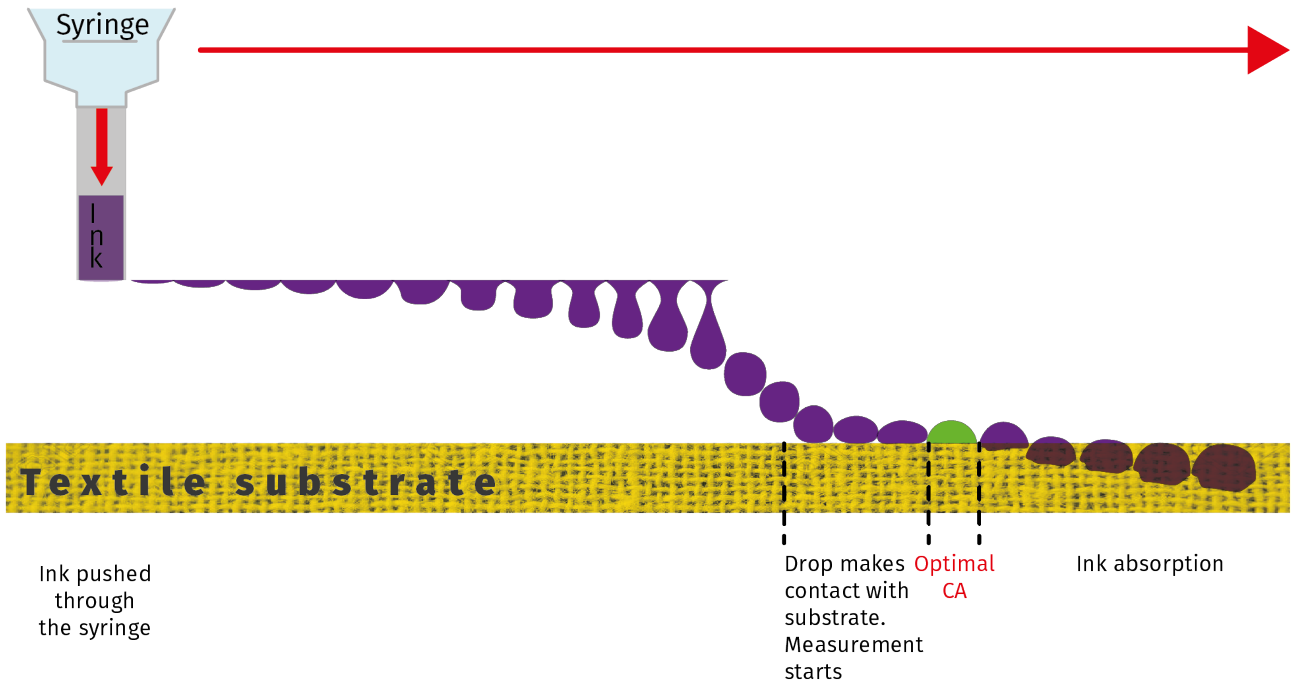


Figure 02.31 CA drop formation and impact process. The ink is expulsed from the syringe, the drop falls and makes contact with the substrate. Once the first impact occurs, the automatic measurements are processed for the time length set. All of this is captured by a camera that can record or capture moments of the process.

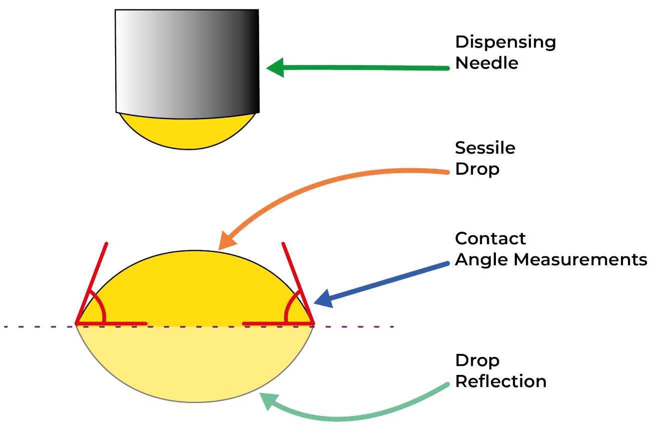


Figure 02.32 Sessile drop goniometer

03 Methodology

This chapter describes the research methodology by explaining the broad philosophical underpinning to the research design.

Research philosophy deals with the source nature, and development of knowledge, meaning it is a belief about the ways in which data about a phenomenon should be collected, analysed and used (Dudovskiy, 2018). The choice of the type of research philosophy to be applied depends on the knowledge being investigated within an area of a research study (Kirongo and Odoyo, 2020). According to Saunders (2016), the research philosophy is a system of beliefs and assumptions about the development of knowledge.

There are five main research philosophies: Positivism, Critical Realism, Interpretivism Postmodernism and Pragmatism. Each of these philosophies can have two different approaches, deductive and inductive (Dudovskiy, 2018; Saunders et al., 2015). However, in order to understand and to choose the best philosophy that can interpret and back up this investigation, is important to understand which are the different philosophies and what they stand for.

Saunders et al. (2012) present within their research onion, fig. 03.1 the integration of these components aims to produce a coherent design that is guided by literature and philosophical beliefs to inform suitable data collection and analytical choices (Saunders et al., 2012).

Positivism, in its essence, is based on the idea that science is the only way to learn about the truth (Dudovskiy, 2016). It is about things that can be measured. Dudovskiy (2016) states that the main principles of the positivist philosophy are that the research should be empirically observable by human senses, and that science must be value-free and should be judged only by logic.

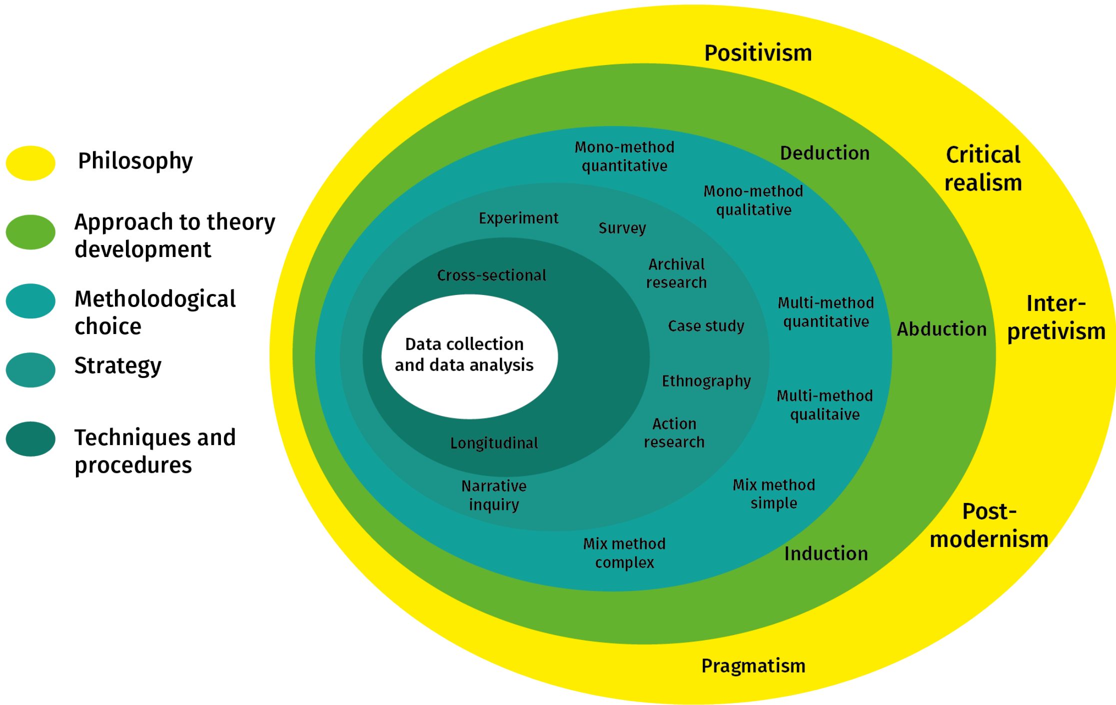


Figure 03.1 Saunders et al. (2012) presents within their research onion (Figure) the integration of these components aims to produce a coherent design that is guided by literature and philosophical beliefs to inform suitable data collection and analytical choices (Saunders et al., 2012).

Critical Realism is objective, it relies on the idea of independence of reality from the human mind. This philosophy is based on the assumption of a scientific approach to the development of knowledge; however, it also states that observable phenomena can provide credible data, always being aware that insufficient data can also mean inaccuracies (Dudovskiy, 2016). Realism can be divided in direct and critical, direct refers to what you see is what you get; and critical realism position is that what we experience are sensations, just images, not the real things (Saunders et al., 2012).

Interpretivism, as its name suggests, it is about interpretation, is a subjective philosophy where the researchers involved their interest and interpretations, its way to collect data is based on a naturalistic approach such as interviews and observations (Dudovskiy, 2016). It is all about how humans try to make sense of what is happening around (Saunders et al., 2012). Interpretivist researcher believes reality is made up by people's perception of it. In this sense there is no such thing as truth which opposes the positivist views (Bryman & Bell, 2015).

Pragmatism is a philosophy that adapts and combines, it all depends on the objectives of the research project. It can either be objective, subjective, or mixed, the only thing that matters is the research question, and from that a mixed research can be designed.

According to Saunders et al. (2019), there are three main approaches to theory development: deduction, induction and abduction.

1. Deduction: a theory and hypothesis (or hypotheses) are developed, and a research strategy designed to test the hypothesis. This type of reasoning is usually selected when for the researched topic there is plenty of literature from which a theoretical framework and hypothesis can be defined.

2. Induction: data is collected, and a theory is developed as a result of the data analysis. It can be appropriate to research into a topic that is new, and where there is debate and on which there is little existing literature. This way of reasoning allows the researcher to generate and analyse data reflecting upon the theoretical themes the data suggests.

3. Abduction: data is used to explore a phenom, identify themes and explain patterns to generate a new or modify an existing theory, which is subsequently tested, often through additional data collection. If there is plenty of literature and information about the research topic in one context, but far less in the one from which the research is carried, an abductive approach will enable to modify or contribute to existing theories (Bryman and Bell, 2015; Saunders et al., 2019).

This research uses a deductive approach which encourages the use of experiments to develop a replicable methodology suitable for the manufacturing of electronic textiles.

The present research adopts the positivist philosophy with an inductive approach, which is related to the aim of this research, which is to discover a novel method to produce and test printed electronic textiles.

The research will follow the list of objectives presented in **Section1.1**. Firstly exploring the methods of printing which already exist in the literature, linked to **Objective 1**. Following this is a set of designed experiments to assess the interaction between materials, linked to **Objective 2**. This evidences the positivist stance as the experiments will assess the interaction between already existing materials. Next, different printing techniques parameters will be tested, which justify the positivist stance and is linked to **Objectives 3** and **4**.

These experiments are expected to produce enough data to move on to a verification/evaluation stage which addresses **Objective 5**. This stage will allow for the integration of electronics which addresses **Objective 6**. These steps will introduce a new method of producing electronic textiles for broader use and not only printed electronic textiles.

The use of quantitative analysis technique for material characterisation as well as printing techniques and electronics integration was adopted. It is guided and supported by the Design Research Methodology Framework by Blessings and Chakrabarti(2009), User-Centred Design (UCD), and E-textiles lifetime cycle of Marculescu et al. (2004). Each of these three methodologies brings specific steps to the research, creating a more integrated methodology, addressing some weaknesses of earlier approaches. As the research of *McCann et al.* states 'There is a great demand in the merging of science and technology with fashion and textile design'.

Firstly, the Design Research Methodology Framework by Blessings and Chakrabarti (2009) fig. 03.2 was used due to the structure that it brings; it is invaluable setting goals, understanding these goals, experimentations, and support, and finally evaluation of these experiments. If it is needed, the two final steps can be iterated until the goals are achieved. This methodology sets the structure of each step and the set of experiments that need to be performed.

In the literature of e-textiles, the methodologies applied are usually engineering-related. However, there is a lack of a common language between designers and engineers to understand the disparate mix of aesthetic, technical and cultural needs of the potential market for smart clothing. If the purpose of these e-textiles is to be worn by a user, then there is a need for User-Centred Design (UCD) fig. 03.3. This approach aims to inform design by employing methods that place the user in a constant dialogue with designers from the ideation stages, right through to product deployment, in an iterative feedback-driven process.

It follows a non-linear design process, that aims to develop an understanding of a given design problem from the perspective of end-users; an approach more commonly employed in social sciences, to investigate the more abstract and unquantifiable qualities of human experience (Scott et al., 2012).

UCD is recognised to employ mixed method approaches composed of investigative and understanding of the user needs through, surveys, interviews, diary-keeping or constant communication with the user. These tools place the user in a collaborative role through the design loop (What is User-Centered Design?, 2018). This research uses the UCD methodology with the purpose taking the traditional steps of garment production, considering the technical and functional aspects of conventional garment production, and incorporating new materials into it. Always considering that these e-textiles will be worn by a user. This means that, they need to have specific characteristics such as thermophysiological comfort, skin sensorial comfort, ergonomic comfort, and psychological comfort. This research does not have a specific end user in mind, however, it is expected to produce e-textiles that can be used for healthcare monitoring purposes. In previous research, the necessity of a systematic design process for technology and garment design has been stated by several authors to address the user issues and reach the potential market (McCann et al., 2005) (Marculescu et al., 2003) (Dunne, 2010) (Cash and Stanković, 2016).

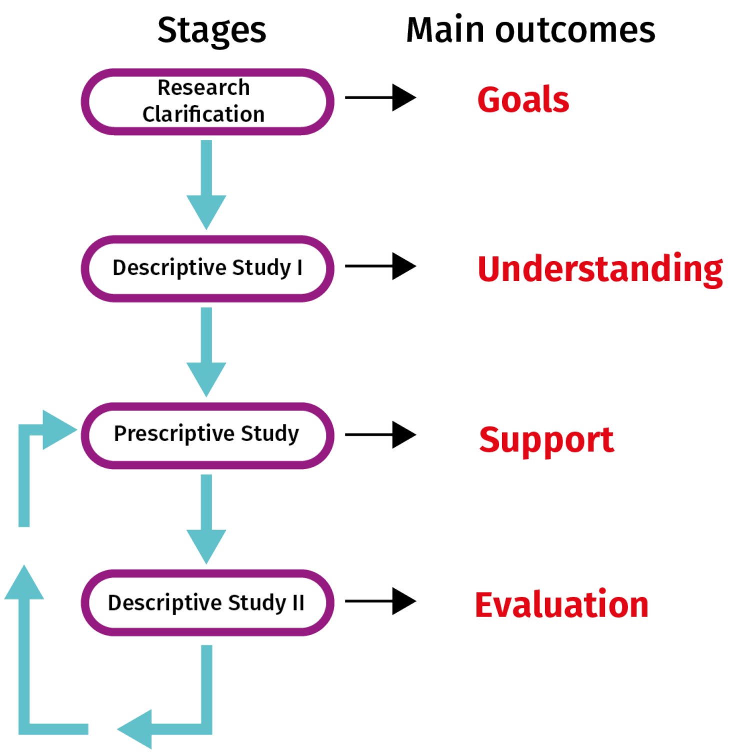


Figure 03.2 Design Research Engineering Methodology Framework Blessing and Chakrabarti, 2009 Research Clarification is about the collection and organization of the information. In the Descriptive study I step, the setting up of measurable criteria and the steps for testing occurs. Prescriptive Study is where the evaluation plan and assumption take place and finally Descriptive Study II is where the success of the evaluation and data is analysed is measured. If it is unsatisfactory, a return to the Prescriptive study step is necessary for re-evaluation and adjustment.

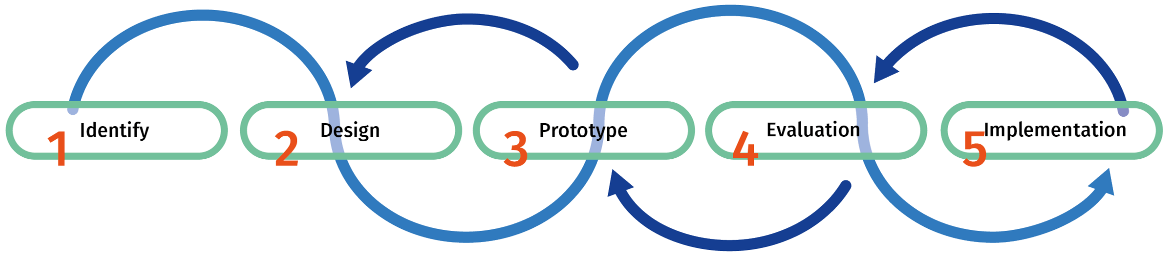


Figure 03.3 User Centered Design Methodology. 1.Identify the use context and users' needs, 2. Design different product proposals according to the information gathered from the user, 3. Make prototype by building the design solutions from rough concept to finished product, 4. Evaluate designs with usability and performance testing. If the product needs redefining and more development, then it is necessary to go back one or two steps depending on the feedback of the user. Once the evaluation receives a positive outcome, then the process finishes at step 5 with Implementation - which refers to develop and deliver the product.

The third Methodology that was incorporated is the e-textiles lifetime cycle fig. 03.4. This methodology was used to overcome the challenges of integrating electronics with the selected textiles. It was also used to prevent failures and achieve regularity. It is mainly focused on the refinement and optimization of different metrics of interest and as for the other methodologies, it also incorporates evaluation and repetition of steps until the goals are achieved.

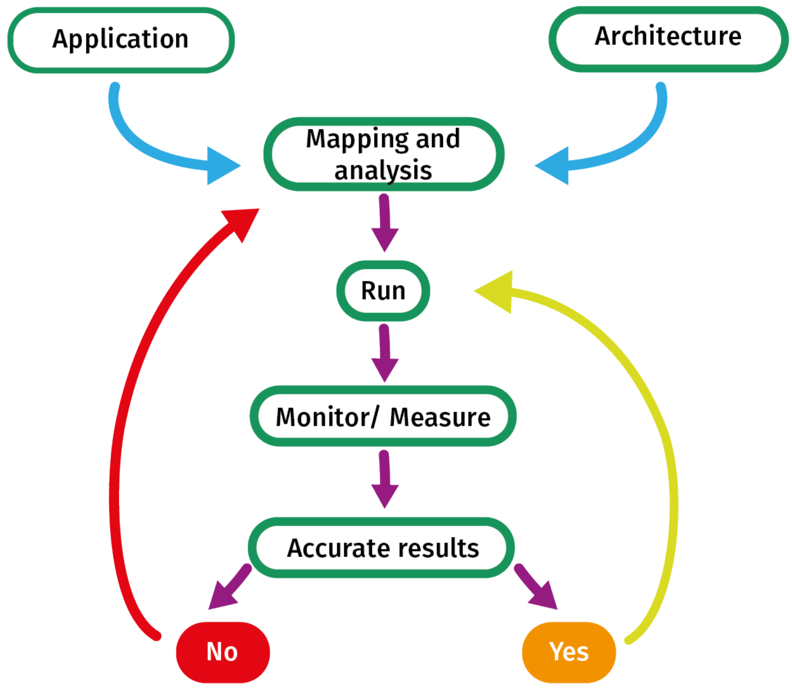


Figure 03.4 Adaptation of the e-textile lifetime cycle diagram of Marculescu et al. (2004). This Diagram proposes a Methodology to incorporate electronics into textiles to create e-textiles. The first steps before moving into mapping and analysis are Application, where the purpose of the e-textile is defined, and Architecture how it is going to be made. Afterward, Mapping and analysis is where the objectives and the steps for manufacturing and testing are followed by running the tests (checking connections and materials). The monitoring and measuring step is where decisions are made if the test had positive results or if it is necessary to go back some steps and re-evaluate.

The following diagram fig 03.5 represents the methodology created for this research by adapting the three previous approaches:

Methodology

Research Clarifi ation where the Aim and Objectives are clearly described to give a detailed structure to the research and the experiments are design.
Identifi ation of the User (following the UCD methodology) and their needs. For this specific research there was no User present however, information regarding garment design for healthcare monitoring was used.
Descriptive Study I Understanding of the findings (Literature review, Ch.02).
Prescriptive Study I Selection or creation of materials to be used.

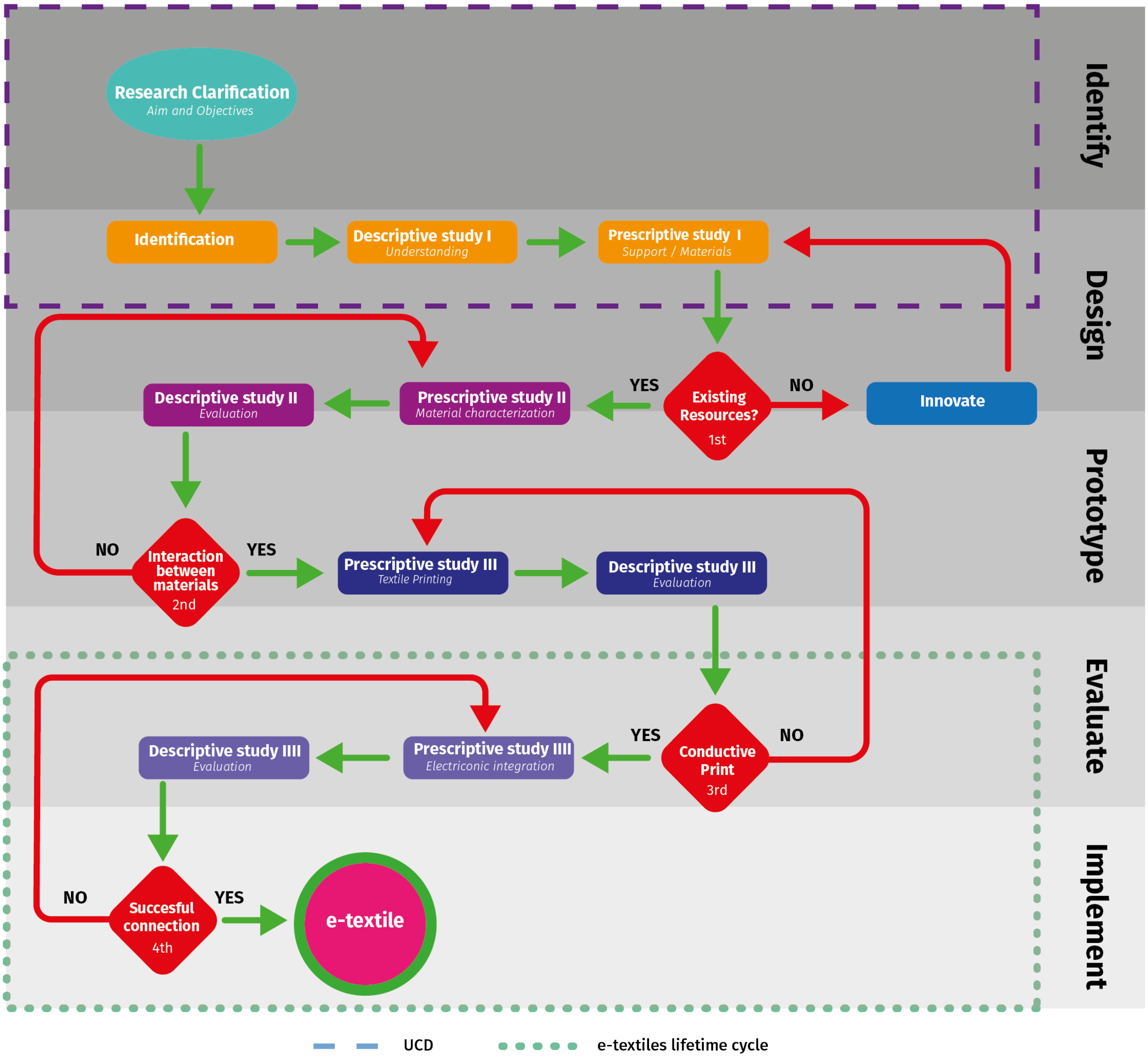


Figure 03.5 Methodology diagram based on the Design Research Methodology Framework by Blessings and Chakrabarti(2009) was used to give the structure of the methodology, User-Centred Design (UCD) was used to demonstrate that the user needs to be taken in account and his needs. And E-textiles lifetime cycle of Marculescu et al. (2004) to follow the integration of electronics into textiles

Decision Point I evaluate if there is a need to innovate or if the research can continue with existing materials.
Prescriptive Study II material characterisation, textile selection & ink selection (Material Characterisation, Ch.04)
Descriptive Study II evaluation of these materials is performed and the interaction between them is studied.
Decision Point II comes next, this decision point dictates if existing materials will be used or if there is a need

to innovate in the material creation. Since it was decided to choose existing materials, the research was able to proceed to Prescriptive study II, where the material characterisation takes place. In this step, the analysis and understanding of each material, its properties, and the interaction between materials which took place in Descriptive Study II is assessed. The Descriptive study II is followed up by a decision point where, if the interaction is possible, then the next Prescriptive study can be performed. Otherwise, a re-statement of the material selection has to be done.

Prescriptive Study III happens after having specific material information and analysis that can dictate the printing process (Screen and Inkjet Printing, Ch.05 & 06).

Descriptive Study III the physical and electrical evaluation of each print to see if these prints are conductive. If they are not conductive, different printing variables need to be tested to achieve a conductive print.

Decision Point III point where a decision to continue or repeat experiments is taken (Electrical Performance, Ch.07).

Prescriptive Study IIII electrical integration.

Descriptive Study IIII evaluation of the electrical integration.

Decision Point IIII testing of the conductance and performance of the print and the sensors. If the results prove not to be conductive, then there is a need to go back one step in order to determine where the failure occured.

Once all these steps are continuously performed and the final decision point shows that the print and the electronic integration worked, then it can be decided that the e-textile is complete.

Material Characterisation

04

"When selecting materials for engineering designs, a clear understanding of the functional requirements for each individual component is required and various important criteria or attributes need to be considered." (Venkata Krishna Rao et al., 2015)

Materials are present in our everyday lives; we design and manufacture everything thanks to the infinite selection of materials. Whether natural or man-made, we depend on them.

However, material selection is essential to design and manufacture any product, especially in the fashion industry. Customers not only look for an aesthetic experience, but also comfortable, sustainable, functional and lovable products (Ashby and Johnson, 2013) (Karana et al., 2013).

As necessary as it is to choose the suitable material for any product being developed, material selection requires technical and manufacturing knowledge (Ashby and Johnson, 2013). It is crucial to prepare them, understand their properties, composition and structure; in other words,characterise them (Cahn and Lifshin, 1993). In multidisciplinary research, there are materials that have been used just for a specific purpose. These same materials are now being tested and put under experimentation to interact with new materials (Zhang et al., 2008) and disciplines. Materials have the power of transcending boundaries of multiple disciplines (Solanki, 2018).

The purpose of testing and characterisation is not only to understand the materials, but also to improve the product performance and quality (Saville, 1999). There is a wide selection of techniques for material characterisation. *'When we begin to study a material, we're immediately launched into an ever more complicated system of scales and structures (Corbin, Liz 2018).*

Interaction and performance testing are important, but also, the manufacturing techniques that materials are exposed to are new and different. They have therefore had to evolve and adapt. Understanding materials gives a broader sense of their mechanical performance, physical properties, and how they will behave under other manufacturing techniques, tools, etc.

There is an extensive list of material characterisation methods; it all depends on the nature of the samples and the information that is required from them (Brundle et al., 1992). Thus, this research focuses mainly on understanding the selected textiles, their structural properties, and their natural properties. Along with the study of textiles, two conductive inks were tested and analysed in order to understand the interaction between the ink and the fabrics.

4.1 Objective

The objective of the textile and ink characterisation is to analyse and examine the impact of fabric properties on printing processes, to identify and determine process requirements when applying conductive inks on porous materials.

The objective was achieved by:
- Providing an overview of the different textile structures (woven and knitted) and fibres chosen for this project (cotton, bamboo, polyester).
- Determining the most suitable ink vs solvent ratio for printing.
- Examining the textile surface energy in relation with the conductive inks, using the contact angle, sessile drop method.
- Analysing and compare the properties of each textile sample, according to their structure and interaction with the conductive ink.

The outcome of addressing this objective is to provide a foundation the further printing tests by understanding the interaction between textile-ink and the challenges that might come during the printing process. In addition, the collected information will help to set up the parameters, such as screen mesh size and fabric pre-treatments, among others, to achieve high-quality conductive prints.

4.2 Textile substrates

Most of the investigations that have been carried out in relation to screen and Inkjet printing with conductive ink have been performed on non-textile substrates. However, there is a great deal of interest and investment on printed textiles (E-Textiles 2018-2028 (IDTechEx Research). Printing with conductive ink has proven to be effective on substrates with smooth surfaces such as films, coated papers and other materials like acrylic

(Perinka et al., 2013). However, with regards to textiles the results are less positive (Tun and Onn Malaysia, 2015). Due to the complex structure that textiles can have, woven knitted or non-woven, there is a lack of positive results on printed tracks and their conductance. At the moment, the biggest research gap is how to achieve an even penetration of the ink through the fabric structure and fibres (Dumitrescu et al., 2014a). This gap also is related to the moisture management of each fabric ; it all depends on the structure and the fibre that the fabric has been made of (Das et al., 2009). The chosen fabrics were: Cotton, Polyester, and Bamboo, each with a knitted and plain weave variation, having a total of 6 different textile samples to test.

The fabrics were primarily chosen because of their different textile properties such as thickness, porosity, weave structure, performance properties and for the advantages and disadvantages they all have, as shown in figure 04.1 Moreover, these are standard fabrics for garment manufacture (Komolafe et al., 2020). They are also engineering material with strong technical capabilities that can be used in various applications such as composites, geotextiles, braided structures, medical use (wound dressing), aerospace applications, and many more (Kumar and Hu, 2017). Most of the research that has been done related to printing with conductive ink using textiles as substrates has used cotton or polyester, however, there is no research being performed using bamboo. Due to the long list of properties this natural fibre has, it was necessary to broaden the focus to include this fibre with its wider application. Materials such as paper, cotton, and polyester are the most popular in the research of conductive prints on textile substrates. However, in previous research it has been stated that synthetic textiles generate static charges and this directly affects any electronics attached to it (Grishanov, 2011), (Ballou, 2016), (Suh, 2009). Futhermore, it has also been studied and proven that natural textiles have a lower static impact which also make them a most suitable material to test and analyse (Fu et al., 2017). Therefore, due to the gap found in research regarding natural fibre substrates, the exploration of bamboo fabric and its interaction with the conductive ink were deemed important to address; along with cotton and polyester textiles.

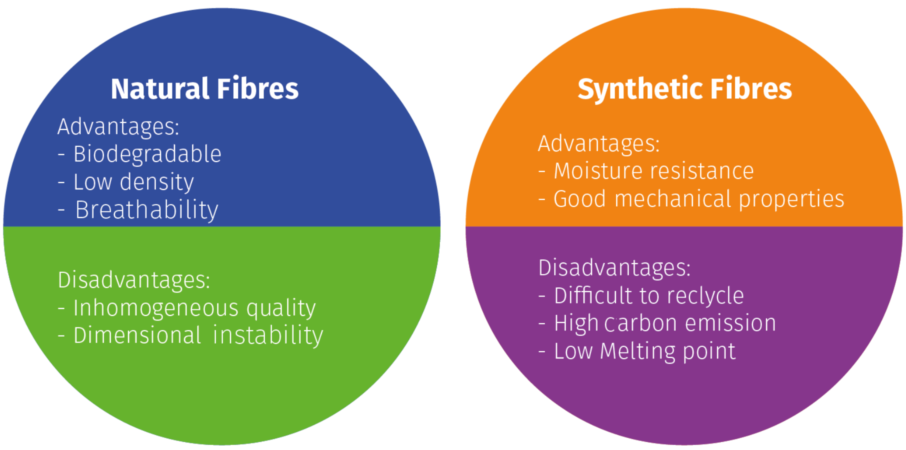


Figure 04.1 Advantages and disadvantages of Natural and Synthethic fibres

Such as stated in **Section 1.1**, this chapter will focus on the understanding of textiles and conductive ink. Before moving into the experimentation, it is essential to study and understand each textile. Their fibre properties and structural composition. Each textile substrate was studied under the microscope to analyse the structure of each sample and their porosity. Additionally, a list of mechanical properties was studied, and finally, the Contact angle experiment was performed.

4.2.1 Selected Fibres

Cotton

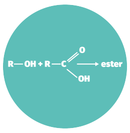
Cotton is one of the oldest textiles in the world originated around 5800 B.C. Today more than 45% of fibre production is cotton, with 27 million tons produced globally per year (Gries et al., 2015). Cotton is a natural fibre that grows up to 2 meters tall. Depending upon the origin and cultivation conditions. The flower of the plant transforms into a capsule full of fibres. These capsules are then, hand or machine picked, followed by the spinning preparation which includes the carding, drawing, combing, and roving. Afterward, the fibres are spun and weaved or knitted (Negm and Sanad, 2020).

This fibre is used mainly for apparel, this can also be processed as 100% cotton or blend with other man-made fibres such as polyester or viscose. The most common applications are shirts, blouses, linens undergarments, and businesswear (Hosseini Ravandi and Valizadeh, 2011). Cotton has excellent properties for garment creation, starting with its high moisture retention. This textile can absorb sweat, letting it evaporate afterwards, it is a breathable textile. It also has good durability properties, it is soft to the touch, comfortable, and washable. However, cotton also has disadvantages such as low crease-resistant and shrinkage.

Bamboo

Bamboo is a natural fibre, coming from one of the fastest growing plants. With great properties such as antifungal and antibacterial properties; it is soft and has high strength and durability. In the last decade this material has gained popularity due to the extensive applications it has and being a natural fibre means that it is a green fibre that has been adopted in the circular economy. The industries that are using this material are not only interested in the properties that can improve the product quality and design, but they also care about the customer comfort. Therefore, the main usage of bamboo textiles are in sportswear, base layers and t-shirts (Alagirusamy and Das, 2010). Even though this is a natural fibre claiming to be sustainable there is still ongoing research regarding the cultivation and process transparency (Shishoo, 2015).

Polyester



Polyester is a durable and strong material, it is not affected by stretch or tear like other fibres. These characteristics make it a perfect material for clothing because it can handle abrasion and it doesn't require special care. Another important characteristic is moisture resistance, however, it doesn't mean that this is suitable for any type of clothing. This property is commonly used in outdoor clothing to protect the user from the environment, however, this also means that the fabrics are less breathable; therefore it can be very uncomfortable for sports clothing or warm weather (Postolache et al., 2017).

For these characteristics, blend fabrics have commonly produced the combination of polyester fibres with other natural or synthetic fibres add not only performance characteristics, but they also create better products with better qualities like comfort. (Hayes and Venkatraman, 2015).

4.2.2 Textile Porosity

As described in Section 2.2.1, textile structures affect the properties of a fabric. Having this in mind, it is important to visualise and analyse in detail each chosen fabric. It is a fact that textiles in comparison with polymer films are highly porous materials. Not only do they have pores or gaps between threads, but fibres between each other have pores, and even fibres in a microscopic scale also have pores. Meaning that textiles are 3D materials with high porosity and uneven surfaces (Section 2.2.1), making it very challenging but not impossible to print on them (Tun and Onn Malaysia, 2015) .

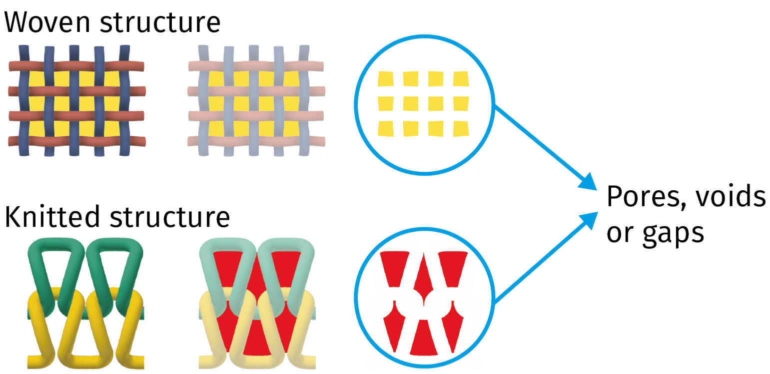


Figure 04.2 Pores or voids of Woven and Knitted structures

Textile pores have a strong influence on the properties of the textile; in fact, it is one of the most important properties. Porosity can affect thermal and mechanical properties. As well as printing and dyeing properties and water retention (Yong et al., 2021) (Rouette, 2001).

" Porosity: The ratio of the total amount of void space in a material to the overall bulk volume of the material." (Hook, 2003)

These pores or gaps may allow the transmission of energy like light or heat, and can contribute to the dispersion of liquid, gas or particles. It is important to determine the fabric porosity due to the technical properties it contributes in relation to the application of the garment use (Dubrovski, 2000). Pores in textiles can be classified into three types:
- Macro- pores, pores between the threads (warp and weft) or yarn porosity. .
- Pores between fibres or terfibrillary porosity.
- Micro-pores, pores of the fibres or intrafibrillary porosity.

The porosity parameters that are needed in most of the cases are the pore size distribution, the average hydraulic pore diameter, the open area for fluid flow and the air volume velocity as a function of the air pressure (Jakšić and Jakšić, 2007) (Rouette, 2001). There are many different methods available for assessing the parameters of porosity, such as geometrical methods, liquid intrusion methods, liquid extrusion methods, air permeability methods, and imaging methods (non-destructive) figure.04.3.

