An investigation of integrated woven electronic textiles (e-textiles) via design led processes

A thesis submitted for the degree of Doctor of Philosophy

By

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Abstract

'Electronic textiles' (e-textiles) are created by the amalgamation of electronics and textiles, where electronics are integrated *into* or *onto* fabric substrates. Woven textiles are specifically considered in this thesis to integrate electronics *into* textiles' orthogonal architecture. This thesis investigates '*How can the weaving process be manipulated to make woven e-textiles with integrated electronics?'*

The methodological approach taken is practice based research carried out via a technical materials approach *and* creative craft methods. An investigation of woven e-textiles *through* design led practice and woven expertise is presented. Previously, woven e-textiles have been investigated either via technical material approaches, (where the main emphasis remains on function) or via creative craft methods, (which emphasise experimental forms, manipulate integration methods and apply craft based knowledge). Both of these approaches have presented only limited investigation of unobtrusive integrated electronics in woven e-textiles, and woven structures have not been fully utilised to support the integration.

The research applies reflective practice through a design process model; this is based on the researcher's previous weaving expertise and designing methods. The work investigates how woven construction may be manipulated to develop novel integrated woven e-textiles. It was found that five woven approaches were particularly of value for electronics integration. These were the use of double cloth, the integration of multiple functions into the textiles as part of the weaving, the use of complex weaving techniques to attach and integrate components, the use of inlay weft weaving and the manipulation of floats (free floating threads). The thesis makes original contributions to knowledge, including identification of key stages in the woven e-textile design process, identification and application of advanced weaving techniques to facilitate integrated woven e-textiles, and compilation of a systematic record of woven e-textile techniques as a technical woven repository. Underpinning design principles that influence the developed e-textile outcomes are identified. A range of woven e-textile samples are designed and made. Three specific examples including an actuator ('RGB colour mixer'), a circuit ('corrugated pleat LED v2') and a soft module ('battery holder module v4'), are described in detail to illustrate their development using the e-textile design process model. The knowledge gained has potential to be applied to industrial woven processes for e-textiles.

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I would like to dedicate this thesis to Bapuji (Bhurabhai Modhwadia)

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Glossary and definition of terms

Amp (ampere) – unit of measure for electrical current

Abductive theory – is the relationship between deductive thinking (logical assumptions based on facts) and inductive thinking (predictions based on speculations)

Beam – bar attached to the front and back of a loom used to wind the warp and finished woven cloth onto

Cheese – small tube to wind weft yarns onto that is inserted into a weaving shuttle

Conductive yarn – yarn with electrical conductive properties, able to perform in an e-textile

Creative craft methods – this approach uses creative investigations of textile design and craft making processes, to develop e-textiles with electronic functional capability. In this approach there is conscious consideration of the textile construction form (i.e. aesthetic and textile structures). The outputs via this approach are mainly unique one-off pieces or small collections of statement designs, to exhibit or for particular applications by predominantly designers, researchers, artists or hobbyists. Specifically woven e-textiles developed via creative craft methods apply *some* consideration to integrate electronic function into the woven construction, i.e. utilising some of the woven architecture to integrate conductive yarns and/ or components. However, this approach does not fully exploit these structures for electronic functionality beyond basic structures, due to limited woven expertise.

Creativity – *"…the ability to come up with ideas or artefacts that are new, surprising and valuable*" (Boden, 2004 p.1)

Cross sticks – sticks used to separate the warp cross on the loom

Dent – refers to the spacing in between the loom reed to keep warp separated and consistently spread when weaving

Design objective – is a goal that is envisaged at the very start of the design process

Design process – sequence of stages between design problem and solution followed by the designer when developing design outcomes

Electrical current – the flow of electrical charge

End/s – refers to each warp thread

Epi – 'ends per inch' applied to the s warp sett

E-textiles – 'electronic textiles' are materials with integrated electronic properties into or onto a textile substrate

Explicit knowledge – knowledge that is openly clarified and rationalised

Fish – tool used to set up the warp when reeding on the loom

Hank – bundle of yarn, often specific to a length depending on yarn type

Heddle – part of the loom that is a rigid wire with an eyelet for a warp end to be threaded through

Ideation – process where possible ideas are formed, through methods such as brainstorming, sketching and discussion

Implicit knowledge – knowledge that is internal and cannot be easily expressed

Inspiration – a source of stimulation and motivation

LED – light emitting diode; light is emitted when current is passed through in the right direction

Loom – a weaving machine that produces woven textile fabrics

Multimeter – a digital tool to measure electrical circuit testing

Ohm – the unit of measure for electrical resistance

Pick – refers to each weft thread woven in a fabric

Praxis – relationship between theory and action, and the consequences of this

Prototype – a translation of an idea into physical model

Raddle – piece of equipment used for setting up a warp on the loom, that is separated by dents of ¼" or ½" to space the warp equally for even warp winding

Reed – metal piece of equipment used to thread the warp through after being threaded through heedless to disperse the warp at the sett density when weaving

Reflective practice – rationally reflecting during and after practice to help build further knowledge

Resistance (electrical) – level of difficulty for electrical current to flow through a material

Sett – refers to epi number associated with a yarn count and warp calculation

Shed – opening of the warp on the loom where the weft is inserted

Shuttle – tool used to weave that hold the weft yarn

Sketching – process of visualising ideas as two dimensional renders through drawing

Spun yarn – fibres in a yarn that are twisted together to make a strand of yarn

Synthesis – process of combining elements to form new outcomes

Tacit knowledge – internal unspoken understanding

Technical materials approach – this approach develops e-textile materials with the focus on function. Empirical investigations are applied to investigate technological functions, electronic components, and/ or testing technical concepts for e-textiles. The dominant emphasis is on a technical objective where technical technology/ engineering expertise is involved in the development of the e-textile. The outputs of this approach are for scientific, engineering and technical domains and are extended for industrial manufacture. Specifically, woven e-textiles developed via technical material approaches are functionally driven, where structures are predominantly selected to achieve the required electrical function. Thus, the woven architecture is not usually utilised in terms of form, and compromises the aesthetics of the material due to insufficient woven knowledge.

Threading – process of setting up the warp on the loom where ach warp thread is inserted through a heddle eyelet

Threading hook – weaving tool consisting of metal hook with an extended handle used for the threading process to bring through the warp threads through each heddle

Threads/ yarns – fibres in a spun or unspun continuous length

Treadle – foot peddle/s a loom is operated by pressing on these

Voltage – measure of pressure (in volts) that push current through a conductor

Warp – continuous vertical threads on the loom, that are lifted by loom shafts

Warp draft – specific designed plan for the warp set up indicating calculations for warp density, length, threading and reeding order

Warping mill – piece of equipment used to wind a warp for transfer onto a loom

Weave structure – patterns/ codes applied to weaving to construct a woven textile

Weaving – process by which a warp and weft are interlaced orthogonally into a woven textiles

Weaving tension – refers to the tightness of the warp/ weft on the loom

Weft – horizontal threads inserted into the warp to construct a woven textile

Yarn Count – numerical reference for a specific yarn type, depending on its quality, fibre composition and manufacture process

1 Introduction

1.1. Research background

The emergence of technical textiles has been driven by scientific and engineering research. New materials for stronger, lighter and more durable fabrics were developed for military purposes during the Second World War (O'Mahony and Braddock, 2002). Since these initial advancements, technical textiles have progressed into commercial fibre and fabric developments. As a result, technical textiles have become popular across utilitarian products and commercial applications due to their diverse textile qualities (McQuaid, 2005; O'Mahony and Braddock, 2002). Innovative technical textiles are widely applied to a diverse range of products, in sectors such as clothing, interior products, healthcare, military, sports, fashion, architecture and automotive.

Innovative technical textile developments are also inspiring a new generation of textile products, particularly through their extended use by the technical and creative sectors. Often these textiles are used in alternative ways to their intended use – this makes technical textiles particularly exciting for exploration by creative sectors (e.g. design, art and craft). Investigations of novel textile applications by the creative sector are enabling new exchanges between textiles and technology. As Bradley Quinn states, "*A new generation of designers envision the forms, shapes and materials of tomorrow, textiles are being transformed from passive substrates into active technological tools*", to make connections with materials that were previously inconceivable (Quinn, 2013 p.7). As a result, these new textile materials aim to enhance experiences via their end applications. This is possible because, innovative engineered technical textile materials for application in industry are considerably influential to design (Gale and Kaur, 2002 p.503). In addition, "*the history of innovation within the textile industry can serve as a map of human inventiveness*" (Sutton and Sheehan, 1989 p.13) where the designer/ maker is integral to creative and alternative outputs of technical textiles, technologies and methods (Philpott, 2010).

The category of 'very smart textiles' (those that can sense, react and adapt their behaviour), as classified by Lieva Van Langenhove *et al.* (Van Langenhove *et al.*, 2004 p.345), includes a sub-group of textiles specifically related to the research presented in this thesis – electronic textiles (e-textiles). E-textiles are materials with electronic properties integrated *into* or *onto* fabric based substrates (discussed further in section

1.1.1). E-textiles are able to function as flexible electronics with conductors, soft circuits, sensors and actuators. In the last twenty years there has been significant development in the e-textiles field, where the advantages of textile qualities in combination with electronic properties have provided many benefits, e.g. the function of electronics in flexible textile forms.

To enable e-textile applications to progress, they will ultimately need to possess considerable advantages over existing technologies that offer similar functions, for example, smartphone technologies that are portable units compiled with a multitude of functions, including some bio-sensors. An obvious benefit of e-textile applications is that they can have direct contact with the user, an advantage for body sensing, body protection, environmental monitoring, body heating/ cooling, for on body and direct human interaction (Buechley *et al.*, 2013 p.212). For e-textiles to truly advance, further research is required to refine design elements, including approaches to unified integration of electronics, user based research for desirability, design aesthetics, acceptance and usability. Design considered e-textiles will be especially valuable where human contact and interaction will be involved in the end applications.

1.1.1 E-textile construction methods

E-textile construction methods, (i.e. the making process) differ from regular textile construction methods. The main difference is the integration process of the electronics. This can occur during the production of the textile material, or the integration of electronic properties can take place as a separate process once the textile is complete. This difference can also be viewed as the integration of electronics *into* the textile construction, or applied *onto* a textile substrate. Using textile construction to build the electronic properties *into* the fabric utilises the existing textile architecture. This method can manipulate the construction process to make the e-textile simultaneously to the textile base material.

Applying electronic properties *onto* a textile substrate utilises the textile as a base support material to hold the electronics; however, the electronics are applied after the production of the textile. Both of these e-textile construction processes (*into* and *onto*) benefit from textile properties and behaviours, such as flexibility, malleability and lightweight materials. E-textiles that have electronic properties integrated *into* the construction can be made by methods such as weaving and knitting. E-textiles that have electronic properties integrated onto existing textiles can be made via methods such as embroidery, and print and hand/ machine stitch methods (Figure 1.1).

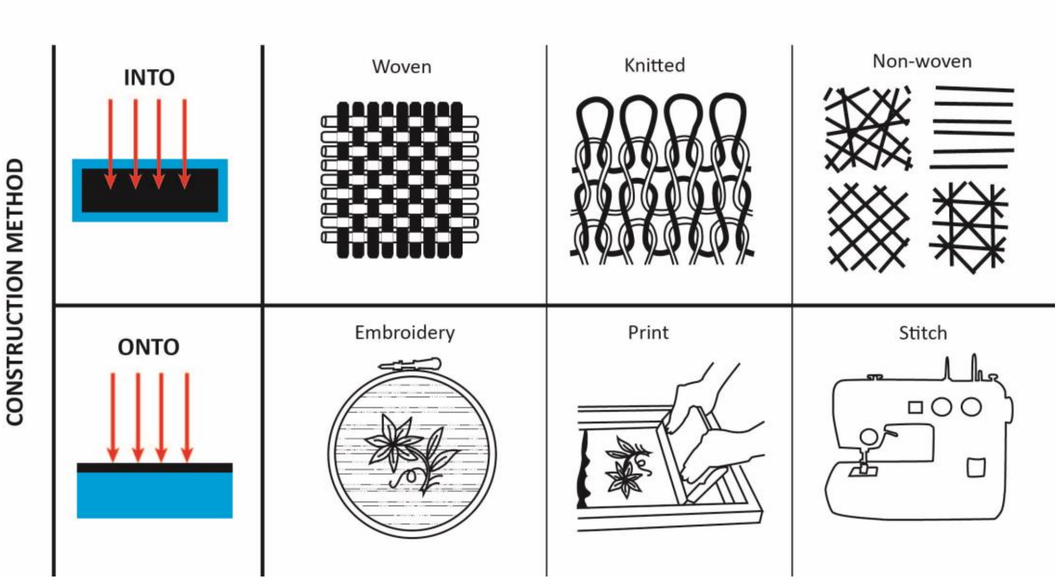


Figure 1.1 E-textile construction methods. Knitted and woven illustrations based on Miller (1984 pp.83-84)

Unobtrusive integration (i.e. discreet and not disruptive integration) of electronics *into* or *onto* textiles substrates is important to preserve textile material qualities, such as fabric tactility, flexibility, drape, etc. Unobtrusive integration methods for e-textiles would enable additional electronic capabilities in seemingly regular textile materials. Therefore, the methods of electronic integration *into* or *onto* textiles have significant influence on the final design of the material. This is particularly important where the end e-textile application requires regular textile material qualities and contact with the body, such as wearable technology garments.

Many e-textile developments have been possible due to the introduction of conductive materials, yarns and pastes. For example, conductive yarns (such as Shieldextrading.net, 2011; Bekaert.com, 2011) are electro active fibres spun into a yarn composition that can conduct electric current. They are yarn like material (i.e. available in linear form, soft tactility, spun/ unspun fibres) that can be applied into woven, knitted and non-woven e-textile constructions, and can also be applied onto fabrics using embroidery and stitch techniques. In addition, miniaturisations of electronic components are working towards improved unobtrusive integration of electronics *into* and *onto* textile materials.

Nevertheless, e-textiles are not a panacea for wearable technology or related products – they are a material substrate to design products, where this material needs to be designed considerately as a core component of the end product application.

1.2. Research question, aims and objectives

Multifunctional woven e-textiles (i.e. woven textiles with electronic capabilities) were investigated through a practice based inquiry. This was achieved by using design led methods and applying expert weaving knowledge combined with electronics design knowledge to synthesise both form and function. The research question focused the line of inquiry and was:

> ***RQ1:*** *How can the weaving process be manipulated to make woven e-textiles with integrated electronics?*

The aims of the research were:

- To combine weaving and electronic design methods to develop e-textiles, through design led approaches
- To apply in-depth knowledge of weaving to make unobtrusive integrated woven e-textiles, utilising the full potential of woven structures.

The research aims were distilled into two objectives:

Objective 1

- *Determine a design process model that can be applied to develop woven e-textiles*

This objective focused on determining a design process (based on the researcher's previous working methods), that distilled all the intermediate stages and methods between the initial design objective (problem) and the final outcome (solution). The design process model was applied to practical investigations of woven e-textiles – this is related to objective 2.

Objective 2

- *Develop novel physical e-textile outputs using the design process developed in objective 1 and reflective practice*

This objective focused on synthesising woven structures and electronics circuit design, led by the e-textile design process model, *through* a technical materials approach and creative craft methods. In-depth woven knowledge was applied to investigate how woven construction could be utilised to integrate electronic properties into the textile architecture, simultaneously, during the woven process.

1.3. E-textile development methods

Woven textiles consist of the orthogonal interlacing of warp (vertical threads) and weft (intercepting horizontal threads) yarns, usually forming a tight stable cloth if woven at a dense sett. Woven e-textiles are of specific focus in this research project, as the reviewed literature in the field revealed a lack of in-depth structural investigation of integrated woven e-textiles (discussed further with examples in chapter 2).

The reviewed literature presented two main development approaches in existing woven e-textiles. These were classified by the researcher as 'creative craft methods' and 'technical materials approach'. This section will define the two approaches. (Specific e-textile examples related to these approaches will be discussed in chapter 2.)

- <u>Creative craft methods</u> – this approach uses creative investigations of textile design and craft making processes, to develop e-textiles with electronic functional capability. In this approach there is conscious consideration of the textile construction form (i.e. aesthetic and textile structures). The outputs via this approach are mainly unique one-off pieces or small collections of statement designs, to exhibit or for particular applications by predominantly designers, researchers, artists or hobbyists. Specifically woven e-textiles developed via creative craft methods apply *some* consideration to integrate electronic function into the woven construction, i.e. utilising some of the woven architecture to integrate conductive yarns and/ or components. However, this approach does not fully exploit these structures for electronic functionality beyond basic structures, due to limited woven expertise.

- Technical materials approach – this approach develops e-textile materials with a dominant focus on function. Empirical investigations are applied to investigate technological functions, electronic components, and/ or testing technical concepts for e-textiles. The dominant emphasis is on a technical objective where technical technology/ engineering expertise is involved in the development of the e-textile. The outputs of this approach are for scientific, engineering and technical domains and are extended for industrial manufacture. Specifically, woven e-textiles developed via technical material approaches are functionally driven, where structures are predominantly selected to achieve the required electrical function. Thus, the woven architecture is not usually utilised in terms of form, and compromises the aesthetics of the material due to insufficient woven knowledge.

Neither of the two approaches has fully exploited woven structures for form and function that woven e-textiles are able to realise. Although creative craft approaches use some woven structural integration, this is not manipulated to push the limits of weaving and its potential for e-textiles. Each of the described approaches have predominantly focused on form (creative craft methods), or function (technical materials approach), where this compromises other parts of the e-textile design. Although there are slight nuances in both approaches of some reviewed projects, i.e. where there is an overlap of approaches (further discussed in chapter 2), the projects mainly use one of the single approaches. Thus, this PhD research sought to investigate both creative craft and technical material approaches to avoid compromising aspects of form or function of woven e-textile designs.

An example of a technical materials approach project is by ETH Zurich, where a strip sensor was developed for integration into a woven textile (Cherenack *et al.*, 2010; Kinkeldei *et al.*, 2009) (Figure 1.2). The researchers who developed this project were from electronic engineering, materials science and IT backgrounds. The project was developed through a focused technical materials approach, where the textile construction was not fully utilised to support the e-textile. Instead the woven construction, a single cloth twill configuration (specific twill type not documented), was used as a frame to hold the electronics where the component was loosely interwoven into the warp. The warp used only two conductive yarn tracks that interconnected with the component. The woven construction was not investigated as part of the design/objective, where it could have potentially helped to enhance the final design. For example, more conductive warp and weft tracks integration would have increased connectivity to the component. Also, a tighter weave structure would have provided securer connection between the weave and the component, potentially negating the use of glue (this example is further discussed in chapters 2 and 8). Although this project successfully achieved the intended temperature sensor function, the research did not extend the capabilities of woven structures.

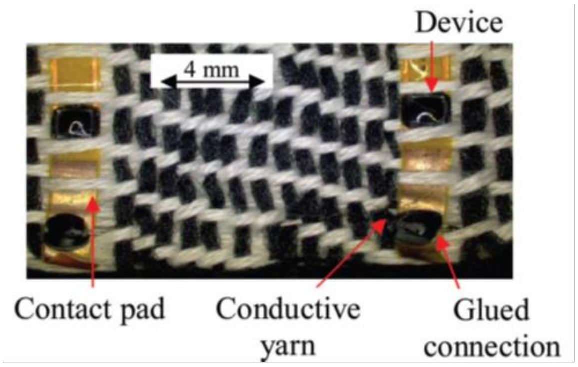


Figure 1.2 ETH's woven e-fibre temperature sensor (Cherenack *et al.*, 2010)

SubTela's Black Wall Hanging piece is an example of creative craft methods applied to a woven e-textile (Figure 1.3, also discussed further in chapters 2 and 8). Barbara Layne is Director at Studio SubTela, where she works with graduates in visual arts and engineering. Layne is a textile artist who has weaving knowledge. The Black Wall Hanging piece adapted weaving processes to integrate electronic function (Layne, Studio Sub Tela and The Hexagram Institute, 2006). The wall hanging utilises the woven structure to position and place each LED in specific spaces during the weaving process on the loom. A basic 2/2 twill woven structure was applied in a single cloth. The space between each 2/2 twill structure (i.e. two threads lifted up, while the next two threads are left down), are used to interweave weft yarn and the LED components; the visible spaces between the twill structures shows the LEDs/ weft yarns. The weave structures were designed for the positioning of the LEDs, however, they could have further contributed to the electronic function by integrating conductive yarns in both the warp and weft, to support and increase the circuit interconnections. Conductive yarns would have been more suitable than hard wires because they are more durable under weaving tension due to their slight fibrous stretch quality.

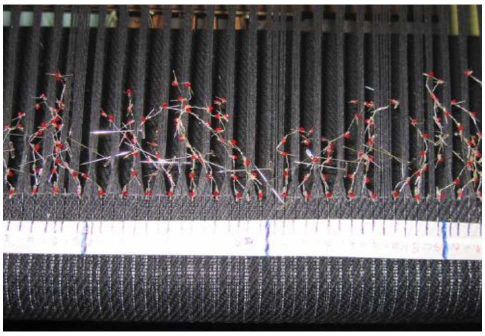


Figure 1.3 LED strands being woven on the loom (Layne, Studio Sub Tela and The Hexagram Institute, 2006)

There is an opportunity to address both form and function of woven e-textiles, by simultaneously considering both of these areas. This can be progressed by establishing closer nuances between technical material approaches and creative craft methods, drawing on in-depth woven textile expertise. This would enable woven structures to be adapted and fully utilised to enhance form and function of e-textiles.

1.4. Challenges of Woven e-textiles

The challenges of woven e-textiles mainly concern unobtrusive integration, electrical functionality, robustness and the design of the physical form. This research is focused on unobtrusive integration of electronics into constructed woven textiles. To overcome these challenges a greater awareness of textile material properties is required, including physical textile design forms (i.e. the constructed woven design), and design considered approaches to better integrate electronics *into* these materials. These aspects appear to be a consistent weakness across a range of e-textiles work, predominantly due to the lack of in-depth woven textile expertise. Additionally, the requirements of electronic circuit function need to be understood to consider how they can be integrated into woven textile material.

1.5. Research practice approach

The research presented in this thesis is focused on the investigation of woven e-textiles *through* design led practice (Frayling, 1993). The empirical research conducted for this PhD project has sought to expose design led approaches to make woven e-textiles, whereby both form and function are synchronised for combined design considered outcomes.

1.5.1 The researcher

The researcher's background in woven textile design, acquired over a number of years through undergraduate, postgraduate, professional practice and academic experience has been essential to structure and execute this research. The expertise of the researcher in woven textiles allows for her to undertake a dual position in this research project – i.e. as designer *and* researcher. Furthermore, the researcher's personal interest in technological and innovative textiles, which has been a consistent theme present in her previous work, has also been an additional motivation to pursue this research. The researcher was able to apply in-depth woven expertise of textile construction and combine this with the research investigation. However, electronics were less familiar to the researcher until embarking on this research project; thus, the researcher's knowledge of electronics developed reflectively (section 3.4.6) throughout the course of this research. On reflection, this basic level of electronics knowledge enabled the researcher to take a novel approach to designing e-textiles.

As the researcher is an expert weaver, the mechanics of woven structures and weaving construction was more instinctive than that of electronics. Basic electronics were studied to initiate circuit formation, inputs, outputs, variables, and so forth, to gain a deeper understanding. This was achieved by learning basic practical and theoretical electronics through taught demonstrations, books, websites and expert advice. The basic electronics knowledge was applied to some initial e-textile pilot samples and technical tests. Building electronics knowledge helped to establish where common parallels fell between the two subjects. Analysis and reflective learning from these initial e-textiles progressively built electronics knowledge throughout this research project.

1.5.2 Craft, design and technology

This research differs to previous work in the field, as it pursued synthesis of electronic circuit design principles with in-depth woven textile construction through design led methods. An empirical methodical approach similar to technical material development has been used to develop the woven process, by focusing on functional objectives and trialling techniques that best achieve the set aim. Simultaneously, a creative exploration of form design and craft led woven techniques to develop the same technical objective are investigated. These utilise the woven structure to produce integrated e-textiles. As Harold Nelson and Erik Stolterman suggest, both the material of design and the craft involved in the production methods are interconnected processes. "*The fact that we distinguish between the act of creativity and more pragmatic or concrete activities does not mean they are separated in the design process*" (Nelson and Stolterman, 2012 p.174). It is this combined approach that is applied to this PhD research, and is what Nelson and Stolterman refer to as a 'tertium quid' when becoming a designer. The teritum quid is described as the 'third way' amongst traditional subjects of science and the arts (Figure 1.4 1.4), i.e. "*This nascent contextual tradition forms a container, a protector, for design learning and eventual design praxis. It forms the crucible that holds the superheated liquid form of inquiry at the centre of design learning as well as design praxis*" (Ibid. p.225). Similarly, Ken Friedman also suggests design is first a process, where insights developed from these processes create design knowledge (Friedman, 2000); thus "*Those who create knowledge through research have a different and richer relationship to their subject field than those who simply teach knowledge that others create*" (Ibid. p19).

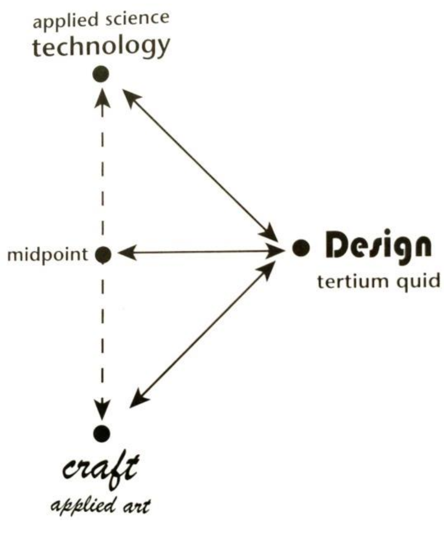


Figure 1.4 Tertium quid the, third way (Nelson and Stolterman, 2012 p.226)

The researcher applied expert weaving knowledge and reflective practice to develop the woven e-textiles in this research; this expert knowledge is unique to the discipline and enables its advanced progression (Bye, 2010 p.3). Although woven knowledge and practice stems from craft subjects, the researcher applied this through design processes combined with electronics. "*The creative processes now found in textiles defy the historical divisions and definitions applied to it*" (Gale and Kaur, 2002 p.31), in that modern textile design processes are often combined with IT, digital tools, cross discipline collaborations and other processes. Thus, in relation to this research the design process combines woven craft knowledge with electronics to enable new outputs. However, it cannot be overlooked that craft does underpin the textiles design process, as the practice of textile design requires a hands-on making approach stemmed from craft skills (Ibid. p31).

Sandra Wilson suggests craft practice should be credited separately to design practice, to preserve the core principles of craft and allow a deeper understanding of its values (Wilson, 2004). However, if craft practice is seen as a set of specialist skills connected to an individual via making processes, there will always be an association with craft skills and materials, regardless of this being related to technology. Craft skills are required to enable technology to progress in areas such as e-textiles, where the maker/ designer/ researcher is tangibly connected with a process. This reconfiguration of craft with technology and how they connect can be an enabler for progressive design (Rosner, 2012; Scali, Shillito and Wright, 2002).

David Pye defines craft differently to workmanship, in that the actions and skills applied when crafting is 'workmanship', and can be present in any made application (Pye, 1980). He further suggests workmanship cannot be expressed, as "*What you see, and nearly all that you can see, in a man-made environment, is design expressed and amplified in terms of workmanship…. Design is what can be expressed in working drawings and a written specification*" (Ibid. p.3). Pye firmly states workmanship *is* design, where the two subjects are closely interconnected for final outcomes (Pye, 1978 p.79). The relationship between a design and the workmanship to realise the final outcome, is a result of the maker's discretion and decisions actioned during the making process. Similarly, Glenn Adamson states craft is a process, and *"…only exists in motion. It is a way of doing things, not a classification of objects, institutions, or people. It is also multiple: an amalgamation of interrelated core principles, which are put into relation with one another through the overarching idea of 'craft'"* (Adamson, 2007 p.4). This process is designing, where a combination of skills, actions and activities use both linear (logical) and lateral (creative) thinking, which is also connected to feeling (Penfold, 1988 p.133). In relation to the e-textile research practice approach, weaving craft skills are applied by the researcher. The application of these skills with electronics through design processes result in the woven e-textiles presented in this thesis.

Design led investigations of woven e-textiles can enable realisation of alternative woven outputs that may not be considered through purely technical materials or creative craft routes alone.

The researcher's previous woven textile design working methods were reflected upon and framed this approach into a model. This design process model helped position the researcher's existing design process. The researcher's previous woven textile design process was then combined with electronics for this e-textile research. This framed the woven e-textiles design process, and synthesises a technical materials approach and creative craft methods to address both form and function. This is unlike conventional textile design processes that are typically related to implicit thinking and tacit knowledge through explorative design approaches, where there is limited research of existing textile design process (Bye, 2010; Gale and Kaur, 2002; Studd, 2002). Underpinning design methods such as tacit knowledge, implicit thinking and others are discussed in chapter 3. The e-textile design process model was applied through reflective practice to develop the e-textiles in this project.

1.6. Thesis structure

Figure 1.5 1.5 illustrates the structure of this thesis and the relationship between chapters.