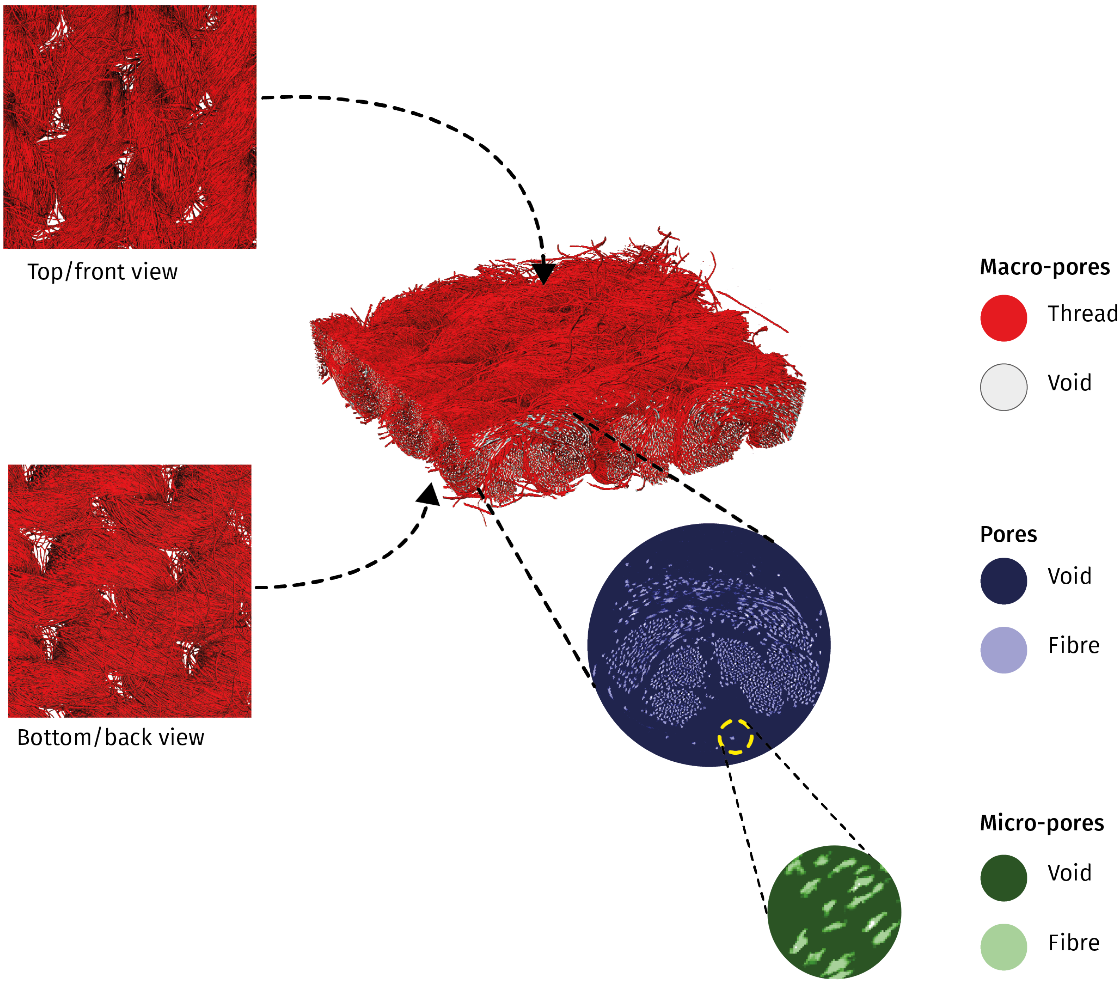


Figure 04.3 Example of knitted cotton textile analysed using X-ray computed tomography (XCT) was performed using a Zeiss Versa XRM520 X-ray microscope. The image shows how complex are fabrics made and displaying the pores between fibres, these images were taken in order to understand the challenges that could be presented while printing in a porous material and how could this affect the electrical performance of the prints.

For this particular research, the main focus is on macro-pores, since printing techniques will be applied.

Therefore, it is highly important to understand the structures and the gaps each fabric has to be able to modify the surface (add pre-treatments) or ink formulation if possible to achieve a successful print.

The six textile samples were studied under the microscope. Under the naked eye, all the knitted fabrics look the same and all the woven samples also looked the same due to the type of structure. However, under the microscope, they are very different; the pores that each fabric shows are in figure 04.4, the different fabrics can be appreciated. Their structures and fibers are visible and can easily be compared. These images were taken in a Digital Microscope with different magnifications to display the differences between each substrate that will be tested. Not only is it important to understand the challenge and complexity of printing on uneven surfaces such as textiles, but to also have a clear and exact image of how porous textile materials are and know what to expect or which methods/materials to avoid. While analysing the images, woven polyester showed to be the fabric with a tight weave and no pores visible. However, it is important to remember that even synthetic textiles are porous materials (Grishanov, 2011). In addition, it is also quite visible the fibres of the yarns coming out; will also affect the interaction of the ink. Mainly because these fibres are not staying in place, creating a rough and uneven surface.

The analysis of each textile structure helped to understand the complexity of each sample and create some predictions of problems, limitations and results of the textile-ink interaction testing. The knitted fabrics have a higher amount of pores, and these pores are more significant in size than the pores found in the woven structures. The conductive inks are expected to be able to stay on the surface once printed due to their composition. However, the need for a pre-treatment or coating might be necessary.

4.2.3 Textile Properties

Moving on, another essential part of the textile analysis is to consider the physical and mechanical properties of the selected fibres. These characteristics, just as the structure, table 04.1, will affect the interaction of the textile with the ink and the performance. The physical characteristics are related to the fabric structure and to the fibre that they are made of. These properties are also directly related to comfort and physiological factors (Morton and Hearle, 2008) (Abu-Rous et al., 2018). The mechanical properties refer to the response of fibre to different mechanical stimuli, such as strength, stiffness, elasticity and flexibility (Cassidy and Goswami, 2017).

Whaleys (Bradford) LTD provided the six different textiles selected for this research. The fabrics do not have pre-treatments. However, they've been through a scouring process, to wash out any impurity and guarantee that any finish performed in the lab, such as coating, printing, dyeing or applying any other pre-treatment, will adhere to the fabric.

Material Characterisation

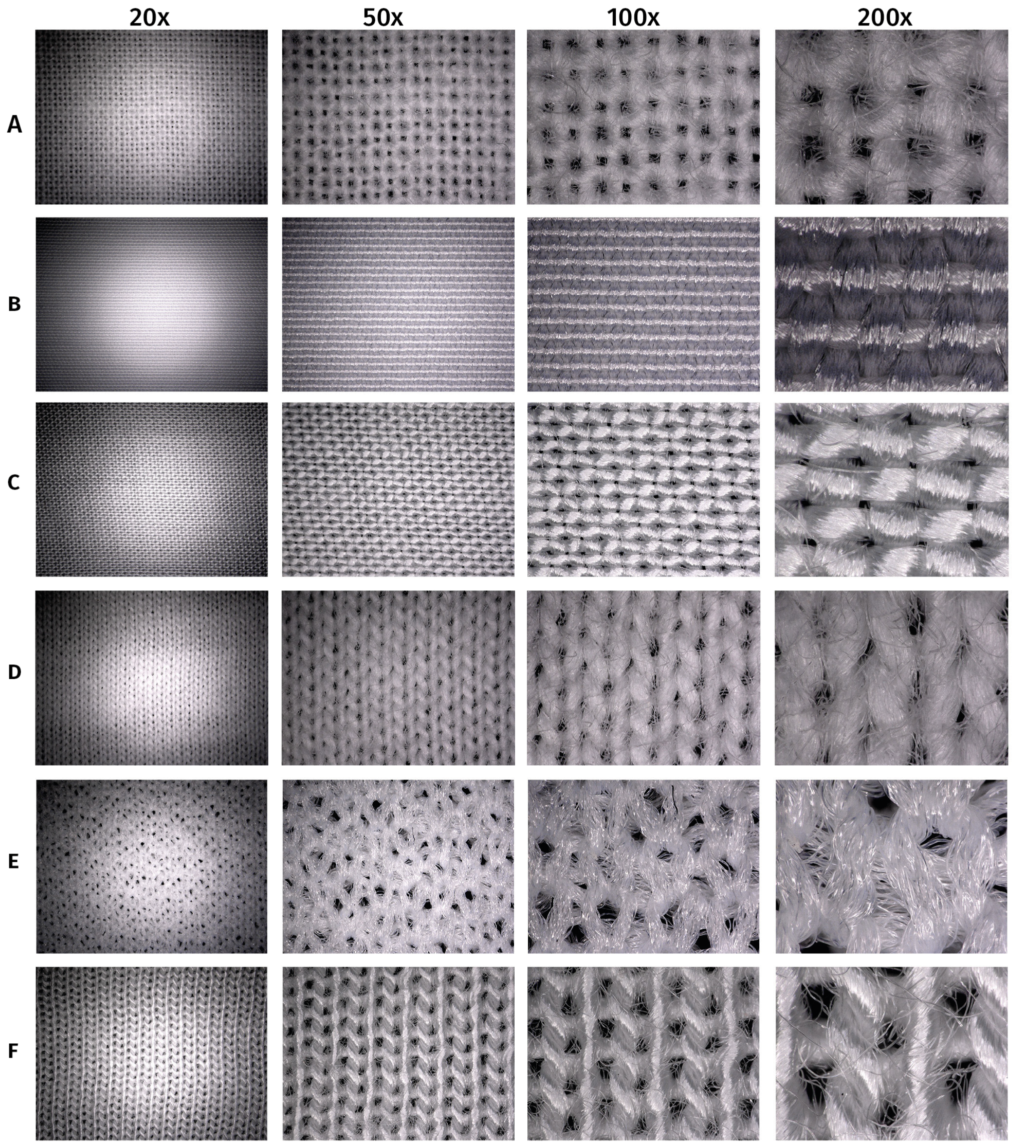


Figure 04.4 **A** Woven Cotton, **B** Woven Polyester, **C** Woven Bamboo, **D** Knitted Cotton, **E** Knitted Polyester, **F** Knitted Bamboo. Samples analysed on Digital Microscope (Keyence) using the ultra-small, high-performance zoom lens with magnifications of 20x to 200x. The chart displays the differences between structures and fibres. It gives a clear example of the complexity of the surface of each textile sample and the environment that inks will be connecting with during printing. Images with scale bar can be found in the Appendix.

It is important to analyse both the mechanical and physical properties of each selected textile to have a better understanding of how these will interact with the conductive inks. Water retention property, for example, can affect how the ink will be absorbed. The melting/degradation point is also crucial since the conductive ink needs to be cured. This melting/degradation point refers to the impact textiles can have when they are exposed to high temperatures. They can melt, change colour or begin to degrade (Mather and Wardman, 2015). Therefore, a selection of physical and mechanical properties was created with the factors that are related to the testing of conductive inks with textiles, table 04.2.

Sample Code	Substrate	Composition %	Structure	Thickness (mm)	Pore size (mm^2)	Surface Weight (g/m^2)
KB	Knitted Bamboo	100 Bamboo	Weft Knit	0.66	0.066	205
KP	Knitted Polyester	100 Polyester	Weft Knit	0.97	0.046647	85
KC	Knitted Cotton	100 Cotton	Weft Knit	0.74	0.031339	210
WB	Woven Bamboo	100 Bamboo	Plain Weave	0.23	0.002478	120
WC	Woven Cotton	100 Cotton	Plain Weave	0.39	0.018	120
WP	Woven Polyester	100 Polyester	Plain Weave	0.26	-	65

Table 04.1 Structure and fibre content of selected fabrics

Fibre	Density (gm/cc)	Potential water retention (%)	Melting/degradation point (°C)	Tensile strength (MPa)	Young Modulus (GPa)
Cotton	1.5 - 1.54	45.0	Change of colour (yellow) at 120°C, (brown) at 150°C	400-700	6-10
Bamboo	0.59 - 1.10	81.2	Change of colour (dark yellow) at 225°C, (dark brown) at 250°C	571	27
Polyester	1.38	4.5 - 6.0	Dry heat resistance at 150°C Melts at 250°C - 266°C	310	68.9

Table 04.2 Physical and Mechanical properties of selected fabrics
((Misnon et al., 2013), (Das, 2010), (Chen et al., 2009), (Faruk et al., 2017), (Omid et al., 2018), (Ali et al., 2011))

4.3 Conductive Inks

Conductive inks differ from conventional, optical inks in the composition of the active component; an electrically conductive material. These components are most commonly comprised of silver, carbon, graphene, gold and copper (Rai et al., 2011). These inks can be used in various ways, including screen-printing, flexographic, spray, dip, and more, however, the screen printing process remains the most used and tested method at the moment (Wang et al., 2017).

Silver nanoparticle inks offer many possibilities for printed and flexible electronics. This material has always been known for its properties on creating electronics thanks to its high conductivity, resistance to oxidation, plasmonic and antibacterial properties (Rai et al., 2011). Apart from this physical properties it is also very cheap and easy to buy. However, on the environmental side, it is not the best option because it is a material that cannot be recycled and a small amount of silver ink can contaminate a large amount of water which then cannot be cleaned, unless it goes through a chemical process (Hong et al., 2019).

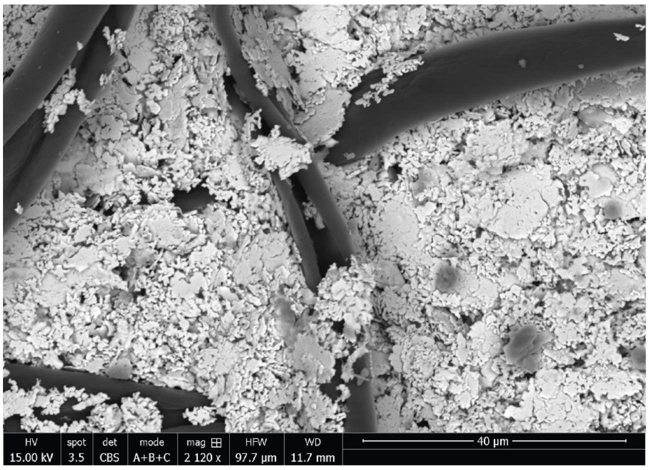


Figure 04.5 Silver nanoparticles, image taken with Scanning Electron Microscope (SEM). The silver flakes are visible in this image and the interaction between each other. This interaction creates conductance among the print. Due to the nature of textiles, threads with very little presence of flakes can also be seen, this demonstrates the complexity of an uneven and porous substrate.

Silver ink can also be coated very easily, and the after printing treatments are very easily to achieve. Typical commercially available silver inks require curing temperatures of 130°C - 150°C for a small amount of time, 5 - 30 min (Inoue et al., 2012). This means that the substrates that are being printed will not be damaged (unless they have little tolerance to heat) but in the case of textiles it will not affect the structure of the fibres. However, in some cases, especially with natural fibres, they can slightly darken in colour. Silver conductive inks contain large quantities of silver particles or flakes that interact with each other, allowing current to travel by them and creating conductive paths. If the particles are not interacting with each other this conductance may not be achieved, or it could affect the signal and information that is being transferred.

These inks can be mixed with other materials which are referred to as ”retention matrix” such as polymers to give protection and thickness, or solvents to mobilise the particles and enable printing. This matrix needs to be reduced, and this can be achieved either by evaporation or curing; this process is defined as sintering. Leaving only metallic content and allowing the particles to interact (Fernandes et al., 2020). Basically, conductive inks need to go through the following process:
Printing is when conductive ink is deposited via any chosen method (screen printing, Inkjet printing, hand-printing...etc), the ink is formed by the matrix and nanoparticles of the chosen material (silver, copper, carbon).
Drying comes next where the particles begin to create bonds and interact, this process can be leaving the print for a couple of hours in room temperature.
Sintering is when the matrix is reduced via curing the print, the method for curing and the temperature needed

variate depending on the type of ink fig. 04.6. It is essential to perform the sintering/curing process. This process is commonly intended for printed circuit boards/components that can be heated without a problem. However, this is not the same case for fabrics. Some of them can change colour or can be damaged due to exposure to high temperatures. Therefore, it is crucial to have the melting/degradation point of the substrates before submitting them to the curing process, table 04.2.

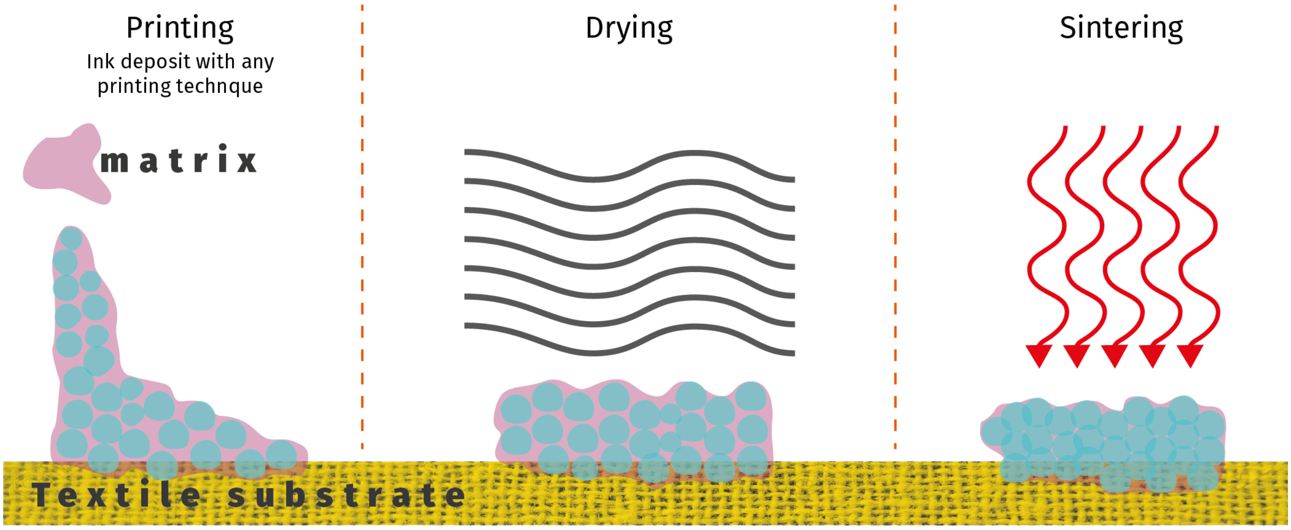


Figure 04.6 Printing, drying and sintering or curing process of conductive ink.

Silver ink is very high in conductance for application by screen printing, dipping, and syringe dispensing. In fact, silver is the metal with higher electrical conductivity. Silver ink has excellent adhesion to glass, coated papers, films, and a number of other substrates, however, it is not common to use this ink to print on textiles since printing on textiles with conductive inks is still ongoing research. The excellent conductance of this ink due to the nanosilver particles allows printing of narrower and/or longer circuit trace lines without compromising maximum ohm values (Alfa Aesar). Specific information such as viscosity, silver percent, resistivity, etc, can be found in tables 04.4 and 04.5.

Conductive inks have unique optical, electrical, and thermal properties and are being incorporated into products that range from photovoltaics to biological and chemical sensors. Examples include conductive inks, pastes and fillers, which utilize silver nanoparticles for their high conductance, stability, and low sintering temperatures. Additional applications include molecular diagnostics and photonic devices, which take advantage of the novel optical properties of these nanomaterials. An increasingly common application is the use of silver nanoparticles for antimicrobial coatings, and many textiles, keyboards, wound dressings, and biomedical devices now contain silver nanoparticles that continuously release a low level of silver ions to provide protection against bacteria.

4.4 Experiment

The objective of this process was to test and analyse the interaction between the substrate (textiles made of different fibres) and the silver ink, to understand how the fibres will absorb the liquid and if the prints will be successful. This type of characterisation is essential because there is a significant lack of information in the literature about the interaction between the ink and the substrate before printing. This procedure is also useful to test different substrates and to decide which substrate is the most successful to perform prints with this ink.

The analysis was based on the framework designed for this research; therefore the experimentation followed the steps of the Prescriptive and Descriptive Study II fig. 04.7.

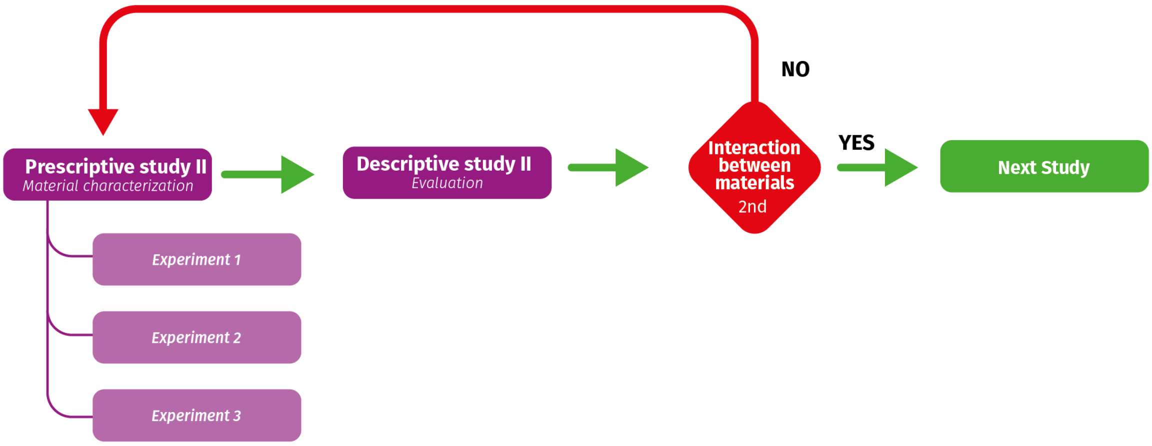


Figure 04.7 Prescriptive Study II

The testing for each textile sample followed the same five steps. The process was repeated 3 times on each substrate in order to remove faulty experiments data and get the most accurate information.

1 Textile samples were prepared following the room conditioning standards to avoid any excess of moisture in that fabric that could affect its performance. The textile samples were cut 3x5 cm and afterward they were taped to a petri dish to maintain them flat during the experiment.

2 The syringe was filled with conductive ink and the camera of the goniometer was calibrated.

3 The experiment was run for 60 seconds for each sample, each measurement was repeated 3 times to increase confidence intervals and ensure the statistical significance of results.

4 The samples were left to dry in room temperature, afterward they were cured in the oven depending on the needed time and temperature of each ink.

5 A visual analysis using the microscope was assessed and the information captured with the goniometer was analysed and compared fig. 04.8.

A series of contact angle measurements table 04.3 were carried out for Silver ink droplets on three different textile backgrounds, applying both computer and manual method sessile drop method. In the drop images, the bottom line and elliptic shape are automatically fitted to the drop profile, fig. 02.30. Wetting angles are measured between the bottom line and the automatically calculated ellipse tangents. A frame of 60 seconds was the standard measurement for all the samples, and this was repeated three times on each textile sample.

Figure 04.8 CA, experiment process

The Sessile Drop Method can measure the Left and Right contact angle and calculate the Mean (CA mean).

Sample Code	Substrate	time[s]	Repetitions
KB	Knitted Bamboo	60	3
KC	Knitted Cotton	60	3
KP	Knitted Polyester	60	3
WB	Woven Bamboo	60	3
WC	Woven Cotton	60	3
WP	Woven Polyester	60	3

Table 04.3 Experiment 1, Contact angle

Experiment 0 CA, Distilled Water on un-treated textiles

Standard Practice for Surface Wettability of Coatings, Substrates and Pigments by Advancing Contact Angle Measurement Active Standard ASTM D7334

Droplet method: a drop is allowed to fall onto a stretched sample of fabric from a syringe or micro-burette, while the liquid is being absorbed the camera that is places just in front of the burette records the absorption and measures the angles created on the sides and the time it takes the liquid to be absorbed. These machines can be set up to any time of recording in order to have a better understanding of the interaction between material (Good, 1992). This experiment was performed to analyse the hydrophobic properties of the textile substrates. The results were also used to prepare the textile samples for the measurements with conductive ink. Testing textiles can be challenging since they have an uneven surface; therefore, they need to be as flat as possible to be able to get clear readings while conducting the CA test.

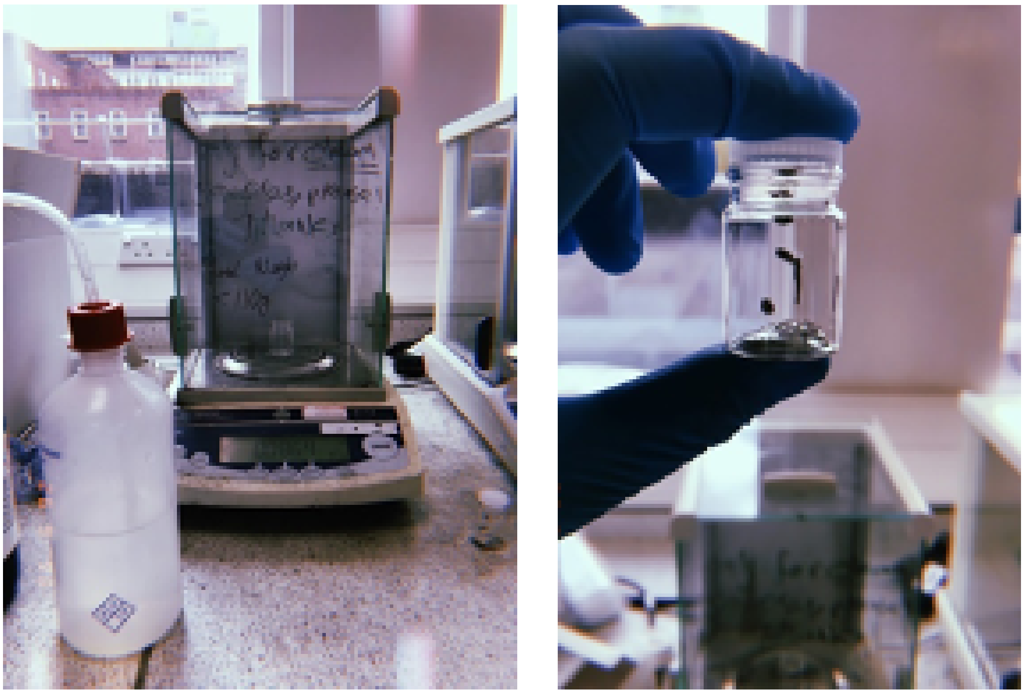
Experiment 1 CA, Alfa Aesar Silver conductive ink and textiles

Ink vs solvent ratio

Alfa Aesar Silver conductive ink (S-020). This ink is a thermoplastic, screen printable and highly conductive thanks to the silver flakes. Carbitol Acetate (Diethylene glycol monoethyl ether acetate) fig. 04.9(a) had to be added to the ink to thin it. The first mix was made by adding 10% of the volume with the solvent. However, it was still thick fig. 04.9(b) and the percentage increased by 15% and a 20%. The optimised concentration was 15%; the ink was thick enough to print and thin enough to go through the screen.

Curing:

Alfa Aesar Silver Nanoparticle Ink is ready to use as supplied, even with the addition of solvent to thin the Ink, the curing properties remain the same. The best properties for most applications result when cured for 3 to 5 minutes at 110°C. Excellent properties are also obtained on a variety of substrates by curing at temperatures ranging from 50° to 175°, manufacturers' ink info can be found in the Appendix.



(a) (b)

Figure 04.9 Ink preparation (a), ink thinning preparation with scale and solvent (Diethylene Glycol), (b) ink dil 15%. Ink viscosity after dilution still had a high viscosity level due to the Polyurathane that it contains, however, it was thin enough to be printed with a 200 wire count mesh (mesh info ,Section 2.3.1). Photos taken with Apple Dual 12MP Ultra Wide camera.

Alfa Aesar Silver Conductive Ink Properties	Values
Viscosity (cps)	17,000 – 32,000
Silver content	64.0%
Sheet resistivity	<15 mOhm/square, 25 micron
Surface Temperature Range	-55 to 200
Curing Condition	Forced air curing, 5 minutes, 130°C (optimal)
Clean up and thinning	Carbitol Acetate (Diethylene glycol monoethyl ether acetate)

Table 04.4 Characteristic properties. Conductive ink(Silver conductive ink- 45661 Alfa Aesar)

Experiment 2 CA, Sigma Aldrich Silver conductive ink and textiles

<u>Ink vs solvent ratio</u>

Using Sigma Aldrich Silver nanoparticles ink. This ink was ready to use, and no thinning was needed. The viscosity is lower than the screen-printing ink this should be in the range of 10 cps, this is due to the inkjet printing process, were the printer needs to create single drops that pass through the nozzles on the print head (Report, 2016).

<u>Curing</u>

The curing process was followed as the manufacturer suggested, 150°C for 30min in an oven box. The samples were attached to a paper sheet to keep them straight and prevent any overlapping while curing with multiple samples inside the oven, manufacturers' ink info can be found in the Appendix.

Sigma Aldrich - Silver Dispersion Ink	Values
Viscosity (cps)	10-28
Particle size	≤50 nm
Concentration	30-35 wt. % in triethylene glycol monomethyl ether
Spec. resistivity	11 μΩ-cm
Surface tension	35-40 dyn/cm
Density	1.45 g/mL±0.05 g/mL at 25 °C
Curing Condition	150°C - 30min

Table 04.5 Characteristic properties. Conductive ink (Silver dispersion conductive ink 736465, Sigma Aldrich)

Experiment 3 CA, Sigma Aldrich ink and Scotchgard pre-treated textiles

Pre-treatment application

As previously discussed, when printing textiles using the Inkjet printing process, it is recommended to use pre-treatments to avoid bleeding and to get a crisp print with high resolution. Therefore, Scotchgard pre-treatment was applied to the six textile substrates in order to test and compare the interaction between treated and pre-treated textiles. This experiment was only performed with the Sigma Aldrich ink since it is the one that could require the Scotchgard pre-treatment for a better print result.

Curing

The curing process was the same as the previous experiment, following the manufacturer suggestions, 150°C for 30min in an oven box, manufacturers' information can be found in the Appendix.

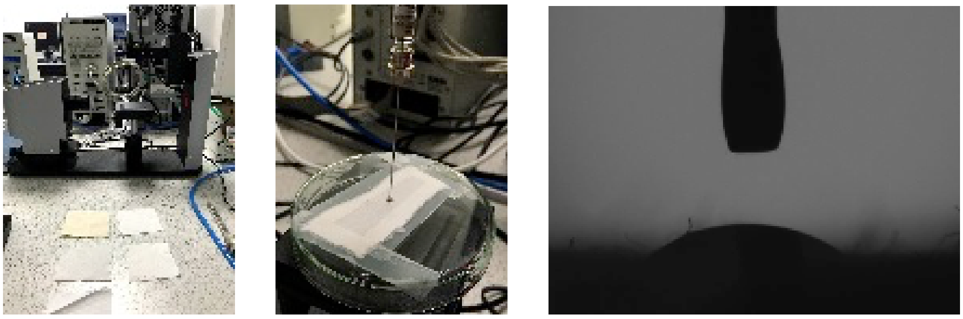
CA Process

The samples were kept on a pre-conditioned room to maintain its properties; afterward they were taken to the lab, where small samples of 5x2 cm fig. 04.10(a) were created to place under the petri dish. The petri dish is needed because the substrate is too thin and malleable, the purpose of using the Petri as a tool is to help the sample to stay in place and flat, so the drop can make contact on an even way and the measurements can be accurate and reliable.

Afterward, with high delicacy a drop is push through the burette until it drops and makes contact with the substrate fig. 04.10(b) and contact with the substrate, that is when the time starts running and the Goniometer starts measuring the contact angle. For this experiment a 60 seconds test was performed 3 times per sample. On this length of time an average of 700 frames fig. 04.10(c) and measurements are taken, creating a mean on the left and right angle.

4.5 Results and Discussion

The purpose of the Contact Angle experiment was to understand the interaction of the six different textile substrates and the conductive ink. Each textile sample had a distinct surface and pore size, which is directly related to the absorption properties. Therefore, it was expected that the interaction between ink and textile in the knitted structures was going to be complete absorption. This assumption was based on the analysis of the pores and their size. However, due to the properties that each fabric possesses, only the polyester fabric followed these assumptions.



(a) (b) (c)

Figure 04.10 Ink preparation **(a)** textile samples prepared for testing, **(b)** drop Formation and contact with the substrate, **(c)** Image recorded where the contact angle is measured. Photos taken with Apple Dual 12MP Ultra Wide camera and Goniometer software camera.

Ink vs Physical and Mechanical Properties

Even though there were only two variations of textile structures (plain weave and weft knit), they all look different under the microscope. However, under the naked eye, the differences are barely noticeable. The images taken with the Digital Microscope showed that the knitted fabrics had bigger pores than the woven textiles, particulary those made of polyester and bamboo. The woven fabrics made of these same fibres had a tight weave, and the pores were barely visible fig. 04.4. Having these images and each fibre's structure and fibre content properties served to develop a deeper understanding of what to expect from the following experiments table 04.2. This analysis of fabrics helped to address the challenges of printing on such porous materials.

Ink best performance ratio

After studying each textile sample's physical and performance properties, the experimentation to achieve the best performance ratio of ink vs solvent for screen printing was performed. For Inkjet printing the ink/solvent ratio was not varied. The reason behind only diluting the ink for screen printing was that the screen printing gives more freedom to the pastes/inks that can be used. This freedom is due to the nature of the screen, a fine mesh that allows ink to go through it to transfer a design. In screen printing, the mesh can have a tight or open weave; it all depends on the paste/ink that will be used, see Section 2.5.1 for more details. However, the ink used for Inkjet printing did not need this experimentation since the manufacturers (Sigma Aldrich) have created the best combination of ink vs solvent to print without clogging the printer nozzles.

The different ink vs solvent ratios tested were as follows: 5% ,10%, 15% 20%. The results of the ink vs solvent ratio tests showed that the perfect ratio for printing was a 15% ratio dilution. This ratio has enough viscosity to be used for contact angle testing. The syringe used was able to push it out without problems; however, it was not as thin as water. The thickness of the ink helped to create perfect droplets for the contact angle analysis.

CA Alfa Aesar Silver Nanoparticles Ink (for Screen printing)

To measure the CA, the lens of the camera on the Goniometer was calibrated to focus on the drop. As expected, some of the substrates (mainly the natural fibres due to the short staples they are made from) were difficult to focus on since the camera was focusing on the loose fibres of the surface. This means that short staple yarns are presented in the surface, affecting the smoothness of the surface.

The measurement result of the CA for the screen printing ink showed the contact angle and the absorption time of the conductive ink for each textile. The absorption time was measured in a 60 second frame, which was determined for all the experiments. Figure 04.11 shows how the ink sits on the textile substrates before being absorbed, and this is also represented on fig. 04.12. In the majority of substrates, the ink was never fully absorbed; it was thick enough to stay on the surface but also to be absorbed enough to cover most of the surface fibres, as discussed in the literature Section 2.3, there are different types of CA, in this case the inks all presented an excellent wetting for several seconds. However, as mentioned before, it was also essential for some of the ink to be absorbed to maintain the connection between flakes and, therefore the conductance.

However, from the previous structure analysis of the fabrics, it was expected that the textiles with bigger pores would present a quicker and higher (if not entire) absorption of the ink. Not only could the structure affect the results, but also the fibres due to their water retention. The hypothesis that an increased pore size led to an increase in absorption was correct. The knitted polyester fabric absorbed the inks so quickly that the Goniometer was not able to record any data in relation to the CA or absorption time.

In contrast to the knitted polyester results, knitted and woven cotton were also expected to have a high absorption of ink due to its 45% water retention performance. However, surprisingly both the knitted and woven fabrics had an outstanding performance, excellent absorption but not a complete absorption, leaving enough ink on the surface and absorbing enough to help maintain the conductance.

Graph 04.12 shows Time[s] and Contact Angle mean in the X and Y-axis. In this graph we can see the time of absorption for each sample. It is quite evident that most of the substrates absorbed the ink in the same range of time. However, the results also show that the ink can sit on the textile as in the case of Woven Bamboo and Woven Polyester and not be completely absorbed. The ink can be absorbed as soon as it contacts the textile, as shown with the Knitted Polyester sample fig. 04.13. These differences in absorption are related to the fibre mechanical and physical properties and the textile structure mentioned before in Section 4.1.3, table 4.1 and 4.2. The main properties that affect the absorption were the structure (physical) and the water retention of each fibre (mechanical). It was expected to see a greater absorption on the knitted fabrics due to their high number of pores between the threads. Surprisingly, the knitted cotton and knitted bamboo, even though they absorbed a high amount of ink, retained a high amount of surface covered with it. This result indicates that there is a strong possibility of there being a homogenous print with silver flakes interacting with each other to produce high conductance. The graphic result for each contact angle in fig. 04.11 reveals the interaction between fabric and ink.

It is essential to mention that the textile samples did not have any pre-treatment. However, it is well known that for Inkjet printing, the fabrics need a pre-treatment. Therefore, in addition to the experiments with the fabrics in their natural state, a pre-treatment with Scotchgard was added to the textiles, and the CA was measured using the Sigma Aldrich Ink (ink used for Inkjet printing). The results improved, and the ink was able to stay on the surface for a two of seconds. However, it was still completely absorbed by the fabric, and there was some ink bleeding present.

The new ink formulation proved to have a suitable combination since it is thin enough to go through the screen without clogging it and printing a crisp design and printed without any bleeding. Keeping as much material on the surface but being absorbed simultaneously. It is also thin enough to go through the screen without clogging it and printing a crisp design. The absorption of the ink is significant because, as mentioned before, textiles are porous materials. If the ink is not absorbed enough, it can affect the conductance if the textiles are manipulated (bent, twisted, stretched etc.) by creating cracks on the print and ultimately breaking the conductive bonds between particles or flakes. However, if some of the ink is absorbed, the metallic particles can keep interacting with each other even when the fabrics are being manipulated.

This testing provided good information for the next set of experiments. The information recorded was useful to adjust the printing parameters and to take into account the complications that might be presented.