This chapter thus far has introduced the research subject, and overviewed background to the motivations of the research conducted. The rest of this subsection will outline and link the context of each subsequent chapter.

Chapter 2 will provide a literature review of woven e-textiles and related work to establish the current state of this subject, and identify the gaps in knowledge.

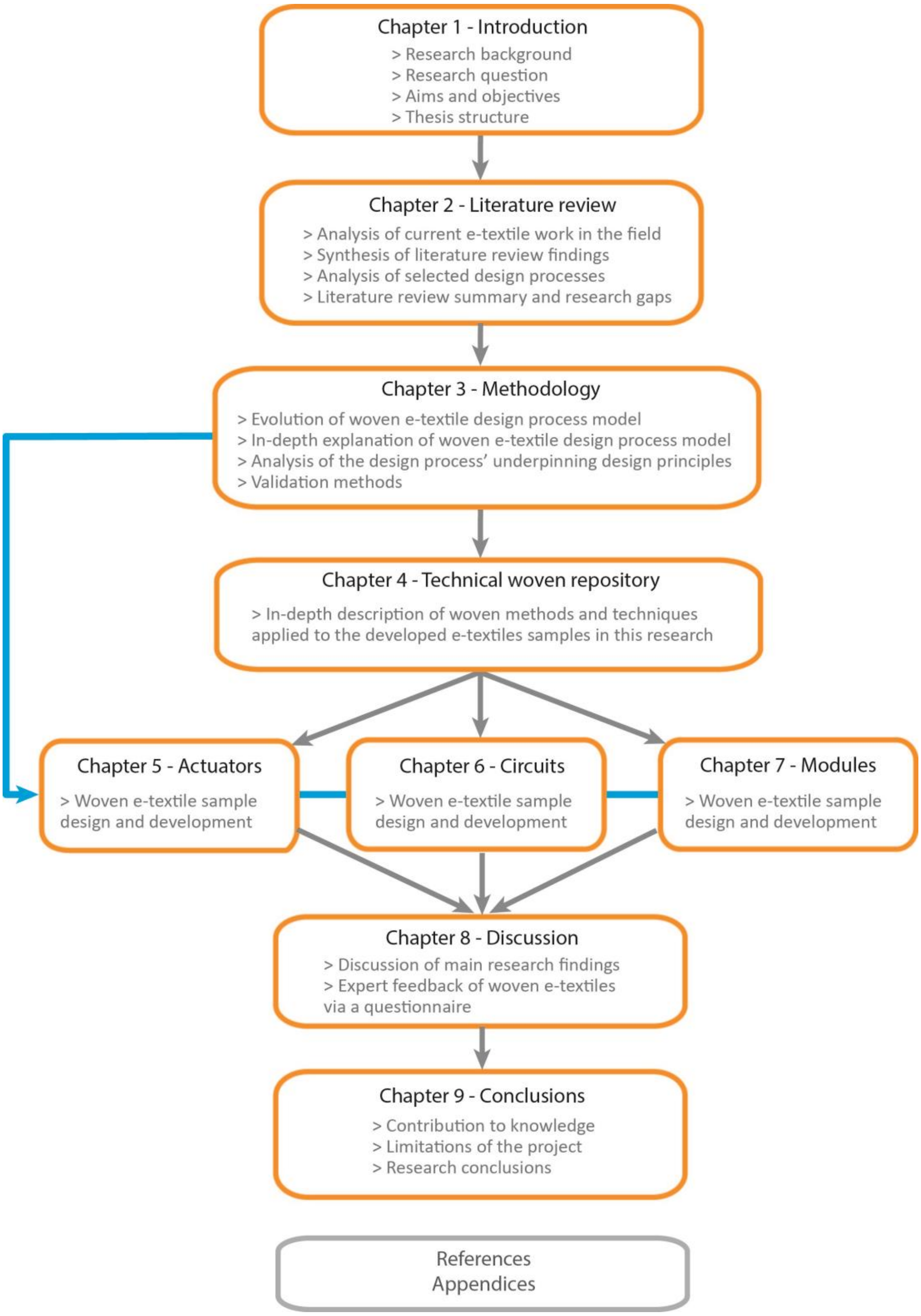


Figure 1.5 Thesis structure map

Chapter 3 explains the selection and justification of the methodology used for this research. The approach taken is design *through* practice, where the research activity is reliant on reflective practice and iterative processes. The researcher's previous working design process is framed to identify the key stages involved in her design practice of woven textiles. This is then combined with electronic circuit design processes to design and develop e-textiles. The woven e-textile design process demonstrates how two disparate sectors such as weaving and electronic circuitry can be combined through a technical materials approach and creative craft methods.

Chapter 4 documents the technical woven repository. This presents cohesive descriptions of woven processes and techniques applied to the execution of e-textiles developed in this research. It also provides a thorough explanation of all the procedures involved in setting up and implementing woven activity, through to final e-textile design finishing techniques.

Chapters 5, 6 and 7 will each focus on the development of a specific sample – 'RGB colour mixer' (chapter 5), 'Corrugated pleat LED v2' (chapter 6) and Battery holder module v4' (chapter 7). Each of these 3 samples will be discussed in relation to the woven e-textile design process model presented in the methodology. Chapter 5 provides an in-depth narrative of the woven e-textile design development process, as this is a consistent occurrence in all the samples developed. Chapters 5, 6 and 7 then concisely describe the design process related to the specific discussed samples, where each e-textile is categorised as 'actuator', 'circuit' or 'module'.

Chapter 8 provides a discussion of the main findings of this research, based on the research question and the research gaps identified. The latter part of the chapter focuses on expert feedback on some of the woven e-textiles developed in this research.

Chapter 9 presents the research conclusions. This reviews the outcomes of the research in relation to the set research questions and objectives in chapter 1. In addition to the concluding insights, the research limitations and improvements are discussed. The contributions to knowledge are stated in relation to the findings of this research. The contributions include identification of key stages in the woven e-textile design process, identification and application of advanced weaving techniques for integrated woven e-textiles, and compilation of a systematic record of woven e-textile techniques as a technical woven repository. Finally, potential implications for future work are considered.

2 Literature review

2.1 Literature review introduction

Woven e-textile literature is reviewed across projects in design, craft and technical developments, focussing on execution approaches and the integration of electronics with textiles.

The two main sub sections discussed are woven e-textiles via creative craft methods (section 2.2), and technical woven e-textiles via a technical materials approach (section 2.4). Section 2.6 will review literature on the design process.

2.2 Woven e-textiles via creative craft methods

The introduction of conductive yarns (section 4.3.3) has been a central factor to allow true integration of electronics and textiles, particularly for woven e-textiles. Conductive yarns integrate very well into textiles due to their malleability, soft textures and durability under the stress of textile construction techniques. Particularly for woven e-textiles, conductive yarns share the same physical forms as regular weaving yarns (both warp and weft). Therefore, the integration of conductive yarns into woven construction is conveniently achieved, as these conductive yarns can directly substitute regular weaving yarn.

2.2.1 Maggie Orth – colour and pattern changing woven e-textiles using double cloths and thermochromic printing

Maggie Orth obtained her PhD in media, arts and sciences from MIT Media Lab in 1997 and later went on to set up her company, International Fashion Machines (IFM) (Maggie Orth, 2009). Orth's work at MIT progresses aesthetics alongside the technical functionality of e-textiles (Orth, 2002). Orth believed that if functional e-textiles were aesthetically pleasing tactile surfaces, over time they would help the e-textiles consumer market to grow, particularly in terms of value, consumer acceptance and adoption of these products.

Some of Orth's early work focused on colour and pattern change in e-textiles using creative craft methods. 'Electric Plaid' used thermochromic inks with electronic systems that transformed the aesthetics of the textiles (Braddock and O'Mahony, 2005). Orth has used this type of technology in her past work (e.g. 'Dynamic Double Weave I' from 2003, Figure 2.1), where hand woven textile panels made slow transitions of pattern and colour when a computer programmed system was activated. This piece used conductive yarns that were integrated into the weave (i.e. woven simultaneously into the textile construction), to control the heat and thermochromic colour transitions. Figure 2.2 illustrates the conductive yarns being woven on the loom into one of Orth's double weave pieces.

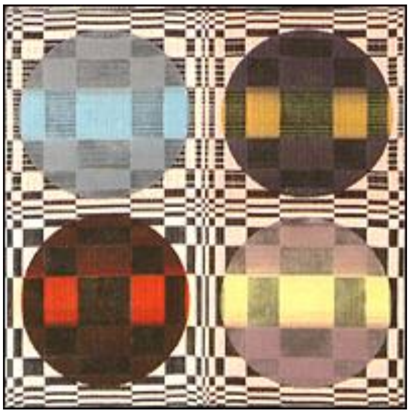


Figure 2.1 Detail of Maggie Orth's 'Double Dynamic Weave', 2003, Hand woven with cotton, rayon, and conductive yarns. The piece used thermochromic inks and an electronic system to change the aesthetic (Orth, 2009).

Figure 2.2 Piece of Orth's double weave e-textiles where conductive tracks are integrated into the textiles on the loom (Bourget, 2007)

Woven constructions were designed to integrate conductive yarns into the structure, such as double weave, where two cloths can be woven simultaneously on the loom (section 4.2.3). Double cloth has enabled Orth to control where the conductive yarns are positioned (i.e. on the top cloth or the bottom cloth); therefore, this determines where the conductive yarn is exposed, and can control colour transition in the thermochromic parts. This is a good example of e-textile woven construction being utilised as part of the aesthetic form, and for the thermochromic transitional function.

Orth's work demonstrates an overlap between form and function, where both aspects have been considered for the final designs. Woven structural manipulations such as double cloth, applied by Orth have considerable further potential to be used for functional devices such as switches, for electrical insulation, and to selectively hide and expose conductive yarn. Further integration of thermochromic yarns into the woven structure would have also been possible. Other woven methods such as jacquard weaving (intricate weaving enabling stricter control than standard dobby shaft weaving), would offer new potential to enhance this work, as it would enable more control over specific sections, multi-layer cloths and complex visual patterns using advanced woven construction.

2.2.2 Spår – woven electroluminescent carpet with pressure sensors

Spår was a development by the Swedish School of Textiles Borås, which used electroluminescent cables that were woven into a carpet patch (90 x 200cm) (Persson and Worbin, 2010). This piece had knitted conductive yarn pressure sensors embroidered on the reverse of the carpet. This enabled the carpet to operate as a system, i.e. the electroluminescent lighting would only light up in the areas of carpet that were walked on, activated by the pressure sensors (Figure 2.3). This project used the function of the carpet to build in an electronic system that utilised the textile substrate. However, electroluminescent lighting cables were woven across the carpet patch using a weft faced single cloth structure (specific woven structure not documented). The woven carpet structure was holding the electroluminescent cable, but did not contribute electro active function – this was achieved by the knitted conductive yarn patches embroidered on the reverse, and with external electronics. Although the electroluminescent lighting has been successfully integrated into the woven structure, there is a clear further opportunity to also integrate the conductive pressure sensors into the weaving of the carpet. The integration of multiple functions through simultaneous weaving is a significant opportunity for future work.

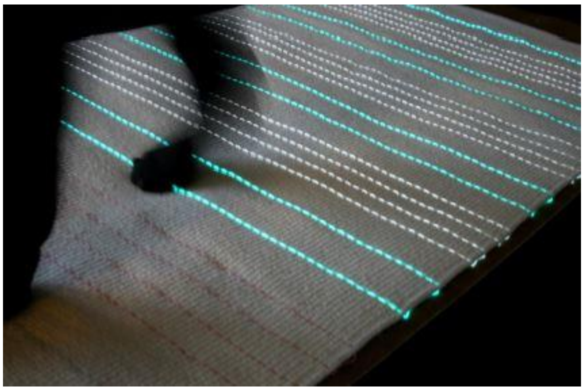
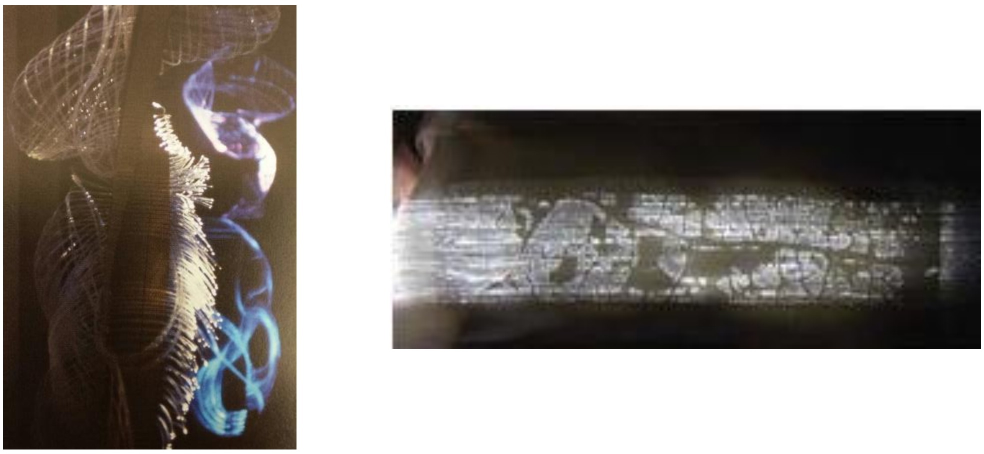


Figure 2.3 Spår's interactive carpet with integrated electroluminescent lighting (Persson and Worbin, 2010)

2.2.3 Laurie Carlson and Barbara Jansen – fibre optic woven e-textiles

Another electronic component used for lighting in woven e-textiles is fibre optics, as used by designers such as Laurie Carlson (McQuaid, 2005 p.192) and Barbara Jansen (Jansen, 2009) (Figure 2.4). Fibre optics also occurs in linear yarn like format, and fits the process of woven construction. However, fibre optic yarn can be difficult to handle during the weaving process due to its rigidity. The textiles with woven fibre optics successfully emitted light, and had programmable transitional colours and intensities. To activate fibre optics, they need to be connected to a main light source that can be bulky. Although the fibre optics can be integrated and housed into the textile structure, the rest of the textiles are not electro active, i.e. they do not provide any electronic function. However, the textile structures can be manipulated as diffusers, to give different overall aesthetic lighting effects. This can be done by designing specific patterns, 3D structures, or loose or dense weaves to cause lighting effects.



a) b)

Figure 2.4 Images of woven fibre optic textiles; where a) is by Laurie Carlson (McQuaid, 2005 p.192), and b) is by Barbara Jansen (Jansen, 2009)

2.2.4 Barbara Layne and SubTela – 'Black Wall Hanging' woven e-textile with integrated LEDs

SubTela studio based in Quebec, Canada is directed by Barbara Layne and is part of the Hexagram Institute, associated with Concordia University. The studio aims to work towards creative functional textiles and e-textile solutions that contribute to design research (SubTela, 2009).

SubTela have approached much of their project work through woven e-textiles. They have successfully integrated electronic components via weaving for outcomes such as LED displays, lighting textiles and interactive sensing. The textiles were used as a foundation base, and functioned as a wired matrix to operate the electronic components. 'Black Wall Hanging' (as mentioned in the introduction chapter), is a piece from The Narrative Cloth, Textiles, Translations and Transmissions project (Layne, Studio Sub Tela and The Hexagram Institute, 2006). A 2/2 twill woven structure was used to make this piece in a single cloth, and the conductive tracks were made using regular hard electric wires. The integration of the components was achieved by a 'wrapping' technique during the hand woven process; however little detail is revealed as to how this was achieved.

Although the LEDs were integrated into the woven construction during the weaving process, hard wires are difficult to handle on the loom due to their rigidity, and have limited stretch when exposed to weaving tensions (woven constructions further discussed in chapter 4). Softer conductive yarns instead of wires could have been applied into the warp and weft, to make circuit interconnections for the LEDs; a combination of woven structures could have enabled this. A 2/2 twill structure is a stable woven structure where the exposed weft yarn is shown every two threads; however, other structures were not explored that may have helped the woven construction. For example multilayer weaving would have allowed them to spread their conductive yarns across two layers (rather than one) giving more insulation and protection. Figure 2.5 shows a detailed image of the LEDs being woven into this piece.

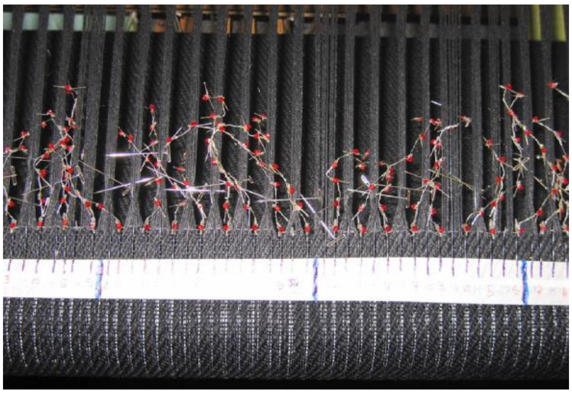


Figure 2.5 LED strands being woven into fabric on the loom (Layne, Studio Sub Tela and The Hexagram Institute, 2006)

An important quality of SubTela's working approach is their consideration of design aesthetics and woven process whilst investigating the e-textile work. An integrated woven approach was a central objective in their work. The combination of electronics, textiles and computing expertise is reflected in the dynamic outcomes of their work. The weaving in this work still remains basic in terms of woven structures; however, some woven manipulation techniques were applied, such as the integration of components on the loom during the weaving process.

2.2.5 Zane Berzina – 'E-static Shadows' interactive woven e-textile

Lead researcher in the project 'E-Static Shadows' 2009, Zane Berzina (in collaboration with multiple partners), created a large interactive woven installation through a rigorous two year project supported by the AHRC. The final outcome explored participants' electrostatic charge interaction with LED light and space. The piece detected the user's shadows of movement by deactivating LED lights through the transfer of body electrostatic charge revealing a shadow shape where LEDs had been deactivated. The E-Static Shadow piece was achieved through the use of jacquard woven textiles, incorporating conductive yarns and the integration of a complex electronic network (Berzina, 2009a).

The design concept of 'E-Static Shadows' was reliant on innovative creative craft methods to make woven textiles. Using a jacquard loom allowed for the project to be sampled quickly, and to make larger pieces with more control and accuracy than with an industrial woven process. Combinations of woven structures applied to make the soft circuits were manipulated (on and off the loom – i.e. floats, cut floats, multiple weft yarns, integration of components, controlled conductive yarn interactions), and enabled the complexities of the electronic circuit to fit more comfortably within the overall fabric. However, the soft circuits were woven to specific designs to allow for the connections of the electronics to map onto. Thus the weaving required absolute precision to align the inter-connections and the components. Testing of all connections, cleaning up of jacquard samples' conductive threads (to avoid short circuits) and the integration of components was reported to be very taxing (Figure 2.6 illustrates some of this process) (Berzina, 2009b). The blankets of woven e-textile circuits required extensive, skilful manual labour to position each electronic component individually, and then solder each one separately.

Although multiple woven structures were designed with weave experts, components were still soldered *onto* the woven fabric after the weaving process. Woven integration methods to combine the components on the loom could have provided an additional integration phase; however, this would have been challenging in the weave and would have added to the complexities

Figure 2.6 Images of the making process of E-Static Shadows textile (Berzina, 2009b)

When exhibited the E-Static Shadows textile successfully engaged participants in an interactive experience (Figure 2.7). The project objective was to design an interactive system using textiles that combined woven e-textiles and electrostatic technology. The project used woven and integrated design methods to achieve these objectives and utilised complex woven structures to enable the form and function.

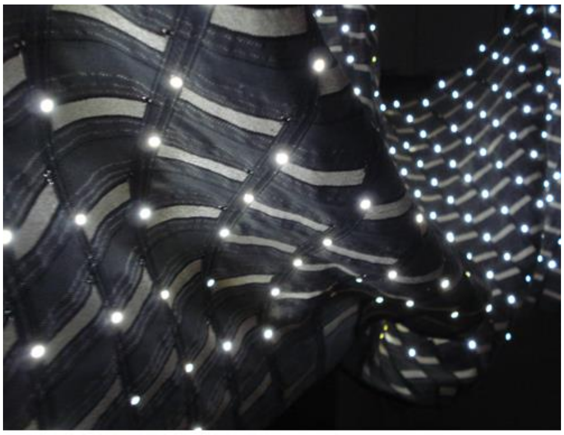
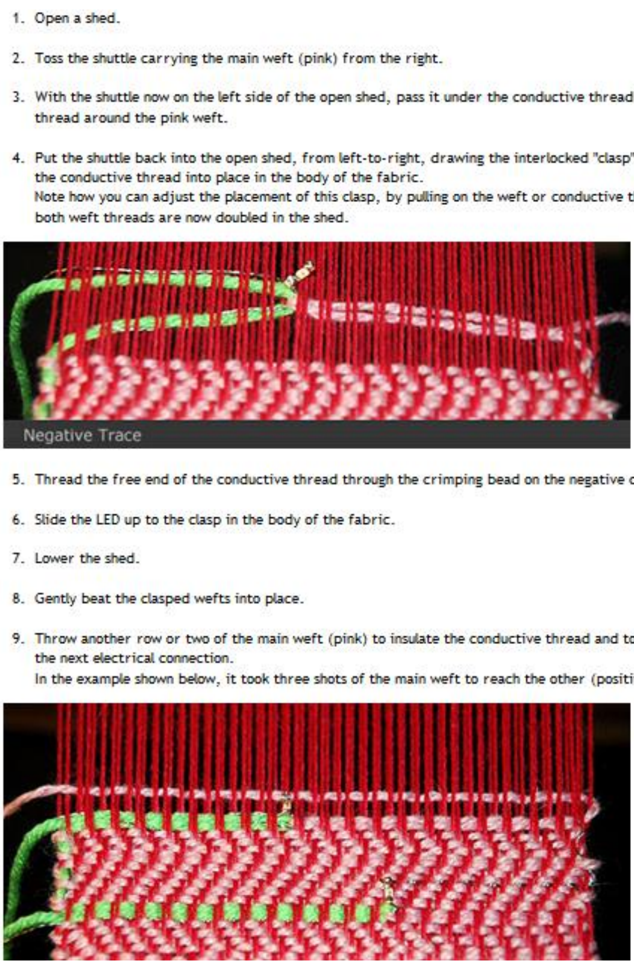


Figure 2.7 Image of E-Static Shadows the final piece (Berzina, 2009b)

2.2.6 Lynne Bruning – clasped weft weaving technique

Lynne Bruning, based in Colorado, USA has a background in neurophysiology, architecture and now textiles. Bruning has established herself within e-textiles by creating a community hub known as the 'eTextile Lounge', drawing interest from active individuals in e-textiles to network and share ideas (Lynne Bruning, 2012). One of Bruning's projects was featured in *WeaveZine* in 2009 'Clasped Weft Weaving' (Figure 2.8) (Mitchell, 2009), and also on the sharing maker projects website *Instructables* (2012). On both sites, step by step instructions are clearly explained with illustrations to show one possible method of integrating conductive yarn and small LEDs through weaving. The woven structure used is a 2/2 twill applied in a single cloth.

Bruning's clasped weft weaving technique originates from tapestry weaving, and in this example it is used on a basic four shaft loom. The technique works well with conductive yarn as it allows for isolation away from a parallel length of conductive yarn, particularly if the conductive yarns are addressing different components. The idea to encapsulate the component using this technique is novel and Bruning has identified woven methods to integrate the component into the weaving process. Bruning's projects present design and making processes where the integration of the LED and conductive yarn are achieved using the woven construction. Although the weaving structures used by Brunning are not complex, the approach does adapt a standard weaving process for electronic integration. This method is beginning to manipulate weaving for electronic integration and function. However, there are a significant number of further opportunities for the use of the clasped weft technique, including slightly adapting this method for the inlaying of conductive yarns.


1. Open a shed.
2. Toss the shuttle carrying the main weft (pink) from the right.
3. With the shuttle now on the left side of the open shed, pass it under the conductive thread to loop the conductive thread around the pink weft.
4. Put the shuttle back into the open shed, from left-to-right, drawing the interlocked "clasp" of the main weft and the conductive thread into place in the body of the fabric.
   Note how you can adjust the placement of this clasp, by pulling on the weft or conductive thread. In addition, both weft threads are now doubled in the shed.

Negative Trace

5. Thread the free end of the conductive thread through the crimping bead on the negative connection of a LED.
6. Slide the LED up to the clasp in the body of the fabric.
7. Lower the shed.
8. Gently beat the clasped wefts into place.
9. Throw another row or two of the main weft (pink) to insulate the conductive thread and to span the distance to the next electrical connection.
   In the example shown below, it took three shots of the main weft to reach the other (positive) side of the LED

Figure 2.8 Screen shot of part of the 'Clasped Weft Weaving' project as documented on WeaveZine (Mitchell, 2009)

2.2.7 Quirk *et al*. – floating wire interconnections in woven e-textiles

In a paper titled *Inclusion of Fabric Properties in the E-Textile Design Process,* Meghan Quirk *et al.* from Virginia Polytechnic Institute and State University, reported the significance of considering both the e-textile physical construction properties and the electronic capabilities (Quirk, Martin and Jones, 2009). They identify clear differentials between designing a regular electronic circuit and an e-textile soft circuit. The main differences identified were scale and connection amongst fibres. Although their project was approached from a technical materials objective, it highlighted the importance of the circuit design within a woven e-textile. Thus, this project applied some creative craft methods to design and adapt woven structures for e-textile circuitry. The work begins to address the possibilities of using the design of woven structures to enable multi-layer cloths, and the manipulation of fibres as sensors. An example of a floated wire sensor can be seen on Figure 2.9. This is where the warp wire has come up out of the warp, been left out for several picks to enhance its function as a sensor, and then woven back in. This work aimed to keep e-textiles as per regular textiles (in terms of comfort, tactility, cost and durability), and to use the fabric construction design to integrate electronic capability.

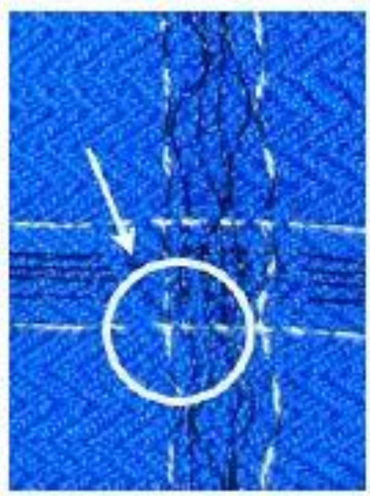


Figure 2.9 Meghan Quirk *et al.'s* woven e-textile floating wire sensor (Quirk, Martin and Jones, 2009)

2.2.8 Kobakant – integrated woven e-textile ITM collection using hand and jacquard weaving

Kobakant is an organisation who uses creative experimentation methods for DIY wearable technology and soft circuits, originally set up by Hannah Perner-Wilson and Mika Satomi (2010). A two week funded research project by the Kobakant team and Linda Worbin conducted at The Swedish School of Textiles, titled ITM Collection (Involving the Machines) investigated woven methods for e-textile properties, such as conductivity, resistance and electronic sensors. One of the main objectives was to use a design considered approach to integrate human design skills with semi-automated weaving machines, and apply a design aesthetic to the textiles (Satomi and Perner-Wilson, 2013a; The Swedish School of Textiles, 2013).

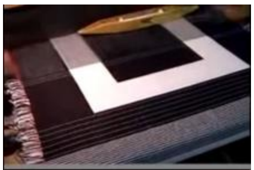
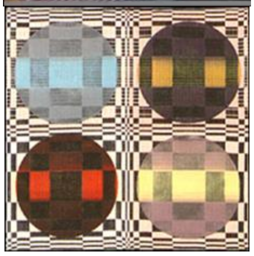
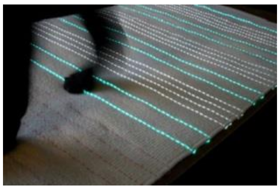
The researchers Satomi and Perner-Wilson were not expert weavers; therefore, they learnt woven theory and practice through the project. This knowledge was then adapted to be used for e-textiles in dobby and jacquard sampling with the assistance of woven experts. The researchers needed to build a comprehensive understanding of woven methods and structures before applying these to woven e-textile applications. The progress and the outcomes were documented online and clearly illustrated the detail involved in adapting woven methods for e-textile devices such as switches, variable resistors, tilt sensors and conductive tracks (Satomi and Perner-Wilson, 2013c; Satomi and Perner-Wilson, 2013b). The project illustrated how woven methods can be used in e-textiles with integrated design after a brief intensive course in weaving. Satomi and Perner-Wilson were able to identify attributes of weaving and electronics to experiment with, particularly manipulating woven structures for electronic capabilities with design conscious and integrated approaches. Woven structures such as multilayer weaving, floating weft yarns and isolating areas of visual patterns to weave with conductive yarns enabled functions such as switches, and conductive tracks to be integrated into the cloth. Examples of this project can be seen in Figure 2.10. Some samples had functional embellishments applied after the fabric was woven (e.g. beaded tassels with conductive beads to act as a tilt sensors).

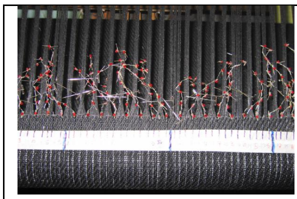
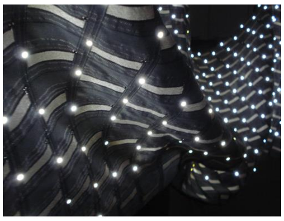
The project investigated how woven form could accommodate electronic function successfully and utilised woven structure manipulations. However, sensing components were not integrated *into* the e-textiles in the weaving process.

Figure 2.10 ITM collection fabric examples. Left: Jacquard pattern conductive fabric. Right: X/Y intersection fabric (Satomi and Perner-Wilson, 2013a)

2.3 Woven e-textiles via creative craft methods synthesis

Table 2.1 summarises the specific woven e-textiles projects discussed in this subsection. As illustrated, all of the projects include integration of electronic capabilities for woven e-textiles via creative craft methods. Some of the projects use a combination of creative craft methods and technical materials approaches.

Key individual/ project name	E-textile construction method/s	Are integrated methods applied to make the e-textiles?	Are creative craft methods used in the developed work?	What woven techniques are applied to the e-textiles?	Potential opportunities
Maggie Orth/ double weave e-textile and 'Double Dynamic Weave'  	Weaving, sometimes with thermochromic printing	Yes – *into* and *onto* the e-textiles.	Yes, and technical development for the computation systems	Double cloth structures, multiple yarns, conductive yarn in the warp/ weft. Utilises and exploits the woven construction for integrated e-textiles.	Thermochromic yarns integrated simultaneously into the woven cloth. Potential further opportunity with complex jacquard weaving for different visual effects. Double cloths for switches, for electrical insulation, and hide/ expose conductive yarn tracks
Spår interactive carpet 	Weaving, and knitted sensors embroidered on the reverse of the carpet	Yes, electroluminescent cables *into* the textiles. Knitted pressure sensor *onto* the textiles.	Yes, and also included functional focus to enable the lighting system to operate when the carpet was walked over	Inlayed electroluminescent cable into woven structure during the weaving process	Construct simultaneous integration of multiple functions in a complete as woven e-textile
Laurie Carlson  Barbara Jansen 	Weaving	Yes, fibre optics *into* the textiles	Yes, the integration of fibre optics are aesthetically considered as part of the installation's design	Fibre optics are interwoven simultaneously during the woven process	Investigation of complex woven structures for different lighting effects, e.g. pattern, 3D structures, loose and dense weaves for diffused light effects
Barbara Layne/ SubTela	Weaving	Yes, *into* the textiles	Yes, creative craft methods are applied for the form and some of the function	2/2 twill woven structure and integration of components during the weaving process	Conductive yarns in the warp and weft for easier integration of conductive

					paths instead of wires. Control interconnections between conductive tracks with combination of weave structures. Multilayer weaving to spread the conductive paths.
Zane Berzina/ E-Static Shadows 	Weaving and electronic finishing (e.g. soldering)	Yes, *into* the textiles	Yes, creative craft methods investigated woven construction for both form and function	Multiple woven structures and complex jacquard weaving construction, including floats, multiple wefts and controlled interactions. Custom e-textile circuit for the final piece.	Integration of components into the woven construction during the weaving process to reduce soldering of components and finishing process
Lynne Bruning 	Weaving	Yes, integration *into* the e-textile	Yes, creative craft methods were investigated for this woven e-textile work	2/2 twill on single cloth. Clasped weaving technique for LED integration that enables isolation of conductive yarn, i.e. does not interfere with other conductive tracks.	Apply technique with other structures that may enhance the lighting effect, e.g. multilayer weaving. Apply finer density of yarn; current example only uses thick weft yarn. Adapt clasped weft technique for inlaying of conductive yarns.
Meghan Quirk *et al.*	Weaving	Yes, integration *into* the e-textile	Yes and no; a technical materials approach project focus, however, a creative craft methods approach was applied to develop the	Manipulation of woven structures (e.g. floats in the warp and weft)) to enable controlled interconnection between conductive wires. Woven	Conductive yarn could be investigated to achieve the same function as the wires applied in this e-textile. Exploit woven construction for better e-textile

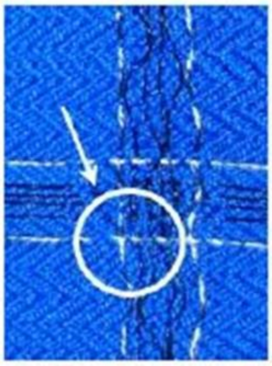
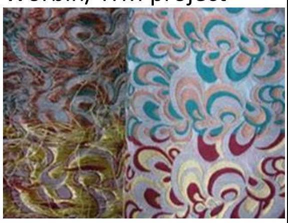
			integration of materials into the woven structures	on 24 shaft AVL loom.	aesthetics. Floated warp and weft yarns for sensors and circuit track interconnection s.
Kobakant (Mika Satomi and Hannah Perner Wilson) and Linda Worbin/ ITM project 	Weaving and some applied embellish ment for electronic function (e.g. tilt sensor)	Yes, integration *into* the e-textile. Also applied finishing techniques and applied embellishme nts *onto* the textile	Yes, creative craft methods were applied for the design approach, function and aesthetics of this project	Multiple woven structures, yarns and complex jacquard weaving applied to achieve conductive fabric, including manipulation of structures such as floats	Integration of components during the weaving process. Enable a full woven e-textile circuit via the woven construction

Table 2.1 Summary of woven e-textiles projects via creative craft methods

The examples discussed thus far have demonstrated and highlighted woven integration for e-textiles; however, this has revealed more focus on the aesthetics, visual effects and the design form. Function has nevertheless been an important element of these designs, as some technical knowledge needs to be applied to enable the e-textile to function. Thus, some of the examples clearly demonstrate overlapped combinations between creative craft methods and technical material approaches. Finding a balance between novel and more design conscious e-textiles is important. Creative craft methods applied to develop e-textiles enable valuable insights to progress new outcomes, knowledge and future developments in the field.

The examples reviewed have highlighted key projects and individuals involved in developing woven e-textiles using creative craft methods, which have helped to demonstrate the potential of integrated woven e-textiles. Although the examples discussed have used woven integration, there has been limited work focused on exploiting the limits of woven construction for electronic integration via in-depth woven structure manipulation, applied via creative crafts methods. Five methods in particular appear to offer opportunities for carrying out novel work. These are:

- The use of double cloth for insulation, switches, and hiding and exposing conductive tracks
- The integration of multiple functions into the textile as part of the weaving process, for example the integration of switches and LEDs in one cloth
- The use of complex weaving techniques combined with friction to attach and integrate components during the weaving process, and reduce soldering of components
- The use of inlay weft weaving to isolate conductive yarns and other yarns during the weaving process
- The manipulation of floats, (free floating threads), pre-designed at the warp set up stage (to enable more elaborate controlled interconnections than achieved by Quirk *et al.)*

The woven methods used have been implemented by designers, researchers, artists or makers who are not necessarily expert weavers. There is a need to fully investigate woven e-textiles with in-depth structural manipulations via creative craft methods, to enable these opportunities be realised for innovation.

2.4 Woven e-textiles via technical materials approach

This section of the literature review will discuss selected technical woven e-textiles, and draws on aspects that are related to this PhD research. Therefore, specifics of data collection, chemical and technical analysis are less relevant here. In particular, integration methods and techniques to develop woven e-textiles will be focused on.

Woven structures can be manipulated to build physical structures to accommodate for electronic properties, either as integrated components or by using the architecture of woven construction to support electronic behaviours. Securely embedding electronics into textile constructions allows for truer integration of e-textiles. Ultimately, an integrated e-textiles approach will lead to more useable e-textile interfaces for interactive smart textile products. A potential outcome of this approach could lead to the technology becoming less obtrusive and the textiles becoming more active and responsive materials.

2.4.1 Eriksson *et al.* – 3D woven capacitive sensor

Woven fabric construction uses historical techniques that are applied to different forms of weaving. Some woven constructions are directly related to conventional two-dimensional fabrics as used for fashion and textiles, whilst others are more sophisticated and have been adapted to fit with innovative weaving methods, such as three-dimensional structures.

In an overview paper by Chen *et al.* they emphasise the significance of a range of woven three-dimensional structures (Chen, Taylor and Tsai, 2011). Woven three dimensional structures have led to the development of advanced three-dimensional weaving equipment (Gokarneshan and Alagirusamy, 2009). E-textiles have and will undoubtedly be inspired by these constructions. There have already been some examples of such outcomes, using adapted traditional weaving methods in technical products with the integration of electronics. For example, Eriksson *et al.* (2011) presented an interactive textile structure woven in three-dimensional form integrating electronic properties to fabricate a capacitive sensor (Figure 2.11). In this project, their objective was to integrate processes to make a three-dimensional multilayer woven interactive fabric, to establish a single process to ease manufacture of such materials. This was achieved by adapting a loom to demonstrate a handmade prototype of a capacitance sensor textile. A three dimensional structure consisting of conductive outer layers, layered between a non-conductive compressive spacer structure successfully demonstrated a functioning capacitive sensor. This outcome had only been possible in this way due to opportunities available to manipulate the woven structural form and weaving loom.

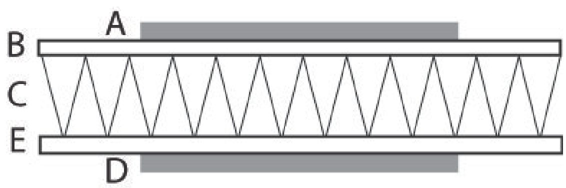


Figure 2.11 Image of Eriksson et al.'s three-dimensional woven capcitive sensor structure with conductive layers and structure schematic; where A and D are conductive layers, B and E are stable insulating layers and C is the compressive spacer layer (Eriksson *et al.*, 2011)

2.4.2 Georgia tech Wearable Motherboard (GTWM) woven e-textile

The GTWM, as shown in Figure 2.12, is another example of the innovative use of woven methods in e-textiles. The engineered vest was a working prototype and used weaving in a singular piece of textiles, facilitating an off the loom wearable technology with considered placement of body data sensors (Firoozbakhsh *et al.*, 2000). The wearable vest was designed to integrate transmittable fibres to enable communication from body data sensors to external devices, directly passing the user's physiological data. At present there are other products that are able to sense, detect and communicate in a similar manner. However, GTWM was one of the first projects to have been initiated with specifically woven e-textiles in the late 90s.

Figure 2.12 Image of GTWM (Smart Shirt GTWM, 2003)

The woven architecture has been mapped with electronic circuit matrices to function as a complete integrated circuit, created simultaneously on the loom. GTWM development was followed by a patent filed by Georgia Tech research Corp in 1998 by Jayaraman *et al.* and patent approval in 2000 (Jayaraman, Park and Rajamanickam, 2000). The vest's aesthetics and comfort factors could potentially be improved upon; although on reflection, this was an early prototype and not developed by designers, but a team of engineers using a technical materials approach (Smart Shirt GTWM, 2003). The work was inspirational for the early advances of woven e-textiles, specifically where integrated woven methods were applied to achieve a specific application.

2.4.3 TITV – *galvanotextile* yarn integrated into a woven e-textile RFID tag

The research centre at TITV Greiz, Germany had also conceptualised a similar woven RFID transponder and prototyped this idea into a physical sample. They demonstrated this in their application of *galvanotextile* yarn research and development (galvanic and electrochemical metal coated yarns on micro and millimetre scale). They used jacquard weaving, to weave three consecutive layers simultaneously, controlling interaction connection points between the conductive tracks in the warp and weft on each layer (Gimpel, 2004 p.184) (Figure 2.13). TITV's paper did not disclose in-depth details of the making method; however, their research did follow a process of e-yarn (electronic yarn) development through to an example of woven material application and function with design consideration. However, parts of the woven design have opportunity to be simplified with other woven construction, such as extra warps (section 4.2.1).

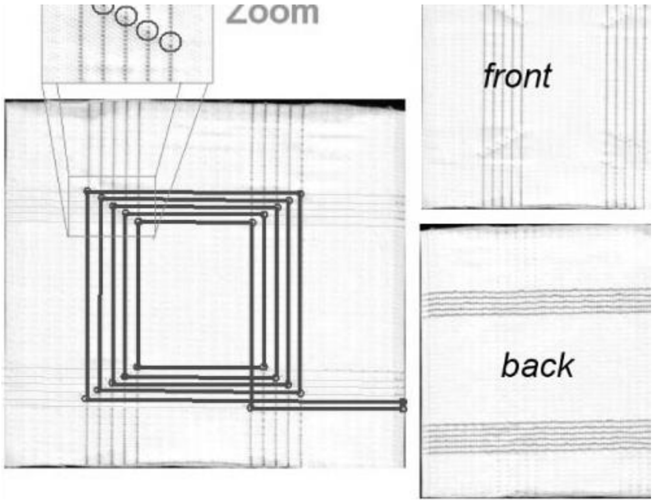


Figure 2.13 TITV's woven RFID tag sample. Three layers are woven on jacquard loom to form interaction points making a coil configuration enabling the structure to work as a transponder (Gimpel, 2004 p.185)

2.4.4 TITV – Conductive and electroluminescent woven e-textile display

TITV have also investigated woven displays using a technical materials approach. By applying woven double cloth structure with conductive weft yarns, these operated as electrodes and were coated with electroluminescent paste through screen printing processes. When a current was passed via the conductive path, the electroluminescent area became charged to activate light emission, highlighting an image or text (Figure 2.14) (Moehring *et al.*, 2006). In this example, although the weaving was only utilised to support the conductive wefts, without electrically charging the entire track the exposed electroluminescent area would not be able to display an output. Therefore, the woven construction allows the textiles to operate as a complete circuit. The project objective was an investigation of electroluminescent properties in textile structures, as TITV operates as a specialist research institution for flexible materials and works with industry based projects.

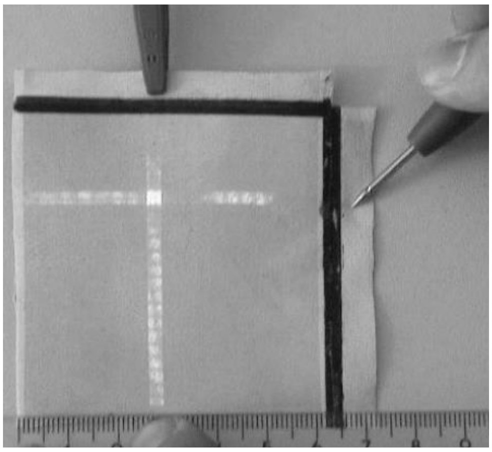


Figure 2.14 Image of TITV's electroluminescent woven display sample, where scale is depicted as 90 x 90 pixels per square inch (Gimpel, 2004 p.187)

2.4.5 Berzowska et al. – 'Karma Chameleon' jacquard woven photonic bandgap (PBG) fibre e-textiles

Berzowska and her research team have investigated photonic textiles through jacquard weaving processes, where the end application of these textiles can be used for electronic visual displays. However, they felt at the time of investigating this project, *"Few functional yarns (other than conductive or resistive yarns) are currently available commercially to enable functionality such as the display of information, sensing, or energy harnessing in a textile. The ability to integrate the desired functionality on the fundamental level of a fiber remains one of the greatest technological challenges in the development of smart textiles"* (Sayed, Berzowska and Skorobogatiy, 2010 p.1). The research team investigated photonic crystal fibres to fabricate PBG fibres, creating photonic textiles and adaptable aesthetic displays. Depending on the light source (whether natural ambient or artificial emitted light), and the angle of exposure, the PBG fibres refract this radiation to emit different coloured light. As a result, the project was named 'Karma Chameleon'. Applying jacquard weaving with the PBG fibres enabled different patterns and shapes to be visibly exposed at varying levels depending on the woven structures, i.e. more weft facing or more warp facing (Figure 2.15), (woven structures further discussed in section 4.2.2).

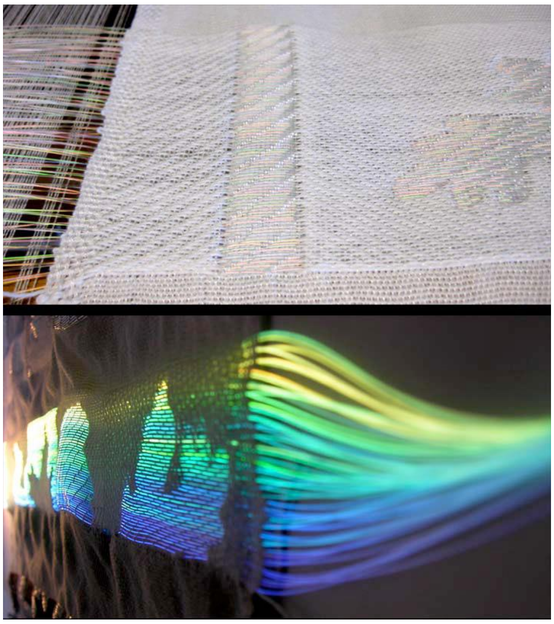


Figure 2.15 Images of Karma Chameleon jacquard woven PBG fibres. Top: sample is exposed to ambient light. Bottom: sample is exposed to emitted light. The woven structure generates visual imagery (Berzowska and Skorobogatiy, 2010 p.298)

Photonic fibres were applied as part of the fabric's construction to make visual displays. This resulted in an effective way to achieve photonic textiles, as they can operate with unpowered or powered light sources. Therefore, this enables photonic fibres to be effective under most lit conditions, although they were less effective under ambient light than emitted light. The fibres were able to operate successfully even after the rigorous process of being woven on an industrial jacquard loom. The applications of these types of photonic textiles are wide, particularly given the different coloured lights emitted depending on the angle at which the PGB fibres are exposed to a light source.

As Sayed *et al.* pointed out in the 'Karma Chameleon' project, development of compatible technology on fibre level is vital for the progression of integrated components for e-textiles. Perhaps with the eventual maturity of micro-components, this may see an evolution of e-textiles' form factor, making other fibre based electronics possible to be integrated directly into woven constructions. In turn, *"...it is possible to obtain a textile matrix that is particularly interesting for future developments in distributed sensor systems made on a textile platform"* (Locci *et al.*, 2007 p.3972).

2.4.6 Eitan Bonderover and Sigurd Wagner – woven inverter circuit

A project by Eitan Bonderover and Sigurd Wagner from Princeton University, sought to investigate the use of the woven construction to distribute different fibres and components in an integrated woven electronic inverter circuit. They proposed and prototyped a woven e-textile where e-fibres were only able to function due to their specific position and contact point within the woven structure (Bonderover and Wagner, 2004). The contacts were held in place solely by the pressure of the woven construction to maintain textile flexibility (Figure 2.16). Although this project had a large amount of technical and scientific knowledge applied in developing the e-fibres, in terms of the woven construction, the prototype only applied a plain weave structure that was sufficient to operate this complex circuit. In this case, much of the technical sophistication was incorporated into the e-fibres.

In describing the woven structure, the researchers called this a ‘basic pattern’ and referred to a ‘simple thread’ that was used in the construction. Clearly, the method of weaving was not fully explored here, or explained in-depth; potentially due to the researchers not being specialised in woven construction and the project only being an initial investigation of this concept. The final physical sample’s aesthetic was partially that of plastic, as the e-fibres were based on Kapton (polyimide flexible film PCB). This was suitable for the integration of this prototype, however, use of a textile substrate base would realise this application as a complete soft e-textile. The final testing of the prototype proved successful.

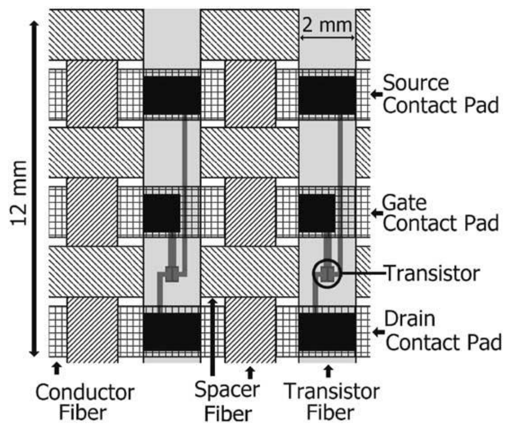


Figure 2.16 Schematic illustration of Bonerover and Wagner’s woven inverter circuit (Bonderover and Wagner, 2004 p.295)

2.4.7 ETH – e-fibre strip temperature sensor integrated woven e-textile

As mentioned in the introduction, ETH Zurich has been researching e-fibres to specifically integrate into woven fabrics. They have investigated various sensors and LEDs on flexible thin e-yarns through their own fabrication methods, using technical material approaches (Figure 2.17).

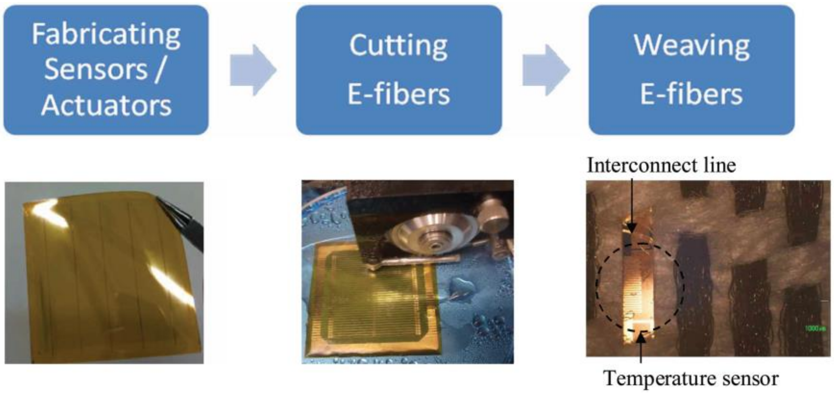


Figure 2.17 ETH's e-fibre fabrication process. In the above example, a temperature sensor is fabricated to be woven into a fabric construction (Cherenack *et al.*, 2010 p.2)

They developed strip temperature sensors which were then integrated into a woven e-textile, where the majority of the fibres were soft textile yarns (fibre compositions were not stated). However, the circuit contact point of the e-fibre was held in place by gluing into position using conductive glue (Figure 2.18), which also helped stabilise the connectivity. Although the woven sample was constructed on an industrial loom, the e-fibres were inserted as weft picks manually by stopping the automatic loom process. The woven structure applied appears to be a basic twill structure, as this is not specifically documented in the research paper, but is visible in the image of the sample.

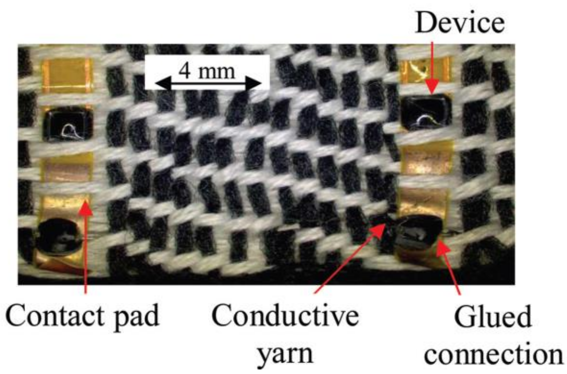


Figure 2.18 ETH's woven e-fibre temperature sensor in a textile circuit with conductive yarn as buses. The e-fibre is illustrated where conductive glue is used to hold the contact in place (Cherenack *et al.*, 2010 p.2)

As with Bonderover and Wagner's work, ETH's woven e-fibre temperature sensor's textile construction has only been used as a mesh scaffold to support the electronics. They have not fully utilised the woven structure as part of the e-textiles circuitry, as conductive yarns could have been integrated into the e-textile to help achieve interconnection with the circuit. In addition, other tighter woven structures and multilayer weaving would have stabilised the component integration.

ETH's woven e-fibre temperature sensor project further progressed to test for electrical properties, mechanical analysis, washability and wearability (Zysset *et al.*, 2012). ETH aimed to combine both electronics and textiles on a level that would result in feasible applications to monitor body motion, bio-physiological data and other e-textile product surfaces (e.g. furniture, automotive interiors, etc.), which could have sophisticated functions and operate successfully. ETH demonstrated that electronic and woven textiles can be combined for successful outcomes and that textiles *"...provide a suitable platform for sensor integration to measure these parameters and signals close to the human body. To increase the acceptance of smart textiles and ultimately their wearability requires an unobtrusive integration of electronics into textiles"* (Zysset *et al.*, 2012 p.1107)

2.4.8 Martin *et al.'s* e-textiles jumpsuit project with integrated fabric network and sensors

At Virginia Polytechnic Institute and State University, a group of researchers developed a jumpsuit for motion capture, specifically focusing on woven construction to design and make integrated fabric networks (Martin *et al.*, 2009). The woven e-textiles for this project have already been mentioned in section 2.2.7 (Quirk, Martin and Jones, 2009). Woven integration of sensors (referred to as 'e-tags') would be connected via different patterned pieces of the garment. Conductive threads were not used in this example, instead wires (insulated and bare) were applied for the electrical tracks. The concept was to make *"...an on-fabric digital network that allows* [them] *to quickly add new sensors and reprogram the garment for a new application"* (ibid). Martin *et al.* used woven construction to their advantage. For example, this can be seen in their use of a broken twill structure with elastic weft yarns, floating extra warp (wire) and floating wire wefts (Figure 2.19). The use of elastic yarn for a close-fitting garment and floating of threads were effective ways to manipulate woven construction to suit the context of this e-textile's fabric use. In this case, the floated yarns were used to attach the e-tags (sensors) at the same point for any size of garment, as this repeated effect could be controlled for consistency and repeatability. The floating wires also helped relieve strain as they were lifted out of the woven construction at this point.

Figure 2.19 Martin et al.'s e-textiles jumpsuit project. Left: close up of the e-textile construction where wire and elastic yarns have been integrated into the structure. Right: the jumpsuit final prototype (Martin *et al.*, 2009)

The loom used to construct the e-textiles for the jumpsuit was a 24 shaft AVL industrial loom, which was more elaborate than a standard handloom and enabled advantages in the weaving structures and styles. The e-textile jumpsuit research also addressed the digital network programming and hardware used in their project, combining a complete wearable system and designing for both attributes. The final jumpsuit was still far from perfect in regards to integration of all invisible electronics. Nevertheless, for a first prototype, and considering all of the technical aspects of this application, it was a successful attempt. It was reported to function effectively to enable recording physical movement when worn. The textiles for this project considered technical materials development from a design perspective that aimed to benefit the finished product utilising existing woven textile properties. However, the aesthetics and integration of softer yarns (e.g. conductive yarns) could improve the form and integration of electronic tracks.

2.4.9 Jones and Wise TWI – welding LED component and conductive e-textile

Jones and Wise from The Welding Institute (TWI), Cambridge, UK, investigated the welding process to join conductive tracks in textiles. They specifically experimented with laser welding, laser soldering, ultrasonic welding, hot bar welding, resistance welding, and applying conductive adhesives to joining woven e-textile conductive paths and components (Jones and Wise, 2005). They reported some successful outcomes with the positioning of connected components arranged in obvious ways, i.e. positioned directly on top of the fabric (Figure 2.20). However, the integration of components (LED in this example), could have been further investigated from an in-depth design approach to benefit both the form and function of the e-textile. (For example, integrated conductive paths and components could be constructed in a single woven e-textile). The research provided technical materials insights into methods of joining woven e-textiles. There appears to be potential for further investigation of complex woven structures designed to aid the joining processes. Selection of particular woven structures could expose more contact area of material for joining, (e.g. a weft faced structure would expose the maximum amount of conductive yarn onto the top side of the textile).

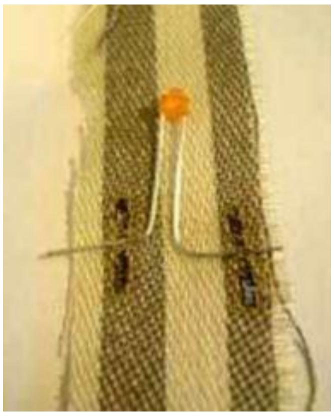
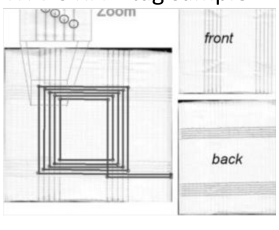
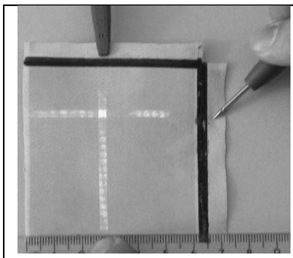
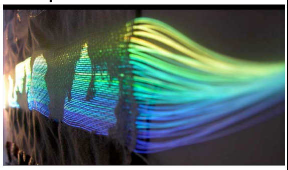
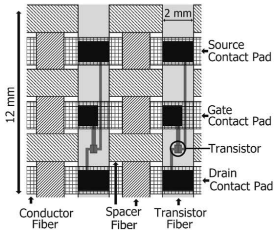
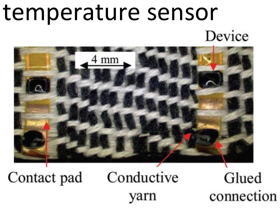


Figure 2.20 Image of Jones and Wise's hot bar welding of LED and woven silver coated nylon/ cotton fabric

2.5 Woven e-textiles via technical materials approach synthesis

Table 2.2 presents the discussed woven e-textiles projects that have been developed via technical material approaches. A recurring theme concerns the circuit interconnection points between the electronic tracks and components. Some have addressed this by gluing, encapsulating the entire structure, pressurising, and/ or physically attaching by another means. The main objective of the connection points is to form consistency for electrical current flow without affecting resistance levels or connection interferences.