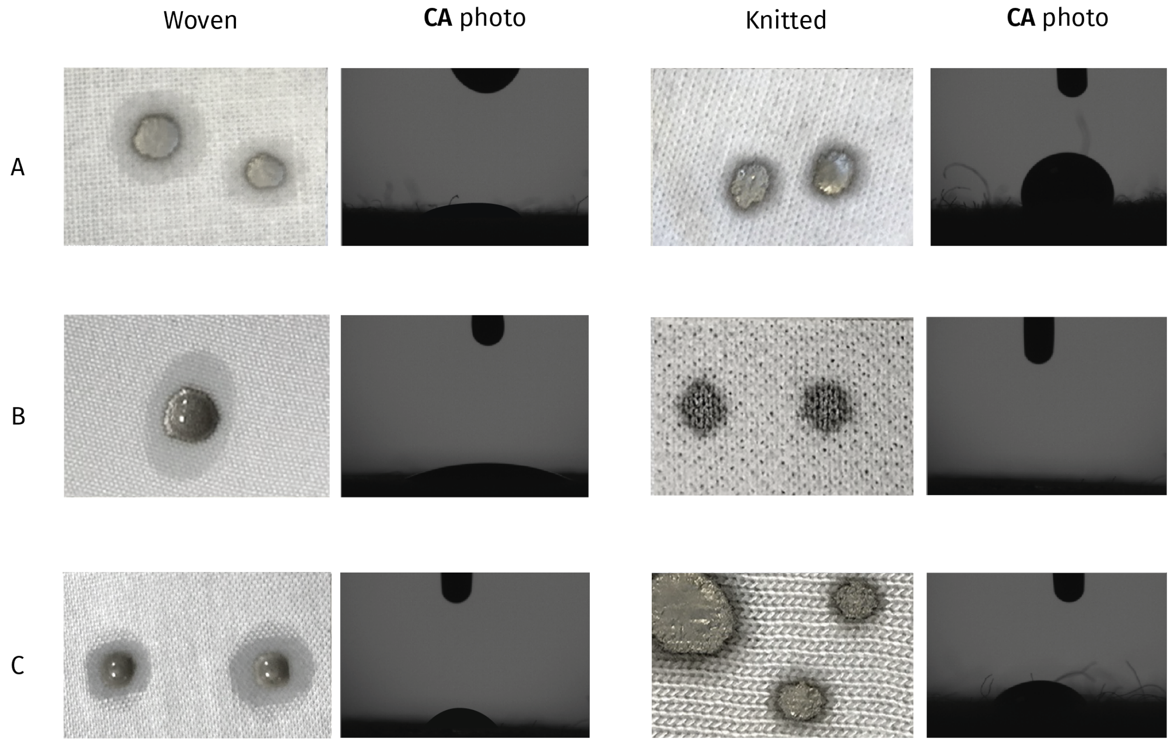


Figure 04.11 Alfa Aesar contact angle sample images. Bleeding and absorption is visible in most of the textiles, however, there is a clear drop on each sample, which means that the ink sticks to the fabric and contains some volume. This bleeding can also be due to the amount of ink that is being deposited with the syringe, when printing the ink is evenly distributed in small amounts. However, in the CA the drop has a larger size to analyse properly the materials. Knitted polyester is the only sample that absorbed 100% of the ink, which is related to the open knit structure that the textile sample has. Photos taken with Apple Dual 12MP Ultra Wide camera and Goniometer software camera. **A** Cotton, **B** Polyester, **C** Bamboo.

CA Sigma Aldrich Silver ink (for Inkjet printing)

All the fabrics instantly absorbed the Sigma Aldrich ink in comparison to the Alfa Aesar ink. This ink was completely absorbed, but it also presented a large amount of ink bleeding. The CA was measured following the same parameters as the CA for Alfa Aesar, 60-second frame. The Sigma ink was absorbed in a time frame of 0-10s (max). The Woven fabrics presented the largest area of bleeding, specifically the polyester and bamboo samples. The sample that presented the most bleeding was the woven bamboo. This is related to the hydrophilic and hydrophobic characteristics of the bamboo; The fabric is trying to absorb and at the same time pushing the ink to the surface. This result is also related to the Sigma A. ink composition (oily and the matrix was different from the Alfa Aesar) which makes it travel along the threads without difficulty. This ink travelling through the threads will reduce the interaction of silver particles and, therefore, affect the conductivity. The fabric with the second worst performance (more ink absorption) was the woven polyester. However, this ink shows different behaviour, maintaining ink in the centre and lighter bleeding on the circumference. This means that the ink particles stayed more in the centre and did not travel through all the threads, unlike the bamboo. The knitted samples

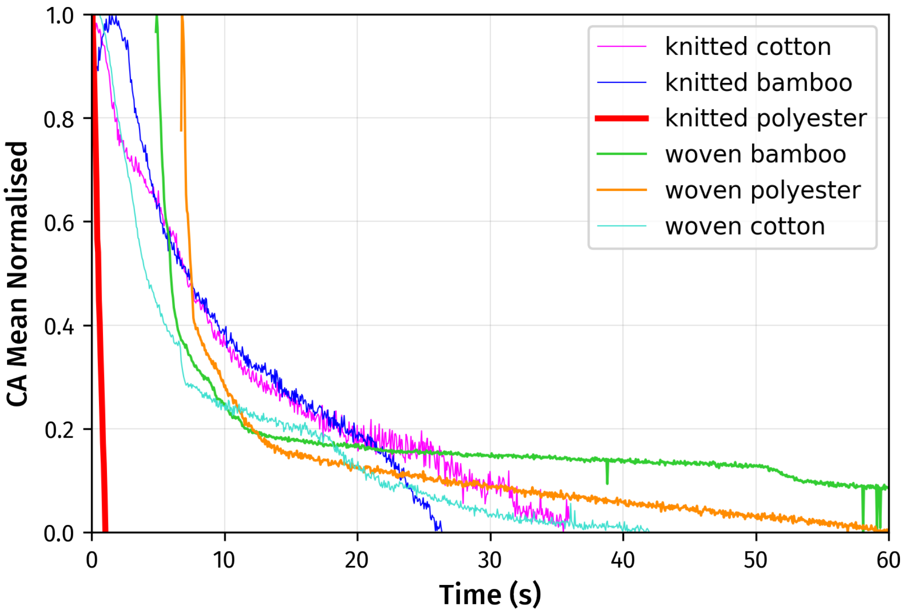


Figure 04.12 The graph shows the time of absorption for each textile sample. All the fabrics show that the ink stayed on the surface for a period between 1-10 seconds before being absorbed, however, the Knitted Polyester was instantly absorbed, and this directly relates to the structure of the fabric and the large pores that it has.

presented the same characteristics as the CA with Alfa Aesar; even though they present some bleeding, it is less than the woven fabrics. The fabric that kept the ink in place with the best performance was the knitted bamboo fig. 04.13, fig. 04.14. Overall, these results provide important insights into understanding the interaction between ink and the different textile substrates. It is clear that the Alfa Aesar conductive ink has better performance, even though there is some bleeding present. This is related to the solvent that the ink contains, but the ink drop maintains its shape. The Inkjet printing ink presented a large portion of ink bleeding.

This testing provided good information for the next set of experiments. The information recorded was useful to adjust the printing parameters and to take in account the complications that might be presented.

Overall, the ink used for Inkjet printing did not stay on the surface of the textiles due to the composition of the ink and the size of the particles. These nanoparticles used for Inket printing tend to be smaller since they need to go through the nozzles to be printed. The difference between structures was an important finding. Even though the knitted textiles' physical properties showed that these samples had larger pores, surprisingly, they were the ones that had less bleeding and that kept the ink on the surface.

The following printing experiment will be performed with both inks and all the textile substrates. However, it is expected to have better results with less bleeding with the screen printing technique using the Alfa Aesar ink, than with Sigma Aldrich ink for Inkjet ink.

Furthermore, with the completion of the material characterisation, the research continued to the next phase; printing with two different techniques: Inkjet Printing and Manual Screen Printing. The following chapters explore and analyse printing parameters to find the most suitable combination for a conductive printed track.

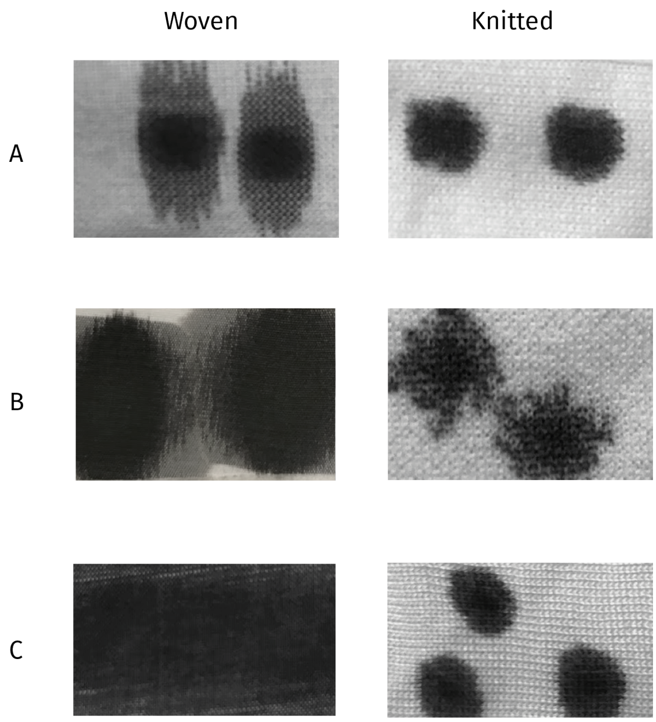


Figure 04.13 Contact Angle comparison with Sigma Aldrich Ink. Large amount of ink bleeding in woven textiles. Knitted bamboo and knitted cotton had less bleeding in comparison to the woven bamboo and polyester. Photos taken with Apple Dual 12MP Ultra Wide camera.
A Cotton, **B** Polyester, **C** Bamboo Photos taken with Apple Dual 12MP Ultra Wide camera.

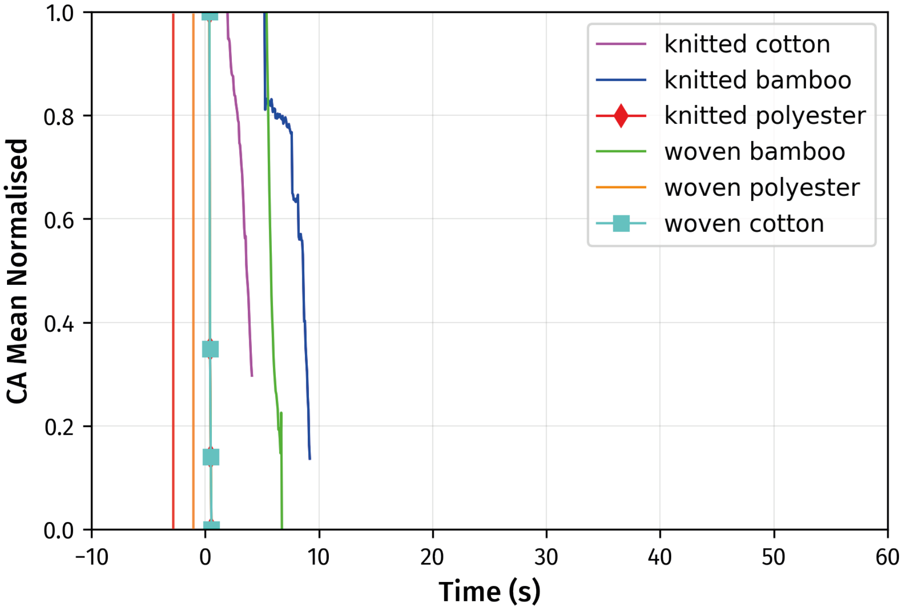


Figure 04.14 The graph demonstrates how the ink was instantly absorbed by the textiles. In comparison to the Alfa Aesar Ink, the droplet did not stay on the surface at any moment. All the tests showed that in less than 10 seconds the ink was completely absorbed

05

Inkjet Printing

"Inkjet is increasingly seen as an evolutionary driver of printing techniques and such evolution enables the printing of increasingly complex materials. The contactless nature of inkjet opens up myriad new markets such as glass, ceramics, tiles, even printed circuit-boards." (Thienard, Régis 2019)

Inkjet printing is one of the most popular digital printing techniques due to its low cost and reduction of material wastage by using only the material needed for each print (Singh et al., 2010). However, Inkjet printing will never be as affordable as screen printing. This printing technique offers high resolution, ranging from 100 dpi to 5000 dpi and a print thickness ranging from 50µm to 10 mm. Additionally, it provides freedom of design, rapid prototyping and mass customization (Kastner et al., 2017) (Ando and Baglio, 2013). Not only that, but it is also a contactless method (Christie, 2003). There is no contact between the printhead and the substrate during the printing process, thanks to the droplet system (Inkjet printing method, Section 2.3.2). Due to these flexible and technological properties, Inkjet has also become very popular in research related to printed electronics (Rida et al., 2009); (Kao et al., 2019). However, Inkjet presents challenges that to date have not been thoroughly addressed. For example, printing tracks with a low volume of resistivity using inks with low viscosity due to the Inkjet process has been hard to achieve (Bidoki et al., 2005).

5.1 Objective

The objective of the inkjet printing experimentation was to explore and determine the most suitable design specifications and printing parameters to produce a homogenous conductive printed track, using the Fujifilm Dimatix Materials Printer, DMP-2850 with Sigma-Aldrich, silver dispersion 736465 ink.

The following list of tests focuses on evaluating the printing parameteres from the inkjet printer, and how these affect the final print:

- Create several track designs, similar to the ones presented in the screen printing chapter, to evaluate the printing process.

- Analyse the impact that each printing parameter (Table 05.1) has on the final print.

- Analyse print homogeneity using Digital Optical Microscope technique.

- Analyse the electrical performance of the print by measuring the electrical resistance of the printed samples.

5.2 Experiment

The Inkjet Printing experimentation follows the designed Methodology (Chapter 04). Once the materials were characterised and the interaction between the different textiles and inks was analysed, the research moved forward to the Prescriptive study III fig. 05.1.

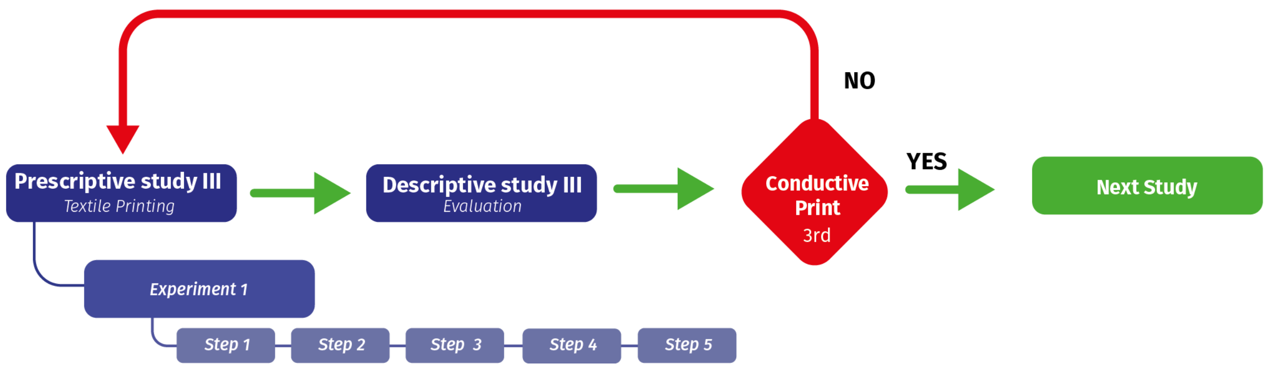


Figure 05.1 Research Methodology, Prescriptive Study III

The printing process follows different phases due to the characteristics (porosity and structure) of the substrate that is being used. These phases started from a simple printed design to a complex design. Followed by the Descriptive study III (Evaluation) where the basic electrical performance (resistance measurement) was measured to move forward to a more complex design.

This experiment aims to define the optimal parameters to print silver ink using six different substrates. The substrate preparation process is akin to that presented in the screen printing experiments. However, since printing substrates using inkjet can require the use of a pre-treatment or coating, an additional experiment using treated substrates was conducted. The latter is to compare if significant enhancements can be obtained using the coating typically used in Inkjet printing. The ink used in these experiments was not diluted, i.e. it is used as recommended by the manufacturer, who developed the inks to be applied in this way (manufacturers' info can be found in the Appendix). This is in contrast with the previous screen printing experiment, where the ink was diluted to prevent screen cloggings by making it thinner.

Step 1 Textile Preparation

The substrates selected were prepared in a conditioned room at 20°C with a relative humidity of 65% (BS EN 20139:1992). These conditions ensure that the substrates' fibres do not have a significant amount of water within them during preparation. The latter can affect both the mechanical and physical performance of the print. The samples were kept inside the conditioned room for 48 hours prior to the printing experiment in accordance with BS EN 20139:1992. While the samples were in the conditioned room, they were trimmed to a size specification of 12 cm (weft/courses) x 6 cm (warp/wales) following the grainline, (grainline info can be found in Section 2.4).

Step 2 Equipment and Material Preparation

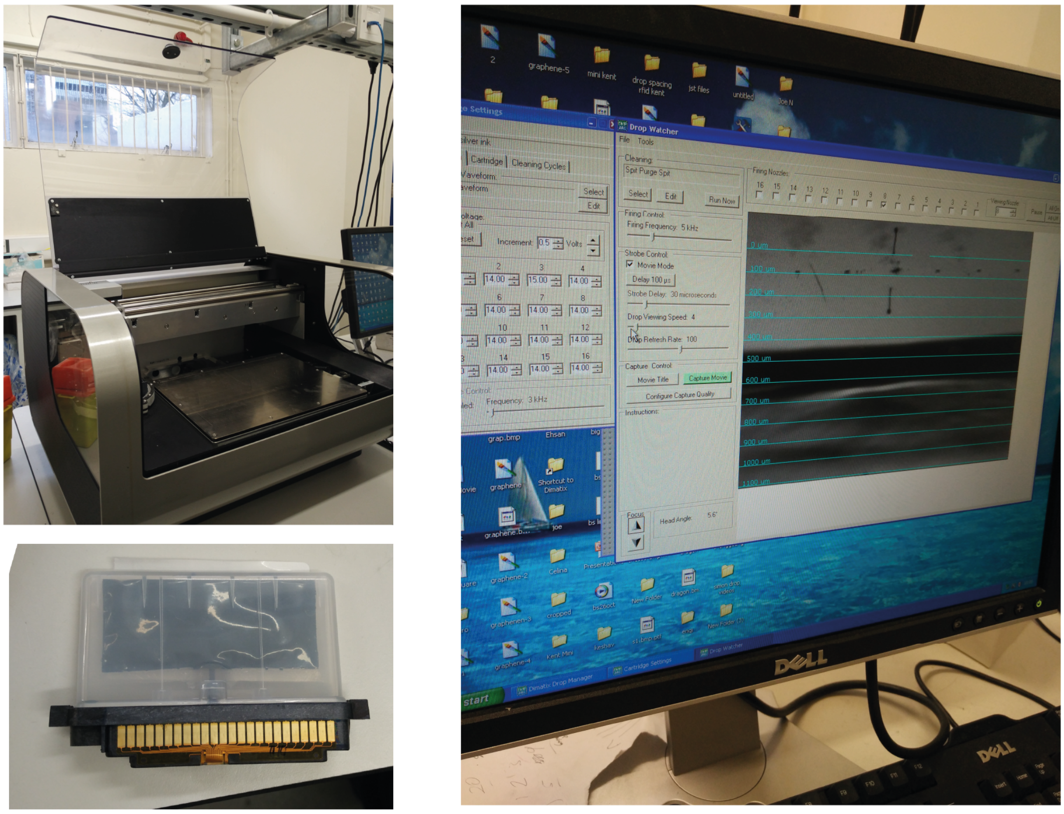
The main equipment used was a Dimatix (Fujifilm Dimatix Materials Printer, DMP-2850) Inkjet printer, due to its multiple printing functions and its piezoelectric Inkjet technology. The print design was drawn directly in the Dimatix proprietary software. The Dimatix parameters associated with the characteristics of the ink were configured according to the ink manufacturer's specification. The thickness of each substrate was measured to configure the printing setup properly. Without this measurement, the Dimatix can not estimate the height between the substrate and the printer cartridge. It is important to know the thickness of the substrate to avoid clashes between the cartridge and the substrate or the opposite effect where there is a significant gap between the substrate and cartridge. Furthermore, the parameters corresponding to the printing control were set based on a trial and error process to find the optimal configuration. Table 05.1 summarises the Dimatix parameters used for the present study.

Controllable Variables	Values	Uncontrolled Variables
Drop Spacing	5-10-15	Cartridge angle
Layers	1-2-3	Working Nozzles
Plate temperature	0°C & 30°C	

Table 05.1 Printing Variables for Inkjet printing.

a

b



c

Figure 05.2 **a** Dimatix Inkjet printer, **b** Ink Cartridge , **c** Drop watcher

Step 3 Printing

The samples were attached to the printing plate using masking tape to fix the substrate in place. Next, the zero coordinate of the print was manually defined for each sample. The Dimatix requires the definition of a starting point to ensure that the print will not go beyond the sample edges. Once the starting point is configured, the Dimatix starts the printing process. One important consideration to note is that between prints, one must clean the cartridge with alcohol and the printing plate. The cleaning of the printing plate is to prevent contamination between prints due to residual ink found in the plate.

Step 4 Drying and Curing

Once the printing process is complete, the samples need to undergo a sintering process. The sintering process removes any residual solvent, thus, improving adhesion and conductance. The latter is due to the non-conductive nature of the solvent. Therefore, by removing the solvent from the surface, the silver ink particles can improve their bonding with each other. The process takes place in a forced-air oven, thus, to ensure the physical integrity of the samples, each substrate was placed on and fixed to a thick paper sheet. The samples were cured following the manufacturer's specifications of 150°C for 30 minutes.

Step 5 Performance analysis

After the curing process, each sample was initially analysed using a simple conductance test with a digital multimeter. The results from these initial tests are to determine the success of the print. Moreover, these results informed the researcher if any printing parameters had to be modified. After the conductance test, the samples were studied under the microscope to have a clearer picture of the ink penetration and travelling within the fibres. The microscope images further explain any performance drawbacks or improvements of the printing parameters.

5.3 Results & Discussion

The Inkjet printing experiment was focused on testing different variables to find the most suitable combination for printing on textile substrates. This experiment was informed by the results of the Material Characterisation analysis, where the interaction between ink and substrate was studied. These results presented a high amount of bleeding with and without Scotchgard pre-treatment. However, it was decided to continue with the printing Experiment, test the different variables and make a comparison between both printing techniques. The first set of prints on untreated substrates was performed, but this showed a large amount of bleeding, just as the CA had previously informed. The objective of printing on non-treated textile was to maintain the substrates under the same conditions and compare the performance of both inkjet and screen printing techniques. Although that was the objective, it was also decided to test the Inkjet printing method with pre-teated substrates. The results improved slightly, it was possible to perform a better analysis.

The tested parameters were the drop spacing, number of layers and plate temperature; these parameters can be controlled. However, although the Inkjet printing technique is automatised, some parameters can not be controlled such as the working nozzles. Their performance depends on the quality of the printhead, and how clean the nozzles are. To avoid any clogging of the nozzles, the printhead was cleaned after and before every print test.

Variation of Layers

The parameter testing started using the smaller values, and it moved forward until reaching the higher parameters set. The samples were positioned on the printing plate, and then the print action was performed. Inkjet printing works by depositing small size drops very close to each other, and this process can be monitored using the fiducial camera (drop watcher). When the printing was starting, it appeared that the ink was staying in place; however, after a few seconds, bleeding was present. The bleeding happened with all the range of layers (1 - 2 - 3). The more ink it was deposited, the more it was travelling along the threads. The prints using only one layer presented light colour (the ink has a dark brown natural colour) and less bleeding. However, on these samples, there were visible spots that were not covered with ink. These samples also presented 0 conductance. Therefore, it was decided to move on to two layers of printing.

Using two layers improved the colour appearance, which meant that more particles were being deposited and kept in place. However, more bleeding was present when the second layer was applied. The conductance test was once again performed, and the results continue to be negative. This is because the particles were highly distributed, and they were not making any contact with each other to maintain the print conductance.

The experimentation moved forward to test three layers; at this point, bleeding was highly present, and the substrate started showing some random ink spotting close to the printed track as shown in fig. 05.3, knitted bamboo. The substrate was saturated with ink where the track was supposed to be, and the fibres were not retaining any silver particles. Surprisingly, the sample that showed better results was the knitted cotton, fig. 05.3. Due to its natural properties of water retention, this substrate could retain the ink in place, and a dark and defined printed track was visible to the naked eye.

The Inkjet printing samples show a large amount of bleeding in most samples, as shown in fig. 05.3, mainly in the woven structures. In the woven polyester figure **c** the ink can be seen travelling through the threads but mainly on the twisted threads. This is due to the wicking effect of the threads and the capillary forces (Wang et al., 2008). The woven bamboo had intense bleeding, and the textile substrate was completely covered with ink. The woven cotton sample was the only substrate where the printed track could be recognised, in contrast to the two other woven substrates. However, none of the prints were conductive.

Variation of drop Spacing

The Variation in drop spacing helped to reduce the bleeding but only for the first few seconds; however, the best combination of drop spacing was 10. The spacing from 5-8 meant that more drops were needed to cover the design area. Therefore, more ink was being deposited, and more bleeding was present. With spacing from 12-15, spots of ink were visible, and even some lines could be seen the drops print following a line, and eventually, all these printed lines create the desired design.

Variation of Printing Plate Temperature

The printing plate is usually set to a temperature ranging from 25°C to 35°C. The Experiment tested printing on hot and cold plates. However, there was no difference found between the two. The printing process was the same. The ink stayed in place for two seconds, and then it was absorbed and distributed through the textile.

The aim of this chapter was to print tracks that were electrically conductive, with different printed designs. However, it was impossible to continue the experimentation due to a large number of negative results and not being able to achieve a conductive printed track. The experimentation with Scotchgard did not improve the adherence of silver nanoparticles nor the conductance. Therefore, it was decided not to move forward to Inkjet printing different tracks and focus on the Screen Printing process, where the samples showed better interaction results between textile and conductive ink.

The researcher acknowledges that while the Inkjet printing process failed, different coatings and pre-treatments can be applied to a textile substrate to improve the results of the Inkjet printing process. These include flexible Polyurethane coating, creating a flat surface on the textile and avoiding any ink absorption from the textile that could cause bleeding. The exploration of other materials is also advised since this research only focused on three main substrates.

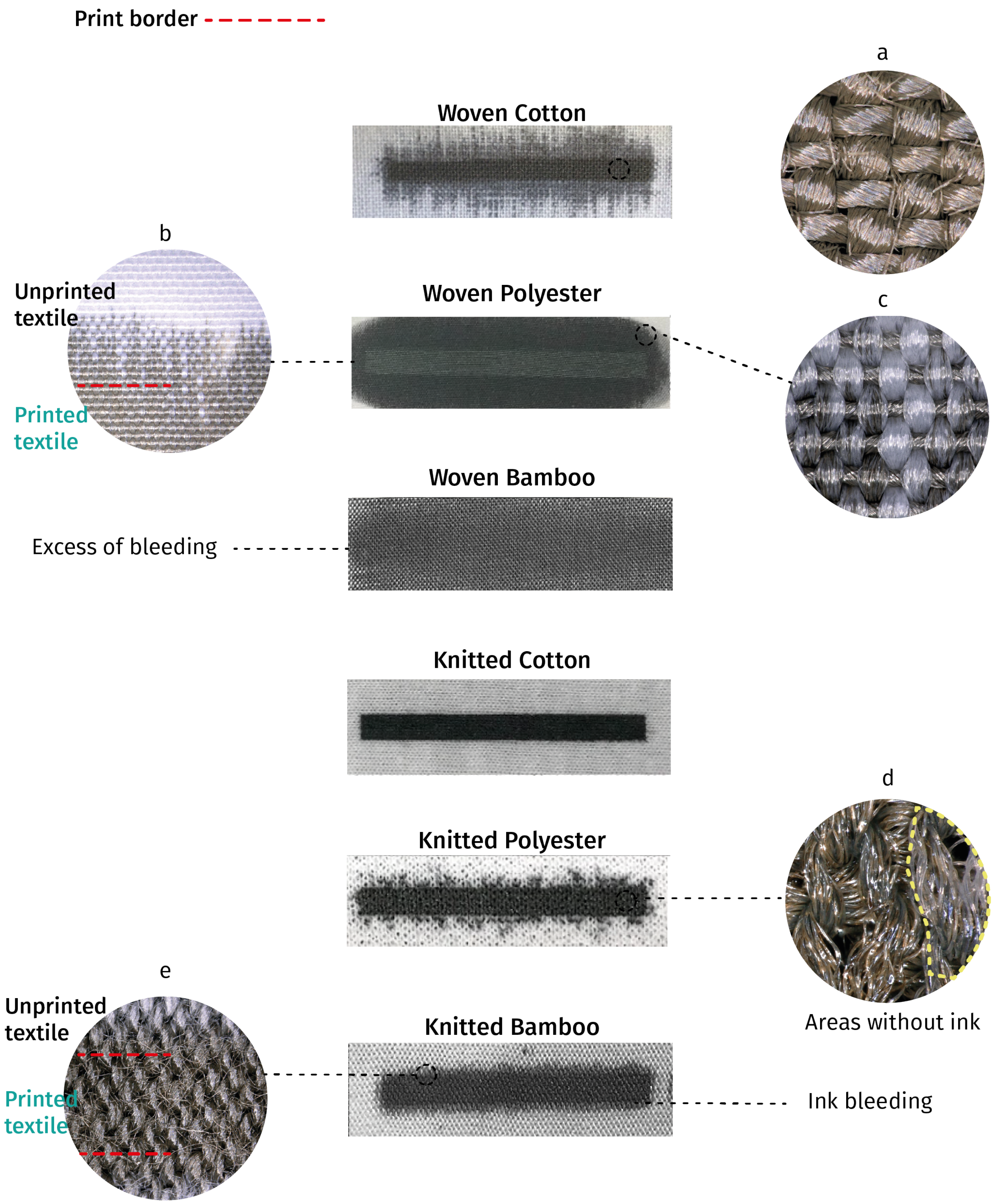


Figure 05.3 Inkjet printing, Experiment 1 results. Photos taken with Apple Dual 12MP Ultra Wide camera and Digital Optical Microscope.

06 Screen Printing

"Textiles have a huge part to play in the reinvention of the print industry. What we print onto is equally important to the technology that facilitates the decorative surface printed product" Debbie McKeegan, 2020 - Textile Designer "

Screen printing is one of the most popular printing techniques. The process can be applied to almost any material, ranging from polymers to metals, wood, glass, paper and textiles (Kazani et al., 2012). This technique is also highly popular in other industries, such as printed press and electronics. Thanks to its accessibility, high design precision, and low cost, it is the oldest technique used for printing electronics fig 06.1 (Izdebska, 2015). Screen printing can be either a manual process, or automated and industrialised, thus making it cost-efficient for commercial and retail applications. In recent years, there has been an increase in interest in mixing electronics and textiles using different printing techniques, including screen printing, to create flexible and lightweight e-textiles. However, as mentioned in the previous chapter, textiles are highly porous materials which create an uneven surface for printing conductive inks (Kazani et al., 2012). Printed electronics are commonly printed on polycarbonate (PC), polyethylene terephthalate (PET), polyamide (PI), and polyethylene (PE) among other man-made non-porous substrates.

Despite the importance and long history of screen printing, one of the greatest challenges still in existence, is to achieve a crisp and continuous print on textile materials using conductive inks. Whilst some research has been carried out on printed e-textiles.

Screen Printing

There is still a lack of scientific understanding of the large range of fibres and structures that could be used for printed e-textiles and their end use.

This research examines the way in which e-textiles can be made using manual screen printing while at the same time focusing on the fibre selection. Previous research has focused mainly on synthetic fibres like polyester and nylon. However, garments are also created with natural fibres, such as cotton, and most recently with bamboo. The use of natural fibres has increased not only to improve the sustainability of the garment industry, but also because these natural fibres offer a wide range of performance properties and comfort for the end user, as presented in Chapter 04.

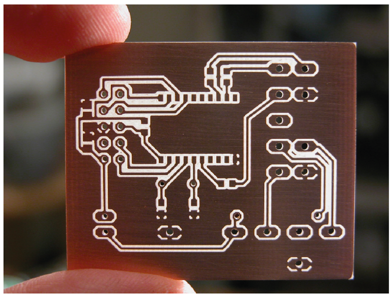


Figure 06.1 Example of screen printed circuit board (PCB)

6.1 Objective

The objective of the printing experimentation was to explore and determine the most suitable printing combination of design specifications and printing parameters to produce a homogenous conductive printed track in screen printing. These will be used to establish the ones that would be most suitable to ensure the most effective printed track.

The objective will be accomplished by addressing the following tests:

- Design of printed tracks with different widths to understand the limitations of the printing method.

- Asses the weight of each printing variable by printing multiple tracks using different line widths and multiple number of strokes on each textile substrate.

- Analyse the print homogeneity by examining the ink distribution and particle interaction under SEM and Digital Optical Microscope.

- Evaluate the conductance of printed tracks through a conductance test via a Digital Multimeter (DMM).

6.2 Experiment

Following the steps from the designed Methodology fig. 06.2 for this research from Chapter 03, the research continued to the Prescriptive study III, printing experimentation once the materials were characterised, and the interaction between the different textiles and inks was analysed. The printing process follows three different

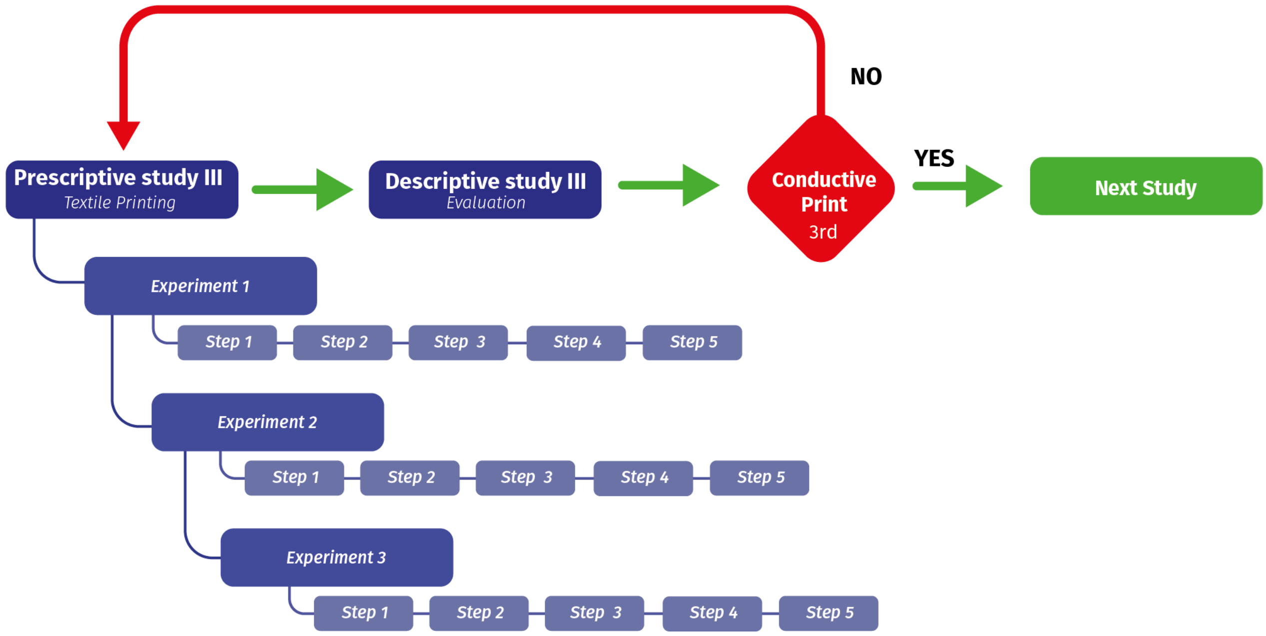


Figure 06.2 Research Methodology, Prescriptive Study III

sequential Experiments due to the characteristics (porosity, structure and fibre content) of the substrate that is being used. Experiment 1 starts with printing a simple design of a straight line with different widths. Experiment 2, a more complex design of a line with curves is printed, followed in Experiment 3 by a printed circuit that will be connected further on to electrical components such as batteries, sensors or LEDs.

Every printing Experiment followed the Descriptive study III (Evaluation) step with a decision point. The basic electrical performance test, resistance test, was measured in order to move to a more complex design. This measurement of resistance was performed to evaluate the conductance of each printed substrate, which helped to understand which combinations of printing variables were the most successful and enabled movement to the next printing Experiment.

The printing process not only involves the actions of printing, curing and testing, Section 2.3.1. The textile samples need to be prepared (kept under specific conditions), as well as the material that was used (prepare the ink, printing table and printing materials). The three printing Experiments follow 5 different, reproducible steps fig. 06.7.

6.2.1 Printing Experiments

The printing experimentation comprises three different experiments in order to understand the limitations of printing and to address these before printing more complex designs that involve circuits. Starting with Experiment 1, printing a simple straight line with a variation of 3 different widths, this Experiment will inform the two remaining Experiments, setting up the most suitable parameters. Moving forward to Experiment 2, which is printing a line with curves to see the variation on resistance if there is any, and finishing with Experiment 3 printing a design that can fit electric components, mixing straight and curve lines fig.06.3.

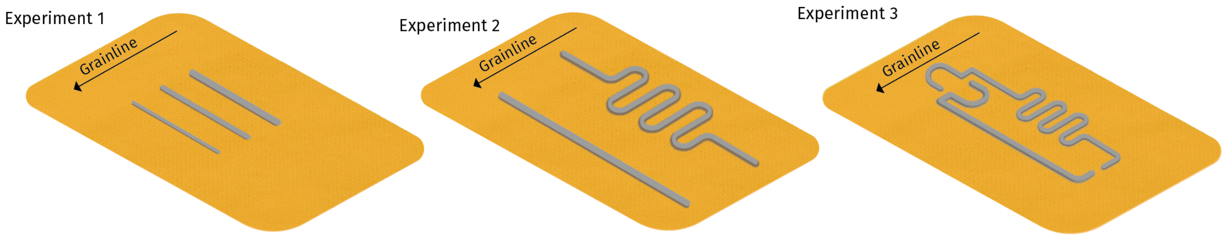


Figure 06.3 Experiment 1- 50mm x 3.44, 2.44 & 1.44. Experiment 2 - 150mm , Experiment 3 - 150mm.

Experiment 1

The purpose of Experiment 1 was to test all the different variables and find the best combination with respect to crispness in the design and electric performance. The constant variables during this printing Experiment were the number of strokes per print and the width of the print. For this experiment, the design selection was three prints with a basic line design; same length (50mm), different widths (1.44mm, 2.44mm, 3.44mm) fig.06.4. The width was defined based on the size of the electrical components that were going to be used. The 3.44mm width fits perfectly with most of the Lilypad sensor collection and other commercial sensors such as resistors. It is important to have these considerations to allow the sensors to be set in place without any complications. Moreover, it is crucial to maintain the conductance and connection through the print and sensors. The prints were measured with a Mitutoyo Digital Caliper that can measure up to 0.01 mm.

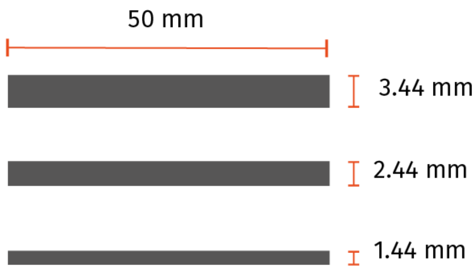


Figure 06.4 Experiment 1, line measurments

The two remaining designs (2.44mm and 1.44mm) were chosen to compare the performance with thinner lines. Less conductive material means less conductance, Section 2.5. Therefore, it was important to compare the performance of these different prints in terms of visual assessment and electric performance. Furthermore, each design was printed six times on each textile substrate and tested following the experiment methodology. This first Experiment served to inform the second Experiment of which printing parameters to use.

Experiment 2

Once the best combination was defined by the printing Experiment1, the experiment moved forward to Experiment 2. This Experiment aimed to print a more complex design on the textile substrate. The design change was to assess the electric performance and compare the simple straight lines against curved lines fig. 06.5. In addition, circuit design requires the use of angled lines and curves, Section 2.2.1. Thus, it was essential

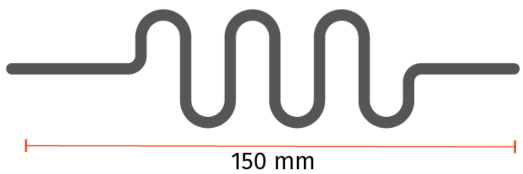


Figure 06.5 Experiment 2, line measurements

to test a curved printed line on each substrate. This Experiment informed about the performance of curved prints, and the experimentation moved forward to Experiment 3.

Experiment 3

Experiment 3 is a mix of Experiments 1 and 2; straight lines with curves. The difference with this Experiment is that the print was designed with specific measurements to incorporate specific electric components such as a battery holder and a LED, both from the Lilypad collection fig. 06.6, more information can be found in Section 8.2. The print was designed following the principles of electric circuits. This is to prevent any electric accident or damage to the components and obtain the best electric performance.

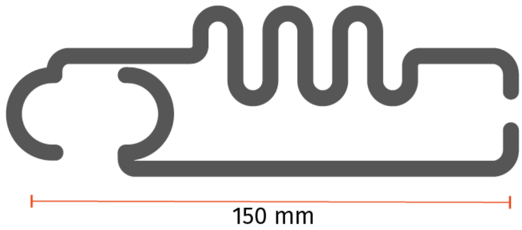


Figure 06.6 Experiment 3, line measurements

6.2.2 Printing Steps

Figure 06.7 These printing steps were performed in the three discussed experiments. Each step follows specif standards to achieve a replicable conductive print.

Step 1 Textile preparation

The six textile samples were held in a room with a relative humidity of 65% and standard temperature atmosphere of 20°C as advised by British Standard,BS EN 20139:1992 - Standard atmospheres for conditioning and testing. These conditions ensured that the moisture absorptions was minimised and the possibility possibility of damaging the print due to these environmental factors. The excess of moisture in a sample can affect the structure and the performance of the textile. In this specific research, the quantity of moisture on the substrate can affect the conductance of the print (Xu and Cui, 2016). Not only that, but it can also affect the adherence of the ink to the textile (Fasolt et al., 2017). This textile preparation was performed before printing (at least 48 hours), during the sample printing preparation (cutting and labelling each sample) and after the printing and curing were performed. The resistance testing was performed in the same conditioned room to keep the sample as stable as possible. The samples for printing the first Experiment were cut following the grainline size 12(weft / courses) x 6cm(warp / wales). For the second Experiment, the samples had a bigger size 20x 10cm, and for the third Experiment, the size, was 20x12 cm. The size of the samples was dictated by the size of the print design of each printing Experiment.

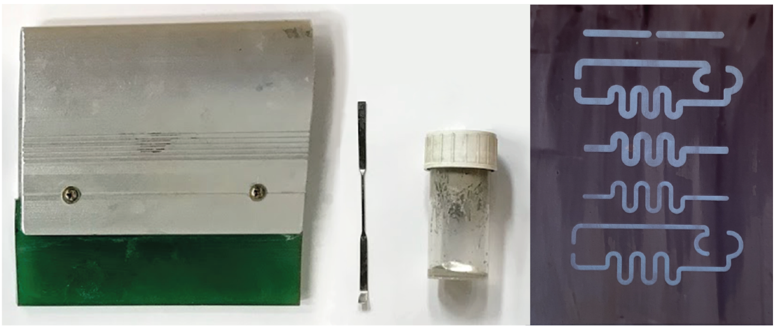
Step 2 Equipment and material preparation

The conductive ink that was used for screen printing contains strong solvents. Therefore, the lab had to have enough ventilation, and the researcher had to wear protective garments (gloves, coat, protective glasses, and facemask). The printing table was covered with a thick paper/cardboard surface to avoid any cross-contamination. This surface was also used to absorb any solvent excess or ink that could cause bleeding or unwanted stains on the substrate. The paper layer was attached to the printing table to prevent mispositioning of the screen or the textile sample.

Afterwards, the textile sample was placed on top of the paper and secured with tape in the corners, maintaining its shape without bending, stretching or warping the threads to achieve a crisp print.

Once the table was prepared, the ink and printing material was placed in the same space where the substrate had been prepared. The ink was kept under special room conditions with enough ventilation to keep the staff safe. Since the ink was prepared with the 15% ratio of solvent, it was necessary to stir it before using it to avoid any sedimentation of particles or solvent separation.

For printing, a rubber blade squeegee with an aluminum holder was used, along with a 200 wire per inch mesh, that was prepared and exposed as the literature advised, more information can be found in Section 2.3.1, with the different designs that needed to be printed. The designs were created using the software in Adobe Illustrator, then printed and finally transferred to the mesh. The printing station also included cotton pads and Diethylene Glycol to clean the conductive ink. Every instrument used had to be cleaned after every print to avoid any screen clogging or contamination that could affect the print results.



a b c d

Figure 06.8 **a** Rubber squeegee **b** Metal spatula **c** Diluted ink 15% **c** Ink **d** Exposed screen with different designs. Photos taken with Apple Dual 12MP Ultra Wide camera.

Step 3 Printing

Once the lab was prepared and the samples were ready to be printed, each design was printed on the substrates. As previously mentioned, the instruments and the screen had to be cleaned after every print to keep the mesh as clean as possible to prevent any stains or ink clogging on the following printed sample. However, this solvent is highly aggressive with the emulsion of the screen. Therefore, the screen had to be re-exposed several times to rule out the possibility of an uneven print. For the printing process, four strokes (layers) were tested for each design. Therefore, each printed line was printed with 1,2,3 and 4 strokes. This process was used in all the textile substrates. An example of the combinations is presentes on table. 06.1. This testing of strokes was to analyse how much ink the textiles were absorbing and how many strokes were needed to create a neat and crisp print. If only a few strokes were used, this will mean that less ink is being printed. However, too many strokes can cause bleeding, and screen clogging. This excess of ink can have the inverse effect, and instead of leaving the ink on top of the substrate, it can remove it.

Textile	1.44 line	2.44 Line	3.44 Line	1 Stroke	2 Strokes	3 Strokes	4 Strokes	5 Strokes
KB	X			X				
	X				X			
	X					X		
	X						X	
	X							X
		X		X				
		X			X			
		X				X		
		X					X	
		X						X
			X	X				
			X		X			
			X			X		
			X				X	
			X					X

Table 06.1 Example of experiment combination of parameters

Step 4 Drying and curing

After finishing the printing, it is important to cure the sample. This will achieve the sintering process, which also helps the conductance, adhesion and abrasion resistance, as previously explained in Section 4.3. The samples were left to dry for 10 minutes at room temperature before moving them from the table. Each sample was kept on its paper base layer and attached with tape to keep them flat during drying and curing. Afterwards, they were taken to the oven and placed inside for 5 min under 130°C. The oven used was a Forced Air oven. The temperature and time for curing is according to the manufacturers' guidance for curing methods for the Alfa Aesar 45661.

Step 5 Analysis

Once the curing was completed, the samples were extracted and taken to the Optical Microscope and SEM to analyse the quality of the print. Furthermore, the resistance test was performed to assess the prints' electric performance. This helped create the best combination of printing variables and move forward to the next printing Experiment. The Multimeter was used by placing one probe on each end of the print, just as fig.06.9 image (c), perpendicular to the sample (90°). This resistance was tested six times per sample to avoid any error, especially since the conductive material (ink) is under a porous substrate.

6.3 Results & Discussion

The first Experiment was focused on testing the different printing variables and finding the most suitable combination for printing. With the results from the previous chapter, this testing used the 15% diluted ink. The

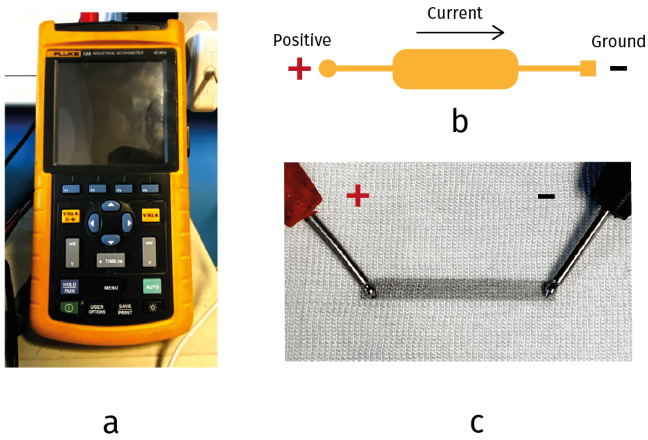


Figure 06.9 **a** Digital Multimeter **b** Current flow example to understand and replicate the arrangement for resistance testing **c** Print resistance test set-up with proves connected to the positive and ground ends.

samples were firstly analysed under Microscope and SEM, followed by the electrical performance testing using the multimeter.

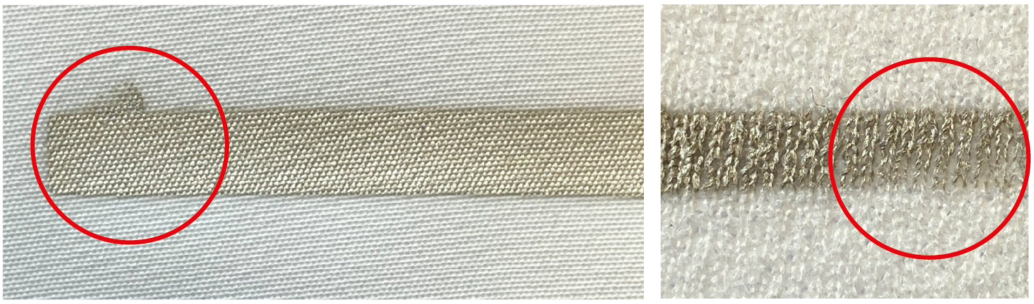
Experiment 1

The printing Experiment aim was to test different widths with different printing parameters. The three widths were printed and analysed, and the print width that presented the best electric performance was the 3.44mm sample. This is directly related to ohms law, formula can be found in Section 2.5; therefore, the print with more ink is the more conductive. However, it was necessary to test the other two widths to compare the performance between prints. Additionally, the 3.44 print was designed to fit with the electric components. For this reason, it was decided that the analysis would focus on the 3.44mm printed samples.

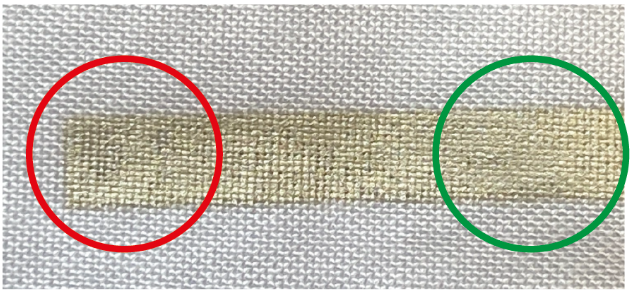
Finding the most suitable number of strokes

Firstly, the prints were analysed in relation to the combination of strokes; they were printed with a range from 1-6 strokes for each print. The visible results of this experiment showed that 1 or 2 strokes were not enough ink to cover the substrates evenly. Some spots were left without ink and some corners were missing. In addition, the ink presented a fading effect along the print, which is not an optimum result and means that the distribution of conductive particles is not even fig. 06.10 image **b**. Clearly, the amount of ink that was being deposited was not enough. This can affect the conductance due to the ink not being absorbed enough by the textile and missing the connection between particles. Afterwards, 3 strokes were tested, and this improved the quality of the print and the design. However, some spots were still visible to the naked eye, meaning that probably under the Microscope these would be even more visible. Subsequently, 4, 5 and 6 strokes were tested. The last two (5 and 6) started showing some bleeding. The corners did not look crisp enough, and the prints did not present an even surface, fig.06.10 image **a**. This is because the surface of the substrate became saturated, and instead of being able to take more ink with each stroke, it started to remove the ink it already had, fig. 06.10 image **c** and **d**. This also caused the mesh to show some clogging and bleeding on the sides, affecting the crispness of the print.

Undoubtedly, the best combination of print strokes with the squeegee was 4 strokes per print. These 4 strokes



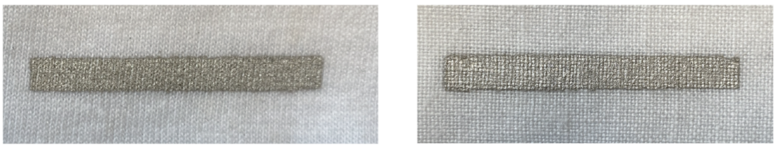
a b



c d

Figure 06.10 **a** 6 strokes example on woven polyester with bleeding, due to the excess of ink, and the corners are beginning to lose their angled shape.**b** 3 strokes showing fading on the print, affecting the design and conductance.**c** and **d** 6 strokes with a homogeneous print on the right side and missing ink on the left side due to saturation of the sample and clogging of the screen.

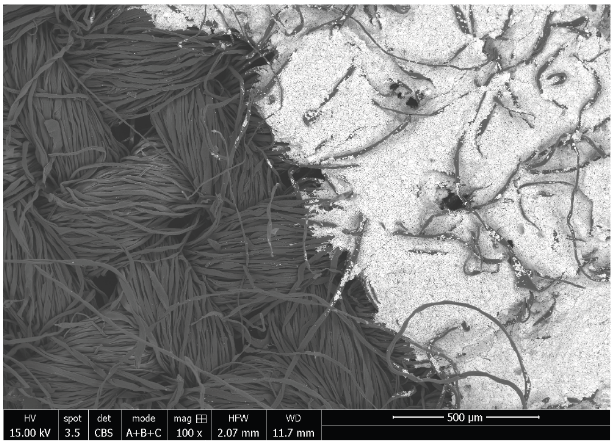
are enough to deposit the material needed to produce a neat print. The prints using 4 strokes look crisp with the naked eye fig. 06.11.



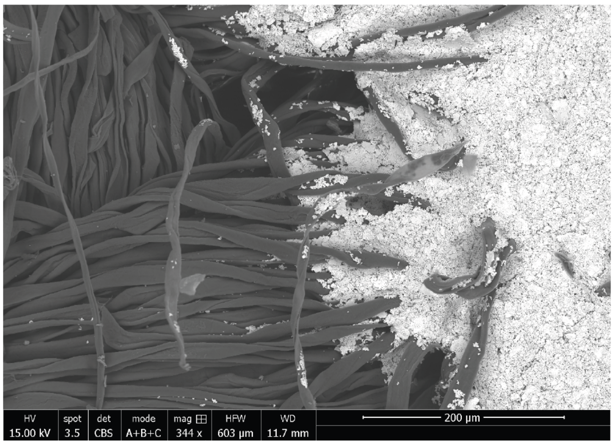
a b

Figure 06.11 **a** Knitted cotton, 4 strokes, **b** Woven cotton, 4 strokes

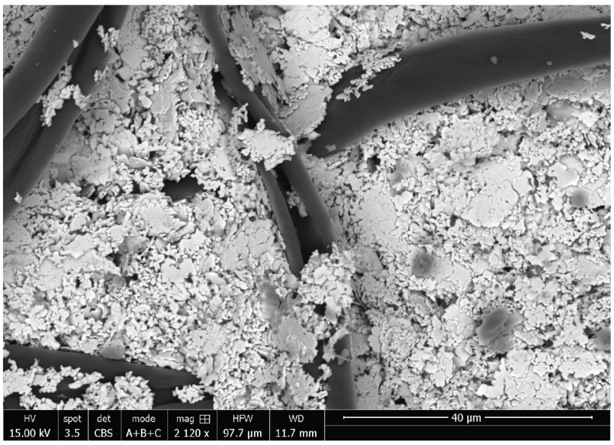
However, under the Microscope, some spots without ink were visible. These small spots do not affect the performance since the interaction between conductive particles is quite uniform through all the track. One example of these missing spots is presented in the Woven Bamboo sample. This substrate showed a crisp and homogenous print with the naked eye. Nonetheless, when the sample was analysed using the SEM kit, it was found that some fibres were not covered completely fig. 06.12 image **A** . This is due to the composition of the textile and the complexity of the different structures. It is important to remember that while working with textiles, we not only need to deal with an uneven surface, but also with threads and a large number of fibres, Section 4.2.2. Although there are fibres without ink, the interaction between particles is still present, and this interaction maintains the conductance of the print fig. 06.12 image **D**.



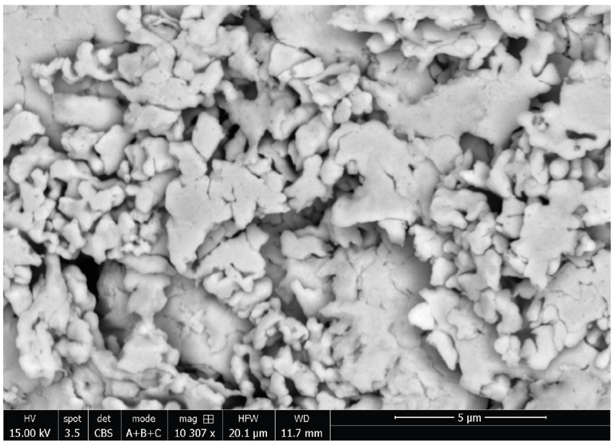
A



B



C



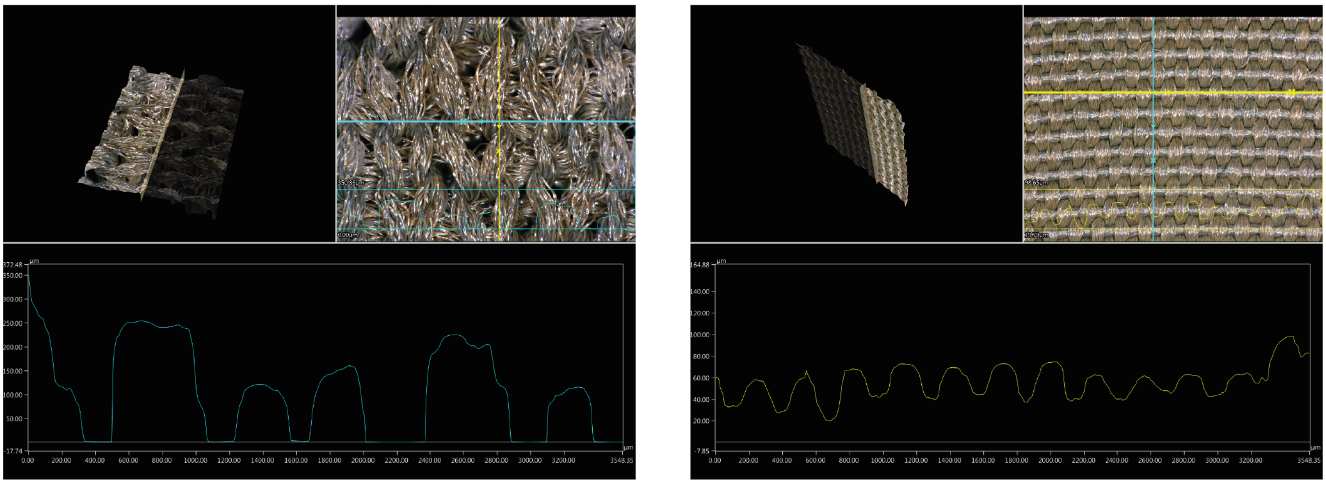
D

Figure 06.12 Woven Bamboo and silver flakes
Image taken with SEM to analyse the interaction of ink and textile substrates. Four magnifications of the same sample: A 100x, B 344 x, C, 2,120x, D 10,307x. In image **D** the interaction of silver flakes is clearly shown, meaning that the print will be conductive. In image **C** some threads without ink are visible, but this is to be expected when working with natural fabrics and specifically textiles. **D** Close up of the silver flakes

Structure vs ink

Some samples are able to keep the particles interacting with each other, however, some prints can also have cracks or big spots without ink, causing a breakage in the connection between particles. These problems are related to the nature of textiles and the natural depth they have as 3D materials. The lack of connection between particles not only creates a non-continuous print, but it is also a huge problem when printing 3D materials which includes, as mentioned before, the depth dimension that includes changes of thickness across the surface, this difference of depth can be appreciated in figure 06.13. These figures show the cross-section perspective of the polyester fabrics, which is useful to understand why it is very complex to print onto textiles and to maintain an even print and cover all the sinks of the fabric, thereby keeping a continuous print with particle interaction. Thus, although it is the same fibre with the same properties, the difference in structure affects directly the quality of the print and the conductance that can be achieved.

An example of how the ink interacts differently with the same fibre but a different structure is presented in figure 06.14. In this image comparison of the quality of print that can be achieved between knit and woven



a b

Figure 06.13 Cross-section analysis of structures
a Polyester knitted structure cross-section, **b** Polyester woven structure cross-section. The sinks are visible in both fabrics, affecting the print and conductance. It is clear that the knitted structure has deeper sinks.

structures is visible. The knit structure shows that the bigger pores are not taking up any ink compared to the woven structure, where the threads are closer to each other, and the ink is distributed evenly through all the surfaces. The knit structure showed a higher number of pores in the material characterisation, Section 4.2.2. Therefore, it was expected to have these results and complications while printing on knitted substrates. Although the difference is significant between both samples, a large portion of macro-pores was covered with conductive ink, meaning that the electric performance may not have been affected. From what is visible from the woven structure, it was expected to have good conductance.

a b

Figure 06.14 **a** Polyester knitted sample and **b** Polyester woven sample. Both images were taken using the SEM kit to analyse the ink particle interaction with the textile.

Differences between substrates

Figure 06.15 shows the results of screen-printing silver ink on six different textile substrates. As mentioned earlier, these substrates consist of three different fibres with two structures. The results show a 3.4 mm by 50 mm conductive line. Image **a** shows that for woven cotton, the print border does not cover some of the macropores. This lack of consistency is not fully visible to the naked eye. The result is due to the textile structure, since the macropores in cotton are considerably more prominent than in the other textiles. Image **c** corresponds to the print of a conductive line in woven polyester. The print resulted in a crisp conductive line with sharp edges. Here it can be observed that the distribution of ink is more homogenous across the sample, and that no macropores are left unprinted. Furthermore, one can note that there is a signifcant bleed of the solvent used for the ink preparation. Image **d** shows the result when using woven bamboo as a printing substrate. Woven bamboo substrates show that even though their macropores are more extensive than in polyester fibres, a uniform distribution of the conductive ink can be achieved. This can be observed in the sharp outline of the print. The latter is due to the bamboo fibres' properties of being hydrophobic and hydrophilic simultaneously, i.e. absorbing the ink and covering the surface at the same time, more information can be found in Section 4.2.1.

Images **f, g**, and **h** correspond to the prints using the same fibres but with a knitted structure. In the case of cotton image **f**, one can observe the same result as with woven structures, where the macropores are not fully covered by the printing process. For knitted polyester image **g** the printing result appears to have a non-uniform outline. Upon closer examination, it can be noted that the ink does not completely penetrate the surface, thus, the outline of the print fades. Furthermore, the macropores in knitted polyester affect the printing process since the course of the structure creates a texture similar to protruded waves. This texture extends the area of the macropores, making the ink go through them without attaching to the surface. Finally, image **i** shows the results of printing on knitted bamboo. The result shows a less defined outline but sharper than that of knitted polyester. While the surface shows an even distribution of conductive ink, a closer look at the threads reveals that the ink particles did not cover the surface evenly. This effect is due to the nature of the textile since the threads are constructed with multiple fibres that create a furry texture where the ink can attach and not reach the surface.

Overall, the printing process works well for woven structures. Nevertheless, this does not mean that crisp and even distribution of ink cannot be achieved in knitted structures. As shown in the knitted cotton result, an even distribution of ink can be obtained with a correct selection of fibre. With these results, the researcher emphasises the importance of selecting the right materials and characterising them through the microscope. While the prints might look acceptable to the naked eye, their poor or improved electrical performance can only be understood when looking at a microscopic level.

Experiment 1 - Electrical Performance Testing

After the samples were printed, their electrical performance was tested using a Multimeter. Each sample was measured six times to reduce the chances of less accurate readings due to human error testing. Afterwards, the mean for each electrical performance of each sample was calculated and compared. Each substrate had three different prints, with three different widths. These results are represented in graph 06.16 where it is clear how the resistance decreased with the increment of the printing width. This demonstrates the electrical resistance formula; the more conductive material is printed, the more conductive it will be. Unsurprisingly, the woven bamboo proved to have the best electrical performance and less resistance variation than woven cotton and knitted polyester and cotton which presented the highest resistivity on their thinner printed tracks. In addition

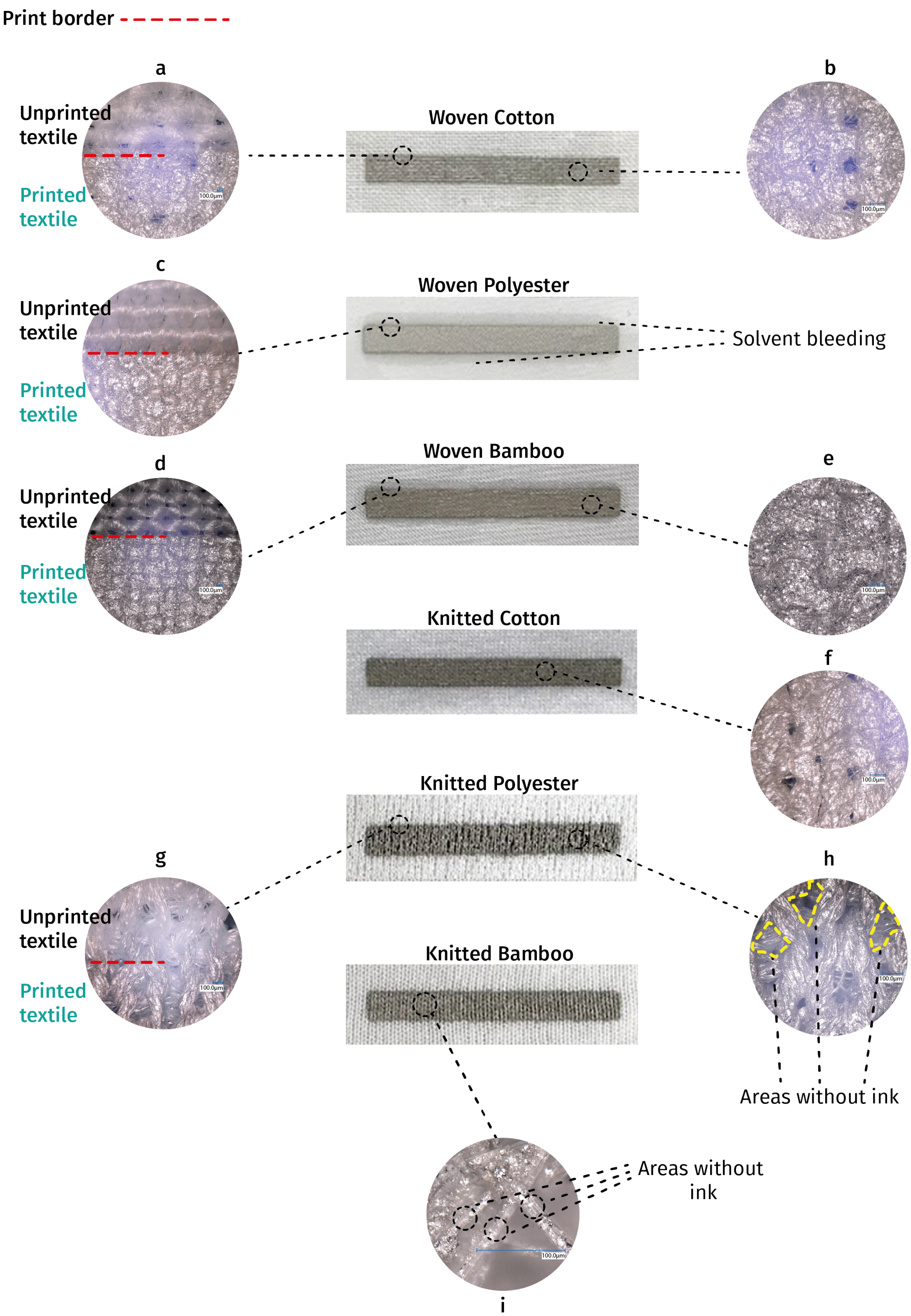


Figure 06.15 Screen printing, results of six substrate samples. Images taken with Apple Dual 12MP Ultra Wide camera and Digital Microscope.

to the comparison between performance, the standard deviation was calculated, and it is represented in the graph to inform the researcher about the measurements' variability. However, this variation corresponds to manual testing. Even though the resistance measurements were taken under the same conditions and with the same equipment, it is quite complex to replicate the setup for each sample.

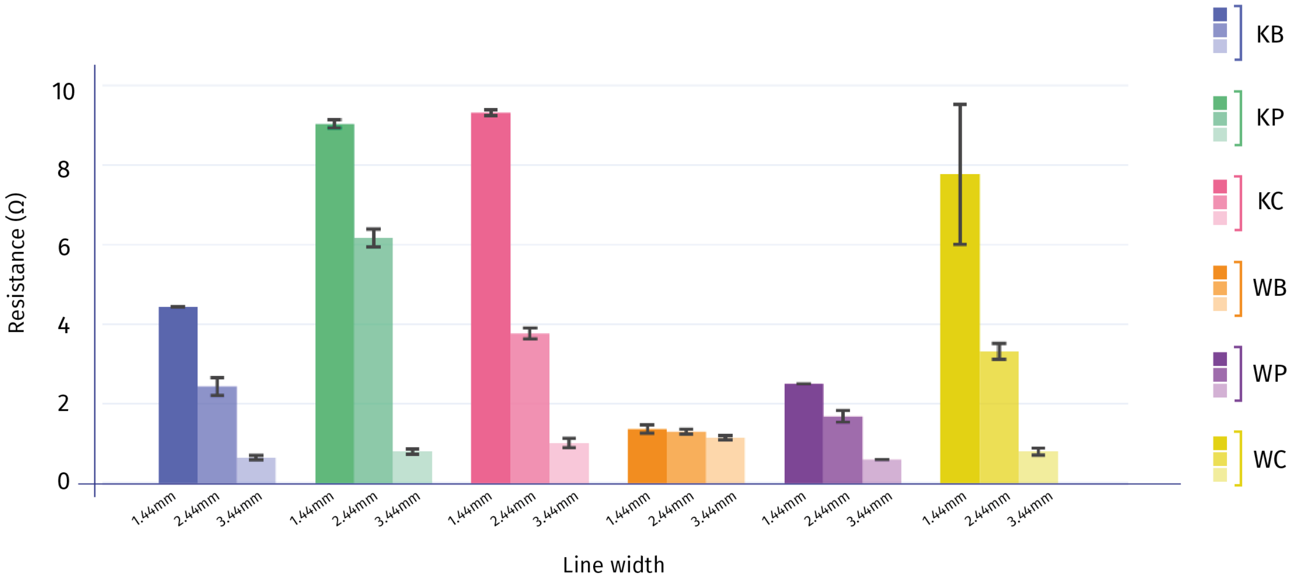


Figure 06.16 Electrical resistance comparison between substrates and printed track width.

The conclusion of Experiment 1 was that the printing parameters that demonstrated better electrical performance were the four strokes in combination with a print width of 3.44mm. The substrate with the best electrical performance was the woven bamboo, which was proven to have the least resistance and best conductance.

Experiment 2

Experiment 2 was guided by the results of Experiment 1, where the printing parameters were tested, and the combination of parameters with the best performance was a print with a 3.44mm width and four strokes per print. As previously mentioned, this experiment's objective was to compare two prints with a different design. The reason for printing one straight line and a meander line was to test the quality of the print and the differences between electrical performance. Both lines had the same length and width.

The printing experiment results reflected that all the prints were able to keep their crispness and homogeneity. In addition, the meander design did not affect the design resolution. Overall both, the straight and meander line looked the same.

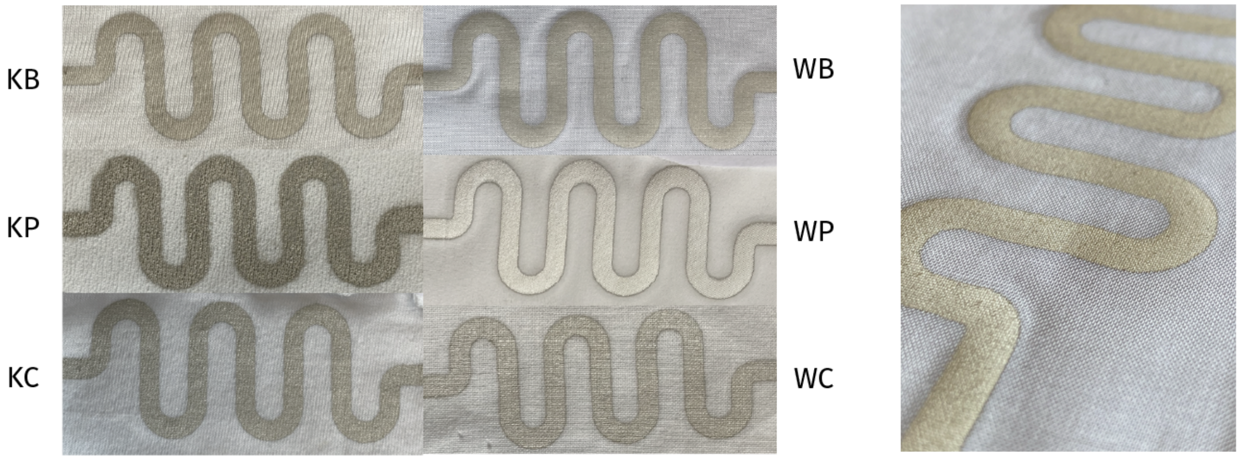


Figure 06.17 Experiment 2 results, printed lines crisp and homogeneous.

Experiment 2 - Electrical Performance Testing

The electrical testing for Experiment 2 followed the same testing standards as the previous Experiment, using the Multimeter to measure the resistance of the six textile substrates. Each measurement was performed six times to achieve the most accurate result. In this testing, the objective was to analyse and compare the electrical performance depending on the design differences. The results demonstrate that the samples with highest conductance are the knitted bamboo. In the previous testing, the bamboo was also the fibre with the best performance. Overall, this fibre has proven to have the best electrical performance and the best print definition. The knitted polyester continues to have one of the highest resistances. Although the printed tracks had a different design, the difference between them was not significant graph 06.18. It is a positive result to see that a meander line can have good electrical performance, which is not affected by the curves.

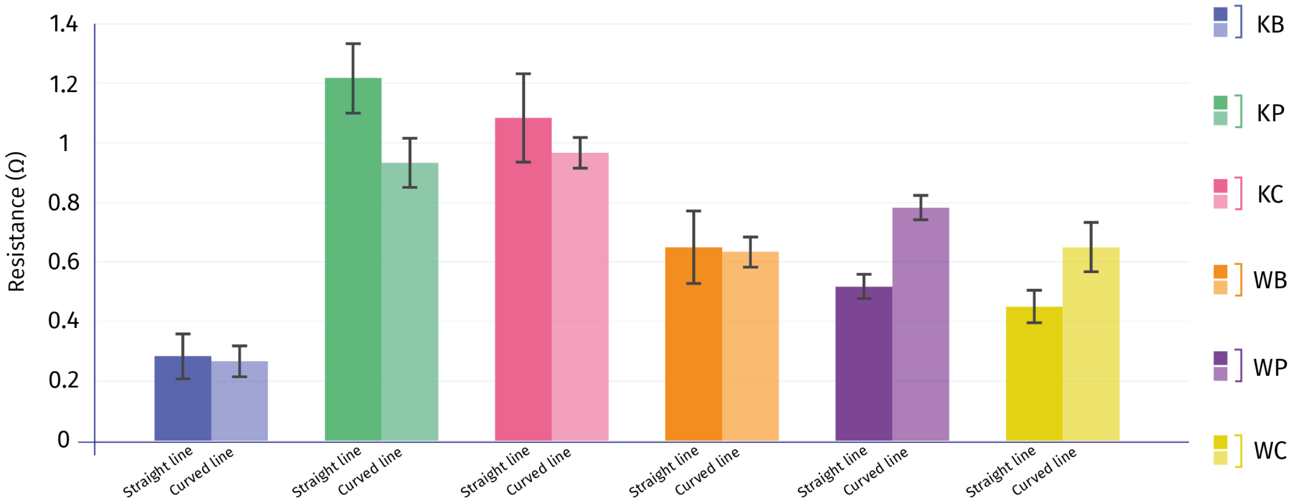


Figure 06.18 Electrical resistance comparison between substrates and printed track design.