Key individual/ project name	E-textile construction method/s	Are integrated methods applied to make the e-textiles?	Are technical material approaches used in the developed work?	What woven techniques are applied to the e-textiles?	Potential opportunities
Eriksson et al.'s three-dimensional woven capacitive sensor 	Weaving – three dimensional textiles	Yes, 3D e-textiles with interwoven conductive yarns *into* the textiles	Yes, the project focused on development of a technical materials woven capacitive sensor and did utilise woven constructions for this objective	Multilayer weaving using complex woven structures on an adapted loom. Simultaneous integration of conductive yarn during the weaving process	Apply same functional concept to standard dobby weaving, i.e. achieve the same function using multilayer weaving and satin/ sateen structures (sections 4.2.2 – 4.2.3). Investigate different aesthetic forms.
GTWM smart shirt 	Weaving	Yes; integrated e-textile circuit *into* the woven textile	Yes, the project aimed to develop a woven integrated material with bio-sensory capabilities.	Transmittable fibres were interwoven simultaneously during the weaving process. A complete integrated circuit was woven as one piece.	Investigate different aesthetic forms to improve the comfort of the textile when applied as a wearable garment. A combination of woven structures would enable this.
TITV's RFID tag sample 	Weaving – jacquard,	Yes; multilayer woven methods are applied *into* this e-textile	Yes, the project focused on weaving a RFID e-textile with complex weaving and integrate galvanotextile yarn	Triple layer cloth using jacquard weaving to control conductive yarn interconnections between warp and weft. Development of e-yarn integrated into woven construction	Different scale and repeatability with a range of structures to evaluate the woven construction and form. Parts of the structure could be simplified with an extra warp instead of multilayer weaving.
TITV's electroluminescent woven display	Weaving and screen printing methods	Yes; interwoven conductive yarns are	Yes, this piece investigated electroluminescent	Conductive yarn is interwoven into double cloth structures.	Potential development of electroluminescent coated yarn

		integrated *into* the textile for electrodes. Electroluminescent printing applied *onto* the textile	technology in a woven e-textiles	Printing is applied on top of the textiles	interwoven with consecutive conductive yarn would enable the same or similar function. Applied using jacquard weaving would enable a variety of visual displays.
Berzowski and Skorobogatiy's PBG Karma Chameleon sample 	Jacquard weaving – complex 2D structures	Yes; interwoven PBG fibres are integrated *into* the textiles during the woven process	Yes, for the integration and function of PBG fibres. This project was also explored via creative craft methods for the complete design	Jacquard weaving using woven structures to integrate a visual pattern, and simultaneously integrating PBG fibres	Integration of same methods in larger scale, industrial jacquard looms and in different forms, e.g. 3D textiles.
Bonerover and Wagner's woven inverter circuit 	Weaving and e-fibre materials development	Yes; the e-fibres are interwoven *into* the e-textiles with plain weave construction	Yes, this work investigated integration and development of technical e-fibres	Plain weave structure applied and integration of e-fibres during the weaving process.	Investigate other woven structures that would enable better integration of e-fibres and improved form. Reduce plastic surfaces of e-fibre to make complete soft e-textile.
ETH's woven e-fibre temperature sensor 	Weaving, e-fibre development and glued connections in finishing process	Yes; the e-fibres are interwoven *into* the e-textiles with basic woven construction	Yes, this work investigated integration and development of temperature sensor e-fibres	Twill woven structure on a single cloth. Integration of temperature sensor e-fibre during the weaving process.	Secure e-fibre and interconnections with more conductive yarns, using tighter woven structure and different warp/ weft yarns would not require gluing. Multilayer weaving could also stabilise component integration.
Martin *et al.'s* jumpsuit	Woven – extensive exploratio	Yes; woven structural manipulatio	Yes, this project investigated	Manipulation of woven structures (e.g.	Conductive yarn could be investigated to

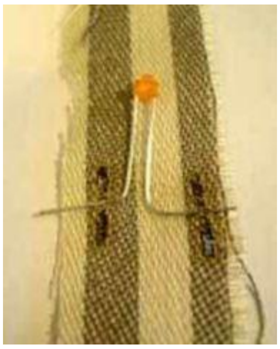
	n of woven structures	ns are applied to integrate electronic properties *into* the e-textile	integrated fabric network for a motion sensor jumpsuit via technical materials approach. However, creative woven methods were also applied to utilise woven structures.	floats in the warp and weft)) to enable controlled interconnection between conductive wires. Woven on 24 shaft AVL loom.	achieve the same function as the wires applied in this e-textile. The fabric was for a wearable jumpsuit application; thus, wires may not be appropriate for comfort. Exploit woven construction for better e-textile aesthetics.
Jones and Wise 	Woven conductive paths and hot bar welding for interconnection points with LED	Yes; for the e-textile conductive paths where conductive yarn is integrated *into* the textile; however the welded connection is applied *onto* the e-textile	Yes, this project focused on a technical materials approach to form welded connections in woven e-textiles	Conductive yarn is interwoven as stripes in the base textiles	Integration of LED component into the woven textile, and welding conductive connection over the integrated component. Weft faced woven structures would enable more exposed conductive yarn to aid joining methods

Table 2.2 Summary of discussed technical woven e-textile projects

All the discussed examples have used woven construction to execute the e-textiles, sometimes with additional textiles techniques. However, manipulation of woven construction to utilise the woven architecture for the implementation of the e-textile function is evident in six of the nine described examples, (i.e. Eriksson *et al.'s* three-dimensional woven capacitive sensor, GTWM smart shirt, TITV's RFID tag sample, TITV's electroluminescent woven display, Berzowski and Skorobogatiy's PBG Karma Chameleon sample and Martin *et al.'s* jumpsuit). In these samples, the woven structures have been specifically used to support the function of the e-textile, in some examples even manipulating structures to better fit and perform the function (e.g. Eriksson et al.'s three-dimensional woven capacitive sensor, TITV's RFID tag sample, Martin *et al.'s* jumpsuit). However, in some examples the woven construction has not been fully utilised to support the technical design. This is because the technical e-textiles are predominantly approached via a technical enquiry, where the technology portion of the project is dominant over the construction of the textile. Instead the woven construction is applied as a scaffold to hold technical e-fibres, where structures could have been adapted to better integrate the e-fibres or improve the function. Some of the discussed projects have only used basic woven structures, where more complex woven structures could potentially have strengthened the form and function of the outcome.

In some of the examples such as Berzowski and Skorobogatiy's PBG Karma Chameleon sample and Martin *et al.'s* jumpsuit, there were also creative craft methods applied to the execution of the material, i.e. an intentional effort to address the form, aesthetic and/ or utilise the woven construction. In these projects, there are overlaps between creative craft and technical materials development approaches, which help support design integration of form and function of the e-textile. However, it is evident from some of the technical materials e-textile projects that an in-depth investigation of woven structures has not been explored. There are opportunities amongst this work to improve the technical output with expert woven knowledge and thorough exploration of woven construction. In particular, reviewing the work of Jones and Wise has indicated there is further potential for complex woven structures to be designed to aid the joining processes.

Woven e-textiles can be beneficial when used directly from fabric to product, such as Martin *et al.'s* jumpsuit project. To achieve working technology that is combined with weaving is a challenging task, as illustrated with the woven e-textile projects mentioned. Amalgamating the two subjects of weaving and electronics to work succinctly can be taxing and complex, particularly as there are more factors to consider between the combined disciplines and can present many unknowns. Interdisciplinary collaborative work helps build a richer context for knowledge and a broader understanding, to address combined disciplines such as e-textiles.

It is evident that many technical material e-textile projects are led by teams of non-textile experts, as it is primarily the technology that is being investigated for specific technical outputs. This highlights the need for stronger cross collaborations and skill sharing, to work across a broad spectrum of disciplines. This would enable the projects to be investigated through different perspectives and realise new opportunities.

Designers' multidisciplinary backgrounds are often an asset in developing e-textiles, which is already a combination of two disciplines (electronics and textiles). Therefore, the 'T-shaped designer' i.e. vertical expertise in one specific area, and a horizontal broader knowledge in other fields (Oskam, 2012; Futt and Rasid, 2011 p.159), is a common feature related to e-textile developers. Specialist knowledge in a single discipline provides significant insight to fully understand any field, where this helps to develop in-depth designs. E-textile material developers may have extensive knowledge in a single subject, such as the researcher in this PhD who had prior expertise in woven textile design. However, even "*the term 'textile designer' no longer has a simple definition – the role comprises a myriad of descriptions, including: engineer, inventor, scientist, designer and creative*" (Gale and Kaur, 2002 p.37). The researcher's position is already that of a T-shaped textile designer. Equally, specialist knowledge can reside in electronics or computing, where this in-depth knowledge can be integrated in textile construction, as demonstrated by some of the technical e-textile projects.

2.6 The design process

The design process is inexhaustible and rarely has a defined end (Lawson, 2004). The design process is an integral part of this e-textiles research, as one of the main objectives sought to investigate woven e-textiles via a design process model. In order to understand more about the design process, this section discusses selected examples of design processes from the broader design field, including industrial product design, architecture and textile design. These design processes have been referenced in the development of the woven e-textiles design process (discussed in chapter 3).

The designer uses their knowledge to find solutions that best fit the design challenge; therefore, it is the designer's responsibility to present the most applicable approach given the design parameters. However, the decision to progress these options can be determined by, and specific to, each design discipline, where levels of authority, standards, procedures and hierarchical structures are used to filter the options to implement, depending on the type of design being produced. In addition, the designer's role is never complete, and depends on the designer's evaluation and judgement of whether the best/ ideal solution is realised. Other options may also be possible, but may not offer any additional value or benefit to the design (Lawson, 2004 p.123); thus, requiring the designer to evaluate and select the final designs. Other factors that can limit design contributions include time, effort, cost and resources.

The design process is a journey between problem and ideal outcomes, where the content of this journey varies depending on the design discipline, the individual designer, and the problem to be solved. Although the overall problem will initiate the design process, the problem will become re-defined when working through this to resolve it. During this iterative process, the problem will recur from different perspectives simultaneously through to potential developed solutions; therefore, the design process is in constant flux.

In this research project, the researcher's prior design process was broken down to explain and position the different stages to design woven textiles (explained further in section 3.2). This process was then adapted for woven e-textiles (examples explicated in chapter 5, 6 and 7). This is an activity that is not usually associated with textile designing (Studd, 2002; Gale and Kaur, 2002) and is more familiar to design disciplines such as product design, engineering and architecture. Thus, there is limited published literature on explicit textile design process (Bye, 2010; Gale and Kaur, 2002). However, one study that has examined the textile design process across several textile practices is by Rachel Studd. This study will be compared with other design processes to draw on similarities with textile design processes in this section.

Studd examined three industrial textile companies, a textile design studio, textile design consultant and a freelance textile designer. Studd's findings differed between the various textile sectors, as each has its own individual priorities. Although there were some similarities amongst these, they appeared in different sequences (Studd, 2002). Owing to similarities in their processes, the results from the three textiles companies analysed by Studd were condensed into one generalised framework (Figure 2.21). Studd's framework suggests a structured system that relates directly to other depending factors in the production of textile company outputs.

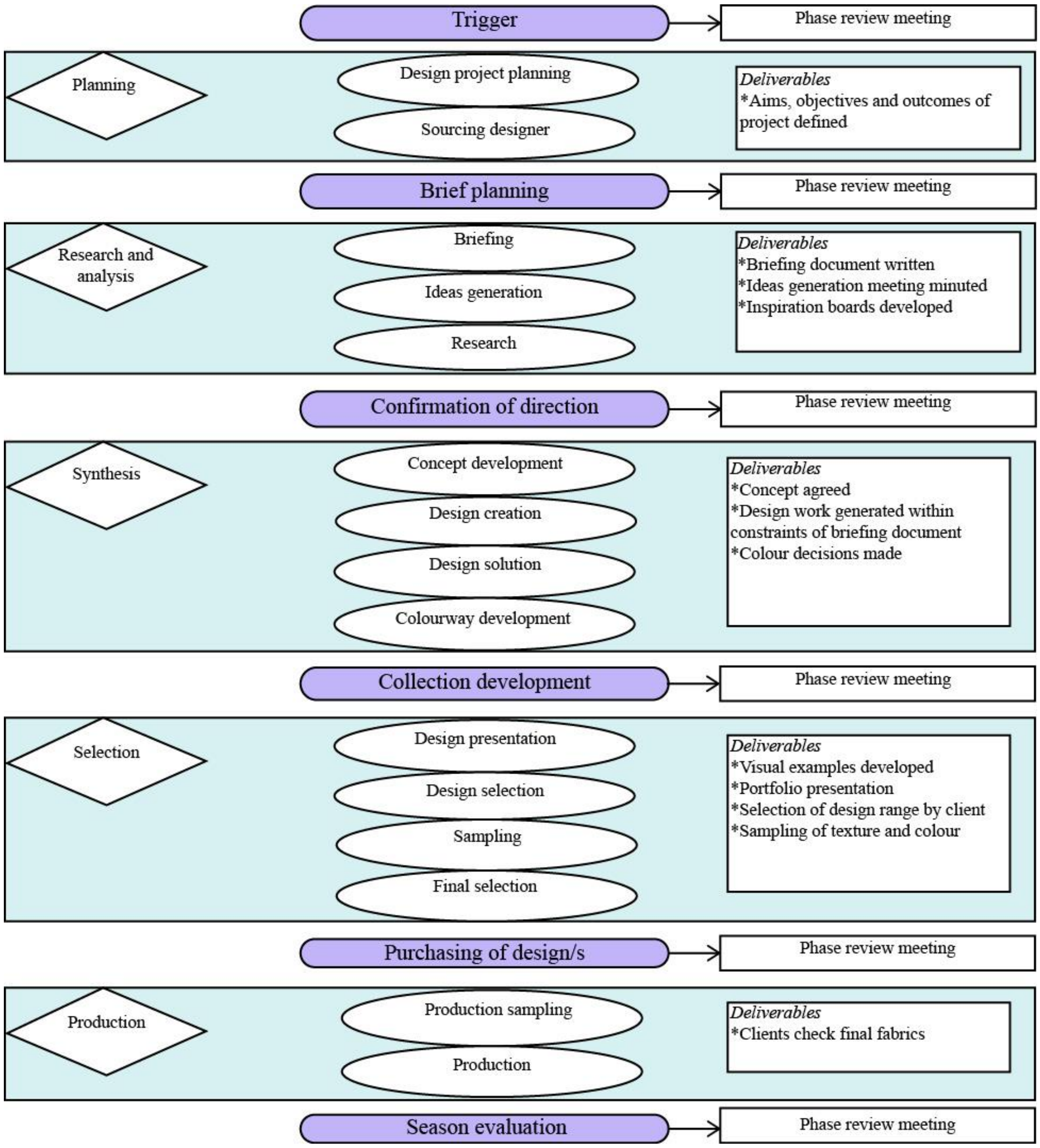


Figure 2.21 Rachel Studd's generic framework for the textile design process by textile design companies. Illustration redrawn (Studd, 2002 p.42)

Studd's framework relates the textile design process for production output. It does not illustrate the intricate details involved throughout the process; however, these are discussed and acknowledged in her study as part of the textile design process. For example, the beginning stages of the design process are sometimes the most chaotic and uncertain. However, as the process progresses over time, this can channel and filter into a clearer and more defined design scenario. Damien Newman's version of the design process squiggle (Figure 2.22) illustrates the beginning fuzzy front end and leads to a more refined end after clarity and focus have been sought (Newman, 2011). The initial stages seek to understand the problem through research, which is analysed and tested via prototyping. This leads to defined paths that are presented as design solutions. Newman uses his design process squiggle to communicate the complexities of the design process when working with clients in architecture, business, graphics, product and interaction design sectors.

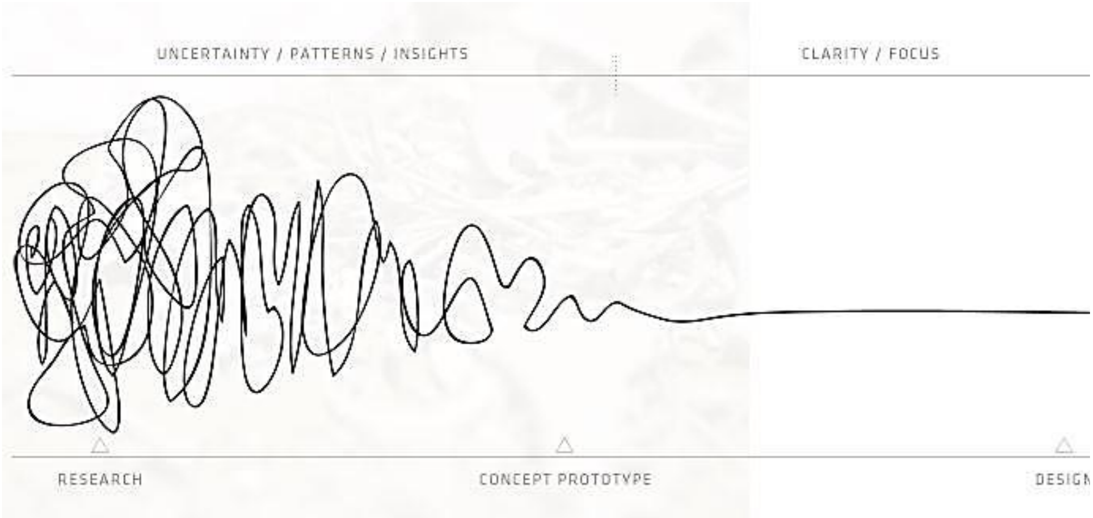


Figure 2.22 Damien Newman's version of the squiggle design process (Newman, 2011)

Although this schematic presents a scribbled line, this goes back and forth on itself at points. Thus, Newman's visualised design process is not linear, as there are many iterations and cyclical mid-stage developments that are not completely presented here. The squiggle helps to illustrate the different stages in the overall design process, leading to a design/ project solution. The outcome of the design process would be infused back into the design process in the same or different project at a later stage. The experience of each design process adds to the designer's experiential learning and knowledge. Newman's squiggle captures the tension between design stages that Studd's illustration does not, however, are present in the textile design process. Newman's squiggle depicts the iterations within each stage that also apply to the textile design process.

Bryan Lawson emphasises the design process as a non-linear one in fields such as architecture, product and industrial design. Lawson states it is highly complex and consists of phases that interplay between the problem at the beginning and the end solutions. Hence, this creates tension that requires negotiation between the mid stages of synthesis, analysis and evaluation (ibid. pp.48-49) (Figure 2.23). The schematic has simplified the complexities involved in the design process, nevertheless, shows the main activities involved.

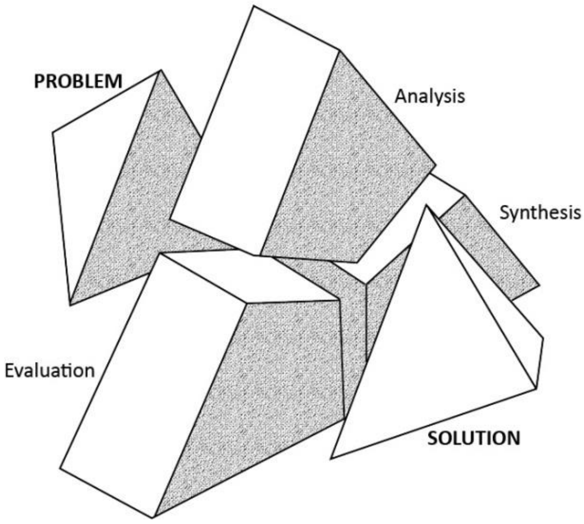


Figure 2.23 Bryan Lawson's simplified illustration of the design process between the problem and solution. Illustration has been redrawn (Lawson, 2004 p.49).

Comparing Lawson's model to Studd's framework of textile design processes, it is evident that both address the same phases, however in different contexts. For example, Studd's framework also presents a problem (design brief) and solution (textile design production), where Lawson relates these to fields such as architecture, product and industrial design. The middle phases of Studd's framework are also analysing, evaluating and synthesising design information for textiles.

In comparison, Swann's model of the design process based on Jones *et al.* (cited in Swann, 2002) stems from design engineering. It relates to action research *for* design using empirical design, and suggests a number of small phases that sit over the three key stages – research, creativity and communication (Figure 2.24).

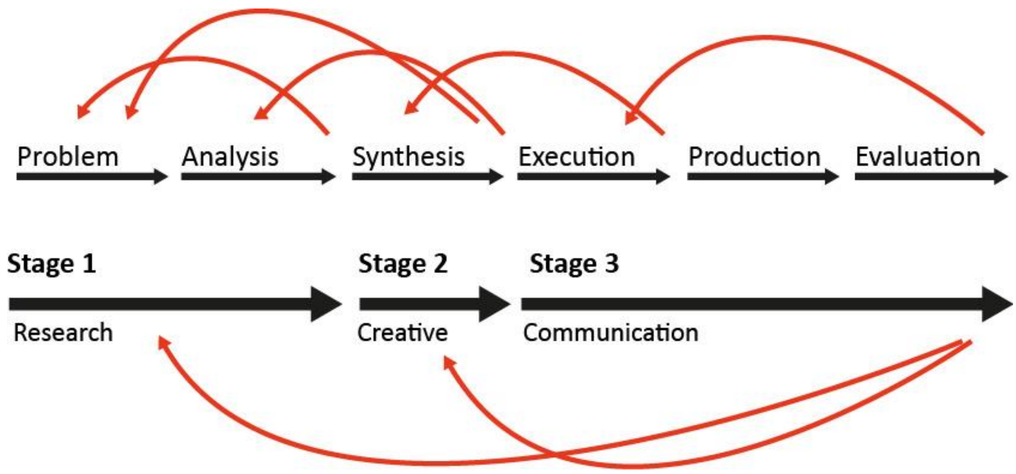


Figure 2.24 Cal Swann's schematic of the design process. Illustrating emphasis of the cyclical iterations involved between phases. Illustration has been redrawn (Swann, 2002 p.53).

Swann emphasises the iterative nature of the design process. Although Swann's schematic suggests a linear format, this is quite the contrary, as each phase feeds back into the process as mini cycles within a larger ultimate cycle. The model refers to the empirical nature of design practice, where constant reassessment and repetition of phases allows for new ideas and outcomes. The stages in Swann's model are also present in the Studd's textile design framework, where there are a number of directional stages. However, Swann's model captures the iterative nature of these stages that also apply to textile design, but are not explicitly visualised in Studd's framework. In addition, Swann's model clearly marks the progressive nature of the three identified stages (i.e. research, creative and communication), which can also be mapped onto the textile design process.

In 2005, The Design Council sought to gain a deeper understanding of the design processes used amongst eleven leading companies in service design and product design. Their findings concluded there were many similarities between the processes of these organisations (Design Council, 2005). They were able to analyse their results further, and produce a single design model to reflect the four main stages identified within the companies' design processes. Such stages included discover, define, develop and deliver (Figure 2.25). The model was titled the 'Double Diamond' design process due to the sequence of linear operating activities with diverging and converging points within the four stages. The Double Diamond is a process that works between the design problem and solution by generating ideas and information to then filter, select and refine options to drive forward to a converging point. This then diverges into a space of focused concept exploration before final refinement for deliverable options are realised.

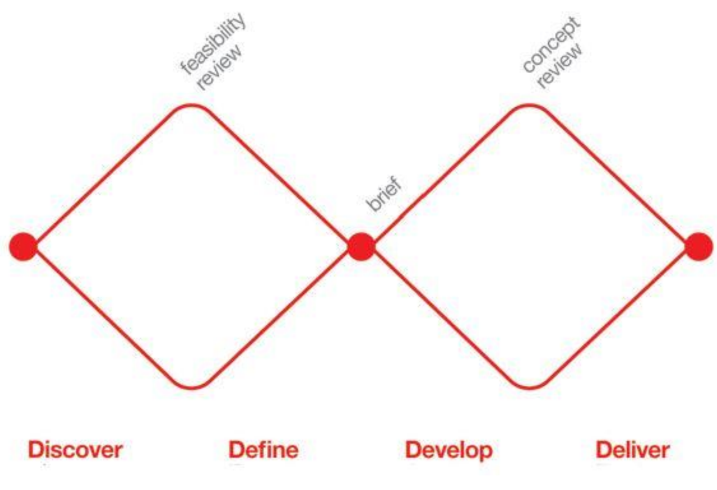


Figure 2.25 Design Council's 'double diamond' design process model (Design Council, 2005)

The model presents an overview of design processes used in commercial design sectors. It operates between individuals across multiple teams and is dependent on cross-disciplinary decisions. The process is much like Studd's generic textile design framework; a common feature between the two design processes are the linear order of stages, but there remain design iterations and complexities within each phase. In addition, the divergence and convergence of ideas to select and progress towards an ultimate design is similarly applied in the textile design process as described by Studd.

Another example of a design process is one proposed by Tim Brown of IDEO (Figure 2.26). In this model the design process is explained as an abstract system of three specific spaces – inspiration, ideation and implementation (Brown, 2008). Although Brown suggests the process must pass via these three stages, this is not a linear process. There are a number of activities occurring in each stage, which reflect on each other and become mini iterations within each space. This then feeds into a larger design cycle. Although this design process model is based on business design processes, there still remain similarities with other design processes across creative, product, industrial and textile design sectors. These include the iteration of activities, design cycle, and a system of design spaces. Brown's design model uses design processes combined with business principles to offer innovative output value, different from traditional business processes. He emphasises design thinking as an essential factor to enable each phase to productively operate in a complex non-linear process, which can be part of a multidisciplinary business. Similarly, some of Studd's case studies were of commercial textile industry that informed her textile design framework, where the practice is informed by business activity. In both Brown's and Studd's design process models, there are clear design activity spaces that follow a direction, but are complex and iterative within these spaces.

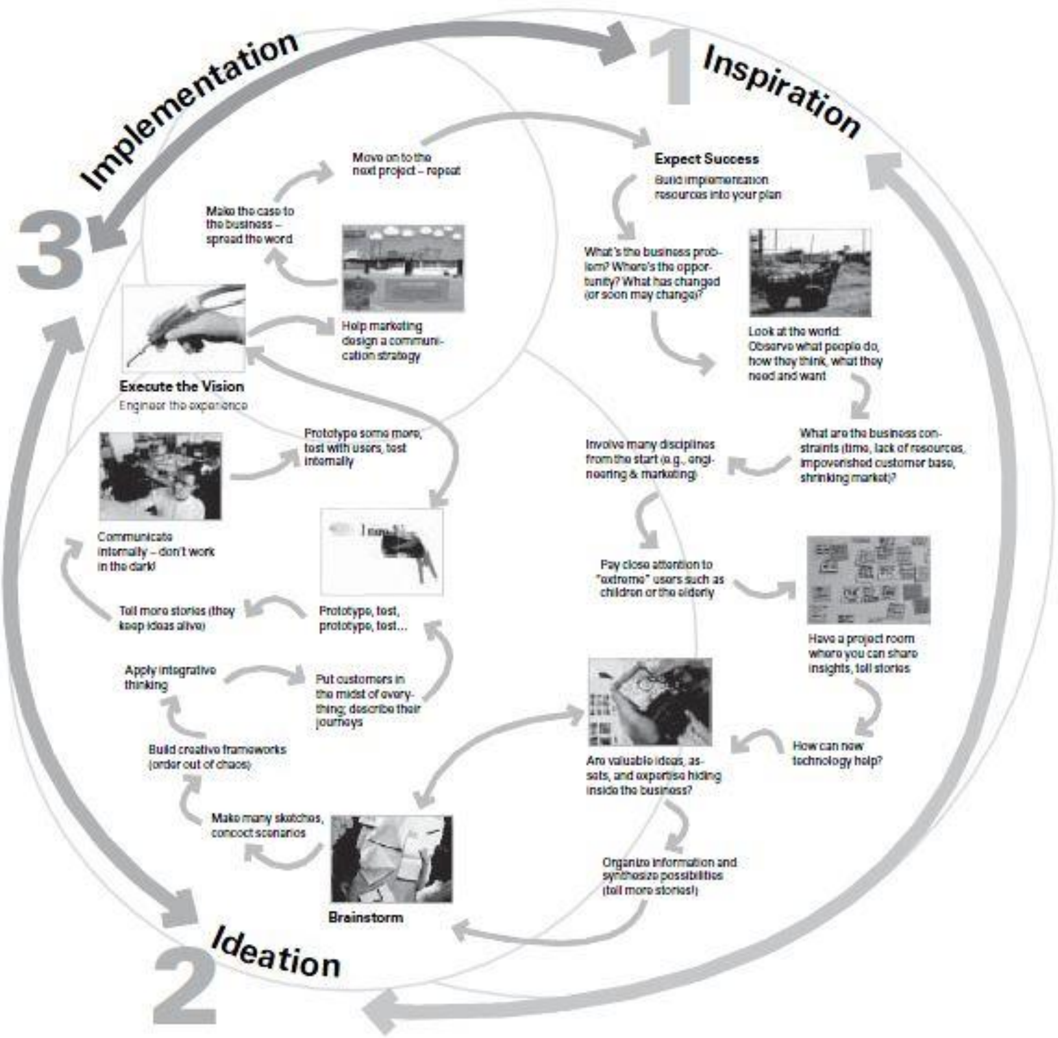


Figure 2.26 Tim Brown's version of the design process – "a system of spaces" (Brown, 2008 p.5)

The example design processes discussed illustrate multiple ways of translating the activities involved in a design process. This is often specific to the design subject area, individual or organisation, usually placed through in-depth analysis of the activities that take place during the design practice.

Each design process model suggests a different sequence of events that lead to design outcomes. A common parallel between each of these design processes is they make a journey between initial design problem to final solution. This can differ between disciplines; however, there does seem to be several common features between these models. Each emphasise different key phases to their translation of the process, predominantly differing by the discipline the process was based on.

2.7 Research gaps and literature review summary

The literature review has presented a range of work related to woven e-textiles, developed through creative craft methods, or technical material approaches. The literature review has also discussed existing design processes, specifically reviewing features that are applicable to the design process applied to this e-textiles research.

The gaps identified to be investigated through this research are:

- Current work in the field has achieved only limited unobtrusive integration of electronics in constructed woven e-textiles. In many cases the woven construction has not been fully utilised for the integration of electronics into the textile structure. A number of specific opportunities to manipulate woven structure to integrate electronics have been identified from the literature, and will be explored in the work in the later chapters. These include the use of double cloth, the integration of multiple functions into the textile as part of the weaving process, the use of complex weaving techniques to attach and integrate components, the use of inlay weft weaving, and the manipulation of floats (free floating threads).
- Woven e-textiles are predominantly developed through a technical materials approach or with creative craft methods; thereby, emphasising either function or form, but have not synthesised the two aspects for closer combined design consideration in the final outcomes.
- Textile design process models are very limited in current literature, and do not explicitly document all the activities that occur in this process. Although there are similarities between design processes across design fields, explicit details of what occurs in each stage of a textile design process are not explained in current work. This includes the tensions and relationships between design stages, and the iterative nature of textile designing.

The woven e-textile design process is further discussed in chapter 3, where underpinning design principles and design process stages are analysed.

In relation to the objectives of this research project, the literature review has drawn out and emphasised the lack of woven exploration in e-textiles. In particular where woven methods have been applied to e-textiles, these are predominantly basic structures to prove the concept/ function. In the projects discussed, there is a lack of in-depth investigation of woven structures to support and enhance the e-textile design. This thesis presents examples of how in-depth weaving knowledge and expertise can be synthesised with electronic circuitry *through* design led processes, to contribute to this unfulfilled gaps in knowledge. The literature review has highlighted the gaps and confirmed the required areas of investigation to make contributions to knowledge.

The following chapter will present the research methodology for this PhD research project.

3 Methodology

The methodological approach for this PhD project is a combination of prior design knowledge and new knowledge arising from this research. Reflective practice and tacit knowledge were a result of previous experience, which were applied as a tool to generate new knowledge in this research. Reflective practice and tacit knowledge have enabled the exploitation of common compatible structures between woven textiles and electronic circuits, where design led practical investigations have developed integrated woven e-textiles. The researcher applied prior woven expertise/ methods with electronics to amalgamate the two subjects. Both form and function of integrated woven e-textiles were considered using a technical materials approach and creative craft methods. This led to the woven e-textile design process that guided the development of the practical e-textiles in this research. The design process is iterative, where reflective practice creates new knowledge through each cycle of design activity.

Initial pilot e-textile samples were trialled to understand basic electronics in woven construction. This included integration of conductive yarn for woven conductive paths, resistance testing and integration of a single LED. Analysis of these initial pilot samples demonstrated electronic behaviours in physical woven e-textile samples (section 4.3.4 and section 4.3.6.7). These outcomes instigated all following woven e-textile developments.

In this thesis, research *through* design practice investigates woven e-textiles. Research *through* art and design practice is a methodological approach defined by Christopher Frayling (1993). This differs from research *into* art and design and research *for* art and design, in that it distinguishes the practitioner as the primary investigator, whereby their actions determine the research inquiry. Design led research *through* practical activities obtains valuable insights that may not be realised without applied primary investigations. Such investigations can help advance practice (Archer, 1995 p.12). The practice of constructed woven e-textiles is a physical, tangible and a slow making process, where rich practical design intensity lies within the progression of each construction. This action of creating by doing is a process of 'design thinking' – a term examined by Lucy Kimbell, to suggest *design-as-practice* (practice/ processes) and *design-in-practice* (outcomes/ results of physical objects) (Kimbell, 2009). It is this definition of design thinking that relates to, and underpins the research process and outcomes presented in this thesis.

The practice based methods used in this research project are predominantly based on the researcher's prior experience as a textile designer. This experience has been developed through academic study and research (undergraduate and post-graduate), professional training, practicing as a textile designer/weaver in industry, teaching in academia, and other design industry experience. The skills that have been learnt and practiced throughout the researcher's design education and professional practice have been applied to, and underpin this research to analyse and breakdown the design process for weaving e-textiles. The woven design process was applied to construct e-textiles using reflective practice.

Chapters 5, 6 and 7 will present specific examples and explain stage by stage how the design process was applied to develop integrated e-textiles. The design process uses both a technical materials approach and creative craft methods to enable integrated electronics in functional e-textiles. To enable integrated e-textiles, electronics required practical functions that were compatible with woven structure. Thus, electronic circuits were systematically trialled (section 3.3.1.6) on breadboards (electronic circuit test boards), before they were empirically reflected on to compare with woven structures (section 3.3.1.7). This progression was guided by the design process and subsequently led to a design specification (section 3.3.1.8). The electronic circuit and woven structures needed to be compatible to enable function and integrated form.

3.1 Design process methodology

The design process applied to develop this e-textiles research is comprised of woven textile design theory applied to practice with the integration of electronics. Prior to commencing this research, the researcher had acquired woven knowledge through training and practising as a woven textile designer for a number of years. The majority of electronics knowledge was acquired during this PhD research. Such knowledge developed as the project progressed, particularly through the use of reflective practice and experiential learning. This is apparent in the development of e-textiles samples and their complexity of design and making, as described in chapters 4 – 7.

3.2 The textile design process

Literature on textile based research is limited (Bye, 2010; Gale and Kaur, 2002), particularly where practice based research is 'emergent' (Gray and Malins, 2004). Many textile design practice processes are connected to tacit thinking and implicit knowledge. As Rachel Philpott suggests, textile design *"…is still carried out intuitively, using hand-making processes informed by tacit knowledge gained through tactile, sensual exploration of materials*" (Philpott, 2010 p.4). Designing and making is an interconnected process (Gauntlett, 2011), where, specifically in textile design practice, this evolves throughout the design process. It is this design process that is valuable to textiles knowledge, which uses research *through* design as a systematic analysis to progress an inquiry (Bye, 2010 p.7).

As discussed in the literature review (section 2.6) the design process varies depending on the design discipline; however, there are many similarities between design processes across disciplines, including textile design. Rachel Studd's (2002) textile design framework (section 2.6, Figure 2.21) was developed from reviewing multiple design processes across the textile industry. Some of the stages in Studd's framework can be found in the textile design process used in this PhD project. This includes the stages of planning, research, analysis, synthesis and production. Such stages are applied in a different order, with variation from Studd's examples, including specific activities within each stage. These will be discussed in this section and in section 3.3.

A standard textile design process will work to a design brief, where "*Typically designers will use suggested colours, sketch initial concepts, formulate designs (perhaps in repeat format) and work with a variety of yarns and fabrics... These activities are then combined with their technical and practical knowledge of fabrics and processes in order to produce designs*" (Gale and Kaur, 2002 p.38). Textile designers use these skills to continually invent new ideas that inspire a range of outputs, often applying finishing processes and techniques to add different effects to the final design. The researcher's textile design practice process was developed prior to commencing this e-textile research, and follows a similar approach as suggested by Colin Gale and Jasbir Kaur.

The researcher's textile design process was always present in previous physical design work; however, this was never formalised or made explicit through writing. The objective of the project focuses the design approach, but can adapt depending on the requirements of the projects. Thus, reflecting on the process/ outcomes helps to determine the design approach. The design process evolved reflectively through multiple iterations; however, intuition and implicit thinking also impact the design process of designing and making woven textiles. Jayne Wallace and Mike Press explain this as "*Intuition is not a reference to a process of reason, but results from reasoned experience over time. Intuition is relational: in the past experiences are drawn upon to guide decisions within a present activity sharing familiarity fragments of the past. It is found in the knowledge absorbed though experience itself"* (Wallace and Press, 2004 p.50).

The researcher's previous working process is summarised in Table 3.1.

	Research stage	Stage description	Research type
	Design brief/ design objective	Receive the brief and decipher the project requirements. Decide on specific visual research areas and actions to take to lead the inquiry for textile design research and development.	Secondary (unless the project brief is self-initiated)
Multiple iterations within each stage and across multiple stages	Inspiration	Source inspiration to help answer the brief/ objective. This can include site visits, tear sheets, library and web research, photography, reflection on previous work.	Primary and secondary
	Ideation	Brain storm ideas to consider as part of the project. This can include sketches, notes, and other visual and technical information.	Primary
	Sketching and sketchbook work	Ideas are progressed to sketches, paintings, collages and combined visual research methods to develop a collection of primary research studies that capture the focus of the design brief as interpreted by the designer. The primary studies are used to inspire colour, textures and patterns for the textile designs. Sketches of woven designs are evolved from this stage.	Primary
	Prototyping	Specific designs are progressed from initial sketch form to two or three dimension prototypes; these enable a physical plan of the design.	Primary
	Weave planning	Woven structures are planned for selected designs to map onto the prototype.	Primary and secondary
	Woven execution/ finishing	Samples are woven according to the prototype and weave plan.	Primary
	Results	The samples are cut and may have finishing processes applied	Primary
Outcomes feedback into the design process as inspiration for new designs	Analysis of outcomes	The samples are reflected on and add to the designer's experiential learning. The results may be used to inspire new samples.	Primary

Table 3.1 The researcher's prior textile design process

The process consists of a starting phase, usually with a design brief or objective that may or may not have specific requirements other than the type of textile designs needed (e.g. woven, market sector, season, colour palette, etc.). Although the initial objective sets the focus of the project, reflecting on each stage of the design process may revise the objective focus, as the reflections can inspire new insight.

The objective would be broken down into actions and directions to initiate the project and to build a comprehensive understanding of the project aims in order to lead the textile development. Inspiration would be next sourced in the form of secondary and primary research. This would include site visits (museum, galleries, exhibitions and other related industry events), photography, and sometimes reference to previous work. Secondary research would include reviewing artists, designers, existing materials, technology and market research related to the design brief. This would lead to the ideation phase, which included note making, initial sketches, technical references and visual research in response to the design brief and ideas from the inspiration stage. The ideation stage began to make sense of the ideas and visual materials collected thus far.

The next phase involved sketching and sketchbook work (e.g. painting, drawing, and collage), where the designer visually synthesises ideas from the previous stages. Primary research developments included colour analysis, pattern and texture development, translating ideas from inspirational photos and combining them with other imagery, visual imagery and ideation notes. There would be multiple ideas generated in the primary research phase. The quantity depended on the timeframe of the project and time allocated to primary research development. Primary research ideas would be generated by reflecting on previous ideas and iterating visual concepts; or combining new design techniques (i.e. collage, drawing, painting) and introducing other visual materials (e.g. photos, tear sheets, photocopies of previous primary studies, etc.). Ideas for weave would be inspired by this primary research development, including patterns, form, scale, texture and colour. This would lead to the sketching of focused ideas and making prototype models of 2D and 3D weave form. Weave structures would also be considered at this time, and the designer would often go back to sketching and prototyping until suitable structures were designed. Often technical information would be referenced, such as specific structure, techniques, specific requirements or technical support. Yarns were selected to match the woven design and prepared for weaving execution. The final designs were woven, where the designer may reflect *in* the process of making and adapt design decisions regarding colour, yarn and proportion; sometimes tweaking the design as they work. The final designs are reflected on, particularly assessing if they meet the requirements of the design brief. The outcomes of the designs may inspire future designs and add to the designer's experiential learning.

Although this series of events would go back and forth in the process to refine ideas for final designs (particularly in the inspiration, ideation, sketching and prototyping phases), the process is similar to Damien Newman's squiggle as discussed in section 2.6. To help illustrate the researcher's prior textile design process, this has been mapped against Newman's design process squiggle in Figure 3.1.

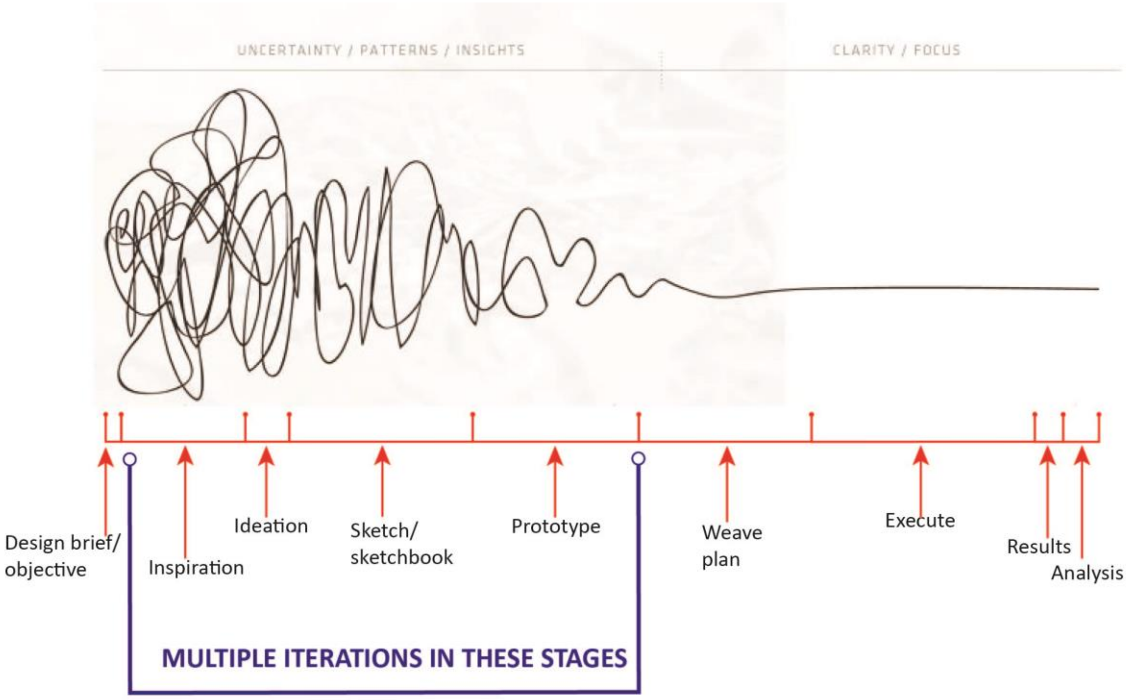


Figure 3.1 The researcher's previous textile design process mapped onto Newman's design process squiggle

The researcher's previous design process was applied to develop the woven e-textiles for this research. However, there were some adaptations to this design process that helped to include electronic design and circuit testing. Essentially, the researcher's previous working design process was exclusively for woven textiles. Therefore, for this research electronics were integrated into the design from the very beginning as a design objective. All of the design stages considered the design development for 'e-textiles' opposed to textiles alone. The e-textiles design process will be specifically discussed in section 3.3.

3.3 Woven e-textiles design process

The review of the design process models referenced in section 2.6, along with the researcher's previous working design processes (as described in section 3.2), led to the positioning of the design process specifically discovered for this woven e-textiles research.

Although Newman's 'squiggle' is based on a non-textile process, it shares common features with the woven textile and woven e-textiles design process. For example, the beginning stages are usually quite broad where many ideas are researched and organised into specific selections to progress forward into further investigation. A sampling design phase helps clarify the final design/s to present. Similarly, the filtering of ideas followed by further investigation of specific concepts in e-textile designing relates to the Design Council's 'Double Diamond' model (section 2.6, Figure 2.25). Further evident is the similarities with the other design processes discussed in section 2.6, (i.e. Lawson's design model, Studd's textile design framework, Swann's design process and Brown's 'System of Spaces' process), including design iterations (cyclical process), different design spaces (initial design objective, middle problem solving phases, final outcomes), constant reflection *on* neighbouring stages (reflective practice section 3.4.6), reflection *in* stages of design and a journey between problem and ideal solution are a few common examples to name. What is clear is the design process in woven e-textiles is an iterative and cyclical one – a common factor amongst most other design based practices.

Each stage plays a crucial role and leads to the next step in the process. Although the design process is proposed as a sequence of events, the movements through the stages were not linear. There are many phases of mini iterations across single or several stages and the entire process leads to a larger overall cycle, where each rotation feeds into potential future designs. Thus, each iteration influences new ideas following on from the previous one. The process as a whole is a cycle that supports reflective practice and experiential learning.

3.3.1 Design process flow – step by step

The woven e-textiles design process in this research is integral to enable the amalgamation of weaving with electronics, as it leads the development process from initial design objective to final outcome. Consequently, it allows both subjects from these previously disparate sectors to be combined through a single route, overlapped between technical material approaches and creative craft methods. The design process is appropriate as it allows creative methods and design led perspectives to progress and develop functional woven e-textile outputs; it works towards answering the research question and meeting the research aims, with design consideration given to both form and function.

The woven e-textiles design process informs the making phase of this research practice. The design process model leads the outcomes of integrated woven e-textiles, which on reflection of the outputs enables further iterative designs via the same design process. This is vital to the outcome of this research, because the design process enables feedback via reflective thoughts to iterate new ideas using the same design process. It uses design principles that are discussed in section 3.4, drawing relevance to this design process and its relationship with this research practice.

To introduce an overview of the design process developed through this woven e-textiles research, Figure 3.2 illustrates the overall process, identifying each of the integral stages (each stage will be discussed in-depth in sections 3.3.1.1 – 3.3.1.8, and with woven e-textile examples in chapters 5, 6 and 7).

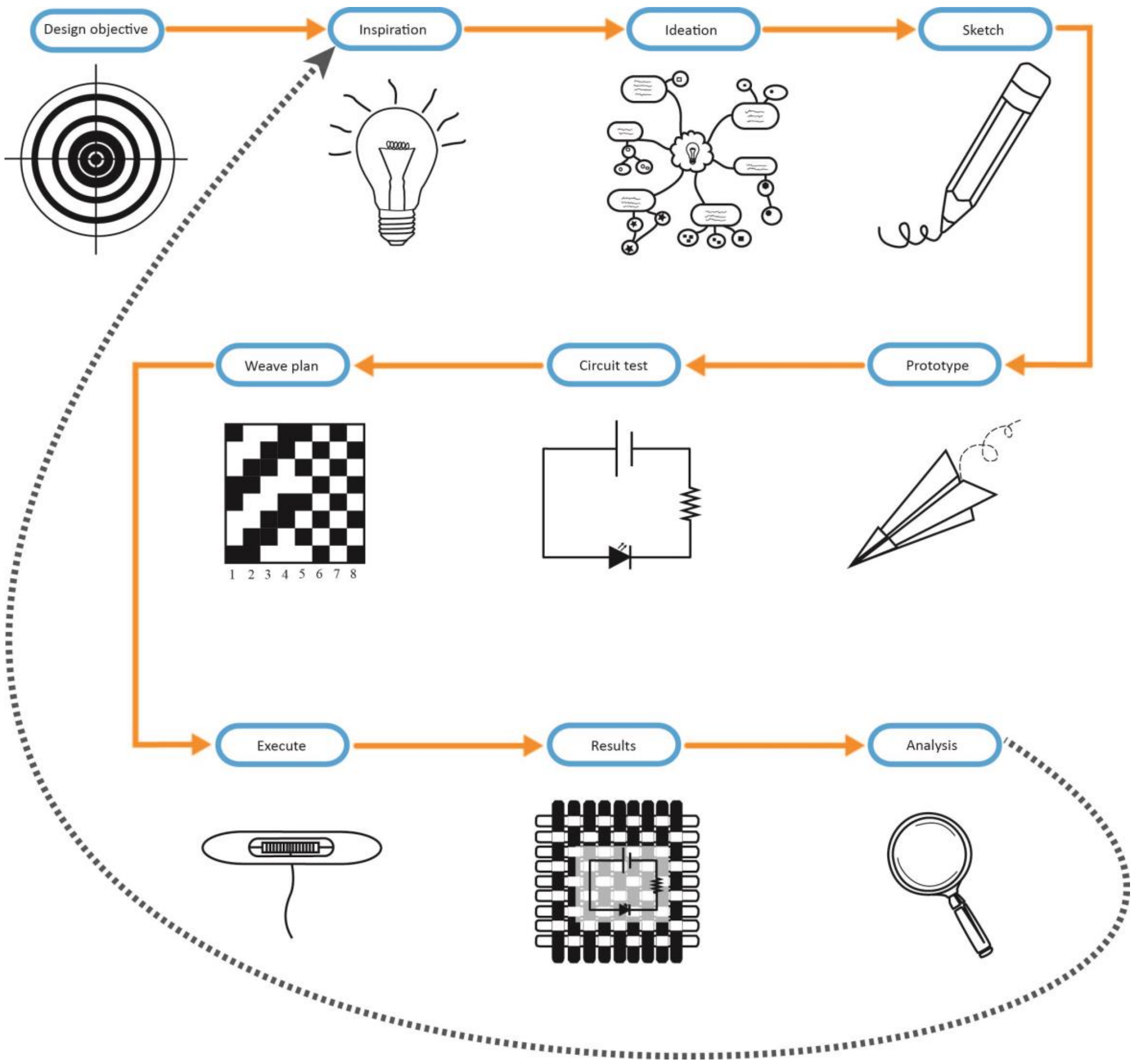


Figure 3.2 Illustration of the design process for woven e-textiles

The design process follows a series of steps that inform subsequent stages in the complete making process, indicated by orange arrows for direction of flow in Figure 3.2. Although this is represented as a linear series of events, the process itself is not linear and has many activities within each stage. The stages in the process are sequential and follow an order. However, there are points when some stages will work concurrently, or even go back to previous stages and iterate in mini-cycles within the overall design process to refine design elements. This can be viewed in Figure 3.3, where the green arrows illustrate which stages may revert back into previous ones, to then follow through the orange path. This happens predominantly in the first three stages, (inspiration, ideation and sketch) and the following three stages (prototype, circuit test and weave plan). Each set of stages are closely related as they occur in the same range of the design process, i.e. what Damien Newman (2011) and Cal Swann (2002) call the uncertain or research stages. The following second set of design stages are referred to as the clarity/ focus or creative stages by Newman and Swann. The last three stages (execute, results and analysis) are directional, as they have been specified and have clear communicated actions to see through to the execution stage.

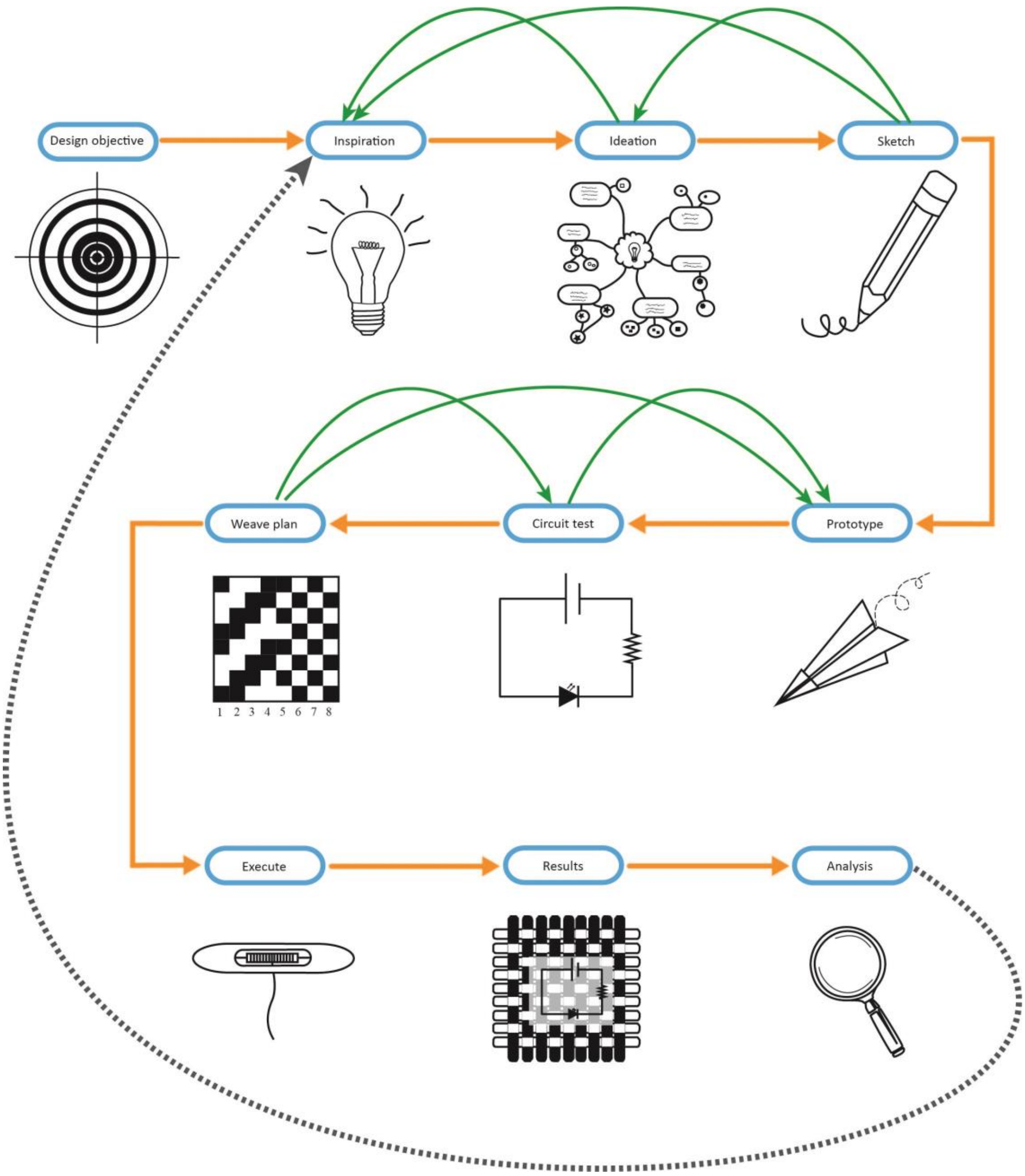


Figure 3.3 The woven e-textiles design process illustrating iterative stages (green arrows)

On occasions, new iterated design developments will be introduced part way through the design process, if this new design's characteristics or specific features have been resolved or inspired from a previous design. Thus, this new design may not require its development to be instigated from the very beginning of the design process. For example, a new design may have the same objective as a previous resolved design. The new design's development may be introduced into the design process at a later stage (e.g. the prototyping stage), to enable the new design to form through the remaining design process. Specific examples of e-textile design development are discussed in chapters 5, 6 and 7.

There are also instances in the e-textile design process where ideas developed in one stage may be progressed into design iterations across non-neighbouring stages; this can be used for the same design or a different design at a later date. These iterations are a result of reflective practice, as illustrated by the pink arrows in Figure 3.4, which then follows through the orange path. Often these iterations are caused by tensions within the design process, to resolve issues or due to an alternative solution being realised.

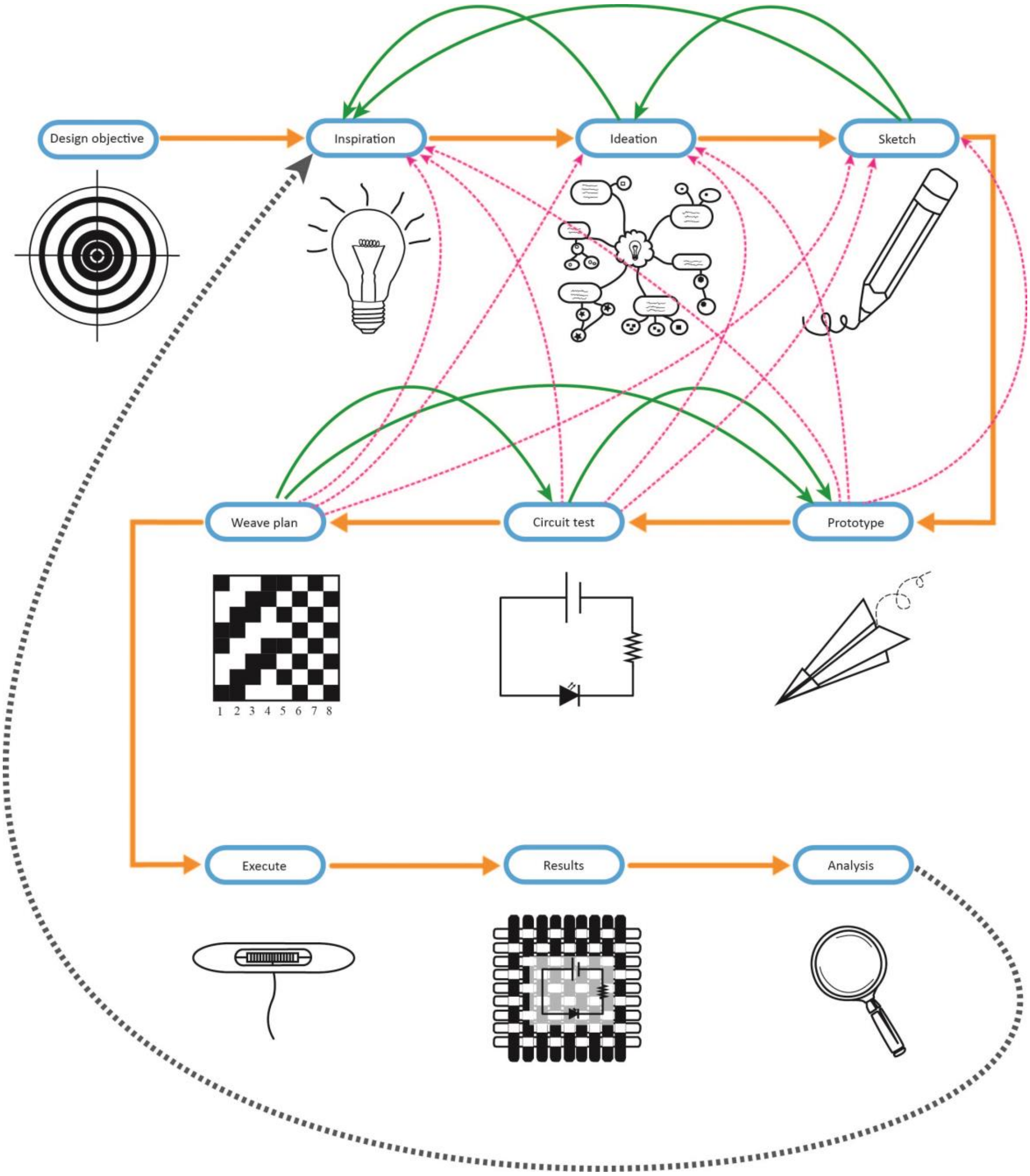


Figure 3.4 The woven e-textile design process depicting iterative stages (green arrows), and iterations of reflected ideas (pink arrows)

The design process accommodates both form and function, and enables both of these aspects to support the overall design. They are considered in every stage of the process and are integral to the outcomes. Each stage does not necessarily follow the other, as they can operate concurrently or where specific stages are emphasised due to certain design developments.