After analysing these results, it was decided to use the knitted bamboo as the final sample. This decision was influenced by the resolution of the print, its electrical performance, and the substrate's structure. Knit is a structure commonly used for fitted garments since it can be stretched without a problem. Moreover, bamboo has excellent physical and mechanical properties that have proven to create highly comfortable clothes and other products.

Experiment 3

The final Experiment's objective was to mix straight and meander lines and design a circuit printed and connected to electronic components, discussed in Ch 8. The textile sample used was the knitted bamboo, and the printing parameters were those from Experiment 2. The design of the print used as a reference the basics of electrical circuit design. It was also decided to incorporate wearable electronic components from the LilyPad collection into the prints. The first things to attach to a textile sample were a battery holder and a wearable LED. Therefore, the design of the track took into consideration the size and positioning of these components. A homogeneous and crisp design was achieved following the same steps from previous experiments. These positive results prove that the printing method and parameters are replicable to produce conductive printed tracks.

Electrical Performance Testing - Experiment 3

The electrical performance of the printed sample was tested according to the proposed methodology. This print comprised two separated lines since they would be connected to electric components. The two tracks showed the same low resistance.

The Screen printing technique was demonstrated to have better performance in both visual and electrical performance. Once the correct parameters are found, this technique is highly replicable. The majority of the samples had low resistance. Even though the knitted samples had larger pores, they maintained the ink on the surface and kept the conductance along the track. The knitted and woven cotton had the lowest performance. This is due to the properties of the fibre; the substrates are absorbing a more significant amount of ink, and making it harder for the particles to stay close to each other and maintain the conductance.

As previously mentioned, conductive inks are made of metal particles contained in a matrix. The ink used for this research had a polymeric matrix. This helped keep the particles in place, and thanks to its high viscosity, it was possible to change the formula by producing thinner ink but thick enough to avoid ink bleeding.

During the printing process, the mesh was cleaned before and after every print to prevent any contamination. The cleaning was performed with Diethylene Glycol. However, this cleaning also affected the emulsion that is applied to transfer the design, which started to show some thinning and peeling in some areas. Therefore, the screen had to be exposed multiple times to prevent printing errors during the printing process.

In conclusion, Screen Printing is a suitable method for printing electronics, and it would be worth looking into printing on other substrates such as recycled fibre substrates. Furthermore, the exploration of automatic Screen Printing is recommended to compare the print quality between the manual and automated processes.

07 Electrical Performance

"Testing is the only way to identify manufacturing faults that could compromise the electrical safety of a product out in the field. Thorough electrical safety testing protects against the risk of electrical shock, so that products can be used for their intended purpose with minimal chance of injury occurring." (Poppe, Russell 2016)

Complicated as they might seem, all electronic devices share one crucial commonality at is core. That commonality is the ability to interconnect several devices together, i.e. to transmit energy from one point to another. Ideally, this transmission of energy is done instantaneously and without losses. Therefore, we require materials that can conduct electricity in this manner, i.e. highly conductive materials that present almost no resistance to the flow of electrons (Chung, 2001). However, as with every science, nothing is ideal, however, we can get pretty close to it. Looking at the periodic table, the indicator of the conductivity of a material is its number of valence electrons. This valence corresponds to the outer shell that covers atoms. Most conductive materials present between one or two valence electrons (Shur, 1996). Furthermore, valence electrons can be seen as almost free electrons that can leave its atom to another one nearby. Therefore, under the presence of an electric field, this electron can move to different places and it is this movement what constitutes electric currents (Kim et al., 2010); (Knipp, 2006).

In practice, the choice of a material does not rely solely on its properties, it also relies on the availability and practicability of using such material. For this reason, one of the most common materials used as interconnectors in electronic devices is copper (Gasana et al., 2006), (IBM, 2021).

Copper is highly conductive, maleable, cheap, and available in high quantities; most wires are copper plated, and copper is also used for large cables that require a high amount of conductive material. The before mentioned characteristics is what makes copper a preferred choice in the industry (Copper Alliance, 2018). In PCBs copper is the material of choice for defining the tracks that will interconnect several devices. Nevertheless, nothing is completely ideal, and as such we have to understand the undesired effects present in all materials.

In electronics, there are three basic components that are the base to explain and design the type of devices that we have today. These three components are resistors, capacitors and inductors. In an ideal scenario each one of them only present their corresponding effect. For instance, a resistor would only show resistance, a capacitor only capacitance, and an inductor would present only inductance. However, in practicality we observe resistors (and by proxy conductors) presenting both capacitive and inductive effects that under DC can be ignored, but when working with AC they can introduce undesired effects (Wang, 2010). The degree of this parasitic effects will vary with the frequency of the AC signal.(Shapiro, 2021) For this reason, it is important to characterise the electrical performance of conductive inks at different frequencies to fully understand the limitations of conductive inks, printing methods, and textile structures (Kim et al., 2010).

7.1 Objective

The objective of the electrical performance testing is to analyse the quality of the conductance for each print, to prove if the printing methodology was successful enough to produce reliable printed e-textiles.

To assess the performance testing, the prints were tested using Electrical Impedance Spectroscopy (EIS) principles under the following scenarios:

- Testing of printed samples using three different textile material and each pertaining to two different type of textile structure were characterised through EIS profiling.

- Testing of bending performance, characterised through EIS profiling using the previously mentioned samples bended on top of a mannequin arm body, average size 12.

7.2 Impedance testing methods

The testing presented in this chapter are reported using the Impedance's reciprocal, i.e. the admittance (*Impedance Measurement Handbook A Guide to Measurement Technology and Techniques 6th Edition*) (Srinivasan and Fasmin, 2021). The admittance Y can be understood as how easily current can flow within a device, and it is represented as:

X Reactance, R Resistance

$$Y = \frac{1}{Z} = \frac{1}{R + jX} \tag{07.1}$$

Furthermore, to ease the computation of a complex number we multiply the expression by its complex conjugate, therefore:

$$Y = \frac{Z^*}{|Z|^2} = \frac{R - jX}{R^2 + X^2} \quad (07.2)$$

$$Y = G + jB \quad (07.3)$$

where the conductance, G, corresponds to :

$$G = \frac{R}{R^2 + X^2} \quad (07.4)$$

and the susceptance, B, corresponds to:

$$B = -\frac{X}{R^2 + X^2} \quad (07.5)$$

The units for the admittance are Siemens or (Ω^{-1}). While the term conductance can be easily interpreted as the easiness for electrodes to flow, susceptance can be understood as how susceptible a devices is to conducting an alternating current.

The use of the admittance in this chapter aims to help interpret the results obtained. Moreover, since the resistance of copper wires is often considered to be in the range of $\times 10^{-9}\Omega$, it makes more sense to write in terms of its reciprocal, the conductivity.

7.3 Experiment

As presented in the previous chapters, the printed samples are highly conductive in nature. Therefore, in order to accurately measure their EIS profiles it is crucial to use the Kelvin approach presented in the Appendix. Using the Kelvin measurement technique, one can reduce the effects of the wires involved in the measurement. This is key in measuring low impedances, as the impedance of the measurement wires can be significantly greater than that of the sample under study. Furthermore, as per suggestion of the Impedance analyser manufacturer, in order to achieve the maximum accuracy at low impedance measurement ranges, the use of the Kelvin approach is highly recommended. This helps the system reach measurement within the 10 mΩ range. Nevertheless, it is worth noting that even when using this approach the presence of parasitic effects (inductive and capacitive) due to the measurement leads, will still be present specially at high frequencies (Keddam et al., 1984) .

7.3.1 Experiment 1, Flat surface testing

The electrical performance of three types of fibres using two different textile structures was characterised by obtaining their corresponding EIS profile. The textile structures selected were woven and knitted, for cotton, bamboo, and polyester. The impedance spectra was measured impedance using a precision LCR meter (4284A, Hewlett Packard, Japan) through a Kelvin clip fixture (TLKB1, BK Precision, China) using a frequency range of 20 Hz - 1MHz. Microcontrollers' communication generally only goes up to 100 kHz (e.g. SPI/I2C). Therefore, the range of frequencies that the LCR meter con provide are enough to test the performance of the prints. All measurements were taken at room temperature (*Impedance Measurement Handbook A Guide to Measurement*

Technology and Techniques 6th Edition).

The setup for the experiment is presented in figure. 07.1. In order to ensure a uniform current distribution, the contact points of each Kelvin clip were separated so that each one would touch a corner of the sample. The LCR meter frequency sweep was programmed using its SERIAL PORT. The system was configured to out an excitation signal of 10 mA to ensure an adequate signal-to-noise ratio. Furthermore, to ensure the reliability of each measurement, the sweep was configured to report the average of 8 measurements at each frequency. Additional, a long integration was set in order to enhance the accuracy of each measurement. To ensure the statistical validity of the results, the population of each sample measured consisted of six subjects printed under the same process.

Sample preparation and setup

As in the previous experiments, the textile substrates were kept under specific BS standards for textile testing. The textiles were kept in these environmental conditions after being printed and prior to the testing. For the first experiment (flat surface testing), two lab stands were needed to hold the measuring Kelvin clips. The stand's objective was to keep the clips in place during the impedance testing to avoid adding noise to the reading and get the most accurate measurements. The clips were positioned at 90°; each clip was making contact with the corners of the print. The textile samples were always handed with protective gloves to prevent any contamination that could affect the conductance of the print.

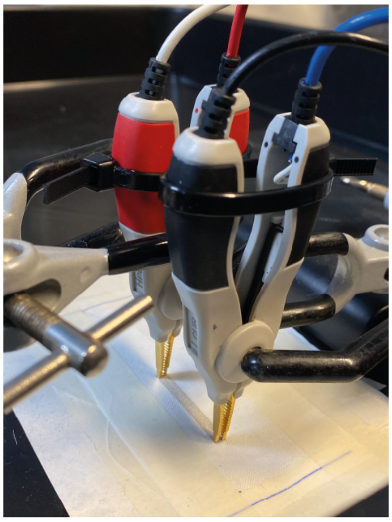


Figure 07.1 Experiment setup, Kelvin clips making contact with each corner of the print

7.3.2 Experiment 2 Electrical performance when bent

Experiment 1 was focused on analysing the conductive prints under a mostly ideal scenario. However, in order to determine the practicability and usability of the print it is important to understand how its electrical performance can be affected when used as a garment. The latter implies obtaining the impedance profile of the print under bent scenarios. This section presents an initial approach for this type of testing. While there is a considerable amount of testing procedures for garments that can determine their physical and mechanical limitations, there is a lack of testing methodologies that consider the evaluation of the e-textiles under scenarios that consider the final user. The approach presented highlights the challenges of evaluating the electrical performance of e-textiles when worn as everyday garments.

Sample preparation and setup

The instrumentation used in this experiment is the same as the one previously presented. The same Impedance Analyser and Kelvin measurement clips where employed. Experiment two followed the same principles for the sample preparation. They were kept in the conditioned room until the test was due to be performed. For this experiment, a mannequin arm was used to simulate the bending that a garment can be exposed to. The bending was measured following the arm's circumference, as shown in fig. 07.2. Four measurement points from the wrist to the bicep were taken. Each measurement point had 10cm of separation between each other. The objective was to test different circumferences and analyse the sample's behaviour on each measuring point. This experimental setup was more complex since the stands could not be used. Therefore, an adaptation had to be made using a sewing pin as a point of contact for the kelvin clips and the print. In this way, the pins could be attached to the mannequin, and the clips could make contact with the sample.

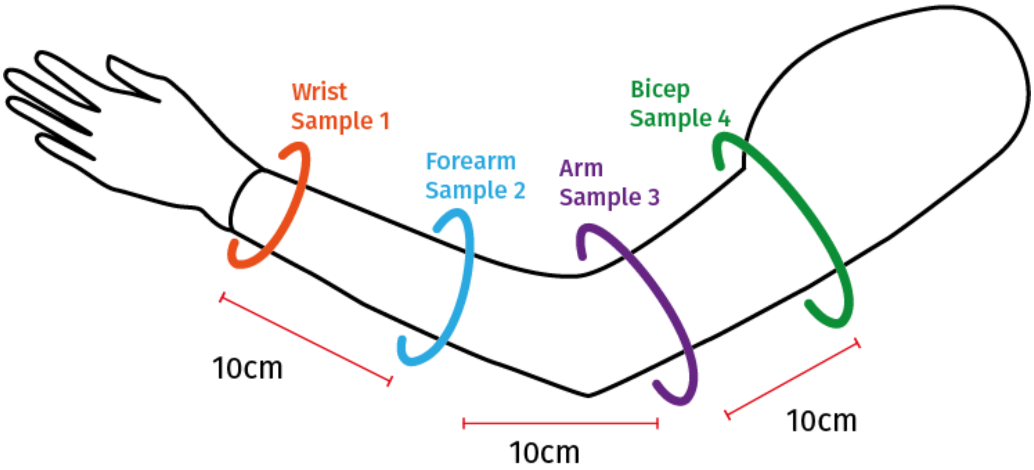


Figure 07.2 Illustration of the setup for the bent profile. Each textile was measured on the circumferences shown above. For terms of the data collection, the term "sample" was used for each circumference.

.

7.4 Results & Discussion

7.4.1 Experiment 1 Flat surface testing

Woven Samples

Figure 07.4 image **a** presents the EIS profile of the woven samples. The results are presented using a conventional Nyquist plot, where the x-axis and y-axis represents the admittance's real part and imaginary part respectively.

Electrical Performance

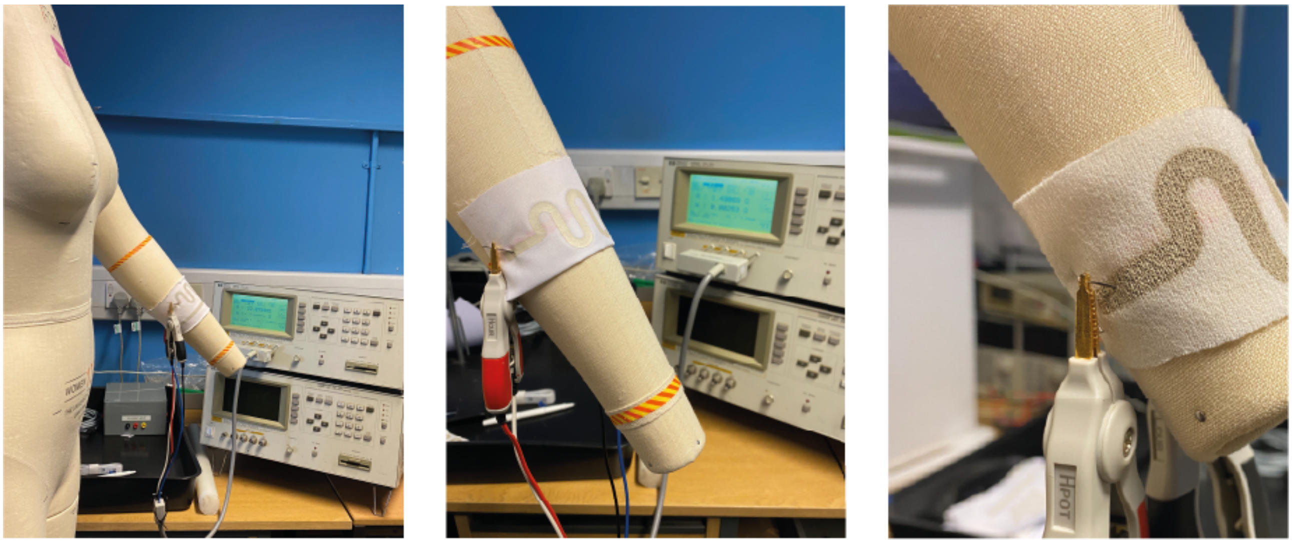


Figure 07.3 Impedance bent setup

As in any Nyquist plot, data acquired at low frequencies are located on the right side of the figure. Furthermore, as the frequency increases, values start shifting towards the left side of the plot. These results show that each sample presents the same behaviour, in which the conductance decreases as the frequency increases. Additionally, it can be observed that both the suceptance and conductance form a semi-circle. This semi-circle is common in EIS profiling, and shows how the materials' admittance, most often than not, present a non-linear behaviour.

The individual contribution of each component is presented in fig. 07.4 image **c** presents the evolution of the conductance as frequency increases. While the values of conductance vary from sample to sample, they stay within the range of 2.6 (S) to 4.0 (S). All samples present a mostly constant conductance up until an approximate frequency of 100 kHz. When close to the latter frequency, a sharp decrease in conductance can be observed. Upon reaching 1 MHz, the conductance exhibits its lowest values. The range of conductance at the latter frequency goes from 0.24 (S) to 1 (S).

The individual contribution of the susceptance on the admittance behaviour is presented in fig 07.4 image **c**. The plot shows almost negligible values at lower frequencies. After 1kHz, it can be observed that the susceptance starts to slowly decrease. When reaching, 10 kHz, all samples present an exponential decrease in their susceptance. Nevertheless, these decreases show a valley near 200 kHz. Upon reaching this valley, the susceptance starts increasing. The range of susceptance values at the end of the spectra goes from -0.9 (S) to -1.35 (S).

As per the definitions of impedance presented in Section 2.5, the real part of the impedance always represents the linearity of resistive elements (or in this case the conductance). In contrast, the imaginary component of the impedance can either be capacitive or inductive in nature. Negative values of susceptance indicate an inductive nature, and in contrast positive values indicate a capacitive nature. In these results we observe that the susceptance is predominantly inductive by how it behaves. Furthermore, due to the almost constant behaviour of the real part, we can model these results using an analogue circuit model. The most basic model for this interaction corresponds to a resistance in series with an inductor as shown in fig. 07.5.

Inductors are proportional to the frequency of the stimulation, thus, its reactance and impedance can be written as

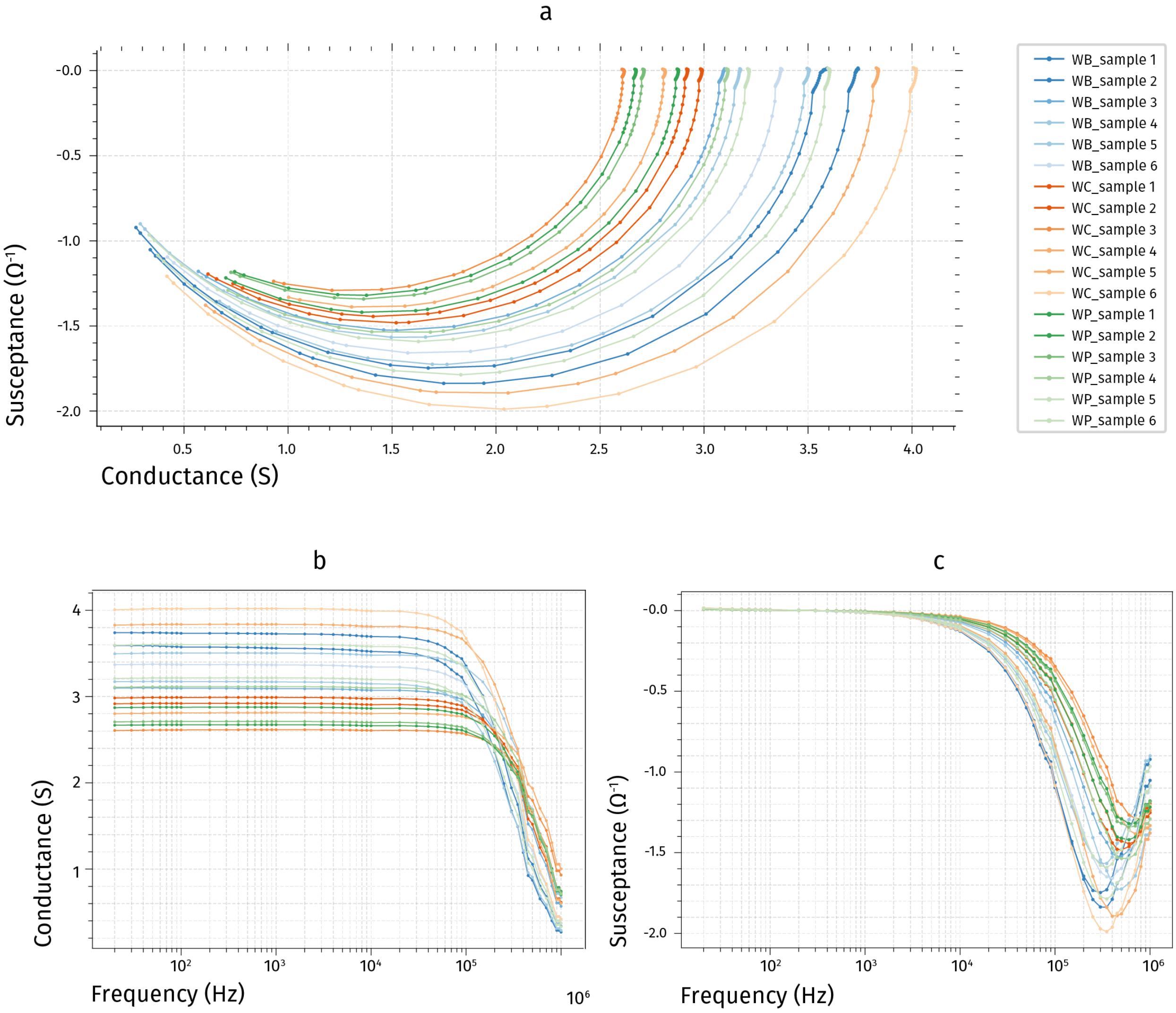


Figure 07.4 **a** Nyquist plot, EIS profile for woven samples, **b** Conductance Vs Frequency (real), **c** Susceptance Vs Frequency (imaginary)

Figure 07.5 RL, analogue circuit to characterise conductive print, where *I* correspond to current.

$$X_L = j\omega L \tag{07.6}$$

this means that the total impedance of the circuit is:

$$Z = R + j\omega L \tag{07.7}$$

representing the equation above as admittance we obtain:

$$Y = \frac{R - j\omega L}{R^2 + \omega^2 L^2} \tag{07.8}$$

Electrical Performance

Each sample was fitted to the above equation using a non-linear least squares regression fit of the model to the measured data using the python package scipy.optimize. Through this fit, both the resistance and inductance parameters were obtained. Table 07.1 shows the values obtained for each sample. Furthermore, this table reports the evaluation of the fit as the root mean square relative error (RMSRE). The latter involves calculating the root mean squared error between measurements and the modelled data. Next the root mean square of the measured data is computed and the RMSRE is calculated as:

$$RMSRE = \frac{RMSE}{RMS_{measurements}} \tag{07.9}$$

It can be seen that the fit procedure is highly accurate due to the small $RMSRE$, with an average $RMSRE$ of 2.74% for all samples. The results presented in table 07.1 show that the samples are highly conductive. In this case, this can be observed in the small resistance values calculated for all samples. Bamboo samples appear to perform better as they present the lowest resistance values with the smallest standard deviation. Moreover, cotton samples show higher resistance values and the highest standard deviation. This is due to the natural properties of cotton. This fibre tends to absorb a high amount of liquids/moisture. Therefore, the ink was absorbed and distributed along the fibres and threads, missing multiple connections between silver particles and making it less conductive. This sample also showed an uneven surface, making it harder to print and keep a homogenous track. Bamboo and polyester have shown to maintain a decent level of resistance polyester is a less fibrous textile, and it can keep the ink on the surface (although it may present big pores). Bamboo has both characteristics, and that is why this fibre has shown to have good electrical performance.

The effect of the inductance can be contributed to the measurement leads. While the Kelvin measurement setup by nature removes the contribution of the leads in the measured impedance, this does not fully eliminate the effects of parasitic reactances from the leads. The presence of parasitic inductance is common when measuring low resistances, and particularly when close to the minimum limit of the measuring device (in this case 10 mΩ). This effect can be explained through the magnetic fields generated around the testing leads when carrying an AC stimulation signal. Moreover, the presence of this magnetic field generates a certain level of error in the voltage measurement leads. Therefore, the presence of an inductor in the model should be understood simply as an undesired artefact and not as a characteristic of the samples. This is not only explained by the usual guidelines of impedance measurement, but also it has been previously clarified in the literature regarding the research of porous electrodes where the inductance effect was mistakenly thought as a property of porous conductive materials.

Nevertheless, taking into account this parasitic element helps modelled the performance of the system more accurately. A typical characteristic of RL circuits is its time constant τ, which corresponds to $\tau = L/R$. In the present work we use this characteristic to find the frequency at which the highest susceptance is found (i.e. the valley seen in the EIS profiles 07.4. The latter frequency is found at $\omega = 1/\tau$. Here ω represents the angular frequency which is expressed in radians. The latter can be expressed in Hertz using $f = \omega/2\pi$.

Moreover, considering the RL circuit as a voltage divider its transfer function can be expressed as:

$$\frac{V_L(s)}{V_{in}(s)} = \frac{Ls}{R + Ls} \tag{07.10}$$

By examining the circuit in this way we can further explain the shape of the Nyquist plot, since the transfer function presents a single pole located at $s = -\dfrac{R}{L}$, which dictates the curvature of the semicircle. The points near the valley correspond to elements with a smaller τ (i.e. with higher relaxation frequencies) appear to the left side of the plot (i.e. at high frequencies in the admittance spectrum)

Table 07.1 also reports the frequency at which the valley can be found using the fitted values of R and L. As can be observed by their standard deviation, the values have a high degree of variability. This is due to the measurement setup. Since the testing experiment employs leads, their effect in the impedance measurement will also depend on the positioning and bending of the leads. To overcome this issue a special leadless fixture should be used.

Textile	**b_s1**	**b_s2**	**b_s3**	**b_s4**	**b_s5**	**b_s6**	**Mean**	**std**	**var**
Resistance (ohm)	2.83E-01	2.70E-01	3.25E-01	3.17E-01	2.87E-01	2.99E-01	2.97E-01	0.019204	0.000369
Inductance (ohm)	1.60E-07	1.37E-07	1.10E-07	1.60E-07	9.50E-08	1.27E-07	1.32E-07	2.40E-08	5.78E-16
RMSRE	5.01%	3.34%	2.84%	0.24	0.0278	0.0351	6.91E-02	0.076769	0.005893
1/TAU (freq)	2.82E+05	3.14E+05	4.70E+05	3.15E+05	4.81E+05	3.75E+05	3.73E+05	77780.47	6.05E+09
Textile	**c_s1**	**c_s2**	**c_s3**	**c_s4**	**c_s5**	**c_s6**			
Resistance	3.44E-01	3.36E-01	3.84E-01	3.57E-01	2.62E-01	2.50E-01	3.22E-01	0.049215	0.002422
Inductance	9.50E-08	1.05E-07	8.50E-08	7.75E-08	9.75E-08	1.18E-07	9.63E-08	1.31E-08	1.72E-16
RMSRE	2.50%	1.85%	4.58%	0.0297	0.0292	0.0237	2.87E-02	0.008528	7.27E-05
1/TAU (freq)	5.76E+05	5.09E+05	7.19E+05	7.33E+05	4.28E+05	3.37E+05	5.50E+05	144164.6	2.08E+10
Textile	**p_s1**	**p_s2**	**p_s3**	**p_s4**	**p_s5**	**p_s6**			
Resistance	3.76E-01	3.49E-01	3.70E-01	3.22E-01	3.13E-01	2.79E-01	3.35E-01	0.033889	0.001148
Inductance	9.70E-08	9.80E-08	9.78E-08	9.50E-08	1.47E-07	1.31E-07	1.11E-07	2.04E-08	4.15E-16
RMSRE	2.40%	1.38%	1.40%	0.0164	0.0301	0.0249	2.05E-02	0.006161	3.80E-05
1/TAU (freq)	6.17E+05	5.67E+05	6.02E+05	5.39E+05	3.39E+05	3.39E+05	5.01E+05	116910.6	1.37E+10

Table 07.1 Experiment 1 - Woven samples data

Knitted Samples

Figure 07.6 shows the EIS profiles, represented as nyquist plots, of the knitted samples. Similar to the previous EIS figures, data points corresponding to low frequencies are located at the right-side, values at higher frequencies are located on the left side of the plot. The results presented in this figure are similar to those of the woven samples. While there are clear differences in the ranges of values between woven and knitted samples, both structures show the similar RL behaviour. However, in this case one can note that the shape of the semicircle is less pronounced than those of the woven samples.

Similar to the previous results, the admittance's individual components and how they change with frequency are presented in fig. 07.6 image **b** shows the conductance of the knitted samples as the frequency increases. Their values remain almost constant between frequencies 20 Hz until approximately 100 kHz, where a drop in conductance can be observed. The conductance range during this period goes from 1.97 (S) to 2.6 (S). When compared to the woven samples, the knitted structure shows higher lower conductance values with a lower range of variability. Upon reaching 1 MHz, the conductance range of the knitted samples is 0.57 (S) - 1.59 (S). Again when comparing these results to the ones from the woven structures, one can note that the conductance range and values is higher for the knitted samples upon reaching the maximum frequency.

The susceptance's response at different frequencies is shown in 07.6 image **c**. Similar to the woven structures, the susceptance of knitted textiles is negligible at lower frequencies. However, a slight downward trend starts to appear when reaching 1kHz. As the frequency increases, the downward slope increases. The key difference between woven and knitted samples is the point at which the main valley can be found. While in woven structures the location of the valley seems to vary greatly depending on the sample, in knitted textiles the valley appears to be located between 700-800 kHz for most samples. The range of susceptance values for knitted structures at 1 MHz goes from -1.15 (S) to 1.05 (S).

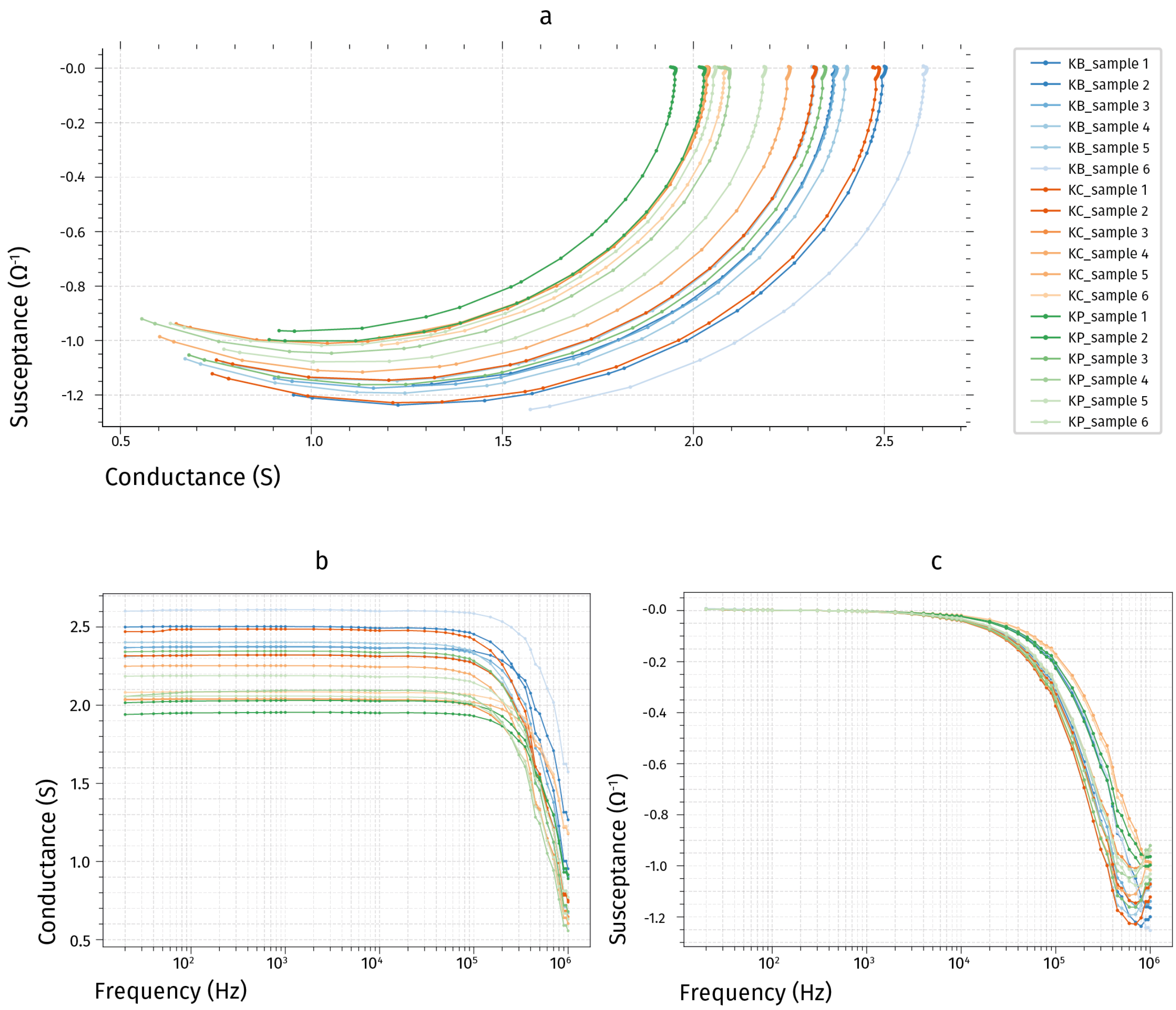


Figure 07.6 **a** Nyquist plot, EIS profile for knitted samples, **b** Conductance Vs Frequency (real), **c** Susceptance Vs Frequency (imaginary)

The EIS data for the knitted samples was fitted to the model presented in the previous section. Using the same procedure as in the previous section, the values for both resistance and inductance were computed. Table 07.2 shows the values used in the fitted model of all samples, as well as the evaluation metric of the fit; here reported as RMSRE. The accuracy of the fitted values is high with an average $RMSRE = 2.02\%$ for all samples. The results from this table show that the samples remain highly conductive due to the small resistance values found. Similar to the previous experiment, the best performing textile is bamboo. The latter shows the smallest resistance values with a low standard deviation between samples. Furthermore, cotton samples show again in this instance higher resistivity values with the highest standard deviation.

Interestingly, while knitted structures present higher conductance values it can be observed that they also present lower standard deviations which indicate a lower degree of variability between samples. This is due, firstly, to the natural bamboo properties of being hydrophobic and hydrophilic. The ink is absorbed, but it is also creating a crisp and homogeneous layer on the surface. The penetration of the ink on the bamboo fibres helps to keep the conductance between particles. Furthermore, the knitting structure (wales and courses) and how the threads are interconnecting is helping this distribution of particles along with the print.

Textile	**b_s1**	**b_s2**	**b_s3**	**b_s4**	**b_s5**	**b_s6**	**Mean**	**std**	**var**
Resistance	4.23E-01	4.01E-01	4.22E-01	4.32E-01	4.17E-01	4.37E-01	4.22E-01	0.011504	0.000132
Inductance	8.50E-08	8.25E-08	8.65E-08	9.80E-08	1.08E-07	6.10E-08	8.68E-08	1.44E-08	2.07E-16
RMSRE	0.021	0.027	0.0158	0.0144	0.0146	0.0358	2.14E-02	0.007805	6.09E-05
1/TAU (freq)	7.92E+05	7.74E+05	7.76E+05	7.02E+05	6.17E+05	1.14E+06	8.00E+05	163400.2	2.67E+10
Textile	**c_s1**	**c_s2**	**c_s3**	**c_s4**	**c_s5**	**c_s6**			
Resistance	4.33E-01	4.04E-01	4.92E-01	4.45E-01	4.92E-01	4.82E-01	4.58E-01	0.033161	0.0011
Inductance	9.93E-08	9.90E-08	1.17E-07	1.18E-07	6.70E-08	6.65E-08	9.44E-08	2.09E-08	4.36E-16
RMSRE	0.0163	0.0164	0.0315	0.0118	0.021	0.0196	1.94E-02	0.006129	3.76E-05
1/TAU (freq)	6.94E+05	6.49E+05	6.69E+05	6.03E+05	1.17E+06	1.15E+06	8.23E+05	240725.5	5.79E+10
Textile	**p_s1**	**p_s2**	**p_s3**	**p_s4**	**p_s5**	**p_s6**			
Resistance	5.14E-01	4.95E-01	4.29E-01	4.78E-01	4.60E-01	4.89E-01	4.78E-01	0.027171	0.000738
Inductance	8.65E-08	8.83E-08	1.06E-07	1.26E-07	9.86E-08	1.16E-07	1.04E-07	1.42E-08	2.02E-16
RMSRE	0.0137	0.015	0.0254	0.009	0.0294	0.0255	1.97E-02	0.007448	5.55E-05
1/TAU (freq)	9.46E+05	8.92E+05	6.44E+05	6.04E+05	7.43E+05	6.71E+05	7.50E+05	127431	1.62E+10

Table 07.2 Experiment 1 - Knitted samples data

7.4.2 Experiment 2 Electrical performance when bent

Woven samples

The Nyquist plot of the EIS profile for woven samples is presented in 07.7 image **a**. The results present the variation in admittance as the location of the samples goes from the wrist to the bicep. When compared to the previous woven EIS profile, it is clear that the conductance in this case is approximately 2 to 3 times lower fig.07.7 image **b**. This is due to the added impedance from using the needles to setup fix the sample to the mannequin. Nevertheless, it can be observed that the shape and overall response remains the same in this scenario. All textile structures show a similar behaviour, i.e. there is a slight decrease in conductance when positioning at higher arm locations. The cotton sample shows a higher conductance in this case, with an initial conductance of approximately 1.54 (S) and a conductance of 1.41 (S) at the final location. A similar range of conductance variation is present in the polyester sample, 1.35 (S) - 1.25 (S) from the initial position to the last position. The highest range was found in the bamboo sample with a range going from the initial position, 1.20 (S) to the last position, 1.08 (S). Nevertheless, while it can be observed that bending the samples does change the conductance, the changes are not significant. The small changes in conductance are considered to be within an acceptable range as there are no significant changes in the parasitic effect observed. Figure 07.7 image **c** shows that the susceptance response remains similar to that of the previous experiments, which, as discussed previously, is primarily dominated by the parasitic inductance present in the measurement leads.