The woven e-textile design process is based on the researcher's previous design processes (as discussed in section 3.2). However, the woven e-textiles design process is specific to e-textiles, where each stage is crucial to the final outcome and to subsequent iterations.

At the start of the process an initial design objective is envisaged. Prior expertise and knowledge are vital to trigger possible design ideas when inspiration is recognised. Inspirations for the form and function of the textiles are sought and are translated into ideas during the ideation process. This can include the original design objective/ concept of the type of soft circuit and physical form of the e-textile. For example, the design in progress may have a specific function such as a sensor or a switch that will need to be considered from the initial stages, as its function will be a key objective to the design process. These ideas are organized to formulate a breakdown of focused ideas to take into the sketching phase. This information is used to evolve ideas and produce visual concepts as the sketching stage is a visual thinking method.

The resulting sketches enable visual filtering, where the designer is able to identify strengths, weaknesses and feasible and viable characteristics of the design against the design objective. Final versions of the sketched ideas are advanced into paper and/or fabric prototypes. These prototypes help to evolve and envisage the physical forms of the textiles, the complexities of the structures, and evaluate the technicalities involved in the execution. A new or existing warp set up will also be referred to here, to enable a more accurate prototype. The electronic circuits are designed, tested and often adapted to work with the woven construction; this stage of the process is developed concurrently with the woven design as the circuit needs to be assessed and designed to be compatible with the woven set up. Warp drafts and woven structures are also referred to in this stage to enable compatibility with the circuit design. Woven structures are then designed and planned to fit each part of the e-textile simultaneously to the integration of the circuit design to produce a design specification of the final e-textile. The sample is then executed via the weaving process. The final samples are tested and analysed by attaching to a power source and assessing against the design objective and design specification. These results can then be used to inspire and inform further sampling.

In instances where woven structures need to be visualised, the researcher may temporarily revisit the prototyping stage before resuming the process. This is an example of internal design iteration and can occur during any of the design stages. The process leads to a larger iterative cycle, where analysis of the sample instigates inspiration for new samples through reflective practice.

The following subsections describe each stage of the design process, explaining the relationship to neighbouring stages, as well as drawing reference to the design principles that are discussed in section 3.4. The weaving execution, results and analysis will be discussed in-depth in chapters 4, 5, 6 and 7.

3.3.1.1 Design objective

The design objective is a goal that is envisaged at the very start of the design process. It is not known at this point how the design objective will be translated, but the concept is thought to be feasible and achievable based on the designer's previous experience, and approached via this design process in order to trial possible options. For this PhD research, the design objective was always related to e-textiles. The main focus remained on building electronics *into* the woven textiles, i.e. taking an integrated approach to constructing e-textiles. Past knowledge in weaving and e-textiles implicitly and explicitly help realise the design objective using abductive thinking, (implicit and explicit knowledge are discussed in section 3.4.2). Abductive thinking is the relationship between deductive thinking (logical assumptions based on facts) and inductive thinking (predictions based on speculations) – further discussed in section 3.4.4. Experiential learning is built through design iterations to add to the designer's wealth of knowledge.

The design objective can be a vague thought or a specific idea that may or may not have defined details; nevertheless, it is this that drives the intention of design exploration. Often this can be a tacit thought that is not clearly identified until a later stage in the design process. Tacit thinking and knowledge are aspects that reoccur throughout this design process and are specifically discussed in section 3.4.1. The design objective can stem from a previous problem or scenario or can be an independent idea that is implicitly or explicitly thought of. However, the design objective is a static phase that needs reflecting on (section 3.4.6) and requires creative input (section 3.4.7), to see progression into the next stage of the design process – this occurs in the inspiration phase.

3.3.1.2 Inspiration

The inspiration for each sample can originate from a number of possibilities such as an object, an idea, previous samples or an association via reflection *on,* or reflection *in* with another experience of design related making or doing. The recognised source of inspiration identifies specific features that can be related to the e-textile design including either, or both, form and function. The designer's judgement, experience and tacit knowledge are used to evaluate the potential design value through abductive thinking. This occurs through creatively linking and synthesising ideas from inspiration and the design objective, allowing the design to progress to the next stage in the process. The designer is able to identify what is and what may be possible by making connections within the important relationship of design concept and inspiration. This is mainly based on their previous experience and knowledge, through both implicitly and explicitly using praxis (section 3.4.3). In early professional design experience this certainly can be more of an experimental phase until substantial knowledge is acquired over time.

In each e-textile case, the designer is able to make links between aspects of the design such as the physical structure, overall concept, function, etc., to draw correlations with the inspirational source. In some cases this relationship may be more obvious, whereas in others the inspiration acts as a trigger that can lead towards the final design. Some samples may work with a single source of inspiration, whereas others may have two or more. From this stage, the ideas that followed are taken through to the ideation phase.

On occasions where an iterative design is developed, this new design may draw inspiration from the analysis of a previously developed design; therefore, previously developed work can also influence the inspiration source.

3.3.1.3 Ideation

The ideation stage uses the inspiration object/s along with the design objective to consider possible ideas that could be taken forward. This phase uses any combination of rough sketching, notes, brain storming and sometimes referencing previous work or samples to help deliberate, identify and filter key elements that become relevant to the design. This can include the physical form and function of the e-textiles.

As ideas progress they also trigger new thoughts as this phase probes deeper into each concept. The ideation process begins to suggest responses for the pre-defined goal of the design objective; this becomes a design planning process (Hertz, 1992). Reflecting *in* and *on* ideas as they develop can help to organise them, and identify which ones should be taken through for sketching (praxis – section 3.4.3). The ideas are not refined at this point and are still being explored as options. They are, however, tacitly, implicitly and explicitly being evaluated throughout this stage, as new ideas may cancel out previous ones as evolving thoughts may reveal inadequacies or alternatives. This process uses dialectic thinking (Thompson and Thompson, 2008 pp.37-38), to break up notions into smaller parts. This enables analysis between conflicts and compatibilities to help form an overview of all options. Ideas evolve via creative thinking (section 3.4.7), by drawing links between various aspects including inspiration, design objectives and ideas that have progressed through the process so far. The designer synthesises these ideas by selecting options that could potentially work in a combination. These decisions are a result of abductive thinking as described in section 3.4.4.

3.3.1.4 Sketching

Visualising ideas via sketching is integral to the design process in order to effectively communicate the designer's thinking and evolve these thoughts graphically (Seitamaa-Hakkarainen and Hakkarainen, 2000). This process uses praxis by applying theory and practice of sketching to visually communicate ideas. The sketching stage extracts ideas by selecting these from the ideation stage, to visualise options to work towards a final design solution. In many ways, sketching is a tacit process as illustrations are not graphically represented until the designer has translated their thoughts onto paper. Therefore, abductive thinking is also linked to sketching, as assumptions to what may or may not be possible need to be visualised in this stage of the design process. Often, even these sketched outcomes do not fully express all of the designer's thoughts whilst producing their drawings (Lawson, 2004 p.41).

Information processed from ideas to visualised sketches uses a combination of implicit and explicit thoughts. These ideas need to be creatively synthesised to link and represent them as visualisations; they need to relate to how the designer intends to portray these graphically. Much of this information is reconstructed several times via multiple renderings of the same drawings. Many of these sketches may not even be visually represented by the end of the sketching process, as they will be adapted, refined, drawn over or erased. The choices a designer makes in their decisions to modify and *"…adapt visual representation through sketching and re-sketching is still one of the least understood phenomena in design research"* (Seitamaa-Hakkarainen and Hakkarainen, 2000 p.4). For this reason, the sketching process is quite an intricate one, as tacit thinking, reflective practice – reflection *on* and reflection *in* the process – are constantly generating silent ideas that are only partially recorded visually in the sketches. The sketches are in constant flux; thus, the entire process can never really be fully captured.

Using sketching to visualise the final ideas in two dimensions initially helps to position details that need to be considered and provides an overview of how the soft circuit could be designed. This is the first time the design is seen in a visual format and has connected all the elements that the designer wants to integrate. The design visualisations overview and communicate aspects that are not always obvious if they are verbally described, or written as text. It is imperative to communicate the design in a two and/or three dimensional form, particularly where the final design outcome will result in a physical object. The sketches of the e-textile designs will use written text alongside the sketches to help explain, label and highlight features. Once the designs are at a point where the sketches are resolved as much as they could be in two dimensions, (depending on the design) the sketches can be taken through to the prototyping stage.

3.3.1.5 Prototyping

Prototyping is a central stage in the design process, as it can help confirm or question design decisions made up to this point. A valuable prototype can help indicate faults and corroborate a worthy idea with minimal errors. The prototyping process can be a quick and effective way to work through options visually, three dimensionally and make decisions efficiently (Kelley, 2001). A prototype modelling technique is a method of output to express making through doing actions; hence, a form of praxis. "*Thus design activity is not only a distinctive process, comparable with but different from scientific and scholarly processes, but also operates through a medium called modelling, that's comparable with but different from language and notation*" (Archer, 1979 p.18). In this research, prototyping is used throughout the design and making of the e-textiles.

The final refinement of the sketches are filtered to select the most relevant ideas to move forward into prototyping as a 'physical hypothesis', by tangibly embodying the designs (Koskinen *et al.*, 2011 pp.60-62). The selection of ideas to take forward is dependent on the designer's judgement, experience and the outcomes of the previous design process stages. Prototyping can use tacit, implicit and explicit thoughts to make decisions to translate ideas into models. Here, abductive thinking also helps to judge how these ideas could translate into three dimensions, based on assumptions of how to interpret the sketches. Converting the final sketches into paper prototypes allows the designer to formulate the designs into three dimensions via a creative process (creativity is discussed in section 3.4.7). The models are used to help synthesise, map and translate the options for woven structures that enable the construction of the e-textile, as well as help interpret the electronic features into weaves. In some instances, prototypes can be remodelled or adapted to reflect any changes in the design which helps to re-visualise such changes. Reiterations could occur several times, transforming the prototype over multiple versions, as one structure can help realise a different option leading to a new prototype; often as an improved version of the last. Physical prototypes also help identify potential issues that may not be obvious in the sketches, as the models are tangible objects that allow different perspectives. To some extent, this stage operates as a test bed for the physical form of the e-textiles; enabling reflection *in* the making of the prototypes and reflection *on* the final prototype models, until the designer is satisfied to progress onto the next stage.

Representing the final designs as three dimensional forms visualises the complexities involved when considering the required woven structures, enabling the circuit designs and the textile form. The designer is aware of the type of woven structures that may be required to enable the overall form of the textile; however, these are not designed until after the circuit is designed to synchronise both to work together.

3.3.1.6 Circuit testing

The finalised prototype model will help realise the physical form plan for the e-textile design and a rough idea of how this will be executed. The circuit design is drafted and worked out to enable the function of the design objective. The electronic circuit design is tested independently on a breadboard (electronic circuit test board), before evaluating and confirming the sequence to weave into the e-textile. Any troubleshooting problems need to be resolved and corrected at this stage, as failure to recognise any circuit issues here will become problematic and more complex to resolve once the circuit is integrated with woven structures. At this point, the circuit is considered from both electronic and woven e-textiles perspectives. It may be possible to configure the circuit in multiple combinations, but an arrangement that is best compatible with woven textiles needs to be selected for the design. Using implicit and explicit knowledge of electronics via praxis, and implementing theory via practice is vital at this stage. If the designer is familiar with the electronics, tacit knowledge can also be present at this point along with abductive thinking.

The prototypes are used to map the final circuit design and translate this into woven structures. This phase is essential in recognising any issues with combining a specific circuit design with the physical form of the textiles. Once compatibility between the physical form and circuit design are achieved (this requires creative thinking to help synchronise the two areas), it is followed by weave planning for the sample. Before this stage, the combination of both the physical form of the prototype and the electronic circuit are translated into a sketched plan. This plan arranges the different sections of the e-textile sample with the mapped electronic circuit back into two dimensional forms. This is in preparation for the woven execution stage. Before this, the plan is used to organise the woven structures needed for each section. The order of weave is particularly decisive in arranging the circuit layout and the sections of the woven sample. During this activity, both reflection *in* and reflection *on* electronic circuit designs and potential weaves are crucial for analysing and selecting the best option to implement.

3.3.1.7 Weave planning

The woven structures for the final defined e-textile are designed in this stage. Planning the woven construction for each sample takes into consideration yarns (warp and weft), warp draft set up, yarn count sett, woven structures, component preparation and order of weave. Warp planning can be a time intensive activity; therefore, a multipurpose warp may already be on the loom from a previous set up. It is possible to amend and re-thread the warp or a new warp can be designed to suit a specific sample. If an existing warp is already on the loom, the designer may need to consider this when initially translating a circuit design into an e-textile. This is not a limiting factor of the e-textile design, but can require an alternative warp design that may not be compatible with the existing one. Once the current warp has been utilised for all the samples that are needed from this set up, the warp can be adapted for new woven designs on an alternative warp draft. Warp designing is explained in detail in section 4.2.1.

Using the sketched plan of the sample instigated in the circuit testing stage, the dissected sections can be allocated to specific woven structures. Designing woven structures for each section of the woven construction enables the e-textile to configure the complete electronic circuit and fabric. The designer decides the appropriate structures that enable the textiles and electronics to be constructed as visualised, and function as required via reflection *on* the designs and reflection *in* the designing of structures. Knowledge of woven structures is specific to the textile designer through their training, experience and expertise. However, the textile designer can refer to their woven knowledge through tacit thinking, implicitly or explicitly, where this knowledge can be applied to the design development based on these thoughts (abductive theory – section 3.4.4). Woven structures react differently according to the warp set up, warp and weft yarn type, density and how they are integrated into the weaving. The weaving execution is described in detail in chapters 4 - 7.

The knowledge of woven structures will inform how the weave is likely to react when woven, and which structures would best suit certain features of a woven textile, for example, weft faced, warp faced, loose or tight structures, multi cloths, floats, patterning, etc. Woven knowledge is crucial to the e-textiles design process, as it determines the final output. The designer makes explicit decisions when synthesising requirements for the e-textile design with woven structures, drawing on experiential knowledge that is usually implicitly stored. Praxis (section 3.4.3) is evidently central in the decisions made during the designing and allocating of woven structures, as prior knowledge and weave theory are needed to realise new designs and apply this via weaving practice. Woven structures can be adapted and reconfigured to fit a specific warp draft or for woven manipulation techniques. It is essential the designer selects structures using their woven knowledge, to identify how woven structures can be adapted and what outputs they are likely to produce; requiring creative thinking to adapt and position structures. In this process the structures need to be drafted out, reflected on and implemented in the weaving. Specific woven structures and manipulation techniques in e-textiles examples are discussed in chapters 4 – 7.

3.3.1.8 Design specification

The result of all the previous steps in the design process leads to a design specification that is ready for use in the woven execution. This uses assumptions based on the previous design process stages (abductive practice – section 3.4.4). The specification contains details of what the design is, consists of, the main objectives of the physical and conceptual design described as visual, diagrammatic and technical information, including warp drafts and calculations. This is prepared by synthesising implicitly and explicitly all previous design components and reflecting *on* these decisions to create an ultimate design specification formula to use in the execution stage. This is usually in a sketched illustration using prototype/s to assist as part of the instruction to make the woven e-textiles. The sketch plan that was initialised in the circuit planning stage is then used to allocate weave structures, which usually assists the design specification. This is a visual plan of the e-textiles sample, broken into sections that indicate which weave structure is allocated to which specific section. The specification also visualises a mapped circuit design to help indicate what part of the circuit will be woven in each e-textile section.

The design specification takes into account all the physical features of the sample and order of weave, specifying when and where woven structures need to change, where components need to be integrated and where sequence of wefts should change. These aspects are communicated through section diagrams of the sample at each stage of construction. In e-textile samples with multiple woven structures, a numbering system is developed to organise and correspond with specific woven structures. The technical specification is cross referenced with the numbered woven structures to correlate this information. Once this is prepared, it can be used as a formula to guide the weaving execution. The design specification is a result of applied theory from the previous steps of the design process, which at this stage is ready to be applied to practice and engages design praxis. The design specification is the final element before weaving can commence. (The weaving process is discussed in-depth in chapters 4 - 7.)

3.3.2 E-textiles design process and design principles

The previous section broke down and presented the e-textile design process; this section will relate the interactions and relationships between the design process stages and the underpinning design principles (section 3.4). Some of the selected design principles have been referenced in earlier discussions; however, Table 3.2 summarises the identified relationships between the two areas. As illustrated, the design principles are integral to the majority of the design process and play significant roles in achieving the woven e-textiles. Table 3.2 notes the relationship between design process and design principles as far as planning the design specification, as the weave execution will be discussed in subsequent chapters 4 – 7, including the results and analysis stages.

Design principles / Design process	Tacit knowledge	Implicit & explicit knowledge	Praxis	Abductive theory	Synthesis	Reflective practice: *Reflection -*		Creativity
						On	*In*	
Design objective	●	●		●		●		●
Inspiration	●	●	●	●	●	●	●	●
Ideation	●	●	●	●	●	●	●	●
Sketching	●	●	●	●	●	●	●	●
Prototyping	●	●	●	●	●	●	●	●
Circuit testing	●	●	●	●	●	●	●	●
Weave planning	●	●	●	●	●	●	●	●
Design specification		●	●	●	●	●		

Table 3.2 Relationship between woven e-textiles design process and design principles

It is clearly visible in Table 3.2 that all the design principles are applicable throughout much of the design process, from the inspiration stage through to weave planning. The design objective stage is related to only some of the design principles, as this acts as an initial catalyst for the design process in each e-textile design. Hence, there is little design activity output generated until the inspiration is applied to the design objective. Similarly, the design specification stage also excludes some of the design principles listed, as this part of the process becomes closer to the end outcome. Therefore, there is intensive design activity in the lead up to the design specification, which then acts as an output plan for the weaving execution. The design activity is also re-intensified in the weaving process, as the plan needs to be employed and applied to weaving practice – this is discussed in detail in chapters 5, 6 and 7.

The design principles are discussed in the following section, to explain what is meant by each of these terms and how they relate to the design process used for this e-textiles research.

3.4 Design principles and methods

Textile design methods and processes are less prominent in design research literature and theory. It is a subject that is not often referred to specifically in design philosophy, but instead tends to borrow design thinking concepts from related design subjects (e.g. product design, industrial design, architecture, fashion, social sciences and engineering) (Igoe, 2010 p2; LaBat and Sokolowski, 1999). Design methods and principles found in literature from these related subject areas underpin the e-textiles design process used in this research work, and are featured in Table 3.2. The design principles help to justify and support the rational underlining the e-textiles design process as proposed in section 3.3 and cross referenced in Table 3.2.

3.4.1 Tacit knowledge

In conventional textile design training, the taught methods are predominantly practical skills and technical processes, driven by designs to be produced. Creative design outputs are expressed through the use of these practical methods; however, how this creativity occurs during this time is not explicitly documented or fully understood. During this phase of the design process, silent, non-verbal and intuitive translations of tacit knowledge are recognised, where subconscious decisions can be made. As Alison Shreeve noted, "*these silently acquired values are what make textiles both interesting and problematic*" (Shreeve, 1998 p.41), highlighting the significant value of tacit communication, as knowledge, thinking and implicit learning. These actions are key contributors that inform the textiles design process and subsequent outcomes.

Tacit knowledge has been identified in craft and textile design as a trait that cannot be fully explained. Peter Dormer defines this as 'taciturn', suggesting a maker who cannot sufficiently articulate their knowledge through verbal language, but is able to define this through visual and physical mediums of their craft and making (Dormer, 1994 pp13-24). Compared to other related design subjects, in the past, textile design research has been held back due to its muted silent ability to explain textile knowledge (Igoe, 2010 p.5; Gale and Kaur, 2002). However, in recent years, textile related research is beginning to emerge and is becoming more prevalent whereby "*In the last 10 years, more international journals have been developed where clothing and textiles research meets* *content criteria…As scholars in clothing and textile design, we need to increase our visibility and voice through published research*" (Bye, 2010 p.6).

Tacit knowledge in design has a certain mysterious value that is only understood by the designer or implicitly by other designers being taught a design method. Sometimes, the issue lies with the designer, who is unable to communicate their thoughts visually, verbally or in written form, where tacit thoughts remain a subconscious automated process. Tacit knowledge is significant, which is present and plays a crucial role in the design process.

Craft culture has traditionally been associated with tacit knowledge and its relationship with making. Ultimately, tacit thinking connects with the making of actions; particularly in exploratory design practice such as textiles, where the knowledge of the discipline is embodied within its own domain and deeply rooted within the designer (Kettley *et al.*, 2010).

Tacit thinking and tacit knowledge are factors that affect the design process of this e-textiles research from the design objective through to weave planning stages. It is also present in the weaving execution of the e-textiles, particularly where some weaving methods are intuitive from previous practice experience. Close analysis of the e-textile design process attempted to extract an insight of what happens during the phases involving active tacit thinking. It enables the designer to quickly and implicitly think through possible options when focused on the design objective. Thus, this process becomes a way to visualise options to evaluate their worth, and ultimately decide whether one should commit to further progression of these options or not. Tacit thinking and knowledge are processes that cannot be accurately described in this research, other than knowing it is present and partially accountable for the design and making stages. It is not known exactly how these instances occur, but they do contribute to the design process; hence, further reinforcing Shreeve's suggestion regarding the value of tacit communication as referenced earlier.

3.4.2 Implicit and explicit knowledge in action

Actions performed by the designer are based on design decisions made, which stem from implicit (closed) and/ or explicit (open) knowledge. Implicit and explicit knowledge can be used in implicit and explicit thinking – the two are intertwined. It is not until design actions become physical, visual and tangible that they are presented as outputs, i.e. explicit information. Explicit knowledge is considered more reliable as it is openly clarified and rationalised; it has the ability to measure and comprehend the process and the outputs more effectively. In order for knowledge and learning to progress, the design decisions and outputs need to become explicit so that future iterations can build on this. Implicit knowledge is typically seen as less reliable as it cannot always be justified and, therefore, is seen as connected to tacit knowledge (Thompson and Thompson, 2008 pp.23-25). However, drawing on implicit thoughts can be viewed as arising from explicit knowledge, as this would be learnt through theories, previous experience and general knowledge (as discussed in section 3.4.1). This helps reinforce tacit knowledge as a considerable influence in the design process.

Designing through performing actions, for either known or unknown outputs, is a design method referred to as action research. Action research often is 'doing' without necessarily knowing where it may lead to, as the designer learns through practical work and iterations of this. The process of action research helps to make implicit knowledge explicit, which in turn adds value to the overall design process that is reapplied to future design iterations (Swann, 2002). A repository of knowledge is accumulated by the designer from practice over time, which helps establish skills to become more refined and tuned to professional practice. As Schön emphasises, "*Our knowing is ordinarily tacit, implicit in our patterns of action and in our feel for the stuff with which we are dealing. It seems right to say that our knowing is in our action*" (Schön, 1991 p.49). Schön suggests that intuition and tacit knowledge can lead to outputs that can make sense of our actions through reflection. Following instinctive thoughts and tacit knowledge through to action can help bring clarity to the work, and in turn make implicit knowledge into explicit; hence, making sense through a physical experience. This process is also referred to as 'surfacing' (Thompson and Thompson, 2008 p.33); it brings ideas to the surface to establish connections between them. This is also central in reflective practice which will be discussed in section 3.4.6.

Action research relates closely to the empirical based approach used in this e-textiles research, as the experimental outputs will be built on acquired knowledge through experiential learning. Testing practical methods uses implicit knowledge, whereby these practical applications transform into explicit outputs by means of this process. Therefore, implicit and explicit knowledge are present in all of the stages of this design process, from the design objective through to the design specification, as well as in the weaving execution. The outputs of e-textile samples help the designer to reflect on ideas and iterate new ideas to test. It is this thinking and implementation of new ideas that builds new knowledge and in part initiates reflective practice, which is in constant development through cyclical activity.

3.4.3 Praxis

The phrase 'knowledgeable doer' refers to designers who are able to apply theory and knowledge to their practice. This leads to the notion of praxis that defines the combination of theory and practice and the interconnected relationship between the two (Thompson and Thompson, 2008 p.22). Therefore, knowledge and thoughts translated into action and the consequences of performing these actions are known as praxis. Praxis addresses the consequences of action in design by extracting information on how these thoughts and outputs can be used. Praxis is a useful method in design research as it addresses and frames design consequences (Crouch and Pearce, 2012 pp.39-44), which can help to form the design process.

Praxis is integral to this research, as previously acquired knowledge, and knowledge acquired during this research, are all applied to practice. Particularly throughout the iterations of the e-textile samples, praxis helps evolve these designs and shape the design process for producing e-textiles. In this e-textiles design process, praxis is evident in the stages of inspiration through to design specification and the weave execution. These stages all use theory in practical application for a design consequence, which leads to the next stage and/or the outcome. Praxis is not present in the design objective stage, as this phase operates independently without practice, but does involve theory to help realise its design potential. Once the design objective meets the inspiration phase, praxis is active as both theory and practice are initiated.

The researcher's knowledge of woven e-textiles has developed through the course of this research project; consequently evolving the praxis of woven e-textiles through the 'development of self' i.e. the researcher. This transitional phase is evident in most practices, where particularly in design "*No one begins his or her career being a designer – emerging as a full-fledged designer at birth… To become a designer, it is necessary to engage in learning processes that lead to our development as skilful individuals – to master the requisite elements comprising adequate design competence*" (Nelson and Stolterman, 2012 p.215). This statement was especially true of the researcher's design knowledge praxis of woven e-textiles.

3.4.4 Abductive theory

Actions intuitive to the designer are a result of implicit thinking as a reasoning process, as Nigel Cross suggests "*…design thinking is abductive: a type of reasoning different from the more familiar concepts of inductive and deductive reasoning, but is the necessary logic of design*" (Cross, 2011 p.10). Abductive thinking is the relationship between deductive thinking (logical assumptions based on facts), and inductive thinking (predictions based on speculations). Abductive assumptions are based on what might be, built on intuition grounded from prior understandings and basic knowledge of the subject (Crouch and Pearce, 2012 pp22-23; Kolko, 2010). In relation to this research, intuition plays a significant role through tacit knowledge; here, abductive thinking can help explain the process of how new ideas evolve. This does not justify specific details of what occurs in each stage, but does provide some insight into the factors that contribute towards new ideas.

In this e-textiles research, abductive thinking is a prominent factor throughout the design process, as well as in the weave execution. It is also a motivating factor for new design iterations.

3.4.5 Synthesis

Through abductive thinking, there is an attempt to make sense of ideas for a design problem and connect these different thoughts; this process is known as design synthesis and enables a phase of sense making for design scenarios. Design synthesis is a process that can help to organise, judge and form connections to allow a designer to make sense of possible solutions to a design problem. It judges relationships between ideas to see if they fit within a context (i.e. design problem); it is less concerned with the 'correct' outcome, but more focused on finding the right relationships (Kolko, 2010). The synthesis process can help identify value in ideas that are sometimes recognised but are not able to underpin where their future use is. Figure 3.5 illustrates the simplified version of Kolko's synthesis process. Kolko emphasises that this process is not as linear or as clean as the schematic depicts, as it is only arranged this way to help communicate the process.

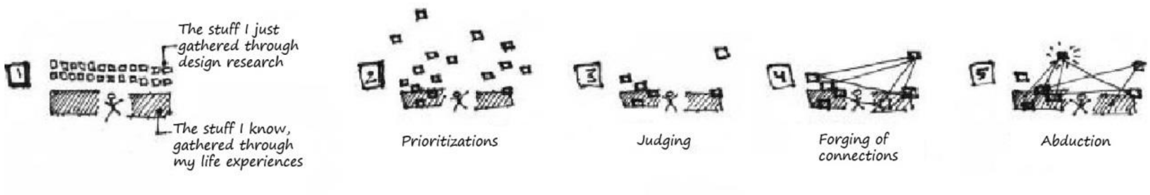


Figure 3.5 Jon Kolko's synthesis process simplified and illustrated. Parts redrawn (Kolko, 2010 p.22)

Design synthesis uses a combination of prior gained knowledge and experiential learning through reflective thinking, to analyse, assess and convert these ideas into unified concepts after an incubation period, i.e. the reflective and ideas processing phase (Kolko, 2010; Hertz, 1992).

When synthesis occurs in the design process, it is active; ideas start to make sense and form design outcomes, particularly in design research where a lot of information and ideas are gathered throughout the process. "*In design, this moment of synthesis is the main focus – to be celebrated and widely communicated as 'inspired'* " (Swann, 2002 p.55). Swann goes on to comment further on the processes in design disciplines being different to other disciplines, particularly as there are key intuitive factors that contribute to the initial inspiration of design ideas that are not as acclaimed, or as valid in science disciplines. "*The design process is a research process*" and synthesis becomes that 'eureka' moment (ibid.).

Synthesis is a reoccurring aspect throughout the design process where at every stage the designer reflects and makes sense of ideas through both micro and macro perspectives. In each stage, solutions are reached via synthesis, enabling overall progression in the design process. It is a significant episode that will recur across several stages of this e-textiles design process and research (i.e. from Inspiration through to design specification and the weave execution). Synthesis is not present in the design objective stage as this is yet to be synthesised with other design stages.

3.4.6 Reflective practice

Reflective practice suggests theory and practice can be seen as equal influencers; therefore, they are mutual and interconnected, where each is dependent on the other. Reflecting in practice involves thinking rationally about the actions that have been performed, and how those reflective thoughts might influence future actions. Thus, this helps to build further knowledge and influence future activity, forming a cyclical process (Crouch and Pearce, 2012 pp.44-47).

In Donald Schön's book 'The Reflective Practitioner', an analysis of reflective practice is deconstructed into two main interrelated activities; 'reflection *on* practice' and 'reflection *in* practice' (Schön, 1991). When a practitioner reflects *on* their work after completing an activity, this is referred to as reflection *on* practice. When a practitioner reflects *in* their work during the activity, this is referred to as reflection *in* practice (Crouch and Pearce, 2012 pp.39-44; Schön, 1991). It is this reflective thinking in practice that Schön called 'reflection in action'. This occurs while engaging in an activity that requires thinking through physical actions, as Schön states "…*'learning by doing' suggests not only that we can think about doing but that we can think about doing something while doing it. Some of the most interesting examples of this process occur in the midst of a performance*" (Schön, 1991 p.54). In this process of reflection in action, existing knowledge and learnt knowledge are combined to enable future iterations of activity, to continue the evolution of new knowledge and novel outcomes. In essence, this is experiential learning where the next iteration takes on new changes and different perspectives to what is already known. Over time this makes practice more focused and valuable for the practitioner (Thompson and Thompson, 2008 p.12).

In textile design practice, a lot of knowledge is acquired through phases of trial and error, particularly when a new skill is being learnt. During these phases, mistakes and unexpected outcomes can often have a significant impact on forming new knowledge via experiential learning. It is here that reflective practice enables the designer to learn and acquire a body of practical knowledge, using a combination of reflection *on* and reflection *in* practice. This still uses tacit knowledge in the initial steps of the design process; however, reflective practice simultaneously occurs to facilitate implicit knowledge to become explicit. Reflective practice also enables the designer to visualise their work as physical outputs and tangible results, to reflect *on* for future reference and activity. Thus, thinking through doing, for example, when embodying an idea through sketching or producing a model the idea is being developed and evaluated at the same time.

Reflexivity is seen as a sub coordinate of reflective practice. It refers to the practitioner recognising and understanding their subjective views relating to objective issues. In design this relates to the designer's thoughts that are intuitive to the individual and these thoughts form relationships with objective decisions in design scenarios. Therefore, reflexivity impacts the design process as it engages "*…with the experiential learning cycle of theorising, action, observation and reflection and dynamics cyclical relationships of cause and effect*" (Crouch and Pearce, 2012 pp.49). Reflexivity helps to take into account other influential factors, both subjective and objective, that contribute to reflective practice. Overall this adds to experiential learning and the cyclical design process.

Reflective practice is an intuitive and active approach used by the researcher in this e-textile design process. Reflection is crucial in analysing the position of the design in order to progress it forward to the next stage. Reflective practice occurs throughout the design process and is evident at every stage (i.e. design objective through to design specification and weave execution). Reflection *in* practice is also vital; although this is more significant in the stages of the design process where there is constant and/ or multiple activities occurring, (e.g. inspiration, design ideation, iterations of sketches, physical rendering of prototypes, circuit testing and weave planning). Reflection *in* practice is not evident in the design objective and design specification stage, as no design activity is generated during these phases; reflection *on* practice is only active after completion of activities.

Working with electronics also uses reflective practice to evaluate and learn from both reflection *on* and reflection *in* practice; thus, this enables the designer's electronics knowledge to grow and progress over the duration of the research project.

3.4.7 Creativity

Creativity is a term frequently used when describing the design process, often linked with that moment of surprise when an idea transpires. Creativity is sometimes phrased as the 'eureka moment' or what Nigel Cross calls the 'creative leap' (Cross, 1997). Creativity has been defined as *"…the ability to come up with ideas or artefacts that are new, surprising and valuable*" (Boden, 2004 p.1), and "…*the ability to make new combinations. The creative process is the means to make them. The new combination is termed as innovative*" (Haefele, 1962 p.6). Although acknowledged as a valuable happening during an activity (Boden, 2004 p.11; Dorst and Cross, 2001 p.426), creativity is also seen as a mysterious occurrence, where little is known as to how and what occurs in this instance.

In relation to the design process, creative thinking is the ability to view and analyse positions from different perspectives that are beyond normal insights – it is an expansion of analytical thinking (Thompson and Thompson, 2008 p.39). There have been many suggested models on how creative thinking occurs in design. One example by Rosenman and Gero based on artificial intelligence (and also relates to product design processes), proposed activities that enable creative thinking to occur including 'combination', 'mutation', 'analogy' and 'first principles' as shown in Figure 3.6, cited in (Cross, 1997). Since their initial proposal of this model, Rosenman and Gero have added a fifth option of 'emergence'. From observation of this model, it appears these behaviours are often prevalent in the processes of textile designers, as similar thought processes are applied to their method of designing.

Judging designs as creative relies on the individual's perception of creativity and how they view and interpret this. Swann suggests creative design can stem from creative energy attached to vague or random intuition about a design scenario; therefore, it can be derived from "*…an intuitive understanding of phenomena*" (Swann, 2002 p.51). In a study conducted by Kees Dorst and Nigel Cross, they investigated creativity in the design process by observing nine industrial designers. They found that creativity was used to explore the space that occurred between the problem and solution, and helped the designers draw relationships between these two areas. The study concluded that the point when an optimum solution is reached is seen as ‘problem framing’ and high levels of creativity are crucial to attain unique solutions (Dorst and Cross, 2001).

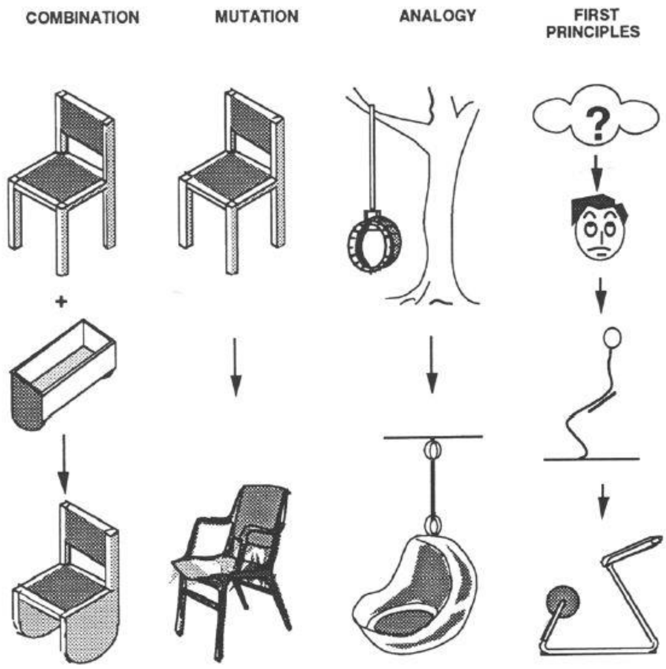


Figure 3.6 Rosenman and Gero’s model of creativity in design using a prototype approach (1993), **cited in (Cross, 1997)**

Creativity plays a significant role in textile design practice, and although it is a strongly characterised quality that is associated and identified in textile designers and their work, it is still not clearly defined in this context. Gale and Kaur state – “*A textile designer has to find the right balance between creativity, innovation and commercialism*” (Gale and Kaur, 2002 p.37). Creativity is also strongly connected with the aesthetics of textiles followed by the process of designing the textiles.

In this e-textiles research, a creative approach is adopted to explore the research context of woven e-textiles. Creativity is linked with intuition and tacit thinking, but is also present in the synthesis of ideas as an influencing factor that contributes to the research process and outcomes. Creativity is consistently active in all the stages of the e-textiles design process from design objective through to weave planning, and also in the weave execution phase. Creativity is not present in the design specification stage, as this phase requires the pulling together all previous information as instruction for execution only.

Some of the design methods that will be used in this research are familiar processes to conventional textile designing and also include creativity. However, given the researcher's previous textile design experience and the integration of electronics with woven textiles, the design process has evolved to become specific to this research (as discussed in the textile design process section 3.2). As suggested by Haefele, Dorst and Cross (and noted earlier in this section), creativity is an integral ingredient to the design process that leads to innovation, and is vital in pursuing the execution of this research project.

3.4.8 Decisions of the design and making process

The process of making as an action of design practice can be considered as physical thinking and a design method. It is the designer's in-depth knowledge that enables the making process to develop into significant outputs. Designing through making becomes an integrated process and is developed by the designer's creative approach (Bunnell, 2000). In her '*Designing Through Making'* paper, Katie Bunnell goes on to suggest that tacit knowledge in design practice is explored for its value in design research. It helps shape models and theories of this work so that it can be formed and disseminated with a clearer understanding and documentation for future reference (ibid. p.2). This insight can be applied to textile design practice to help influence the way we articulate and use this knowledge to pass it forward into research, education and industry. Thus, helping to avoid 'tacit synthesis' that was previously (and in instances still is) an acceptable standard in academic and professional practice (Igoe, 2010 p.8).

Designers make decisions based on their experience, intuition and knowledge. However, it is the designer's ability that enables them to interpret theory and knowledge that is specific to their practice. Hence, designers must "*…concentrate on 'designerly' ways of knowing, thinking and acting*" (Cross, 2000 p.97) to support and encourage their design process. Linking cognitive thoughts of tacit knowledge, theory and creativity with physical making is a skill that a designer forms through practice. This becomes the designer's design process, which is complex and differs by design discipline, and often by practitioner. We cannot expect "*…the design process to be as clear, logical and open a process as the scientific method. Design is a messy kind of business that involves making value judgements between alternatives that may each offer some advantages and* *disadvantages*" (Lawson, 2004 p.81). The relationship between thinking and doing produces connections, leading to both successful and unsuccessful outcomes. These outcomes are what enable learning (regardless of the level of success), which is used to evolve and feedback into the design process.

The decisions made throughout the design process in this project have direct impact on this research; they are a consequence of the researcher's judgements and actions. These decisions are based on knowledge, theory and experience acquired from previous practice, training and learning. Applying this to new outputs continues to generate different knowledge through actions of making and doing; in turn, fulfils the design objective and initiating new questions of design investigations.

3.5 Validation methods

Validity relates to checking accuracy of information; *"…in many ways the most important criterion of research is validity, which is concerned with the integrity of the conclusions generated by a piece of research*" (Bryman and Teevan, 2005 p.25). Although this definition is derived from a social research context, it is applicable for a wider scope of research including design practice.

Reflective practice is one method that helps build validity into practical based research. At the time Donald Schön wrote his book 'The Reflective Practitioner', the validity of reflection in action was not widely accepted, as technical expertise was regarded higher as this was seen to hold more validity in science based practice. Schön concluded that reflection in action is an effective and suitable protocol of validity, however, requires more epistemology of practice based subjects to extract how problems are resolved via reflection. Hence, this "*…links the art of practice in uncertainty and uniqueness to the scientist's art of research*" (Schön, 1991 p.69), and would provide the rigor that was claimed to be missing. In-depth subject insights are provided through abductive practice of design research via resolving problems for potential unknown answers that may or may not be found. Nigel Cross also emphasises the point of validation in design research and classes 'best practice' with specified characteristics:

- "***Purposive*** *– based on identification of an issue or problem worthy and capable of investigation*

- ***Inquisitive*** *– seeking to acquire new knowledge*
- ***Informed*** *– conducted from an awareness of previous, related research*
- ***Methodical*** *– planned and carried out in disciplined manner*
- ***Communicable*** *– generating and reporting results which are testable and accessible by others.*" (Cross, 2000 p.98)

Applying Cross' points of validation to the woven e-textile design research presented in this thesis, the purpose is highlighted in the introduction chapter 1, emphasising the inquisition and objectives set for this research. The literature review in chapter 2 drew attention to prior related research and reinforced the gaps in knowledge that have informed this research inquiry. The methodological approach is explained in this chapter (3), where it has rationalised the approaches and design process applied to execute the woven e-textiles. Chapter 4 presents an in-depth technical repository, which systematically guides through methods and techniques adopted to execute the practical outcomes. Chapters 5, 6 and 7 will present examples of woven e-textiles, communicating their formation against the design process from initial conception to execution and analysis.

Part of the communicable approach in design disciplines is based on highly visual work, especially as design is a visual language where the outputs can be physical objects, and the processes of execution are experiential, tacit and implicit. As Swann infers, "*visual form (as manifested in a design model) is a valid form of knowledge, albeit more problematic to verbally explain to 'readers' not accustomed to seeing and understanding visual/ spatial concepts*" (Swann, 2002 p.52). Therefore, this visual discipline should be information focused and descriptively rich. Nevertheless, some of this information is inevitably lost in translation, particularly as the making process involves tacit knowledge that cannot always be expressed and can only be experientially practiced.

Management, organisation and explicit documentation of this practice based research have been conveyed in a systematic and communicable arrangement; the methods have explicitly explained the processes involved in developing this research. As a result, all processes and criteria documented in this research have been made explicit in this thesis, to provide an in-depth understanding of design led woven e-textile as investigated in this research project. In addition, "*…all measurements (even observations) are indexes to constructs of interest, not the constructs themselves*" (Cobb *et al.*, 2003 p.13). Hence, the decisions implemented to establish levels of 'measures' (in relation to this research, these are design decisions) are some of the most significant judgements and choices made, as this impacts consistency, objectivity and 'rigor' of the research output. Therefore, the design process is equivalent to Cobb *et al.'s indexes* where validity is designed into the design methodology.

Carole Gray and Julian Malins suggest visual related research (including design research) needs to establish methods that will translate this way of thinking, analysing and interpreting information that is relevant and contributes knowledge to the research discipline. Therefore, "*Our task as researchers in the visual arts is to try and develop more appropriate research methodologies: this will not be accomplished without risk, without error, but certainly will not be accomplished by repetition and regurgitation of orthodoxy*" (Gray and Malins, 2004 p.95). To develop such methodologies we need expertise in the field.

3.5.1 Expert validation

The level of specific field expertise held by an individual will impact the significance and validity of knowledge produced; this is a topic that has been widely discussed, in particular with relation to ability. The specific subject of weaving differs vastly between novices and experts, as shown in the study by Pirita Seitamaa-Hakkarainen and Kai Hakkarainen (2001). Their study concluded domain specific knowledge applied by experts (as opposed to novices) was used confidently for competent designing, reflectively and simultaneously in both visual 'composition' and technical 'construction' spaces. Similarly, Dorst (2004) presented a cross comparison between Heubert Dreyfus' model of seven stages of expertise development (2002/2003, cited in ibid.) and Nigel Cross' eight basic design abilities (2001, cited in ibid.) in order to position a design expertise model. Dorst concludes a more rigorous model is required to precisely capture the qualities designers possess in design thinking and that this requires further investigation resulting in deeper insight. Nonetheless, there are clear differences between the different levels of design experts, where amongst them the intermediate boundaries between expertise and abilities are not so clear.

Expert insights to specific domains should add further value to a discipline; this view was applied to gain feedback of the woven e-textiles produced in this research. Two of the woven e-textiles pieces were exposed at the eTextiles Summer Camp 2013, where e-textile experts provided insights and feedback of the research outputs. Chapter 8 (discussion) will explain the woven e-textiles questionnaire.

3.6 Design research by practice – summarising points

This research project is led by weaving; hence, the research is defined by the design practice of woven e-textiles. The research takes a creatively led approach following a design process to execute the woven e-textiles. The researcher's prior knowledge and expertise in weaving are essential to form the basis of this research.

The practical elements of weaving and making e-textiles are the main activity informing this research. Making is partially an intrinsic process that connects to tacit knowledge and implicit thinking, which in turn helps to translate this research into explicit knowledge and physical woven e-textiles (evolving the praxis). Decisions made during the design process and practical making stages significantly impact the final outcomes, as they are a consequence of the analysis and synthesis from the problem to the solution. The process of making the woven e-textiles uses praxis to iterate back into the design process for new outputs; hence, the design process becomes cyclical and iterative. To support the iterative design process, reflective thinking during (reflection *in* practice) and after (reflection *on* practice) the practical design activities feed into future iterations of designs through reflexivity. This adds value to both the outcomes and the researcher through experiential learning. In this case, the e-textiles will grow from a single idea into other and/ or refined ideas via iterations of one design. Therefore, the design process model plays a significant role in enabling these activities to synchronise and perform as a catalyst for further outputs. Validation is built into the design process through the methods used and judgements actioned by the designer; this requires design research to be translated and communicated *through* the practice of design.

4 Technical woven repository

The woven execution is one of the final stages of the design process before results are obtained for analysis. This chapter explains details of the woven process, such as woven methods, designing warps, woven structures, yarns and finishing processes. This is followed by specific explanations of e-textile weaving techniques and woven manipulation methods, as applied in this research. The amalgamation of electronics and weaving construction will be the focus of this chapter and is presented as the technical woven repository in the sections 4.1 – 4.3.

4.1 Textile construction processes

This research focuses specifically on woven constructed textiles for e-textiles. As mentioned in chapter 1 the main methods of e-textile constructions fall into two main divisions; those that are constructed *into* a textile material or those that are constructed *onto* a textile material. Other methods of constructed textiles fall into three main categories of woven, knitted and non-woven textiles, as shown in Figure 4.1. Each textile construction offers a different textile quality due to its structural composition.

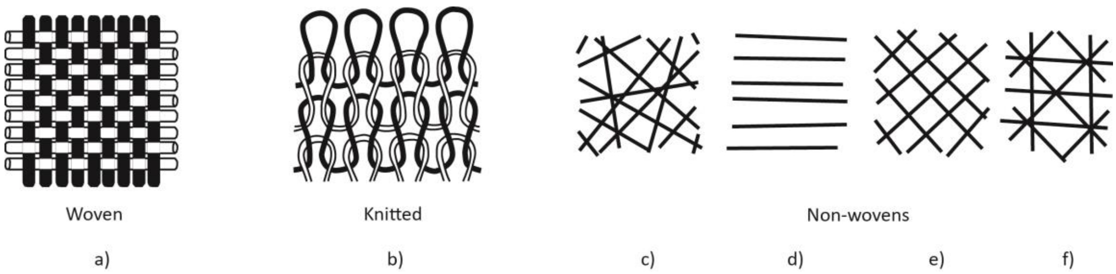


Figure 4.1 Textile construction schematics; a) plain weave structure b) plain knit structure c) – f) examples of non-woven fibre dispersions. Knitted and non-woven Illustrations based on (Miller, 1984)

Woven fabrics are constructed on a loom where the interlacing warp and weft can be controlled via lifting woven structures. Knitted textiles consist of a succession of inter-looping loops, usually possessing a degree of stretch depending on the space between the courses (vertical) and wales (horizontal). Knitted fabrics are constructed on knitting machines or traditionally by hand. Non-woven fabrics are comprised of a dispersion of short fibres in random or arranged laid web configurations. These are then combined with variables such as heat, washing, chemicals, needle punching and a compression method to fuse and bind the fibres together for sheet material. This can be a quicker manufacturing method for disposable textiles; however, thin non-wovens can be fragile and are not as durable as woven or knitted construction due to the short fibre construction, opposed to continuous fibres interacting throughout a fabric construction.

As discussed in chapter 1 the introduction, the main reasons to develop woven construction for e-textiles are predominantly due to lack of exploration in this field. In-depth woven construction has not previously been fully utilised for e-textiles. The common orthogonal structures between woven textiles and electronics present opportunities to investigate these compatible architectures further for e-textiles. In addition, weaving is able to manipulate isolated parts of the woven cloth independently to the rest of the textile, which is a very useful attribute for e-textiles.

4.2 Weaving execution

The woven e-textiles executed in this research were woven by hand on a 24-shaft (harness) Patronic ARM loom. The loom is operated with a 'Selectron' computer assisted module (manually programmed) dobby loom that was manually controlled via foot treadle (Figure 4.2).

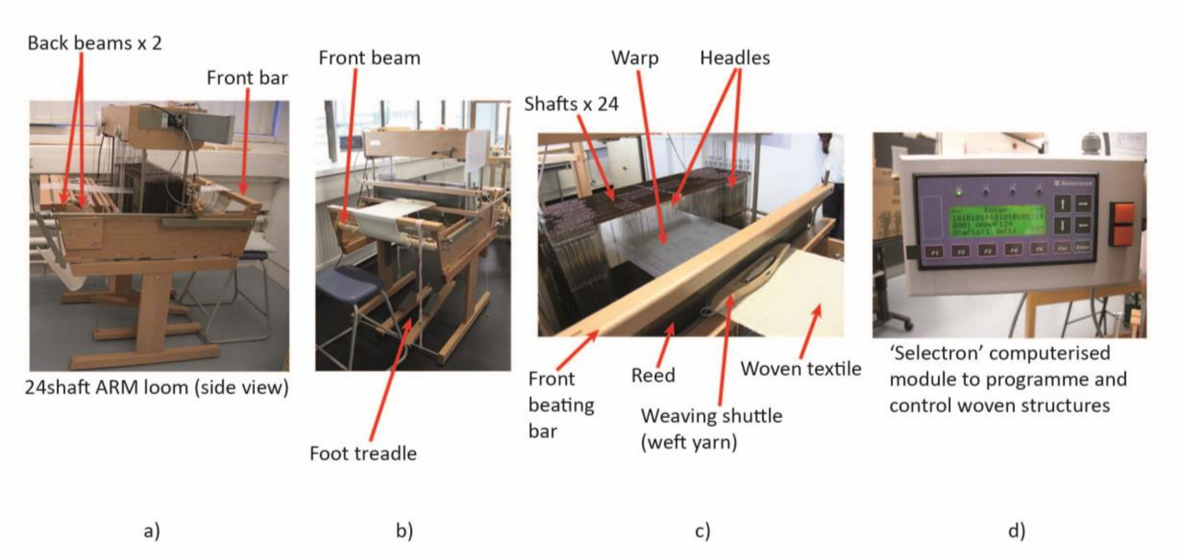


Figure 4.2 ARM loom navigation: a) side perspective of the 24shaft ARM loom; b) front perspective of loom and foot treadle operation; c) details of loom parts; d) Selectron module

Each weft pick was inserted by hand after every treadle lift, i.e. the right foot treadle was pressed down to engage the next woven structure pick (auto selected in sequence via the computerised Selectron module). The weft was inserted with a boat shuttle and the front beating bar was bought forward to compress the weft taken into the woven cloth. The left foot treadle was pressed to disengage the current structure lift, and then the right foot treadle was pressed again to repeat the last action for the next weft pick insertion. The action of a single pick insertion can be seen in Figure 4.3.

a) b) c) d)

Figure 4.3 Weft pick insertion: a) weft pick structure engaged to open cloth shed, b) weft boat inserted RHS, c) weft boat extracted LHS, d) treadle pressed to disengage current structure and engage next pick and weft pick is beaten into the cloth.

At the point of the weft pick being inserted, the woven structure needs to open the warp. This opening is known as the warp shed (Figure 4.4). Although the warp shed will always need to be open for the weft pick to be taken, the combination of which warp threads are lifted and which are left down are dependent on the woven structure applied.

Figure 4.4 Warp shed opening (indicated by the red arrow)

Manual weaving is a slow process and the rate at which the cloth is woven / built up depends on a number of factors such as density of warp, density of weft, woven structure, speed of weaving and compression of weft yarns. The Patronic ARM loom is a sampling loom (i.e. maximum of 60cm woven width can be produced) using dobby weaving. This refers to each shaft controlling every thread on that allocated shaft. This

differs to jacquard weaving where a single warp thread can be controlled individually across a given repeat width. Therefore, jacquard weaving enables more manipulation over a woven cloth. Dobby weaving has been applied to this research work, where the outcomes have potential to be adapted for commercial dobby or jacquard weaving.
Dobby weaving was chosen for the purpose of this research as it enabled controlled manipulations over areas of a textile, which needed to be tested and proved through standard weaving and dobby looms before adapting for more complex or simpler weaving. Some woven manipulation techniques used in this research were better suited to dobby woven textiles, where adjustments could be made to accommodate for specific woven methods. This cannot always be done on industrial or jacquard looms due to their pre-set machinery and weaving methods. For this reason, some of the weaving methods applied to this research were industrially unconventional, but this was intentional to explore what the potentials of these methods were for e-textiles. If these explorative methods proved successful in the outputs, they could be adapted for industrial looms or have machinery build to inform these methods. Re-appropriating existing technology for new methods or outputs is not an unusual concept. This has previously been applied to and has been seen in woven textiles such as 3D woven fabric, velvet and tri-axial weaving to name a few.

The design specification developed from the e-textile design process was applied to the woven execution; this includes all of the details needed to weave a sample, including reference to the warp, weft yarns, woven structures, integrated components, and when and where these aspects become active or de-active. Essentially, the design specification is a formula used to achieve the e-textile design. The details listed in the design specification are specific to each e-textile design; hence, they must be read and interpreted accurately to acquire that particular design. Any errors in this translation result in malfunctions in the design. It was important that the design specification was read correctly by the researcher to reduce errors. Errors in weaving are not reversible if they were not identified on the loom at the time of being woven, (i.e. woven errors identified on the loom could only be reversed/ unwoven if they were caught near the position/ time at which they were woven).

The weaving process includes woven drafts, woven structures, warp set up, sample cut off and sample finishing, these are discussed in the subsequent sections 4.2.1 – 4.2.7, and convey the complete process involved in the woven execution.

4.2.1 Warp drafts

The initial step for the woven method includes designing the warp that was directed by the design specification. Warp drafts are instructions of the order of the warp to thread up on the loom. The warp order then remains fixed for the duration of the weaving process. It was imperative the warp draft enabled all the features of the e-textile design to function; therefore, the warp design needed to take into consideration all these details when drafting.

Warp drafts were designed to enable the e-textile design specification. As warp designing and setting up is an extensive and time consuming process, the warp drafts were designed as multifunctional warps, i.e. they could be used for more than one specific sample. A warp draft may have already been set up on the loom when a new e-textile design was being specified. Therefore, the warp draft had to be considered at this stage to assess if the e-textile sample was compatible with the existing warp draft, or if a new warp draft needed to be designed.

Warp drafts reflect woven structures, so it was important to design a draft that would enable the quality of cloth required. There are a number of warp draft order options including straight, point/ mirror, broken, intermittent, corkscrew, grouped, combination and divided (Oelsner, 1952). Most of these warp drafts enable specific woven qualities with the exception of straight draft, which is the simplest warp set up. For this e-textiles research straight drafts were predominantly used in the warp design, as the required woven cloths could be executed on this set up.

Using a 24 shaft loom allowed for substantial variation in warp draft designs. Industrial dobby looms usually operate on four or eight shafts. A basic weave structure e.g. a plain weave, would only require 2 shafts to lift alternate threads using only 2 weft picks (Figure 4.5). Each **X** mark represents a warp thread pulled through the corresponding shaft; therefore, when a woven structure is applied to this set up, the shafts lifted correspond and react to the warp draft. There are ample warp draft options where the combinations increase when there are more shafts available to work with. This is why it is possibleto use 24 shafts for multiple blocks to control smaller sections of a warp, either independently or simultaneously.