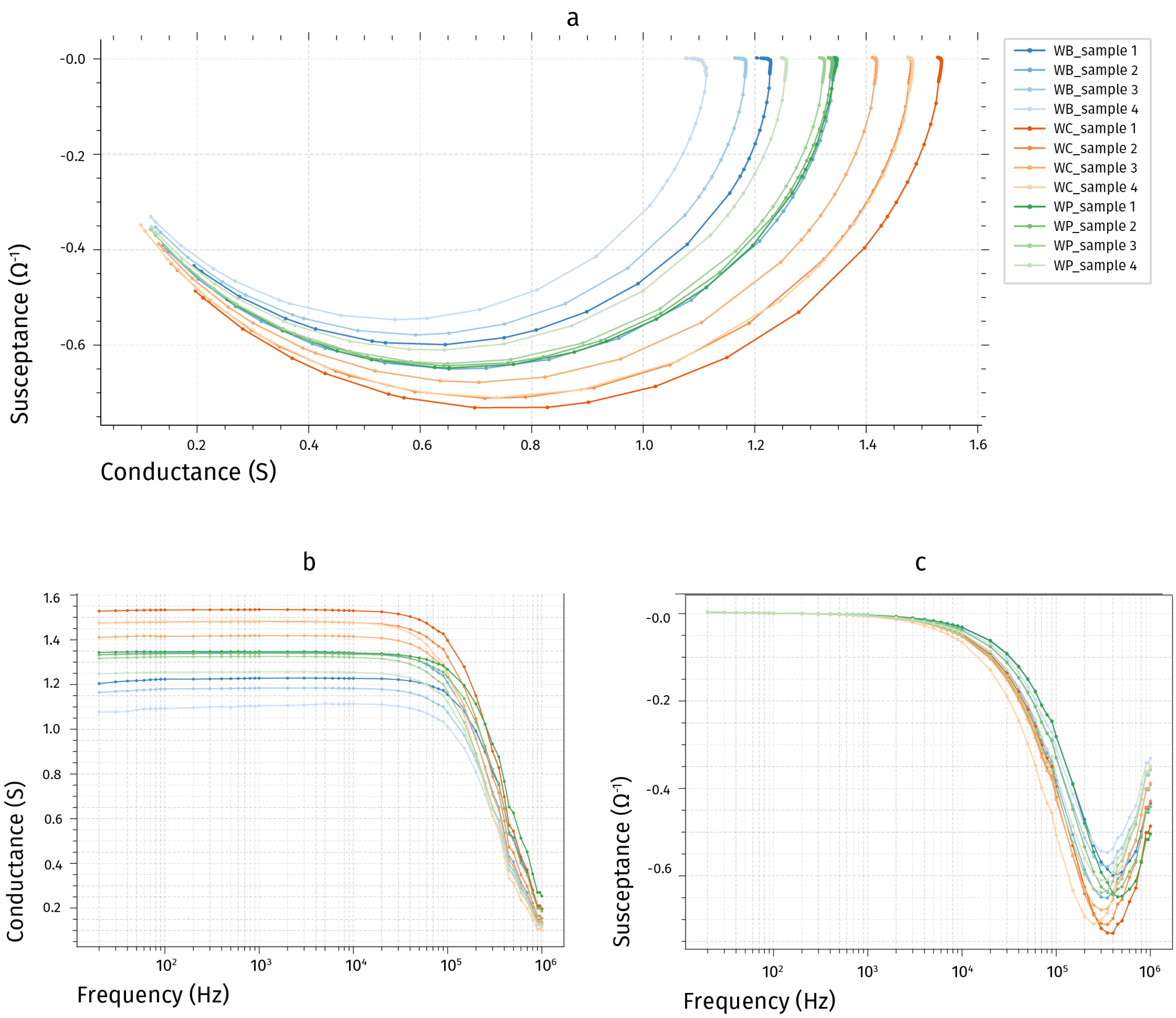


Figure 07.7 **a** Nyquist plot, EIS profile for woven bent samples, **b** Conductance Vs Frequency (real), **c** Susceptance Vs Frequency (imaginary)

Knitted samples

The EIS spectra for the knitted samples at different arm locations is presented in fig. 07.8 image **b** as a Nyquist plot. The overall shape and behaviour is similar to that of the previous results. However, there is a notable outlier that corresponds to the cotton sample, shown in fig 07.8 at the bottom of the list. Due to the textile structure and pore size of cotton, a good contact between the needle and the conductive ink is not guaranteed. Therefore, at the first location one can observe that the response of the cotton sample is somewhat erratic across all frequencies. For this reason the EIS profile at this location does not present a smooth transition from frequency to frequency and a sharp contrast is observed with the EIS curves at the other arm locations. The results in fig. 07.8 image **b** present a similar behaviour as with the previous results, where at higher arm positions the conductance decreases. In this case, the plots that show higher conductance values correspond to the polyester substrate fig. 07.8 image **b** with a range that goes from 1.14 (S) wrist location to 1.04 (S) the bicep location. Without considering the cotton outlier, both cotton and bamboo substrates show a similar conductance range from 0.64 (S) to 0.56 (S). Similar to the previous results, it can be observed that the bending of the substrate can change its conductance value slightly with no changes to its susceptance behaviour fig.

07.8 image **c**. The susceptance of the samples is similar to the ones explored previously where the contribution of the measurement leads determines the inductive susceptance seen at higher frequencies.

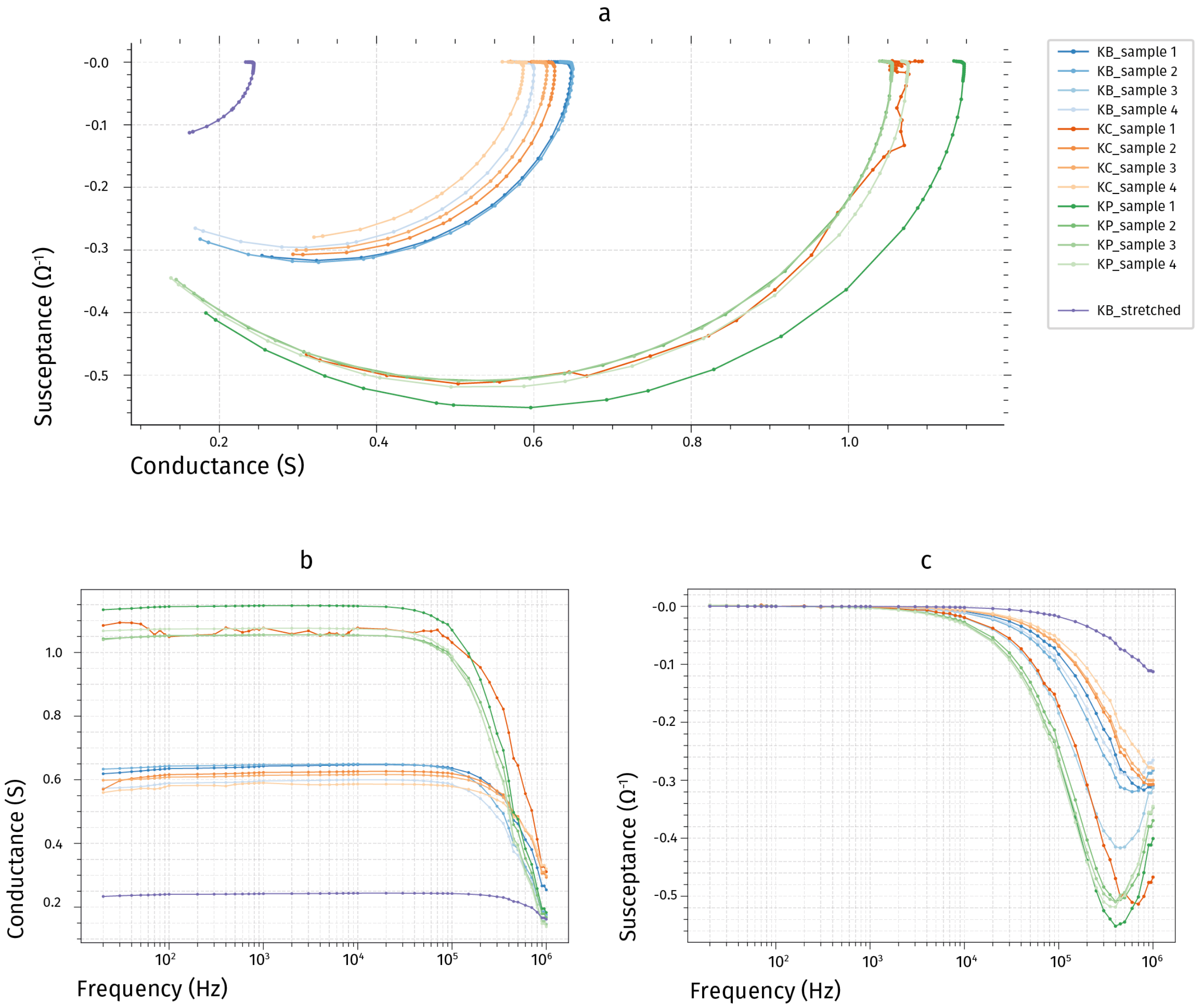


Figure 07.8 **a** Nyquist plot, EIS profile for knitted bent samples, **b** Conductance Vs Frequency (real), **c** Susceptance Vs Frequency (imaginary)

Additional to these EIS spectra, the EIS profile for a stretched sample is shown. This sample was selected as it was previously determined that cotton is a challenging substrate that presents a high degree of variability when printed. Therefore, its electrical performance was evaluated under the 'worst-case' scenario that of being stretched. The results show a considerable decrease in conductance, showing the lowest conductance across all experiments (0.2 (S)). Furthermore, due to this substantial increase, it can be observed that by effectively increasing the resistance of the sample, the parasitic effects of the measurement leads are less noticeable 07.8 image **b**. The decrease in conductance is due to the effect of stretching the fabric and separating the threads. Threads have particles placed on the surface when these threads are separated, then the particles of the surface are not making contact with each other. Therefore, the conductance decreases because the conductance relies on the particles that were absorbed and kept in contact. However, this connection is not as strong as it should be. The stretching showed cracks on the surface after testing, and this also affected the electrical performance overall.

Electrical Performance

As seen by the above results, measuring the electrical performance of e-textiles considering the case where they will be used as garments, is not a straightforward process. While fixing the sample to a mannequin can be done through traditional methods (e.g. fixing them with needles), ensuring an adequate electric contact between the sample and measurement leads can be difficult. In this case, the study employs needles as contact points. Using the needles as contact points can help define constant and repeatable contacts when moving the sample across the mannequin. However, this is an invasive approach that can significantly disrupt the conductance of the print. In this case it was observed, that the needle increased the resistance of all samples by similar amounts (between 0.2Ω-0.3Ω). Not only that, but as seen in the cotton sample, this approach does not guarantee that the needle will have an adequate contact with the conductive particles of the ink, which increases the chances of human error. Future work in this area should consider the creation of adequate mechanisms and instrumentation to measure e-textiles under similar conditions more reliably.

08

Embedded Electronics

'Smart clothing has to be comfortable, so it has to be adaptable to the human body. Moreover, clothes that embed electronics must be safe and have to be flexible to adapt to the body movements.' (Fernández-Caramés and Fraga-Lamas, 2018)

This chapter explains the integration of LilyPad electrical components, presented in **Section 2.2.3**, into the conductive prints achieved and selected from previous chapters. The printing and integration follows the basic principles of PCB design, such as track positioning, track angle, component positioning, and printing tolerance.

In the past years, the evolution of technology towards increasing the quality of people's lives has promoted the fast development of wearable electronic devices. These devices aim to translate personal and environmental information into measurable electrical signals that people can interpret and use to improve the myriad of their life experiences. It is individuals that demand integrative wearable devices and governments, healthcare systems and the military, amongst others. However, embedding electronics into wearable products comfortably and efficiently (under both wet and dry conditions) has been one of the main challenges of developing these technologies.

Research on flexible electronic materials and deformable textile strain sensors has provided a solution to this problem. One well-explored way is to incorporate conductive fillers into common textiles, with well-known wearable properties (lightweight, flexibility, biocompatibility, washability and adaptability).

In this way, several textile-based sensors have been developed, but they are still limited in their connectivity, and most require external electrical instruments to function fully. Furthermore, by weaving with conductive yarns or Inkjet printing conductive ink onto textiles, it has been possible to interconnect electronic devices and conductors in manufacturing smart or electronic clothing. Using conductive ink, compared with embroidering and weaving, provides design freedom and rapid prototyping for the production of e-textiles.

There is, of course, a caveat; printing onto textiles is quite difficult due to their porous surfaces and the specific highly variable properties of each textile. One way of breaching this gap is using the printed circuit boards (PCB) principles and translating them to textiles. One of the main software to design PCBs is Altium Designer System Engineering (SE). The editor enables the creation of schematics with a wide variety of tools that can design, measure, edit, simulate and create lists of components, among other features. The challenge is how to incorporate rigid components into flexible and porous materials.

Sensors are now being adapted for e-textiles use, reducing their size, changing rigid materials for flexible ones, and modifying their design by adding features that make the integration with textiles much easier. LilyPad is one of the biggest brands looking into this. Their components are designed to be attached with conductive thread and are made as flat as possible. These features make them easier to use and for users to adapt to them.

8.1 Objective

The objective of the embedded electronics experimentation is to integrate electronic components from the LilyPad collection into the textile substrates using the conductive ink as electrical solder.

This will be accomplished by addressing the following tests:
-Incorporation of LilyPad electrical components into the existing printed samples using the same conductive ink.
-Testing and analysis of the electrical performance of the printed track once connected to the components.

8.2 Experiment

This chapter follows the final step of the Methodology created, where the selected print is connected to an electronic component, making an e-textile 08.1 .

Prior to commencing the study, the substrate and print with the highest electrical performance was selected. This was done to avoid any connection problems due to the quality of the print. As previously stated, all the printed tracks were specifically designed to fit specific electronic components. Therefore, they were expected to fit without any issues.

The samples, as in all the other experiments, were kept in a conditioned room that follows the BS for textile testing. This final experiment was performed in the printing Lab to reduce any risk of intoxication with the

Figure 08.1 Final step Methodology

solvent and conductive ink.

In the process of embedding components to the print, a small drop of ink was deposited at the end of the track. In this way, the component was fitted, and the fresh ink acted like a soldering paste. 08.2 shows the specific points where the ink needs to be deposited with delicacy, using the metal spatula that was used in the previous experiments to mix the conductive ink.

Once the components were perfectly positioned, a small portion of ink was deposited on the connecting points of the components. The print was cured in the oven following the manufacturer's adivce of 130°C for 5min.

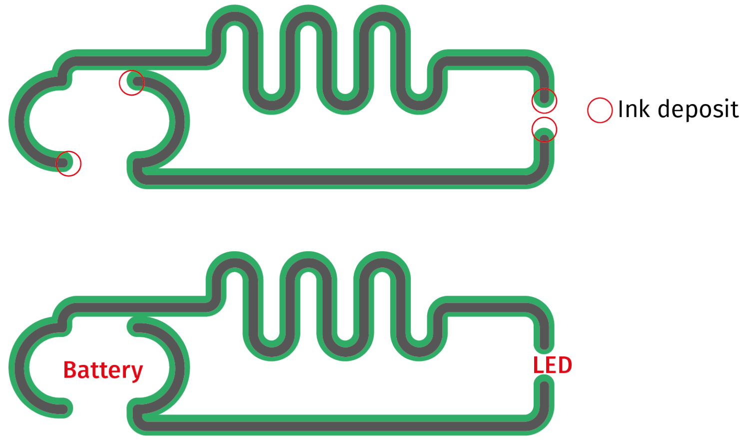


Figure 08.2 Areas where ink need to be deposited and components placed

8.3 Results & Discussion

The aim of this experiment was to attach electronic components to the printed tracks on textiles, using conductive ink as soldering paste.

The experiment had to be repeated three times to get the right amount of ink on the track. The first experiments had a high volume of ink. Therefore, when the component was attached, the ink covered a larger portion of the textile surface than expected and created a connection between tracks.

It is essential to have in mind that the print design follows the basics of electronic circuits. Therefore, there are positives and negatives connection points. For this reason, the conductive tracks need to stay separated from each other. Otherwise, the connection would not be successful.

After the third attempt, the right volume of ink was deposited, and the print was able to be cured. After the curing process, the textile did not show any colour difference, nor did the printed track.

Finally, a 3V Coin cell battery was placed on the battery holder to test the success of the conductive track connected to the components. The LED, functioned and produced bright light. The resistance was tested to analyse if anything had changed from previous experiments, the print proved to have a stable resistance reading without major variations.

Overall, the experiment of attaching electrical components and testing their electrical performance was successful. The LED lit up, and the resistance was constant. These positive results are related to the previous experiments, determining the right parameters, the right volume of ink, along with the number of strokes to produce a crisp and homogeneous print. All these factors were involved in the process of achieving a successful e-textile.

Using soldering paste is one way to attach the electronics; however, a combination of materials can also be used. Conductive thread can be connected to the component and then to the print, making sure that the conductive materials are always in contact. However, this combination of materials could reduce the electrical performance. Research on how these components could be attached is something that still needs a great deal of exploration and experimentation. One solution has been to print the sensor directly to the textile sample without having to deal with the rigid components. However, only a small range of sensors can be directly printed. Furthermore, the exploration with encapsulation should be investigated, as well as the use of pre-treatments for natural textiles.

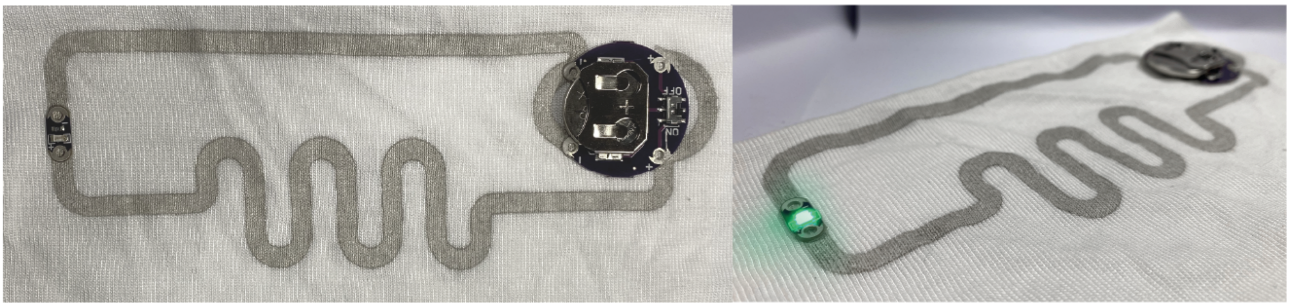


Figure 08.3 Knitted Bamboo,connected to a LilyPad Battery holder and a LED,

This study has shown the need for collaborative research in the e-textiles field. Different disciplines like Electrical Engineering, Chemistry, Materials Engineering, Garment Technology, Textile Engineering, and Fashion Design are some of them. However, it all depends on the purpose and functionality of the e-textile. In some cases, the feedback of a Medical researcher could be needed during the designing and testing process. This study has found that there is a wide interest in the research of conductive materials for wearable electronics; however, these studies are not looking at the more extensive scope, and they are only focusing on their subject. Therefore, E-textiles offer a big area for multidisciplinary research needed to improve the existing wearables and produce more functional and user-friendly products that can improve people’s life and experience.

09 Conclusions & further work

E-textiles have become of great interest to the wearables and garment industries due to the immense possibilities that the integration of electronics into garments can provide, offering a diverse range of monitoring technologies. The fast development of wearable electronics allows us to produce more user-friendly products, and the creation of flexible and miniaturised electronics has brought us the opportunity to integrate these into our daily garments. While different disciplines are working on the wearable sector, the current literature lacks multidisciplinary approaches within this area. The main focus is on developing new materials for embedded circuits and circuits themselves. However, the end-user and garment manufacturing processes are overlooked. The creation of embedded systems is as important as the selection of materials to create a garment. Therefore, this thesis adopted different research methodologies to develop a multidisciplinary approach for manufacturing screen and Inkjet printed e-textiles.

The original contribution to knowledge and aim of this research is the development of a replicable methodology suitable for the manufacturing of electronic textiles. Current literature shows significant advances in printing techniques using synthetic and coated substrates. However, these materials are not recommended for the production of garments that will be in direct contact with skin. For this reason, the focus of this thesis is on printing techniques using natural fibres commonly used in the fashion industry.

Conclusions & Further work

This study shows that even when using established printing methods such as Screen Printing or Inkjet Printing, the final result can vary greatly depending on the nature of the textile used.

Following the aim and objectives presented in Section 1.1, the researcher considers that in order to print conductive inks on natural fibres successfully, it is essential to understand the physical and mechanical properties of the materials being used (**Objective 2**). By understanding these characteristics, one can determine the limitations of using a specific type of material, and in some cases, understand how to overcome certain limitations. For instance, in this work, the Contact Angle (CA) test helped determine the interaction between materials and further evaluate the proper solvent vs ink ratio for printing. The best combination found for the use of the Alfa Aesar conductive ink for screen printing was 15% of dilution (15% Diethylene - 85% silver ink). This ratio creates an ink that is dense enough to be applied on a substrate surface and thin enough to be absorbed by a porous material with low ink and low solvent bleeding. Following the printing methodology established in this work, six different textile substrates were characterised before printing. This characterisation showed that the Knitted structures are prone to absorb the inks quicker (approximately between 0s-3s) due to the large pores of the knit. Interestingly, the knitted polyester was the sample that could not retain any ink on the surface due to its pore size. In contrast, the bamboo substrates showed good retention of ink with a small amount of bleeding. This is due to the physical properties of the fibre; liquids can be absorbed but can also be retained on the surface. For the Sigma Aldrich 736465 ink, a high amount of bleeding was present. Furthermore, the absorption was immediate; thus, measuring the CA was challenging. For this ink, a test with pre-treated textiles was also performed. However, the results only showed slight improvements. The ink was completely absorbed, and bleeding was present again. This effect is due to the ink composition and the particle size. Unlike the screen printing technique, modifying the ink composition presents a different challenge due to the printing specifications of the Inkjet printer (size of nozzles vs ink particle size).

As important as the material characterisation is the definition of the optimal printing parameters of the printing technique (**Objective 3 and 4**). The methodology presented proposes an approach in which the printing is divided into three experiments to identify the optimal combination of printing parameters while testing the electrical performance on different textile substrates. The first experiment is to understand how the electrical performance is affected by the width of the printed line. Thin lines present less conductive material, thus, the electrical resistance of these lines will be higher than that of a wider line. The previous statement, regarding the electrical performance result, would be expected from the traditional formula for calculating the electrical resistance of an object when printing on textiles.

The number of actual conductive particles present in the print is limited not only by the width of the line, but also by the print definition and ink adherence. During this experiment, it was found that the Inkjet printing process was more complex than expected, thus, the prints obtained showed high levels of bleeding and zero conductance. Such an effect is due to the ink composition as it is oil-based with conductive nanoparticles highly distributed across the threads that can travel along the bleeding direction. This limitation can be overcome through the use of pre-treatments or coatings. For this reason, the further experiments of the printing methodology were performed using only the screen printing method.

The second experiment corresponds to the comparison of straight conductive lines and meandering lines. This comparison was to evaluate the obtained parameters from the first experiment as well as to understand the limitations of the printing method. Since screen printing involves the use of woven mesh, it can affect the sharpness of the final print. Printing a meandering path not only tests the sharpness of the definition in screen printing, but also helps test how different shapes can affect the overall conductance of the print. Moreover, meandering paths are commonly used in PCB design to create matched impedance tracks, therefore, it is relevant to test their performance in textile substrates. The results showed that the screen printing mesh is an adequate medium for printing highly defined edges, and that the conductance can be further tailored through the use of traditional PCB design techniques.

The final experiment of the printing methodology corresponds to printing a circuit design onto a textile. This experiment helps evaluate the feasibility of integrating electronic components with the final print. Moreover, this experiment involves the circuit design, component footprint specifications, and in this case, the translation of the design into the printing mesh.

The use of this printing methodology is a practical and analytical approach that can help designers to not only better understand their materials and their limitations, but also to define the optimal printing parameters to produce conductive printed tracks by following a structured guide.

In addition to the methodology presented, the researcher encourages using a traditional tool employed in characterising electronic components and electrochemical reactions, known as EIS (**Objective 5**). The EIS profile of the printed inks further informs of the electrical performance of the print. This knowledge is crucial for electronics designers to fully understand the capabilities of the print, as they (designers) can underperform when compared to traditional PCB manufacturing. Due to the complexity and requirements of current electronic devices, the EIS profile gives a clearer picture of any underlying effects of the print. Moreover, the results show that depending on the textile structure and substrate used, the conductance obtained can vary greatly from sample to sample. For instance, the results from the Cotton knitted and woven samples show higher conductance variability between them. The high degree of variability, in this case, is due to the pore size of the textile structure and the fibre. By obtaining the EIS profile, one can not only define the frequency operating range of the prints, but can also determine the reproducibility of the printing process. Defining the operating range is crucial for any high-end application using e-textiles since parasitic effects, which can also be found in traditional PCB designs, can affect the overall performance of electronic components. Depending on the textile, the uniformity of the print is not guaranteed, and with the ink travelling along the threads, one can expect not only a reduction in conductive material, but also unwanted parasitic effects. The results show that establishing a methodological printing process can obtain a reproducible and reliable conductive print that does not present substantial parasitic effects.

In the final part of the experimentation, the electrical components were added (**Objective 6**). After selecting the fabrics with the best print and electric performance, the components such as LED and coin battery cell were added to the print, using conductive ink as soldering paste and curing the sample to achieve the sintering process. This experimentation was successful, and the components not only stayed in their original position, but the connection between the ink and the components was also successful. The print was able to conduct electricity throughout the design, and the LED functioned without connectivity complications.

The present research aimed to explore and develop a novel method to produce and test printed electronic textiles adopting different methodologies. The aim was achieved, and a methodology was designed not only for printed electronic textiles but also for wider use in producing e-textiles, fig 09.1. This methodology presents different steps and decision points to test the performance of the sample that is being manufactured. These steps will allow better electric performance by decreasing the possibilities of faults with the interaction between textiles and conductive materials and the connections of these materials to electric components.

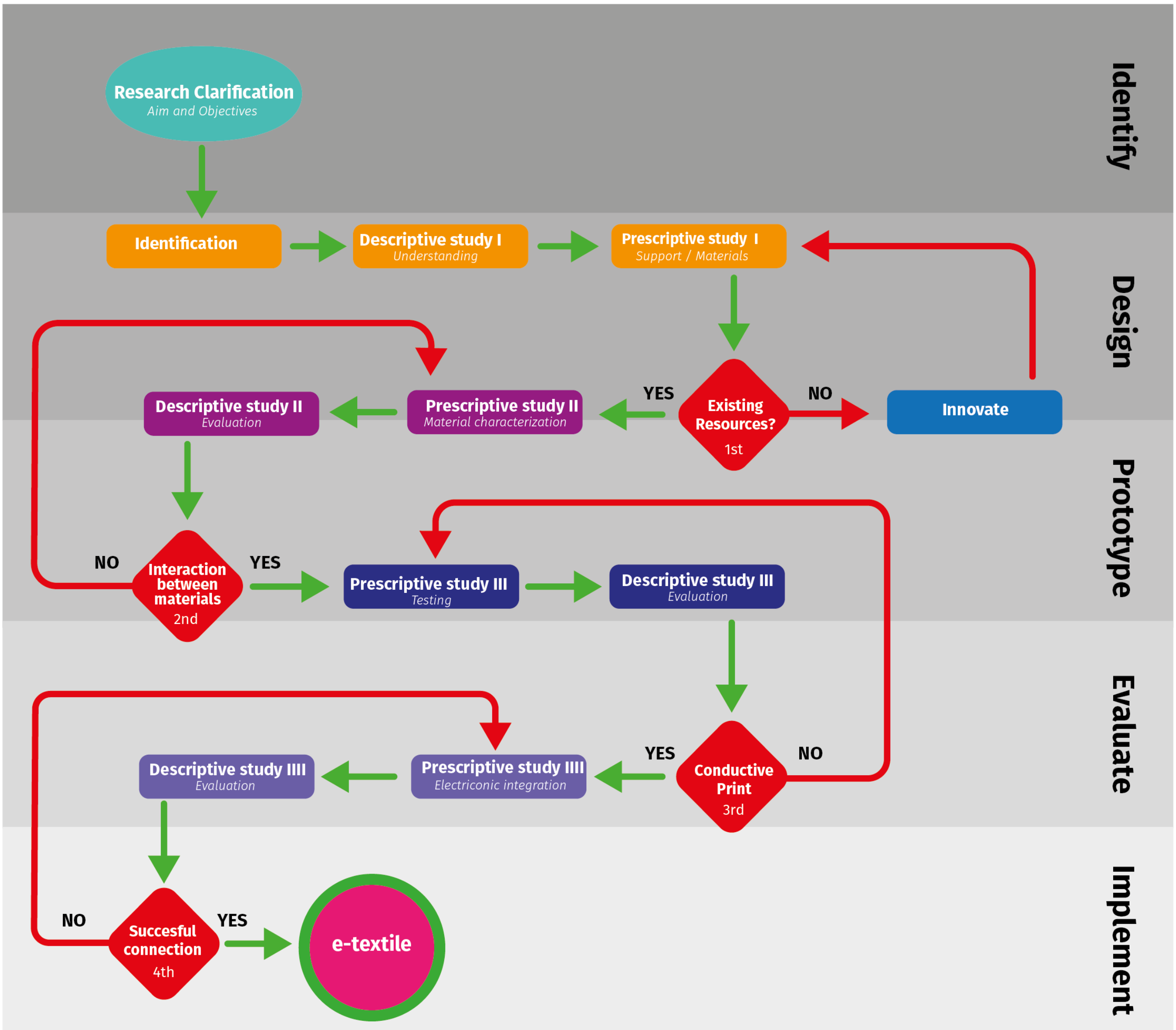


Figure 09.1 E-textile manufacturing Methodology.
Diagram based on the Design Research Methodology Framework by Blessings and Chakrabarti(2009), User-Centred Design(UCD) and E-textiles lifetime cycle of Marculescu et al. (2004).

Limitations

As with any study, this thesis does not fully explore all the printing processes standards in the industry. The latter, in conjunction with a lack of existing manufacturing methodologies, limited the extent of the present research. Nevertheless, by acknowledging such a gap in knowledge, the researcher has presented a methodology to create a bridge between multiple disciplines to encourage new developments in this area of study.

Additional to the limitations mentioned above, the researcher acknowledges that while the Inkjet printing process failed, there are methods to create conductive prints that involve the use of pre-treatments or coatings. The use of pre-treatments can create non-porous surfaces where the conductive ink can be deposited without being absorbed, effectively creating a new layer on top of the original substrate. The focus of this work is on the use of natural substrates; thus, while the use of Inkjet printing is of relevance due to the easiness of automation, testing the viability of Inkjet printing using pre-treatment coatings was not considered for this work.

In the textile industry, it is common to lack the complete manufacturing information of a textile sample. For this reason, the researcher acknowledges that the textiles fibres can be different at a thread level. The gauge of the thread can be different from batch to batch due to the manufacturing process. For instance, in polyester fibres the thread gauge can present lower variability as the structure is less porous and can be standardised during manufacturing. In contrast, cotton and bamboo thread gauges can vary significantly between batches as they are manufactured from organic compounds. The reproducibility of this work can be improved by having more control over the textile thread manufacturing process and by knitting or weaving the threads in-house to a specific specification. The latter is to ensure tight and uniform textile structures.

One of the main challenges of electronic textiles is the continuous interaction with the human body. The human body can act as a capacitor in certain scenarios, storing electric charge when insulated. A simple example of this is the interaction between synthethic fabrics and skin; friction can charge the human body with approximately 3 to 5 kV. Such charges can cause unwanted behaviour when operating electronic devices or even damage equipment. On the other hand, it can also be used to generate a response (e.g. touch sensors). For this reason, it is important to fully understand the response of conductive inks in textiles, since both inductive and capacitive parasitic effects can generate unwanted device behaviour, specially at high frequencies.

Another significant limitation of the study is the frequency range used in the EIS characterisation of the sample. Current microcontroller are high speed, but their inter-connects/coms are unlikely to be more than 100 kHz. For I2C coms, interconnect capacitance is an issue. Moreover, as shown in the results, the setup employed in the EIS experiments was far from ideal as the use of cable clips further introduced a parasitic element to the final impedance spectra. The latter can be improved by using a static fixture to analyse all samples without the variability of the cables. Furthermore, the present work uses a network analyser that can measure impedances as low as 10 mΩ. Therefore, using highly specialised impedance analysers that can measure below the mΩ can further enhance the electrical characterisation of e-textiles.

The researcher acknowledges that the conductive ink used in the present experiments is highly toxic and harmful to the environment. This thesis focused on the use of the most common inks and creating a printing methodology. However, the methodology can be reproduced using inks that offer a more sustainable approach.

Futher Work

The present study shows that there are multiple avenues for the improvement of e-textiles. The author has identified multiple aspects that are relevant to the area of study:

- Extend the methodology to include print testing under harsh environments. In order for e-textiles to be considered for every-day use, they should be able to last and be used as regular garments. This will help end-users to adopt the technology much faster.
- Analyse eco-friendly inks. Proven conductive inks have demonstrated the feasibility of the technology; nevertheless, it is our duty as designers and engineers to create new technologies for the betterment of the world, including our environment.
- Study of automated screen-printing. The present work shows that screen printing is a viable printing method; however, the manual approach will inherently introduce a degree of human error. For this reason, an automated approach should be considered to extend the control of the printing parameters and reduce human error.
- Explore more textile structures. This work was focused on the use of basic textile structures. Nevertheless, the

fashion industry employs a mix of textile structures that vary depending on the application. Therefore, the study of other textile structures would better inform which printing processes are more suitable for them.

- Analyse other materials. The textile substrates used in this thesis were selected to show the feasibility of organic materials as e-textile substrates. As the fashion industry is moving towards more sustainable materials, designers should consider the use of the methodology presented in this work as a means to create conductive garments or to understand their limitations.
- Study the integration of complex circuitry. PCBs can be considered as the gold standard of substrates for electronic components. Therefore, it is essential to explore how to translate industry-led design requirements into e-textiles. PCBs rely on the use of multi-layer interconnectivity, something that is quite common in the fashion industry.

We are never without textiles; whether used in garments, accessories or upholstery, textiles are ever present in our daily life. They offer endless possibilities to help us improve the way we live and improve our environment. The development of wearable sensors has opened the door to collaboration between electronics and textiles. Thanks to the versatility textiles offer regarding materials and structure, combined with the intelligence and monitoring capability of electrical components, e-textiles can exist. However, this sector urges the collaboration between designers, engineers, chemists, user experience experts, product designers and other disciplines to provide user-friendly products. Until now, we have witnessed a large amount of research, and we have arrived at the point where electronic components can be embedded on a thread. However, many other manufacturing techniques such as textile printing can offer user-friendly solutions, technology integration and aesthetic and comfort considerations. This research has proven that bridges between engineering, product design, and fashion design can be built to enhance the research on e-textiles. It is for future researchers in these fields to take on the challenge of building these bridges between disciplines and also the bridge between the manufacturer and the end user.

Bibliography

- Abu-Rous, M., Dabolina, I., and Lapkovska, E. (2018). “Fabric physical properties and clothing comfort”. In: *IOP Conference Series: Materials Science and Engineering* 459.1 doi: 10.1088/1757-899X/459/1/012028.
- Aileni, Raluca Maria et al. (2019). “Health Monitoring Using Wearable Technologies and Cognitive Radio for IoT”. *Cognitive Radio, Mobile Communications and Wireless Networks*. EAI/Springer Innovations in Communication and Computing, Springer International Publishing, pp. 143–165.
- Alagirusamy, R. and Das, A., (2010). “Technical textile yarns : industrial and medical applications”. CRC Press, Woodhead Publishing. pp.140-148.
- Ali, Aidy et al. (2011). “Development of Anti-Ballistic Board from Ramie Fiber”. *Polymer- Plastics Technology and Engineering 50*, pp. 622-634. *doi: 10.1080/03602559.2010.551381*
- Ando, Bruno and Baglio, Salvatore. (2013). “All-inkjet printed strain sensors”. In: *IEEE Sensors Journal* 13, 4874–4879. doi: 10.1109/JSEN.2013.2276271.
- Andrew, Trisha L. (2020). “The Future of Smart Textiles: User Interfaces and Health Monitors”. *Matter* 2, pp. 794–795. doi: 10.1016/J.MATT.2020.03.011.
- Ariyatum, B., Holland, R., Harrison, D., & Kazi, T. (2005). “The future design direction of Smart Clothing development”. *Journal of the Textile Institute* 96.4, pp. 199–210. doi: 10.1533/joti.2004.0071.
- Ashby, Michael F. and Johnson, Kara. (2014). “Materials and Design : the Art and Science of Material Selection in Product Design: Third Edition.” Elsevier, doi: 0.1016/C2011-0-05518-7
- Atae-Allah, C., Cabrerizo-Vílchez, M., Luque-Escamilla, P.L., (2001). “Measurement of surface tension and contact angle using entropic edge detection”.*Measurement Science and Technology* 12, pp. 288–298. doi: 10.1088/0957-0233/12/3/307.
- Ballou, J.W. (1954). “Static Electricity in Textiles:”. *Textiles Research Journal 24*, ,pp. 146–155. doi: 10.1177/004051755402400209
- Basadur, M., Gelade, G., and Basadur, T., (2014). “Creative Problem-Solving Process Styles, Cognitive Work Demands, and Organizational Adaptability”. *Journal of Applied Behavioral Science 50*. pp. 80–115 doi: 10.1177/0021886313508433.
- Behera, B. K., (2015). “Role of fabric properties in the clothing-manufacturing process”. *Garment Manufacturing Technology*, Elsevier. doi: 10.1016/B978-1-78242-232-7.00003-5.
- Bidoki, S. M., McGorman, D., Lewis, D., Clark, M., Horler, G., Miles, R.E., (2005) “Inkjet printing of conductive patterns on textile fabrics”. *AATCC Review 5.6,* pp. 11–14.
- Blessing, L.T.M.,Chakrabarti, A. (2009). DRM, a Design Research Methodology, Springer London, doi:10.1007/978-1-84882-587-1

BIBLIOGRAPHY

- Bonato, P., (2005). “Advances in wearable technology and applications in physical medicine and rehabilita-tion”. *Journal of NeuroEngineering and Rehabilitation*. doi.org/10.1186/1743-0003-2-2.
- Bonato, P., (2010). “Advances in wearable technology and its medical applications”. In: *2010 Annual Interna-tional Conference of the IEEE Engineering in Medicine and Biology Society, EMBC’10*. pp. 2021–2024. doi: 10.1109/IEMBS.2010.5628037.
- Bralla, J. G., (2007). “Stainles Steel”. In: *Handbook of Manufacturing Processes*, Industrial Press, Inc, New York, USA, p. 761.
- Brookes, A.M.P., (1975). “Basic Electric Circuits”. *Basic Electric Circuits*, Pergamon International Library of Science, Technology, Engineering and Social Studies. p. 353. doi: 10.1016/c2013-0-05683-6.
- Brundle, C. R., Evans, C.A., and Wilson., (1992). “Encyclopedia of materials characterization : surfaces, interfaces, thin films”. *Gulf Professional Publishing.* pp. 5-57.
- Buechley, L., (2010). “LilyPad Arduino: rethinking the materials and cultures of educational technology”. *Proceedings of the 9th International Conference of the Learning Sciences 2,* pp. 127- 128, doi: 10.5555/1854509.
- Buechley, L., Eisenberg, M., (2008). “The LilyPad Arduino: Toward wearable engineering for everyone”. *IEEE Pervasive Computing* 7.2, pp. 12–15. doi: 10.1109/MPRV.2008.38.
- Buechley, L., Hill, BM(2010). “LilyPad in the Wild: How Hardware’s Long Tail is Supporting New Engineering and Design Communities”. *8 th ACM Conference on Designing Interactive Systems.* pp.199-207. doi: 10.1145/1858171.
- Buechley, L., Eisenberg, M., Catchen, J., Crockett, A., (2008). “The LilyPad Arduino: Using Computational Textiles to Investigate Engagement, Aesthetics, and Diversity in Computer Science Education”. *Conference on Human Factors in Computing Systems - Proceedings.* pp. 423–432. doi: 10.1145/1357054.1357123.
- Cahn, R. W., Lifshin, E., (1993). “Concise encyclopedia of materials characterization”. *International Materials Reviews 39*, pp. 48. doi:10.1179/imr.1994.39.1.48
- Carpi, F., De Rossi, D., (2005). “Electroactive polymer-based devices for e-textiles in biomedicine”. *IEEE Transactions on Information Technology in Biomedicine*. doi: 10.1109/TITB.2005.854514.
- Carron, A.L. (1911). *Electric-Heated Glove.* U.S. Patent 1,011,574.
- Cash, P., and Stanković, T., Štorga, M., (2016). " Experimental Design Research Approaches, Perspectives".*Experimental Design Research: Approaches, Perspectives, Applications. Springer International Publishing.* doi:10.1007/978-3-319-33781-4.
- Cassidy, T., Goswami, P., (2017). “Textile and Clothing Design Technology”. *Textile and Clothing Design Technology.* CRC Press. doi: 10.1201/9781315156163.
- Castano, L.M., Flatau, A.B., (2014). “Smart fabric sensors and e-textile technologies: a review”. *Smart Materials and Structures*. doi: 10.1088/0964-1726/ 23/5/053001.
- Chen, A., Kong, H., (2020). “The Design and Creation of Tactile Knitted E-textiles for Interactive Applications”. *Fourteenth International Conference on Tangible, Embedded, and Embodied Interaction (TEI '20). Association for Computing Machinery,* pp. 905–909. doi: 10.1145/ 3374920.3374959.
- Chen, H., Miao, M., Ding, X., (2009). “Influence of moisture absorption on the interfacial strength of bamboo/vinyl ester composites”. *Composites Part A: Applied Science and Manufacturing 40*. pp. 2013–2019. doi: 10.1016/J.COMPOSITESA.2009.09.003.
- Chen, S., Chiu, H., Wang, P., Liao, Y.-P., (2015). “Inkjet Printed Conductive Tracks for Printed Electronics”. *ECS Journal of Solid State Science and Technology 4.4,* pp.3026-3033. doi: 10.1149/2. 0061504jss.

- Christie, R.M., (2015). “Colour Chemistry 2nd edition”. *Royal Society of Chemistry*. Thomas Graham House. pp 168 - 212.
- Chung, D.D. L., (2001). “Applied Materials Science : Applications of Engineering Materials in Structural, Electronics, Thermal, and Other Industries ”. doi: 10.1201/ 9781420040975.
- Cicek, M., (2015). “Wearable Technologies And Its Future Applications”. *International Journal of Electrical, Electronics and Data Communication* 3.4, pp. 45–50.
- Cooklin, G., Hayes, S., McLoughlin, J., Fairclough, D., (2011) “Cooklin’s garment technology for fashion designers”. John Wiley & Sons. pp. 55-99.
- Copper Alliance. (1990). "Properties of copper - electrical and thermal conductivity". 2018. url: https : / /copperalliance.org.uk / about-copper / copper-alloys / properties-copper/, (date accessed 09/03/2021).
- Mirvis, P.H., Csikszentmihalyi, M., (1991). “Flow : the psychology of optimal experience”. *The Academy of Management Review 16, 636.* doi:10.2307/258925.
- Custodio, V., Herrera, F., López, G., Moreno, J., (2012). “A Review on Architectures and Communications Technologies for Wearable Health-Monitoring Systems”. *Sensors 2012, Vol. 12.* doi: 10.3390/S121013907.
- Das, B., Das, A., Kothari, V., Fanguiero, R., Araujo, M., (2009). “Moisture flow through blended fabrics - Effect of hydrophilicity”. *Journal of Engi-neered Fibers and Fabrics* 4.4. doi: 10.1177/155892500900400405.
- Das, S., (2010). “Fibres and fabrics used in home textiles”. *Performance of Home Textiles*, pp. 22–41. doi: 10.1533/9780857094032.22.
- Dubrovski, P.D., (2000). "Volume Porosity of Woven Fabrics". *Textile Research Journal 70.10,* doi: 10.1177/004051750007001011.
- Dudovskiy, J., (2016). "The Ultimate Guide to Writing a Dissertation in Business Studies: A Step-by-Step Assistance." url:http://research-methodology.net/about-us/ebook/, (date accessed 05/09/2020).
- Dumitrescu,I., Nello, L., Iordache, O., Bima, G., (2014). “The influence of the textile materials structure on the screen printed circuits’ characteristics”. *Industria Textila* 65.6 , pp. 310–317.
- Dunne, L., (2010). “Smart Clothing in Practice: Key Design Barriers to Commercialization”. *Fashion Practice 2.1*, pp. 41–65. doi: 10.2752/175693810x12640026716393.
- Elmogahzy, Y.E., (2020). “Basic attributes of textile products”. In: Engineering Textiles. Elsevier,, pp. 299–doi: 10.1016/B978-0-08-102488-1.00012-5.
- Everett, C., (2015). “Can wearable technology boost corporate wellbeing?” *Occupational Health 67.8*. pp. 12–13.
- Faruk, O,. Tjong, J., Sain, M., (2017). "Lightweight and sustainable materials for automotive applications."
- CRC Press, doi: 10.1201/9781315152967.
- Fasolt, B., Hodgins, M., Rizzelo, G., Seelecke, S., (2017). “Effect of screen printing parameters on sensor and actuator performance of dielectric elastomer (DE) membranes”. Sensors and Actuators A: Physical 265, pp. doi: 10.1016/J.SNA.2017.08.028.
- Fernandes, I.J., Aroche, A.F., Lamberty, P., Peter, C., Hasenkamp, W., Rocha, T.L., (2020) “Silver nanoparticle conductive inks: synthesis, characterization, and fabrication of inkjet-printed flexible electrodes”. *Scientific Reports 10.1.* doi: 10.1038/s41598-020-65698-3.
- Fernández-Caramés, T.M., Fraga-Lamas, P., (2018).“Towards the internet-of-smart-clothing: A review on IoT wearables and garments for creating intelligent connected E-textiles”. *Electronics (Switzerland) 7.12.* doi: 10.3390/electronics7120405.
- Fu, K.K., Padbury, R., Toprakci, O., Dirican, M., Zhang, X., (2017). "Conductive textiles". Engineering of High-Performance Textiles, Elsevier, pp. 305–doi: 10.1016/B978-0-08-101273-4.00017-2.

BIBLIOGRAPHY

- Gasana, E., Westbroek, P., Hakuzimana, J., De Clerck, K., Priniotakis, G., Tseles, D., (2006). "Electroconductive textile structures through electroless deposition of polypyr-role and copper at polyaramide surfaces". *Surface and Coatings Technology 201*, pp. 3547–3551. doi: 10.1016/SURFCOAT.2006.08.128.
- Gersak, J. (2013). "Design of clothing manufacturing processes: A systematic approach to planning, scheduling and control". *Design of Clothing Manufacturing Processes: A Systematic Approach to Planning, Scheduling and Control*, pp. 1–306. doi: 10.1533/9780857097835.
- Ghosh, T. K., Dhawan, A., & Muth, J. F. (2006). "Formation of electrical circuits in textile structures". *Intelligent Textiles and Clothing*, pp. 239–282. doi: 10.1533/9781845691622.3.239.
- Godfrey, A., Hetherington, V., Shum, H., Bonato, P., Lovell, N., Stuart, S., (2018). "From A to Z: Wearable technology explained". *Maturitas* 113. doi: 10.1016/j.maturitas.2018.04.012.
- Gonçalves, C., da Silva, A. F., Gomes, J., & Simoes, R. (2018). "Wearable E-Textile Technologies: A Review on Sensors, Actuators and Control Elements". *Inventions 2018*, Vol. 3, doi: 10.3390/INVENTIONS3010014.
- Gong, H., Ozgen, B. (2018). "Fabric structures: Woven, knitted, or nonwoven". E*ngineering of High-Performance Textiles*. Elsevier, pp. 107–131. doi:10.1016/B978-0-08-101273-4.00007-X
- Good, R.J., (1992). "Contact angle, wetting, and adhesion: a critical review". J*ournal of Adhesion Science and Technology* 6.12, pp. 1269–1302. doi: 10.1163/156856192X00629.
- Gregersen, E., (2018). "Electric circuit, Diagrams and Examples". Encyclopedia Britannica, url: https://www.britannica.com/technology/electric-circuit.
- Gries, T., Veit, D., Wulfhorst, B., (2015). "Textile Technology". Textile Technology, doi: 10.3139/9781569905661.
- Grishanov, S., (2011). "Structure and properties of textile materials". *Handbook of Textile and Industrial Dyeing: Principles, Processes and Types of Dyes, Vol 1,* , pp. 28–63. doi: 10.1533/9780857093974.1.28.
- Hayes, S.G., George., Venkatraman, P., (2015). "Materials and Technology for Sportswear and Performance Apparel". CRC Press, 2015, p. 358.
- Hayward, J., (2020). E-textiles and Smart Clothing 2020-2030: Technologies, Markets and Players. url: https://www.idtechex.com/en/research-report/e-textiles-and-smart-clothing-2020-2030-technologies-markets-and-players/735, (date accessed 08/16/2021)
- Hazen, R., (2021). "Electric Circuits: Components, Types, and Related Concepts." url: https://www.wondriumdaily.com/electric-circuits-components-types-and-related-concepts/, (date accessed 09/11/2021)
- Hong, H., Hu, J., Yan, X., (2019). "UV Curable Conductive Ink for the Fabrication of Textile-Based Conductive Circuits and Wearable UHF RFID Tags". *ACS Applied Materials and Interfaces 11.30*, pp. 27318–27326. doi: 10.1021/acsami.9b06432.
- Hook, J.R., (2003). "An introduction to porosity". 2003. url: https://onepetro.org/petrophysics/article-abstract/171017/An-Introduction-to-Porosity, (date accessed 09/28/2021)
- Hopper, L., Joyce, R., Irving, K., (2016) "Using Assistive Technology to Support Therapeutic Interventions with People with Dementia: Findings from the Dem@Care Intervention Studies in Ireland". *Alzheimer's and Dementia. Abstract Supplement 12.7*, doi: 10.1016/j.jalz.2016.06.2088.
- Hughes-Riley, T., Dias, T., Cork, C., (2018)."A historical review of the development of electronic/textiles". *Fibers 6.2,* doi: 10.3390/fib6020034.
- IBM. IBM100 - Copper Interconnects: The Evolution of Microprocessors. 2021. url: https://www.ibm.com/ibm/history/ibm100/us/en/icons/copperchip/ (date accessed 09/28/2021).

BIBLIOGRAPHY

- Inoue, M., Tada, Y., Muta, H., Hayashi, Y., Tokumaru, T., (2012). “Development of highly conductive inks for smart textiles”. *14th International Conference on Electronic Materials and Packaging (EMAP)*, doi: 10.1109/EMAP.2012. 6507896.
- Izdebska, J., (2015). "Printing on Polymers: Fundamentals and Applications". Elsevier, https://doi.org/10.1016/C2014-0-02411-2
- Jakšić, D., J akšić, N., (2007). " Assessment of Porosity of Flat Textile Fabrics". *Textile Research Journal 77.2* doi: 10.1177/ 0040517506065892.
- Jamale,A.P ., Bhosale, C.H., Jadhav, L.D. (2016). “ Effect of Screen-Printing Mesh Opening Diameter on Microstructural and Electrical Properties of $La_{0.6}Sr_{0.4}Co_{0.2}Fe_{0.8}O_{3-\delta}$ Thick Films”. *Journal of Electronic Materials* 4 5.1, pp. 509–514. doi: 10.1007/S11664-015-4139-0.
- Kao, H., Chuang, C., Chang, L., Cho, C., Chiu, H., (2019). “Inkjet-printed silver films on textiles for wearable electronics applications”. *Surface and Coatings Technology*, pp. 328–332. doi: 10.1016/j.surfcoat. 2019.01.076.
- Karana, E,. Pedgley, O., Rognoli, V., (2013). “Materials Experience: Fundamentals of Materials and Design”.*Materials Experience: Fundamentals of Materials and Design*. doi: 10.1016/C2012-0-02198-9.
- Karim, N., Afroj, S., Malandraki, A., Butterworth, S., Beach, C., Rigout, M., Novoselov, K., Casson, A., Yeates, S.G., (2017). “All inkjet-printed graphene-based conductive patterns for wearable e-textile applications”. *Journal of Materials Chemistry C* 5.44, pp. 11640–11648. doi: 10.1039/C7TC03669H.
- Kastner, J., Faury, T., Außerhuber, H., Obermüller, T., Leichtfried, H., Haslinger, M., Liftinger, E., Innerlohinger, J., Gnatiuk, I., Holzinger, D., Lederer, T., (2017). “Silver-based reactive ink for inkjet-printing of conductive lines on textiles”. *Microelectronic Engineering* 176 , pp. 84–88. doi: 10.1016/J.MEE.2017.02.004.
- Kazani, I., Hertleer, C., de Mey, G., Schwarz, A., Guxho, G., van Langenhove, L., (2012). “Electrical conductive textiles obtained by screen printing”. *Fibres and Textiles in Eastern Europe* 90.1, pp. 57–63.
- Keddam, M., Rakotomavo, C., Takenouti, H., (1984). “Impedance of a porous electrode with an axial gradient of concentration”. In: *Journal of Applied Electrochemistry* 14, pp. 437–448. doi: 10.1007/BF00610808.
- Kekade, S., Hseieh, C.H, Islam, M., Atique, S., Mohammed Khalfan, A., Li, Y., Abdul, S.S., (2018). “The usefulness and actual use of wearable devices among the elderly population”. *Computer Methods and Programs in Biomedicine* 153, pp. 137–159. doi: 10.1016/j.cmpb.2017.10.008.
- Fu, K.K., Padbury, R., Toprakci, O,. Dirican, M., Zhang, X., (2017). “Conductive textiles”. *Engineering of High-Performance Textiles.* The Textile Institute Book Series. Woodhead Publishing, pp. 305–334. doi:10.1016/B978-0-08-101273-4.00017-2.
- Khukharev , V.V., (2016). “Electric circuits”. *Gas Lasers*, Addison-Wesley, pp. 183–199. doi: 10.2307/1798844.
- Kim, Y., Kim, H., Yoo, H., (2010). “Electrical Characterization of Screen-Printed Circuits on the Fabric”. *IEEE Transactions on Advanced Packaging 33.1*, pp. 196–205. doi: 10.1109/TADVP. 2009.2034536.
- Kirongo, A.C., Odoyo, C.O., (2020). “Research Philosophy Design and Methodologies : A Systematic Review of Research Paradigms in Information Technology”. *Global Scientific Journals 8.5*, pp. 33–38.
- Knipp, D., (2016) “Introduction to Electronic Devices”. University of Bremen. pp. 1–64. url: http://www.faculty.iu- bremen.de/dknipp/
- Komolafe, A., Nunes-Matos, H., Glanc-Gostkiewicz, M., Torah, R., (2020). “Influence of textile structure on the wearability of printed e-textiles”. I *FLEPS 2020 - IEEE International Conference on Flexible and Printable Sensors and Systems* . doi: 10.1109/FLEPS49123.2020.9239562.

BIBLIOGRAPHY

- Komolafe, A. O., Nunes-Matos, H., Glanc-Gostkiewicz, M., Torah, R. N., (2021). "Evaluating the Effect of Textile Material and Structure for Printable and Wearable e-Textiles". *IEEE Sensors Journal* 21.16, pp. 18263–18270. doi: 10.1109/JSEN.2021. 3086235.
- Krykpayev, B., Farooqui, M.F., Bilal, R., Vaseem, M., Shamim, A., (2017). "A wearable tracking device inkjet-printed on textile". *Microelectronics Journal* 65, pp. 40–48. doi: 10.1016/j.mejo.2017.05.010.
- Kumar, B., Hu, J. (2017). "Woven fabric structures and properties". *Engineering of High-Performance Textiles. Elsevier* , pp. 133–151. doi: 10.1016/B978-0-08-101273-4.00004-4.
- Kuroda, T., Takahashi, H., Masuda, A., (2020). "Woven electronic textiles". *Wearable Sensors* , pp. 249–275. doi: 10.1016/b978-0-12-819246-7.00009-7.
- Kwok, D.Y., Gietzelt, T., Grundke, K., Jacobasch, H., Neumann, A.W., (1997). "Contact Angle Measurements and Contact Angle Interpretation. 1. Contact Angle Measurements by Axisymmetric Drop Shape Analysis and a Goniometer Sessile Drop Technique". *Langmuir* 13.10, pp. 2880–2894. doi: 10.1021/la9608021.
- Lakafosis, V., Rida, A., Vyas, R., Yang, L., Nikolaou, S., Tentzeris, M.M., (2010). "Progress towards the first wireless sensor networks consisting of inkjet-printed, paper-based RFID-enabled sensor tags". *Proceedings of the IEEE* 98.9, pp. 1601–1609. doi: 10.1109/JPROC.2010.2049622.
- Levine, D.M., Lipsitz, S.R., Linder, J.A., (2016). "Trends in seniors' use of digital health technology in the United States, 2011-2014". *JAMA - Journal of the American Medical Association* 316.5 (2016), pp. 538–540. doi: 10.1001/jama.2016.9124.
- Li, Y., Yong, S., Hillier, N., Arumugam, S., & Beeby, S. (2020). "Screen Printed Flexible Water Activated Battery on Woven Cotton Textile as a Power Supply for E-Textile Applications". *IEEE Access* 8, pp. 206958–206965.. doi: 10.1109/ACCESS.2020.3038157.
- Lim, H. B., Ma, D., Wang, B., Kalbarczyk, Z., Iyer, R. K., & Watkin, K. L. (2010). "A soldier health monitoring system for military applications". In: 2010 International Conference on Body Sensor Networks, pp. 246–249. doi: 10.1109/BSN.2010.58.
- Locher, I., & Tröster, G. (2007). "Screen-printed Textile Transmission Lines". *Textile Research Journal* 77.11 , pp. 837–842. doi: 10.1177/0040517507080679.
- Lund, A., van der Velden, N. M., Persson, N. K., Hamedi, M. M., & Müller, C. (2018). "Electrically conducting fibres for e-textiles: An open playground for conjugated polymers and carbon nanomaterials". M*aterials Science and Engineering: R: Reports* 126 , pp. 1–29. doi: 10.1016/J.MSER.2018.03.001.
- Marculescu, D., Marculescu, R., Zamora, N. H., Stanley-Marbell, P., Khosla, P. K., Park, S., ... Nakad, Z. (2003). "Electronic textiles: A platform for pervasive computing". *Proceedings of the IEEE. Vol. 91. 12*, pp. 1995–2016. doi: 10.1109/JPROC.2003.819612.
- Mather, R. R., & Wardman, R. H. (2011). "Chemistry of Textile Fibres : Edition 2". *Royal Society of Chemistry,* pp. 260–314.
- McCann, J., Hurford, R., & Martin, A. (2005). "A design process for the development of innovative smart clothing that addresses end-user needs from technical, functional, aesthetic and cultural view points". *Proceedings - International Symposium on Wearable Computers*, pp. 70–77. doi: 10.1109/ISWC.2005.3.
- McLaren, A., Stevenson, F., & Valentine, L. (2017). "Collaborative user-centred textile design research for health-care: improving wellbeing and increasing performance". *Intersections: Collaborations In Textile Design Research Conference, Loughborough University London, Queen Elizabeth Olympic Park*, pp. 1–15.

- Meng, K., Zhao, S., Zhou, Y., Wu, Y., Zhang, S., He, Q., Wang, X., Zhou, Z., Fan, W., Tan, X., Yang, J., Chen, J. (2020). “A Wireless Textile-Based Sensor System for Self-Powered Personalized Health Care”. *Matter* 2.4 , pp. 896–907. doi: 10.1016/J.MATT.2019.12.025.
- Misnon, M. I., Islam, M. M., Epaarachchi, J., (2013). “Textile material forms for reinforcement materials: a review”. pp. 105–123.
- Mondal, K., (2018). “Recent Advances in Soft E-Textiles”. *Inventions 2018, Vol. 3, Page 23* 3.2 , p. 23. doi: 10.3390/INVENTIONS3020023.
- Morton, W.E., Hearle, J.W.S. (2008). “An introduction to fibre structure”. *Physical Properties of Textile Fibres* , pp. 1–81. doi: 10.1533/9781845694425.1.
- Nayak, R., & Padhye, R., (2015). “Garment Manufacturing Technology”. *Garment Manufacturing Technology* , pp. 1–498. doi: 10.1016/C2013-0-16494-X.
- Negm, M., & Sanad, S., (2020). “Cotton fibres, picking, ginning, spinning and weaving”. In: *Handbook of Natural Fibres: Volume 2: Processing and Applications*, Woodhead, pp. 3–48. doi: 10.1016/B978-0-12-818782-1.00001-8.
- Novikov, A. M., & Novikov, D. A., (2013). "Research Methodology: From Philosophy of Science to Research Design". CRC Press. isbn: 0203764722.
- Omid, N., Sujan, D., Jack, K. B., Mohammad, Y. A(2018). “Mechanical performance and moisture absorption of unidirectional bamboo fiber polyester composite”. *Materials Science Forum* , pp. 88–94. doi: 10.4028/WWW. SCIENTIFIC.NET/MSF.911.88.
- Orzada, B. T., (2001). “Effects of grain alignment on fabric mechanical properties”. *Clothing and Textiles Research Journal* 19.2 , pp. 52–63. doi: 10.1177/0887302X0101900202.
- Otim, T., Díez, L. E., Bahillo, A., Lopez-Iturri, P., & Falcone, F., (2019). “A comparison of human body wearable sensor positions for UWB-based indoor localization”. *International Conference on Indoor Positioning and Indoor Navigation*, pp. 165–171.
- Oura, K., Katayama, M., Zotov, A. V., Lifshits, V. G., & Saranin, A. A.(2003). “Wearable Sensors". *Oxford: Academic Press,* pp. 1–2. doi: 10.1007/978-3-662-05179-5_1.
- Pan, J., Tonkay, G. L., & Quintero, A., (1999). “Screen printing process design of experiments for fine line printing of thick film ceramic substrates”. *Journal of Electronics Manufacturing 9.3* , pp. 203–213. doi: 10.1142/S096031319900012X.
- Pang, C., Koo, J. H., Nguyen, A., Caves, J. M., Kim, M. G., Chortos, A., Kim, K., Wang, P., Bao, Z. (2015). “Highly Skin-Conformal Microhairy Sensor for Pulse Signal Amplification”. *Advanced Materials 27.4* , pp. 634–640. doi: 10.1002/ADMA.201403807.
- Paul, G., Torah, R., Beeby, S., & Tudor, J. (2014). “The development of screen printed conductive networks on textiles for biopotential monitoring applications”. *Sensors and Actuators A: Physical 206* , pp. 35–41. doi: 10.1016/j.sna.2013.11.026.
- Pentland, S.A., (2004). “Healthwear: Medical Technology Becomes Wearable”. pp. 42–49. doi: 10.1109/MC.2004.1297238.
- Perelaer, J., & Schubert, U. S., (2012). “Inkjet printing of interconnects and contacts based on inorganic nanoparticles for printed electronic applications”. *Inkjet-based Micromanufacturing*, pp. 347–doi: 10.1002/9783527647101.ch21.
- Perinka, N., Kim, C. H., Kaplanova, M., & Bonnassieux, Y., (2013). “Preparation and characterization of thin conductive polymer films on the base of PEDOT:PSS by ink-jet printing”. *Physics Procedia*. Elsevier, pp. 120–129. doi: 10.1016/phpro.2013.04.016.
- Postolache, O. A., Mukhopadhyay, S. C., Jayasundera, K. P., & Swain, A. K., (2017). "Sensors for Everyday Life Healthcare Settings." *Springer, Volume :22.*

- Prudenziati, M., & Hormadaly, J., (2012). “Technologies for printed films”. In: *Printed Films: Materials Science and Applications in Sensors, Electronics and Photonics*, pp. 3–29. doi: 10.1533/9780857096210.1.3
- Vásquez Quintero, A., Camara, M., Mattana, G., Gaschler, W., Chabrecek, P., Briand, D., & De Rooij, N. F., (2015). “Capacitive Strain Sensors Inkjet-printed on PET Fibers for Integration in Industrial Textile”. *Procedia Engineering. Eurosensors* , pp. 279–282. doi: 10.1016/j.proeng.2015.08.613.
- Rai, P., Kumar, P. S., Oh, S., Kwon, H., Mathur, G. N., & Varadan, V. K., (2011). “Printable low-cost sensor systems for healthcare smart textiles”. *Nanosensors, Biosensors, and Info-Tech Sensors and Systems.* 79800E. doi: 10.1117/10.1117/ 12
- Rida, A., Yang, L., Vyas, R., & Tentzeris, M. M., (2009). “Conductive Inkjet-Printed Antennas on Flexible Low-Cost Paper-Based Substrates for RFID and WSN Applications”. *IEEE Antennas and Propagation Magazine 51.3*, pp. 13–23. doi: 10.1109/MAP.2009.5251188.
- Rizwan, M., Kutty, A. A., Kgwadi, M., Drysdale, T. D., Sydanheimo, L., Ukkonen, L., & Virkki, J., (2017). “Possibilities of Fabricating Copper-based RFID Tags with Photonic-sintered Inkjet Printing and Thermal Transfer Printing”. *IEEE Antennas and Wireless Propagation Letters,* pp.99, doi: 10.1109/LAWP.2017.2682319.
- Romero, D., Molina, A., (2016). “A multidisciplinary framework and toolkit to innovate customer-centric new product development”. *IEEE International Conference on Engineering, Technology and Innovation/International Technology Management Conference*. doi: 10.1109/ICE.2015.7438638.
- Rouette, H.-K., (2001). "Encyclopedia of Textile Finishing". Springer. pp. 148-155. doi: 10.1007/978-3-642-85271-8.
- Ruchi Kholiya, S.J., (2011). “Beginning of a new era with Electronic Textiles”. *Technical Textiles.*
- Sadiku, M. N. O. (2013). “Fundamentos de Ciruitos Electricos”. McGraw-Hill Interamericana. pp. 26.
- Sahin, O., Kayacan, O., & Bulgun, E. Y., (2005). “Smart textiles for soldier of the future”. *Defence Science Journal 55.2*, pp. 195–205. doi: 10.14429/DSJ.55.1982.
- Saville, B P., (1999). "Physical testing of textiles". *The Textile Institute,* Woodhead Publishing. pp. 209-243.
- Sazonov, E., & Neuman, M. R., (2014). "Wearable sensors: Fundamentals, implementation and applications". *Elsevier,* pp. 1–634. doi: 10.1016/C2013-0-06896-X.
- Scataglini, S., Andreoni, G., & Gallant, J., (2019). “Smart Clothing Design Issues in Military Applications”. *Advances in Intelligent Systems and Computing,* pp. 158–168. doi: 10.1007/3-319-94619-1_15.
- Schneegass, S., & Amft, O., (2017). "Smart Textiles: Fundamentals, Design, and Interaction."
- Scott, K., Bakker, C., & Quist, J., (2012).“Designing change by living change”. *Design Studies 33*, pp. 279–297. doi: 10.1016/j.destud.2011.08.002.
- Sensoria. Smart sock v2.0. 2021. url: https://store.sensoriafitness.com/smart-sock-v2-sensoria-core/, (date accessed 09/28/2021).
- Seymour, S., (2008). "Fashionable Technology: The Intersection of Design, Fashion, Science and Technology.", Springer. p. 249.
- Shapiro, S., (2021). "Resistors, Capacitors, and Inductors - Electronics Reference". url: https://electronicsreference.com/module3/resistors_capacitors_inductors/
- Shishoo, R., (2015). "Textiles for Sportswear". *Elsevier Science & Technology*. doi: 10.1016/C2013-0-16491-4.
- Shur, M., (1996), “Introduction to electronic devices”. Wiley. *pp.* 1–64. isbn:9780471103486.

- Singh, M., Haverinen, H. M., Dhagat, P., & Jabbour, G. E., (2010). “Inkjet Printing—Process and Its Applications”. *Advanced Materials* 22.6, pp. 673–685. doi: 10.1002/ADMA.200901141.
- Siren Care. *Siren - The Next Step in Foot Care*. 2021. url: https://www.siren.care/(date accessed 09/28/2021).
- Solanki, S., (2018). “Why Materials Matter: Responsible Design for a Better World”. Prestel Publishing. p. 239.
- Spark Fun. *About LilyPad - SparkFun Electronics*. 2018. url: https://www.sparkfun.com/about_lilypad, (date accessed 07/18/2021).
- Spinali Design. *ZAVO - Spinali-Design*. 2021. url: https://www.spinali-design.com/pages/smart-bandage, (date accessed 06/03/2021).
- Srinivasan, R., Fasmin, F., (2021). "An Introduction to Electrochemical Impedance Spec-troscopy". CRC Press,. doi: 10.1201/9781003127932.
- Srinivasan, S., McKinley, G. H., & Cohen, R. E., (2011). “Assessing the accuracy of contact angle measurements for sessile drops on liquid-repellent surfaces”. *Langmuir* 27.22, pp. 13582–13589. doi: 10.1021/la2031208.
- Stoppa, M., & Chiolerio, A., (2014). “Wearable Electronics and Smart Textiles: A Critical Review”. *Sensors* 14.7, pp. 11957–11992. doi: 10.3390/s140711957.
- Stringer, J. E., Smith, P. J., & Derby, B., (2004). “Droplet Behaviour in Inkjet Printing”. *Materials Research Society Symposium Proceedings. Materials Research Society,* pp. 1–6. doi:10.1557/proc-860-ll2.6
- Suh, M., (2009). “Static Generation and Dissipation in Textiles”. http://www.lib.ncsu.edu/resolver/1840.16/2780.
- Suikkola, J., Björninen, T., Mosallaei, M., Kankkunen, T., Iso-Ketola, P., Ukkonen, L., Vanhala, J., Mäntysalo, M., (2016). “Screen-Printing Fabrication and Characterization of Stretchable Electronics”. *Scientific Reports* . doi: 10.1038/srep25784.
- Szentgyörgyvölgyi, R., Novotny, E., & Weimert, M., (2018). “Determining and Selecting Screen Printing Form Parameters for Printing on Paper and Textile”. pp. 347–356. doi: 10.24867/grid-2018-p42.
- Technologies, Keysight. Impedance Measurement Handbook A Guide to Measurement Technology and Techniques 6th Edition. url: www.keysight.com, (date accessed 07/22/2021).
- Technologies, Komodo. AIO Smart Sleeve , Fitness Tracker, Activity Monitor. 2021. url: https :/ / komodotec.com/product/aio-sleeve, (date accessed 08/03/2021).
- Tyler, D.J. (2008). “Carr and Latham’s Technology of Clothing Manufacture”. *Wiley-Blackwell*, 4. p. 344.
- Under Armour. Women’s UA RUSH™. 2021. url: https://www.underarmour.com/en-us/p/tops/womens-ua-rush-tricot-1-4-zip/1365127.html?dwvar_1365127_color=001&start=0& breadCrumbLast=UARecover™. (visited on 06/15/2021).
- Ujiie, H., (2006). "Digital Printing of Textiles". Woodhead Publishing. pp. 1-53. isbn:184569158X.
- Urbaniak-Domagala, W., Skrzetuska, E., Komorowska, M., & Krucinska, I., (2016). “Development Trends in Electronics Printed: Intelligent Textiles Produced with the Use of Printing Techniques on Textile Substrates”. *Printed Electronics - Current Trends and Applications* doi: 10.5772/62962.
- Venkata Krishna Rao, R., Venkata Abhinav, K., Karthik, P. S., & Singh, S. P., (2015). “Conductive silver inks and their applications in printed and flexible electronics”. *RSC Advances 5.95* , pp. 77760–77790. doi: 10.1039/c5ra12013f.
- Vervust, T., Buyle, G., Bossuyt, F., & Vanfleteren, J., (2012). “Integration of stretchable and washable electronic modules for smart textile applications”. pp. 1127–1138. doi: 10. 1080/00405000.2012.664866.

BIBLIOGRAPHY

- Vilumsone-Nemes, I., (2015). “Fabric spreading and cutting”. In: *Garment Manufacturing Technology*, pp. 221–246. doi: 10.1016/B978-1-78242-232-7.00009-6.
- Wang, G., Hou, C., & Wang, H., (2020). “Flexible and wearable electronics for smart clothing”. *Flexible and Wearable Electronics for Smart Clothing* , pp. 1–346. doi: 10.1002/9783527818556.
- Wang, Meizhong. (2010). “Understandable electric circuits”. *Understandable Electric Circuits* , pp. 1–371. doi: 10.5860/choice.48-1501.
- Wang, Ni, Zha, Anxia, and Wang, Jinxiu. (2008). “Study on the wicking property of polyester filament yarns”. In: *Fibers and Polymers* 9.1 , pp. 97–100. doi: 10.1007/S12221-008-0016-2.
- Wang, Z., Wang, W., Jiang, Z., & Yu, D., (2017). “A novel and simple method of printing flexible conductive circuits on PET fabrics”. *Applied Surface Science* , pp. 208–213. doi: 10.1016/j.apsusc.2016.09.155.
- Watkins, S., & Dunne, L., (2015). "Functional Clothing Design: From Sportswear to Spacesuits." *Bloomsbury Publishing.* Fairchild Books.
- Wearablex. Nadi X. (2021). url: https://www.wearablex.com/pages/how-it-works (date accessed 09/28/2021).
- Wei, Y., Torah, R., Yang, K., Beeby, S., & Tudor, J., (2013) “Screen printing of a capacitive cantilever-based motion sensor on fabric using a novel sacrificial layer process for smart fabric applications”. *Measurement Science and Technology*, p. 75104. doi: 10.1088/0957-0233/24/7/075104.
- Weremczuk, J., Tarapata, G., & Jachowicz, R., (2012). “Humidity Sensor Printed on Textile with Use of Ink-Jet Technology”. *Procedia Engineering. 26th European Conference on Solid-State Transducers*, pp. 1366–1369. doi: 10.1016/j.proeng.2012.09.410.
- Xu, D., & Cui, P., (2016). “Simultaneous determination of thickness, thermal conductivity and porosity in textile material design”. *Journal of Inverse and Ill-Posed Problems*, pp. 59–66. doi: 10.1515/jiip-2013-0084.
- Yang, K., Isaia, B., Brown, L. J. E., & Beeby, S., (2019). “E-Textiles for Healthy Ageing”. *Sensors 2019, Vol. 19*. doi: 10.3390/S19204463.
- Yong, L., Jian, L., Xian, L., & Bei, W., (2021). “Test and analysis of the porosity of cotton fiber assembly:” *Journal of Engineered Fibers and Fabrics 16*. doi: 10.1177/15589250211024225.
- Younes, B. (2017). “Classification, characterization, and the production processes of biopolymers used in the textiles industry”. *Journal of the Textile Institute* pp. 674–682. doi: 10.1080/00405000.2016.1180731.
- Zhang, S., Li, L., Kumar, A., (2008). "Materials characterization techniques." p. 328.

Appendix 10

Analysis Tools/Background

Digital Optical Microscope

This research used a Keyence Digital Optical Microscope, VHS -5000 Ver 1.2.1.0. It was used to analyse and characterise in detail the textiles before and after printing. The Digital optical microscope is a variation of a traditional optical microscope. The difference is that in digital microscopes a digital/microscope camera is connected, and image output is displayed on a screen and/or monitor. Most models require software and a computer to use them. The magnification of digital microscopes is determined by the size of the monitor hence their magnification capabilities are greater than those of an average optical microscope. Furthermore, the ergonomics of a digital microscope are better since they allow viewers to sit in an upright position, this is especially beneficial for those who spend many hours working with a microscope. Also, a digital microscope can be connected to a computer and projected to a large screen for audience viewing. Depending on the model the software may also allow recording video, measure, label and edit the photos taken with the digital microscope. There are many types of digital microscopes suitable for medical, industrial and research purposes, some of them are even portable. Some of the most used types of digital microscopes include:

- Biological Digital Microscopes
- Fluorescence Digital Microscopes
- Inverted Digital Microscopes
- Metallurgical Digital Microscopes
- Phase Digital Microscopes
- Polarizing Digital Microscopes
- Stereo Digital Microscopes
- USB Microscopes
- Handheld Digital Microscopes
- Portable Digital Microscopes

Figure 010.1 Keyence Digital Microscope

Micro Computed Tomography, **MicroCT**

For this research, non-destructive porosity method was used to characterise the six textile samples. These samples were studied using the Micro-CT imaging technique utilizing X-rays to see inside the textile, slice by slice. This was used to demonstrate and understand the composition of the textiles in a microscopic way, where even the fibres can be seen. Micro-CT is also called microtomography or micro computed tomography. With greatly increased resolution, it can provide volumetric information about the structure of any material. Samples can be imaged with pixel sizes as small as 100 nanometres and objects can be scanned as large as 200 millimetres in diameter. It functions by capturing a series of 2D planar X-ray images and reconstructing the data into cross-sectional slices that are then processed into 3D models.

Electrical Performance

One of the aims of this research is to analyse the electrical performance of the produced samples. Therefore, two main tests were performed; conductance test with a Digital Multimeter and the Impedance spectra, which was measured impedance using a precision LCR meter (4284A, Hewlett Packard, Japan) through a Kelvin clip fixture (TLKB1, BK Precision, China).

Resistance

For this research, the resistance was measured after each printing test to assess the electrical performance and analyse the printing parameters, making adjustments after each print until the results were favourable to continue to the next printing step.

The electrical resistivity of a material is also known as electrical resistance. Resistance is defined as how strongly a material opposes the flow of electric current.

Resistance should be measured per-unit length and unit area, the more material there is the more conductive the track will be fig. 010.2.

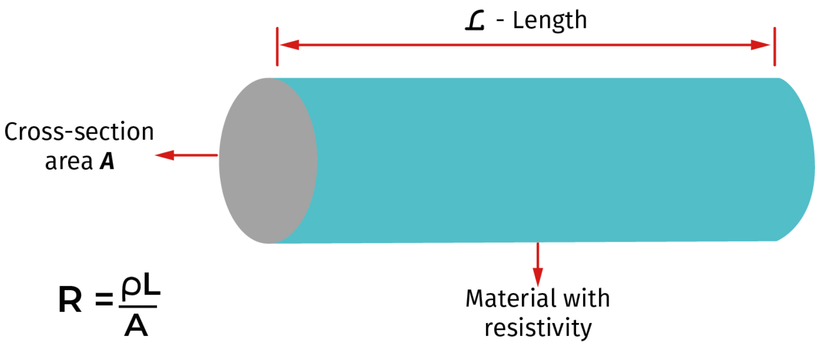


Figure 010.2 Electrical resistance
R is the resistance in ohms (Ω),L is the length in meters (m),A is the area in square meters (m^2),and where the proportional constant ρ (the Greek letter "rho")is known as Resistivity.

Electrical Impedance

Electrical Impedance represents the ability of any material to oppose alternate current (AC or in the case of direct current (DC, this term is known as Resistance (R All materials have some degree of electrical resistance, which causes some energy to be lost as heat in the circuit; this has the effect of reducing the flow of current (Sadiku, 2013. In the case of direct current (DC, resistance depends completely upon the materials from which the circuit is made. However, for an alternating current (AC, two additional factors can contribute to impedance: capacitance and inductance. These are known as reactance, which is a measure of opposition to a change in current that depends on its frequency, as well as on the components of the circuit (Srinivasan et al., 2011).

Kelvin Impedance Measurement

The Kelvin measurement is used to avoid errors by wire resistance. This measurement uses specific equipment called ”Kelvin clips” these facilitate the 4-point connection avoiding errors and noise from the cables. However, it all depends on the setup and the sample that is being tested (*Impedance Measurement Handbook A Guide to Measurement Technology and Techniques 6th Edition*).

The Impedance measurement was used to characterise the electrical performance of the textile samples under different frequencies. This information is highly useful since it can advise on which components can be connected, how they will perform, and how reliable they will be.

Multimeter

A multimeter also known as a multitester, a volt/ohm meter or VOM, is an electronic measuring instrument that can measure voltage, current, and resistance for DC and AC signals. There are analog multimeters (where the point of a microammeter moves over a scale calibration for the different measurements) and digital multimeters (which display digits or a bar of a length proportional to the quantity measured). Multimeters are usually hand-held devices and are mostly used to troubleshoot electrical problems ranging from industrial to household devices. For this research a multimeter was used to verify the conductance of the used inks.

Textile samples with scale bar

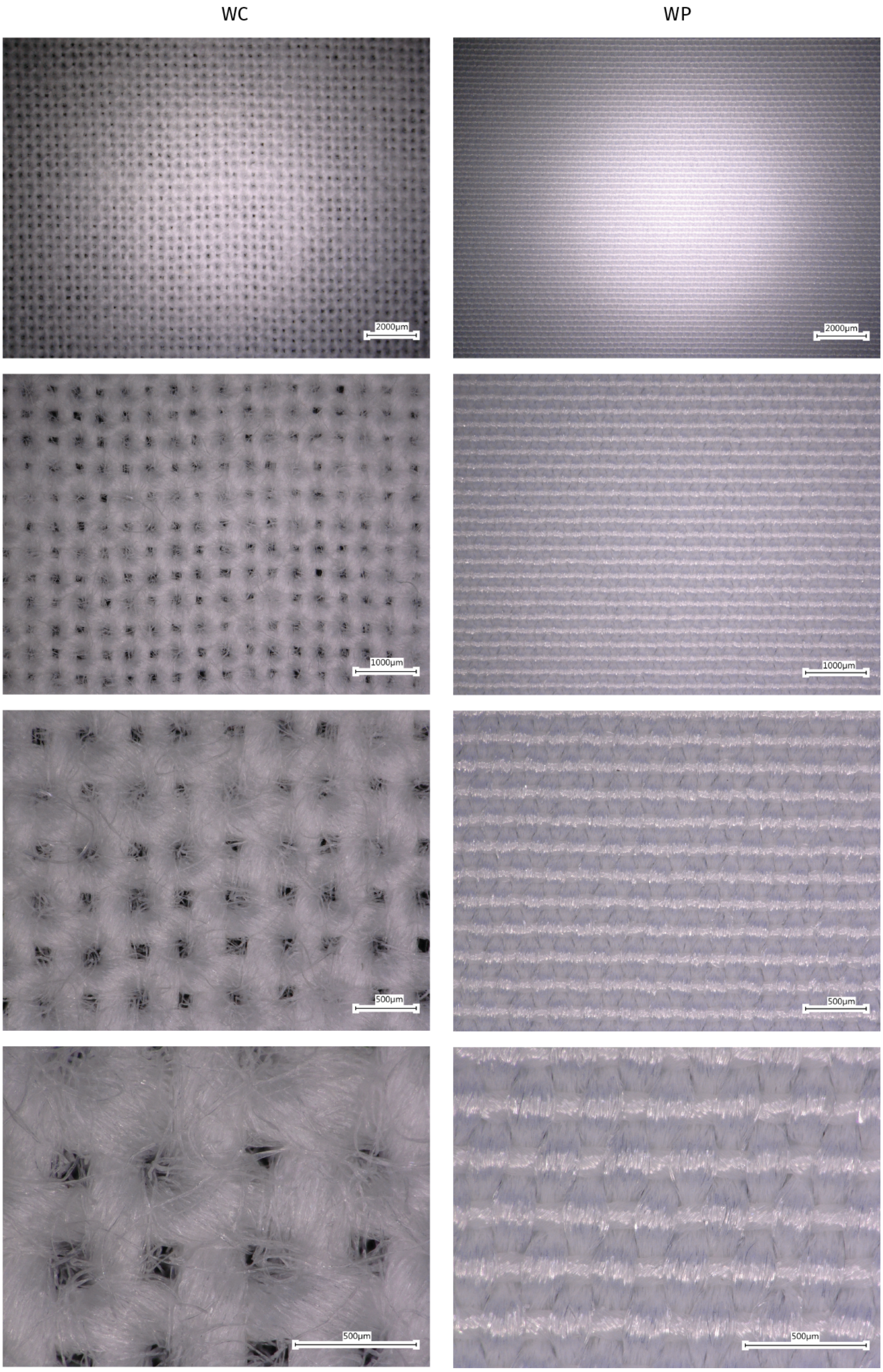


Figure 010.3 WC- woven cotton, WP- woven polyester

Textile samples with scale bar.

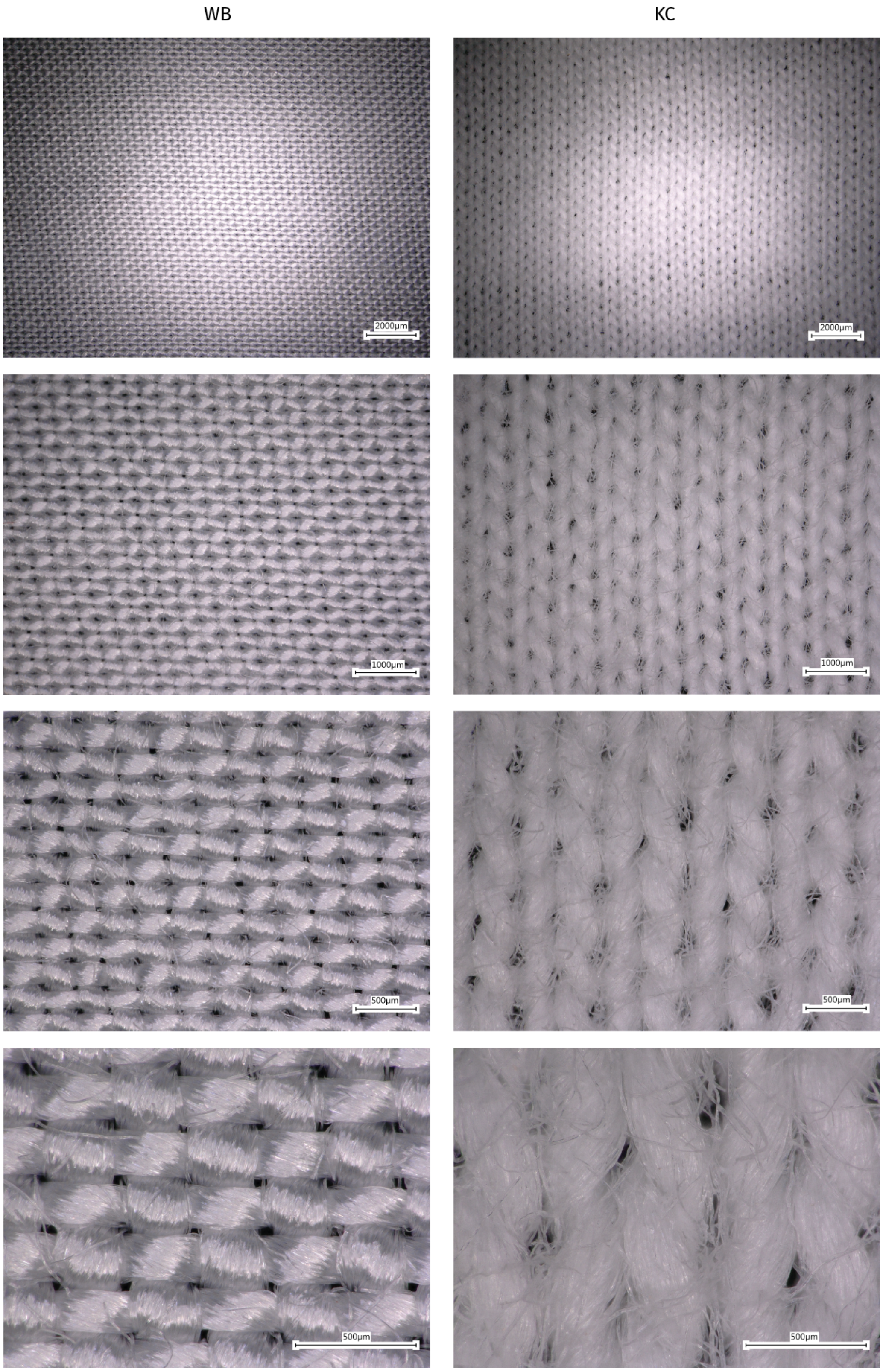


Figure 010.4 WB - woven bamboo, KC - knitted cotton

Textile samples with scale bar.

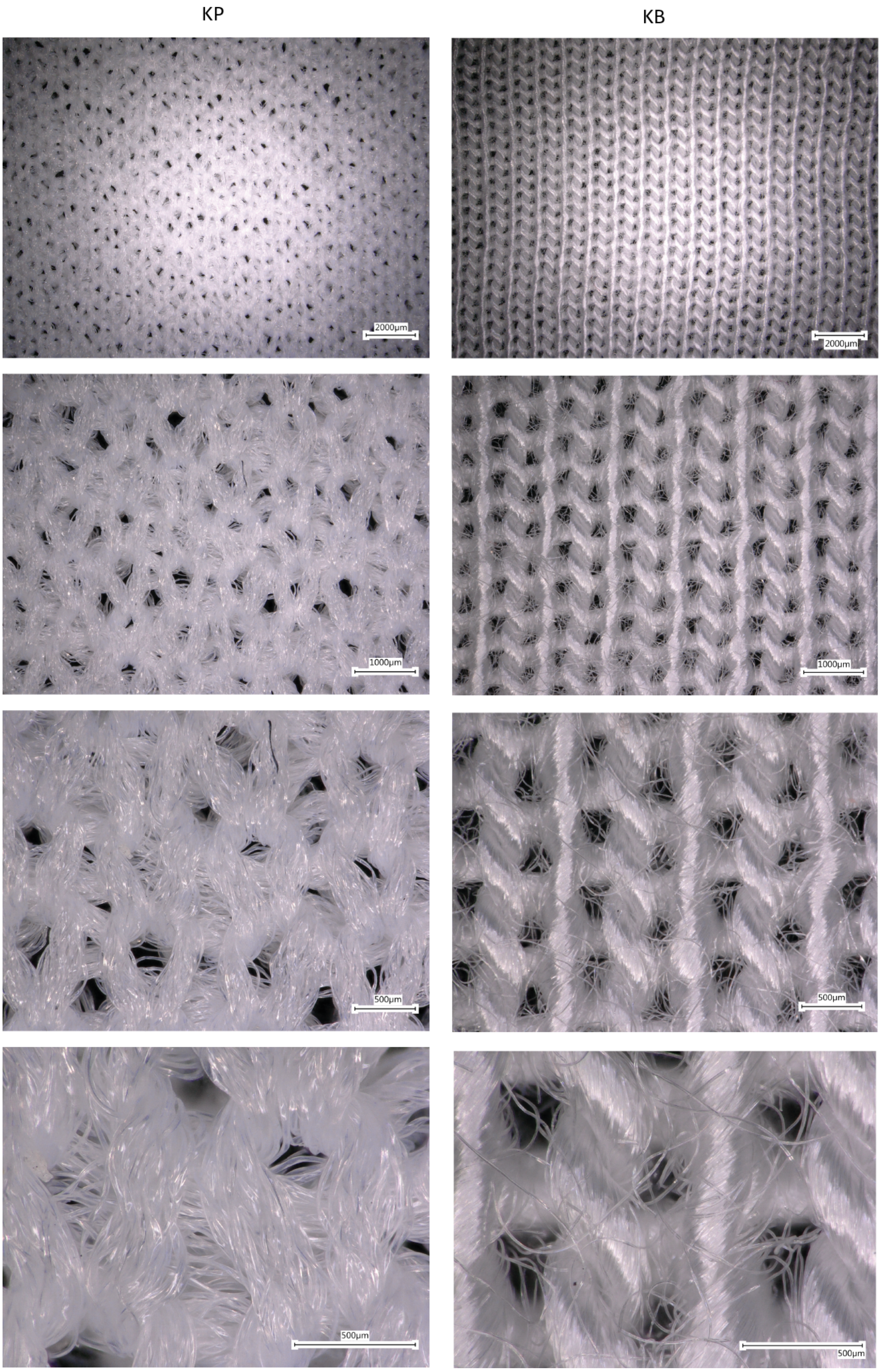
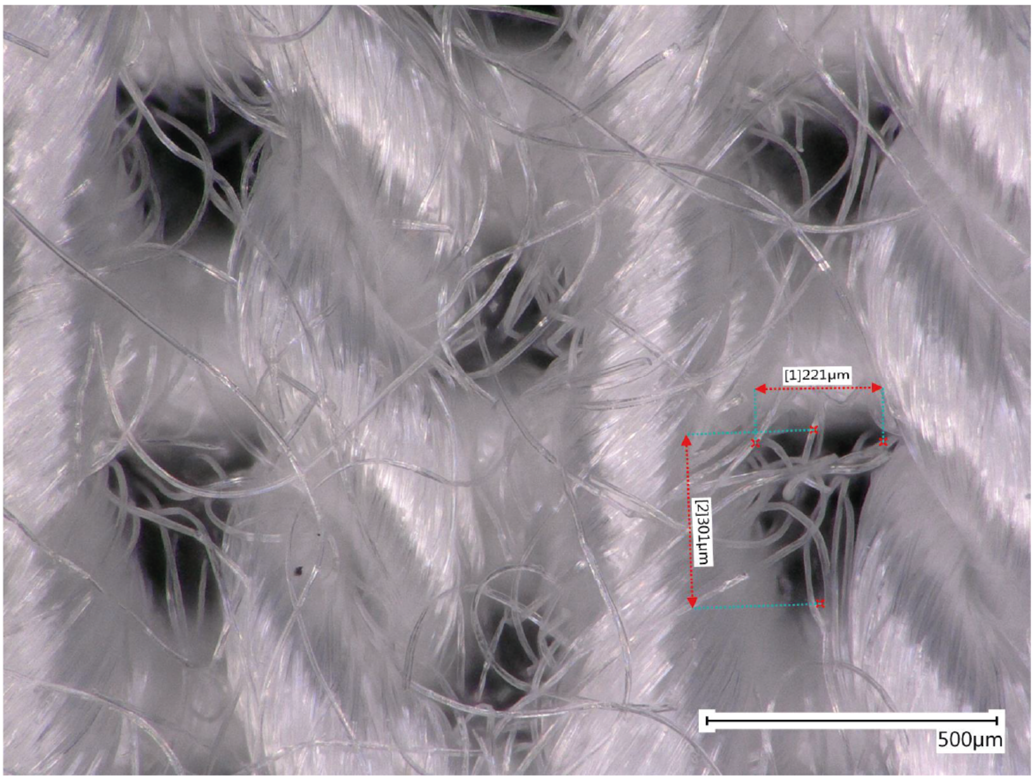


Figure 010.5 KP - knitted polyester, KB - knitted bamboo

Textile samples pore size.

KB



KP

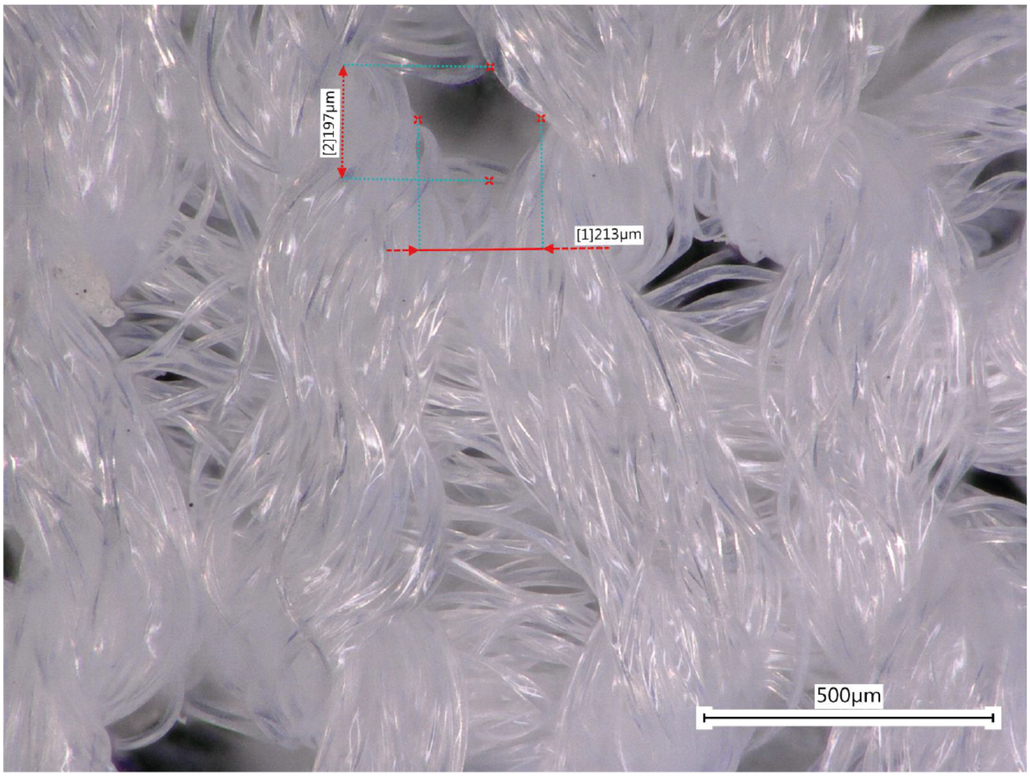
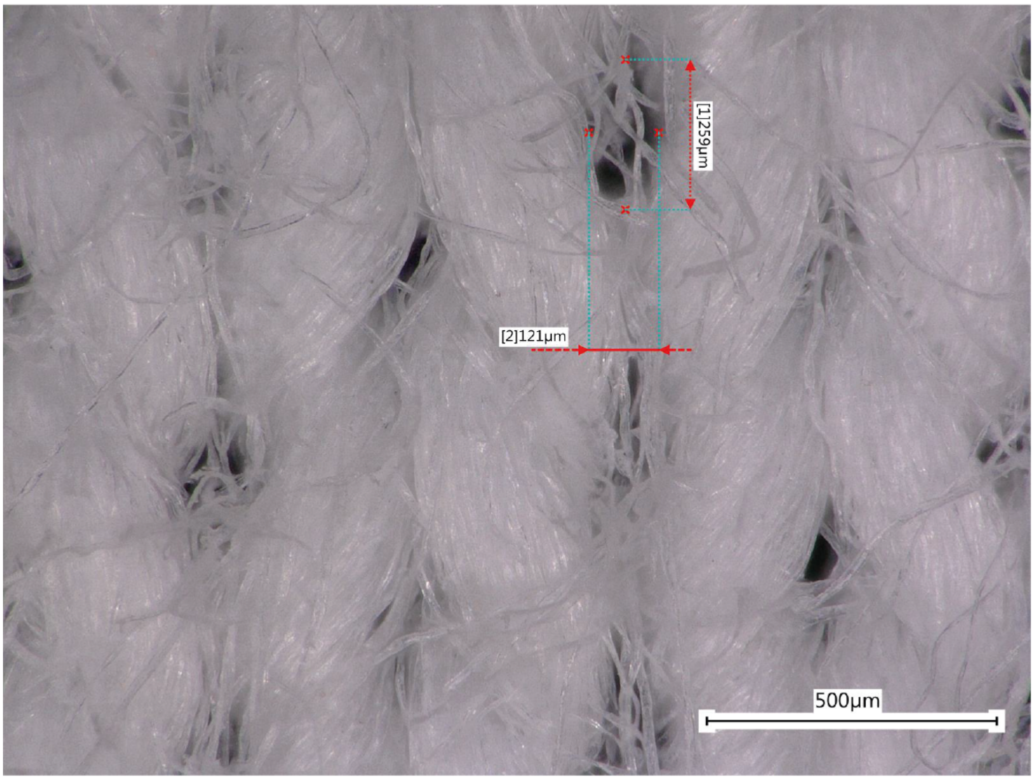


Figure 010.6 KB - knitted bamboo - KP- Knitted polyester

Textile samples pore size.

KC



WB

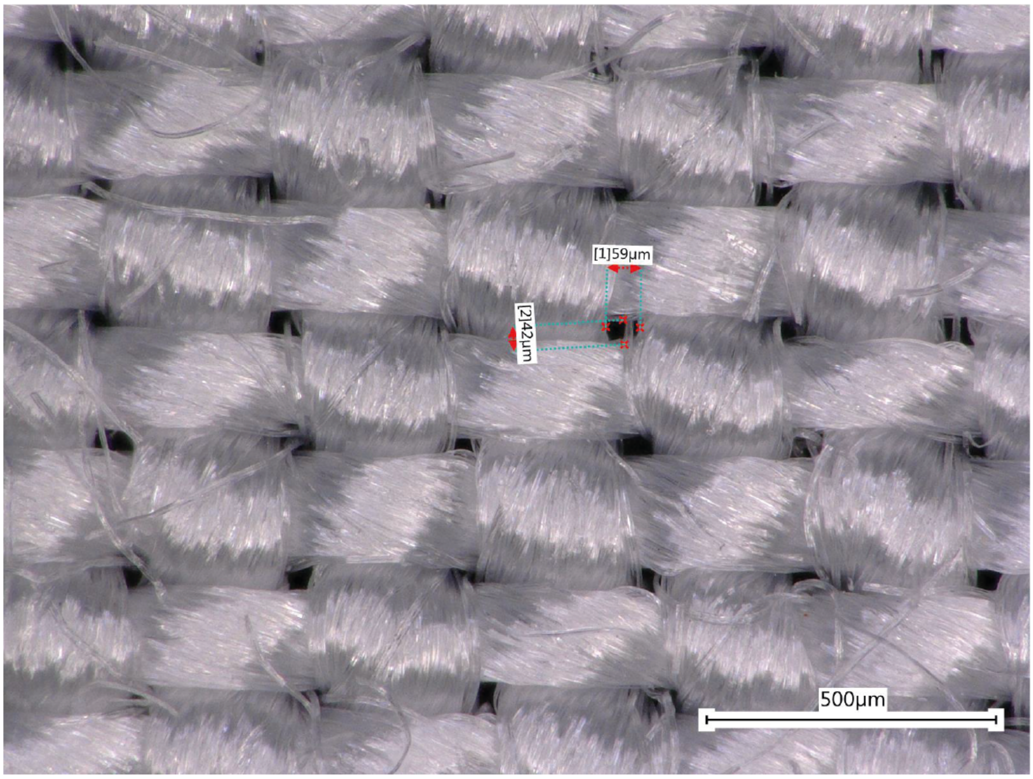
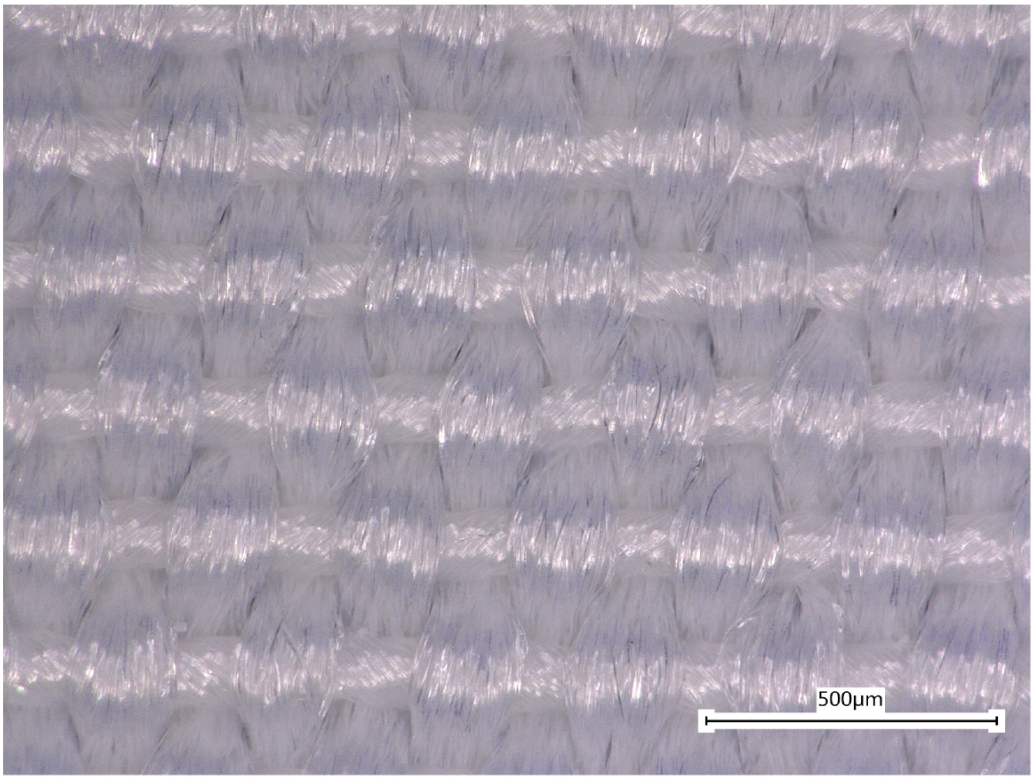


Figure 010.7 KC- knitted cotton, WB - woven bamboo

Textile samples pore size.

WP



WC

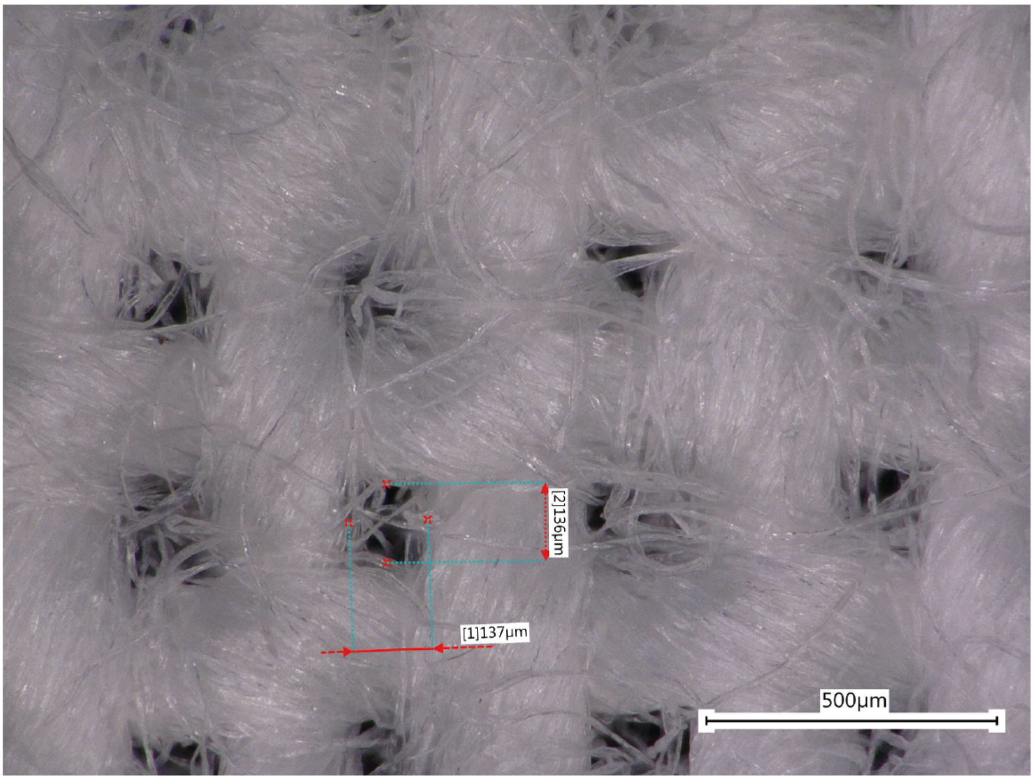


Figure 010.8 WP- woven polyester, WC - woven cotton

Conductive Inks data sheet

SIGMA-ALDRICH®

sigma-aldrich.com

3050 Spruce Street, Saint Louis, MO 63103, USA
Website: www.sigmaaldrich.com
Email USA: techserv@sial.com
Outside USA: eurtechserv@sial.com

Product Specification

Product Name:
Silver, dispersion – nanoparticle, 30-35 wt. % in triethylene glycol monomethyl ether, spec. resistivity 11 µΩ-cm, for printing on plastic films

Product Number: **736465**

Ag

Formula:	Ag
Formula Weight:	107.87 g/mol
Storage Temperature:	2 - 8 ℃

TEST	Specification
Appearance (Color)	Grey
Appearance (Form)	Suspension
ICP Major Analysis	Confirmed
Confirms Silver Component	
Proton NMR spectrum	Conforms to Structure
Solid Content	30 - 35 %
Viscosity	Confirmed
Approximately 10-18 cp	
Surface Tension (dyn/cm)	35 - 40
Approximately	
Assay	Confirmed
Curing Condition: 120~ 150 Deg C/ 30~ 60 min	
Recommended Retest Period	-------------------------
9 month	

Specification: PRD.2.ZQ5.10000023782

Sigma-Aldrich warrants, that at the time of the quality release or subsequent retest date this product conformed to the information contained in this publication. The current Specification sheet may be available at Sigma-Aldrich.com. For further inquiries, please contact Technical Service. Purchaser must determine the suitability of the product for its particular use. See reverse side of invoice or packing slip for additional terms and conditions of sale.

1 of 1

Figure 010.9 Sigma Aldrich manufacturers' product specification

Conductive Inks data sheet

Alfa Aesar

Product bulletin

Silver Conductive Ink(S-020)
Catalog Number**: 45661**

Alfa Aesar #45661 is a thermoplastic, screen printable, highly conductive Silver ink based on advanced Silver flake technology. It is suitable for use in membrane switches and flexible circuits. It has long screen life and is compatible with all commonly used PET and flexible plastic substrates.

Features

- Excellent adhesion to polyester film
- Excellent line definition
- Excellent screen life
- Good shelf life

Properties

Silver content	64.0%
Solids Content	72.56 – 74.00%
Sheet Resistance	<15 mOhm/square @ 25 micron
Viscosity	17,000 – 32,000 cP (Brookfield RVT, spindle 6 @ 20 rpm, 25°C
Curing Conditions	15 minutes @ 120°C in box oven
Shelf Life	12 months @ 20°C

Storage
Store in a dry place @ temperature of 15 - 20°C. Do not freeze.

Mixing
It is recommended that the ink be stirred briefly by hand before use. It can also be jar rolled before use if required. Care should be taken that excessive amounts of air are not introduced into the ink in mixing.

Screen Printing
This ink may be used with either manual or semi-automatic screen printers. Screen mesh size will serve to determine print thickness. A standard steel screen with a mesh size of 200 wires/inch and an emulsion thickness of 2 micron will result in a cured deposited thickness of typically 10-15 micron.

Thinning
The ink is supplied ready-to-print. Contact Alfa Aesar Technical Service for recommended solvent. As a guideline, an addition of 1.0 wt% solvent will produce an approximate 10-15% reduction in viscosity.

Curing
The conductivity, adhesion, and abrasion resistance achieved with the ink is strongly dependent on the curing condition used. Final film properties such as Hardness and Adhesion will improve with aging of the cured ink. A minimum time of one hour is recommended before further processing of the printed sheet.

Typical curing schedules are:
Box oven-15 minutes @ 120°C (typical)
Forced air curing-5 minutes @ 130°C (optimal)

Clean Up
Use either Carbitol Acetate (Diethylene glycol monoethyl ether acetate), L13446 or 2-n-Butoxy ethyl acetate, L09515.

Figure 010.10 Alfa Aesar manufacturers' product specification

Electrical Testing Screen Printing Stage 1

Sample	R1	R2	R3	R4	R5	R6	Mean	Standard Deviation
KB	4.400	4.600	4.500	4.400	4.300	4.400	4.433	0.103
KP	9.100	8.900	9.100	9.100	9.100	8.900	9.033	0.103
KC	9.400	9.300	9.300	9.300	9.400	9.200	9.316	0.075
WB	1.300	1.500	1.500	1.300	1.300	1.300	1.366	0.103
WP	2.500	2.500	2.500	2.500	2.500	2.500	2.500	0.000
WC	9.500	8.600	5.600	5.600	9.300	8.000	7.766	1.760

Table 010.1 Resistance results 1.44

Electrical Testing Screen Printing Stage 2

Sample	R1	R2	R3	R4	R5	R6	Mean	Standard Deviation
KB	2.500	2.400	2.800	2.200	2.200	2.500	2.433	0.225
KP	6.500	6.400	6.000	6.000	6.000	6.100	6.166	0.225
KC	3.500	3.800	3.900	3.800	3.800	3.800	3.766	0.136
WB	1.300	1.300	1.300	1.200	1.400	1.300	1.300	0.063
WP	1.500	1.800	1.800	1.700	1.500	1.800	1.683	0.147
WC	3.700	3.300	3.300	3.200	3.300	3.100	3.316	0.204

Table 010.2 Resistance results 2.44

Electrical Testing Screen Printing Stage 3

Sample	R1	R2	R3	R4	R5	R6	Mean	Standard Deviation
KB	0.700	0.700	0.600	0.600	0.600	0.700	0.650	0.054
KP	0.700	0.900	0.800	0.800	0.800	0.800	0.800	0.063
KC	0.900	1.000	1.000	1.100	1.200	0.900	1.016	0.116
WB	1.200	1.200	1.200	1.100	1.100	1.100	1.150	0.054
WP	0.600	0.600	0.600	0.600	0.600	0.600	0.600	0.000
WC	0.900	0.900	0.800	0.800	0.700	0.700	0.800	0.089

Table 010.3 Resistance results 3.44