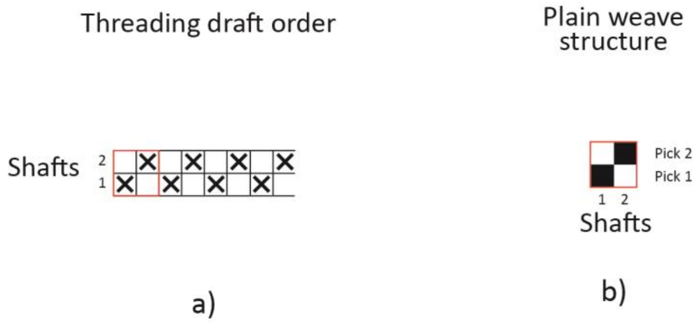


Figure 4.5 Straight warp draft on two shafts: a) threading draft order across two shafts calculated according to required warp width, b) plain weave structure two shafts by two picks (2 x 2 structure)

To explain this further, a basic straight draft on 8 shafts is shown in Figure 4.6; this would be repeated a number of times depending on how wide this section needed to be. The calculation is based on the density of yarn and width required. Across 24 shafts, 3 blocks of 8 shaft drafts can be applied; similarly, 6 blocks of 4 shaft drafts can be applied; hence, any derivative of 24 can be placed in blocks – this is referred to as a woven block draft.

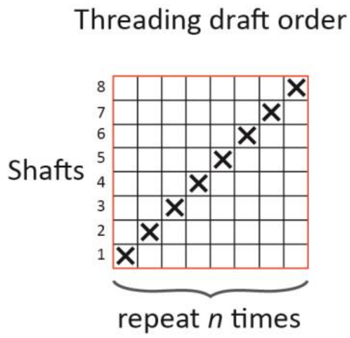


Figure 4.6 Straight warp draft across 8 shafts

The multifunctional warps used in this e-textiles research all used block drafts. An advantage of using block draft is that it can enable several different features to be controlled independently or simultaneously across the same warp. For example, across 24 shafts, 3 blocks could be controlled independently by applying shafts 1 – 8 (block A), shafts 9 – 16 (block B) and shafts 17 – 24 (block C). Figure 4.7 illustrates how this would be visually represented. Weaving on a block draft warp set up enables each block to be treated independently. Therefore, the blocks can be woven with the same or different structures.

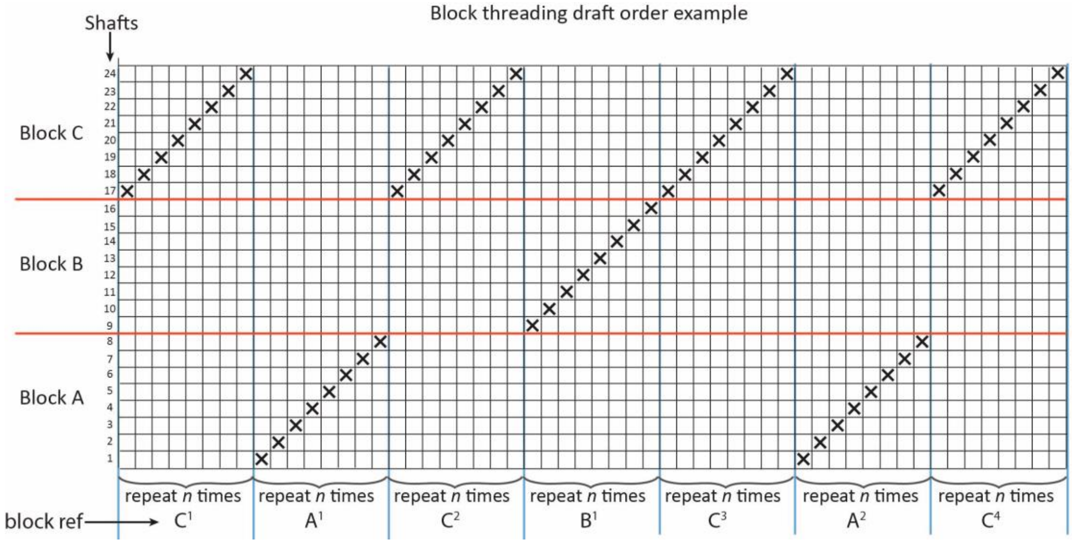


Figure 4.7 Block draft warp plan example across 24 shafts, where shafts 1 – 8 control block A; shafts 9 – 16 control block B and shafts 17 – 24 control block C

As illustrated in example Figure 4.7, blocks A, B and C have been allocated eight shafts each. Along the bottom of the warp draft, each block is referenced with a number to help identify them in sequence. The blocks are threaded across the allocated shafts and repeated per block as per calculated times – this is dependent on the section width, yarn count and sett. Therefore, all the block sections can be different widths but would appear in the same sequence as per Figure 4.8.

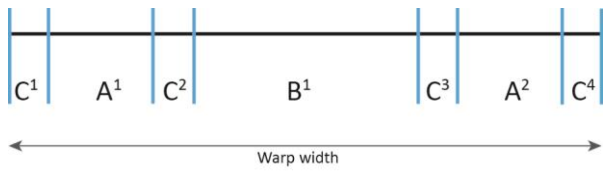


Figure 4.8 Warp width illustrated with blocks in sequence

The block width sizes are calculated based on the yarn count, (i.e. the thickness/ density of the yarn) and the sett at which the warp is made (i.e. how densely the warp is set across one inch, thus determining the sett of the warp width). The yarn count is predetermined by the manufacturer. This differs depending on the yarn compositions and type. The warp sett is calculated by knowing how many yarn ends fit in one inch, i.e. ends per inch (epi). This can be worked out by wrapping the chosen yarn around an inch of a ruler. The compression/ density needs to be determined by the weaver and their knowledge of warp setting, as if this is too dense, it will cause problems when weaving, or if set too spaced, this will result in an open/ loose cloth. Other factors to consider are the type of structures to apply and the textile quality required from the warp, as this can affect the warp design. Once the warp width is determined and the yarn type is selected, the epi can be worked out as well as the total ends across the block sections and the complete warp width. For example, using a 2/20s cotton, set at 44epi across an 8 inch warp would equal 352 ends; across two equal blocks (i.e. 4" per block) each block would need a total of 176 ends; divided by 8 (number of threads per straight draft per block) equals 22 repeats of each block. Below is the described example:

Epi x warp width" = total ends in warp	→	44 x 8" = 352 total ends in warp draft
Total ends / warp width" x width of block = total ends per block	→	352 / 8 x 4 = 176 ends per block
Ends per block / number of shafts in block = repetition per block	→	176 / 8 = 22 repetitions across 2 straight draft blocks across 8 shafts

This gives a basic overview of warp calculations; however, the calculations become more complex as the warps became more sophisticated.

For the woven e-textiles in this research, conductive yarns in the warp and weft have played a significant role in the e-textile construction. One technique that had been applied to several of the warp designs is called an extra warp (EW). The EW set up is drafted in as per a regular warp; however, this is in addition to the ground warp, hence its name. Usually an EW is integrated into the ground warp without altering the ground warp sett, as the EW would only intercept as and when needed. The EW operates on predetermined shafts; therefore, these EW shafts need to be allocated when designing the warp draft. Depending on how the warp conductive yarns were going to be used, factors that required consideration included their positioning in the warp, i.e. to keep them isolated or consecutively placed, which was subject to the woven e-textile circuit design. For example, on a block draft warp plan across 24 shafts, three blocks could be arranged; 2 x 8 shaft blocks and 1 x 4 shaft block. In this case the remaining 4 shafts can be used for the EW (Figure 4.9), although any number of shafts could be allocated for the EW.

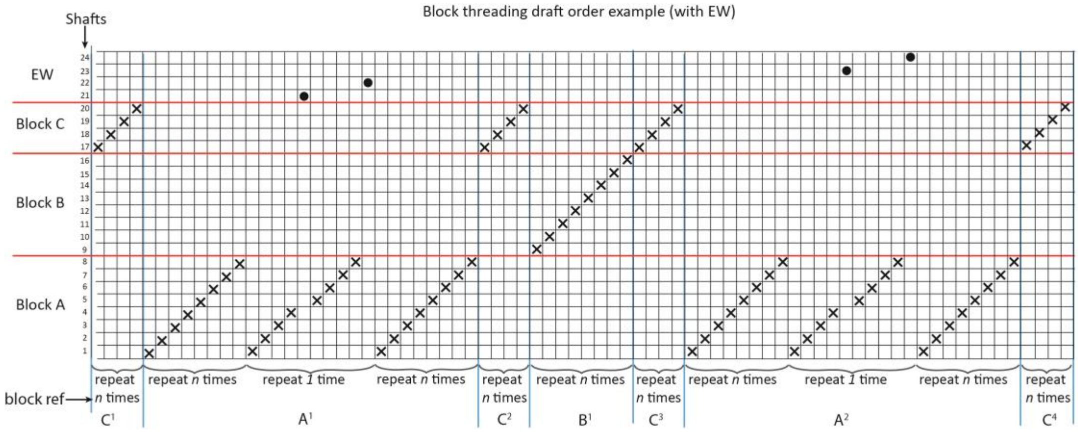


Figure 4.9 Block draft warp example across 24 shafts, using three blocks and an EW across 4 shafts

In the example illustrated above, there are a total of four EW threads; each thread is controlled independently by a separate shaft. Multiple threads could be allocated across the same EW shaft, although these threads would be controlled simultaneously on the same shaft. The placement of the EW threads can be situated in any position on the warp, and the spacing between the EW threads can also be designed into the warp plan. Figure 4.10 illustrates the visual spacing of the block sequence and where the EW would intercept with reference to Figure 4.9.

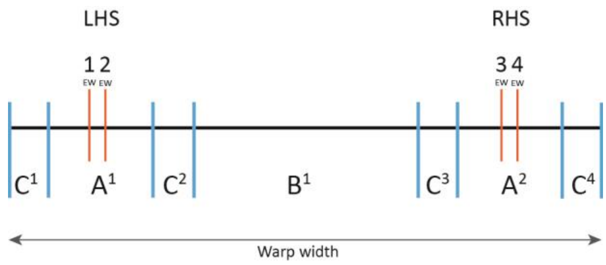


Figure 4.10 Warp width illustrated with blocks in sequence. Orange intercepting lines depict EW threads 1 – 4 on the LHS and RHS (not to scale).

EWs were a key warp design feature to this woven e-textiles research, particularly as the warp conductive yarns needed to be precisely controlled to enable the circuits to function. The EW also enabled the conductive yarn to be kept isolated to stop short circuits between these different tracks. If the EW was not used/ woven, this would not alter the woven textile as this was in addition to the ground warp density. In the reeding stage (section 4.2.5), the EW threads were pulled through in addition to the ground warp.

Once the warp design is finalised, this is followed by the warping process to make the warp. The warp design sets the foundation for how the woven structures will react when woven – this is discussed in the next section 4.2.2.

4.2.2 Woven structures

Plain weave (as mentioned in section 4.2.1) is the most basic woven structure and can be applied to any woven draft with two or more shafts. It is one of the most commonly applied woven structures in industrial weaving. As a result of plain weave's constant movement between alternative threads and picks, the cloth disperses wider than a woven structure with less consistent movement, i.e. bigger floats between warp and weft; therefore, plain weave is the tightest woven structure. Figure 4.11 illustrates how a plain weave structure would be applied to a straight draft warp.

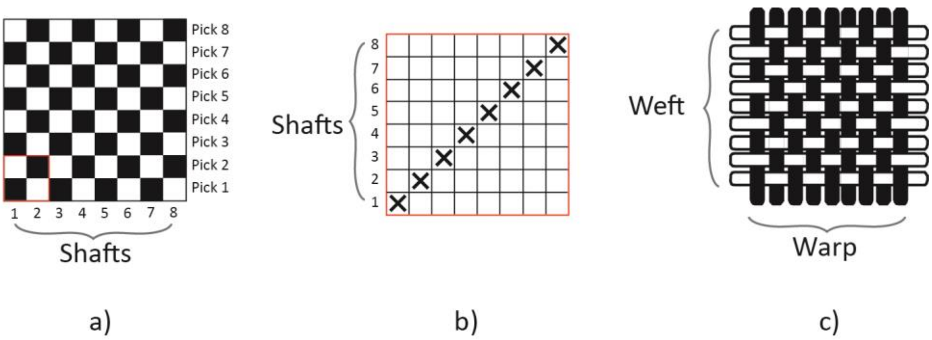


Figure 4.11 Plain weave structure: a) plain weave structure across 8 shafts and 8 picks, b) straight draft across 8 shafts, c) schematic of plain woven structure

When woven structures are drafted, the corresponding shaft numbers are positioned along the bottom (left to right). Each weft pick is read from the bottom to the top as this is the direction the cloth is being built up on the loom. There is no limit to how long a woven structure can be, but standard practice would complete the woven structure up to the last pick before repeating the structure. Thousands of woven structures exist and each structure fits a specific number of shafts, but can vary on the length/ number of weft picks. The black square denotes the shafts that are lifted for that pick, and the white squares denote the shafts that are left down. In plain weave this would read as 1 shaft up, 1 shaft down, etc. When a pick is woven, the weft is visible in the white spaces on the woven cloth face side; thus, the black squares show the warp on the woven cloth face side.

Figure 4.12 illustrates some other basic woven structures where the red box outlines the repetition within the structure. The 2/2 twill refers to 2 shafts down, 2 shafts up, etc., moving across by one shaft every pick, forming a diagonal linear pattern. The satin and sateen structures weight the weft either on the face side or reverse side respectively. The distribution of the weft in satin and sateen structure results in no obvious visible patterns, but enables near complete coverage or exposure of warp.

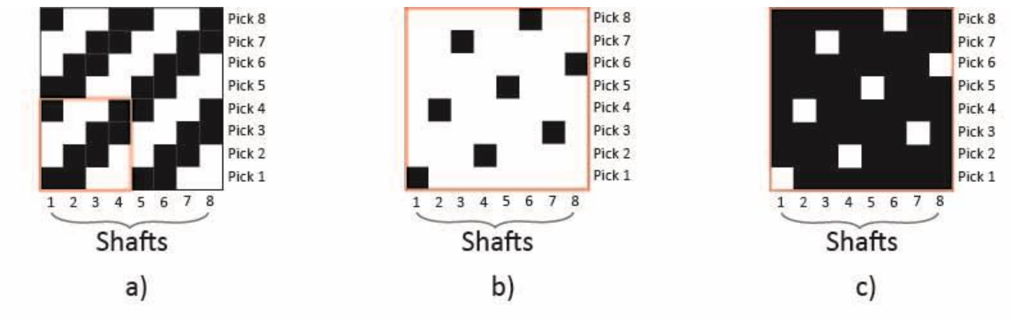


Figure 4.12 Woven structures: a) 2/2 twill, b) weft faced 3-step satin, c) warp faced 3-step sateen

4.2.3 Double cloths

The structures discussed so far form single cloths when woven. Woven structures can be adapted to manipulate specific reactions in a woven cloth. Woven manipulation techniques can be controlled via the woven structures to intentionally alter the textiles' physical form, often for specific application; for example, composite materials (Ganesh *et al.*, 1997) or 3D textiles (Gokarneshan and Alagirusamy, 2009). Multilayer weaving is a woven manipulation technique that was applied to much of the e-textiles in this research. Specifically, double cloth was used to weave two independent layers simultaneously via woven structures. Double cloth structures were designed to fit the warp draft. There are many ways double cloth structures can be drafted, but this would require compatibility with the warp draft. Using a block draft warp design can apply double cloth structures in several ways; woven as two completely separate layers, woven as horizontal tubular configurations, or woven as vertical tubular configurations (Figure 4.13).

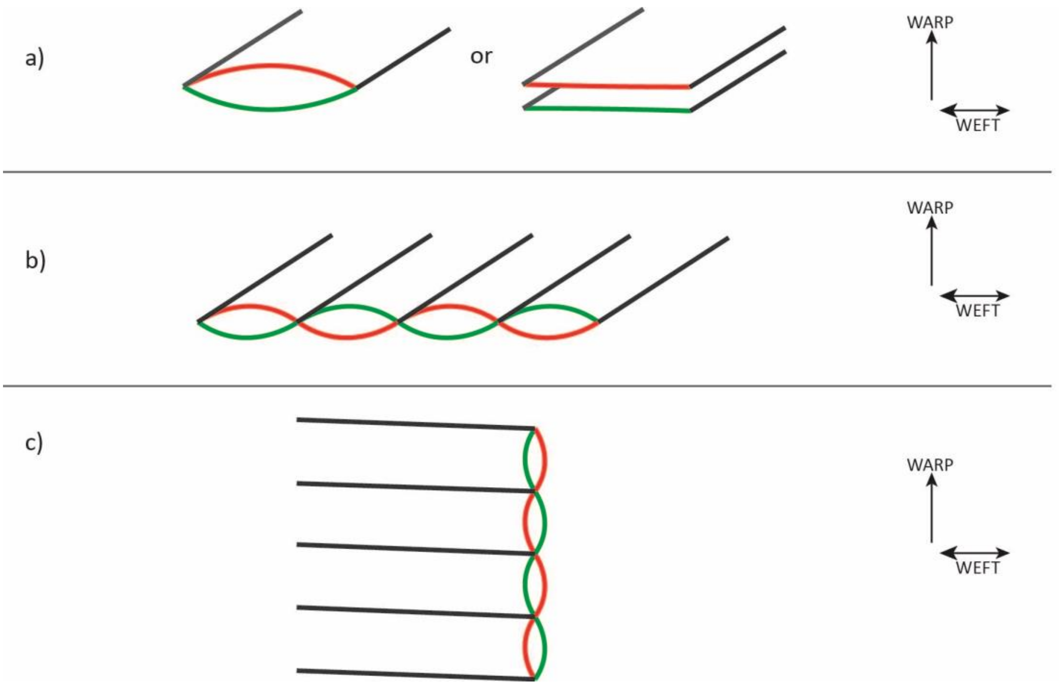


Figure 4.13 Double cloth variations: a) double cloth in two separate layers, b) double cloth vertical tubes on block draft, c) double cloth horizontal tubes

In vertical double cloth, the tubular widths are predetermined by the width of the blocks. With double cloths, the weft order can control which weft yarn is visible on each layer. In vertical and horizontal tubular double cloths, the layers can interact to switch between top and bottom layers. The point of interaction between the layers is a woven seam (not stitched together post-production). Single and double cloth structures are illustrated in Figure 4.14. The schematics show how woven construction changes when the respective weaves are applied.

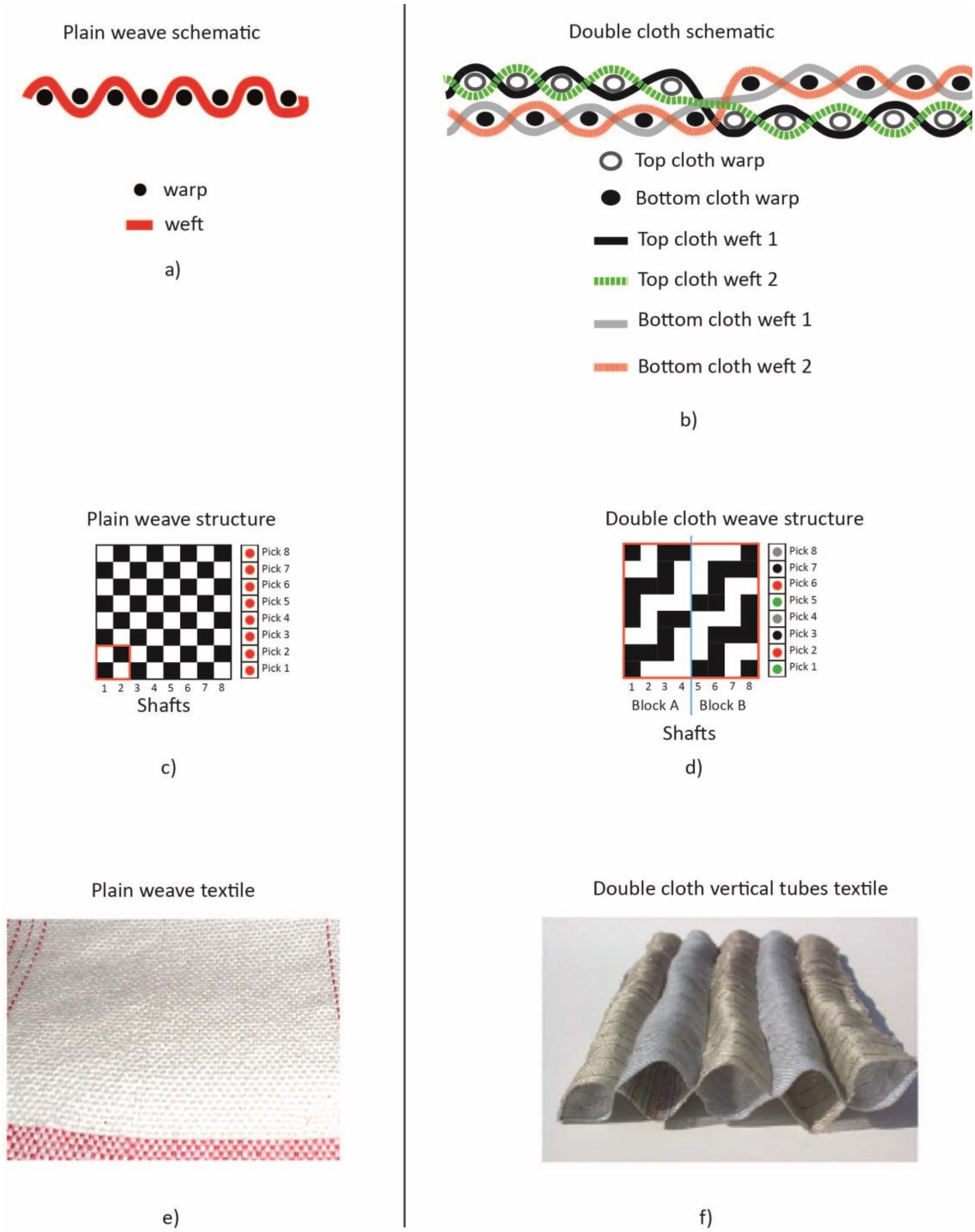


Figure 4.14 Single and double cloth structures, where: a) plain weave schematic, b) double cloth schematic indicating the wefts, warp and layer interaction, c) plain weave structure, d) double cloth structure based on plain weave for vertical tubes on block draft, with weft pick order indicated, e) plain weave textile image, f) vertical tubes double cloth textile where the interaction between the tubes are opened to make visible

Double cloths require a minimum of 4 shafts to weave 2 layers, or on block draft, each block requires 4 shafts. A double cloth weave can be based on any regular structure, however, each layer would require the number of shafts as per the complete structure e.g. 2/2 twill is a four shaft structure; therefore, each layer would need a minimum of 4 shafts to achieve a 2/2 twill double cloth.

Double cloths were particularly useful in weaving e-textiles, as controlling parts of the warp in layers also enabled woven pockets to be formed to house components for example, hold batteries or form electronic switches. Although double cloth was the main multilayer weaving technique used in this research, triple cloths, quadruple clothes, etc. are all possible. Consequently, as the warp is split between multilayers, the density per cloth also divides by the number of layers woven. However, if all the layers are positioned in one fabric, this will still result in dense cloth. Weaving multilayer cloths is more time intensive and uses more weft materials to build the length of the fabric than single cloths. The warp sett may be set higher if denser cloths per layer are required for the designs.

Applying double cloths to a block draft set up also enables the combination of this with other single cloth structures. For example, across block A a single cloth structure can be applied, while across block B and C a double cloth structure can be applied. Whether the double cloths are interacting or treated the same (i.e. combining the blocks as one large block) is also a variable the weaver can control.

4.2.4 Weaving process

Once the woven structures were designed, they were programmed into the Selectron weaving module, which was a manual task and needed to be completed accurately to avoid errors in the lifting plans. The structures could then be selected and activated, ready to weave.

Using boat shuttles, the weft yarns were wound onto cheese (spindle to hold the weft yarn). The shuttle was inserted into the warp shed from either the right or left side at every pick and then reinserted for the next pick from the other side. The continuation of weaving with the same weft yarn enabled a selvedge to be formed, however, the weaver needed to ensure the tension of the weft yarn was equal for every pick. If the woven textile required several weft yarns to be woven in a single sample, these were prepared as one weft per shuttle. The weaver was then responsible for integrating the required weft at the required position, as per the design specification (Figure 4.15). Multi-weft weaving can be complex as each shuttle needs to be managed and only inserted at the correct point. This was especially important for conductive yarn weft, as these picks would form circuit connections and tracks; therefore, any errors would cause the circuit to malfunction. The weaving process used in this research was hand weaving, thus every aspect was manually controlled. If these processes were adapted for industrial automated looms, such factors would be machine controlled.

a) b)

Figure 4.15 Weft shuttles; a) six different wefts prepared for a single sample, b) three wefts being woven in one sample simultaneously

4.2.5 Loom set up

Setting up the loom was a meticulous process. The calculations from warp planning dictates the number of threads required per warp and how many warps per yarn type. The warps were wound on a warping mill across the length required as specified – this would need to allow for a minimum of 1.5 yards for wastage and setup. If an EW was included, this would be wound separately to the ground warp. For the e-textiles in this research, the ground warps were all set on two beams to enable manipulation techniques such as pleating.

Figure 4.16 illustrates the warp making process where two threads were wound as one – this helps speed up the process as opposed to using a single warping thread. Pegs are situated on the top and bottom of the warping mill for crosses to be placed in the warp. The crosses are important as they separate every single thread. The tension needed to be held at the same level throughout making the warp. Therefore, each warp was made in one sitting as to avoid warp tension problems. Once the warp was complete, this was placed in a bag to help keep it from tangling. The bottom loop was left out of the bag as this was required first when raddling onto the loom.

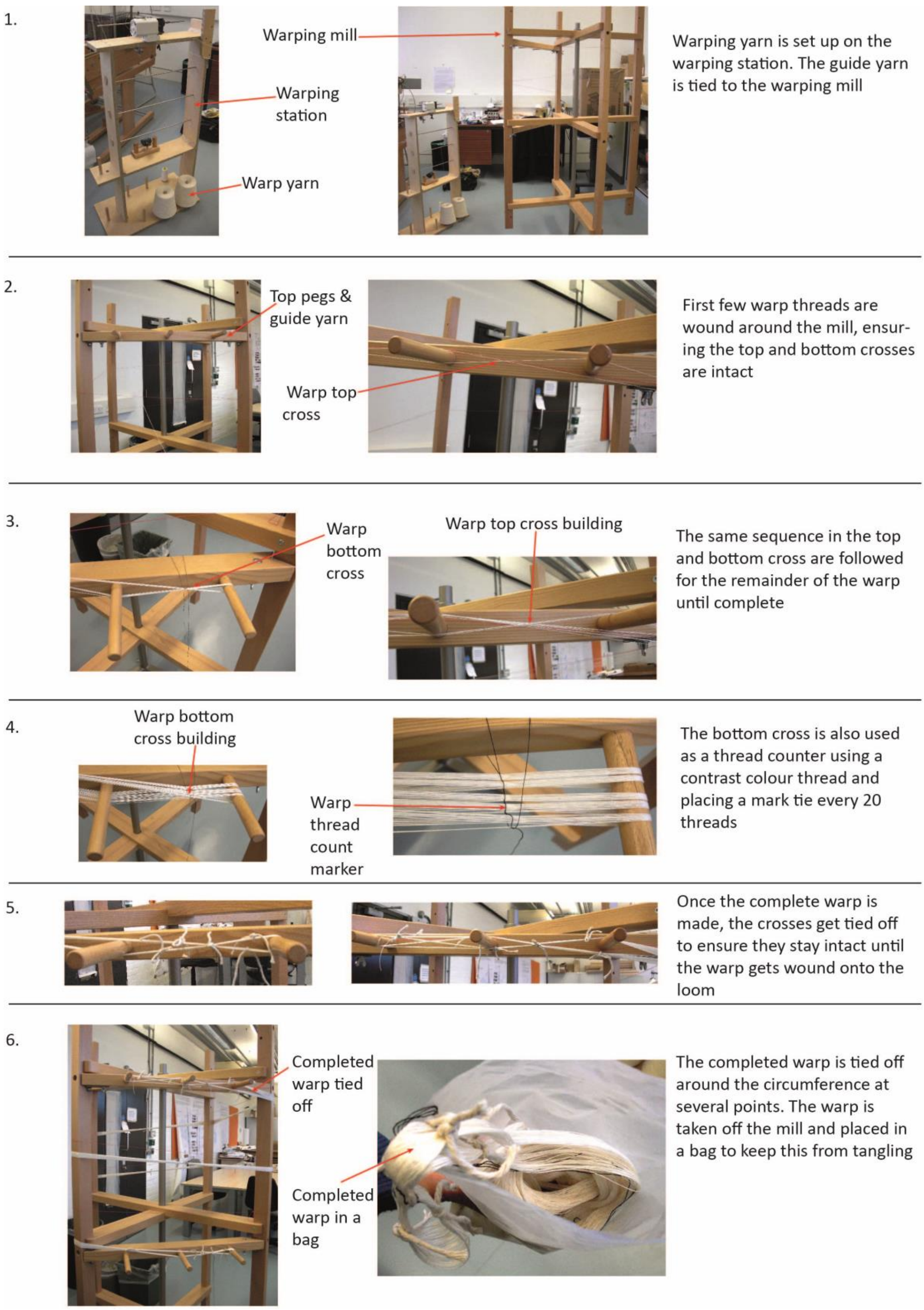


Figure 4.16 Warp making process

Once all the warps had been made for the loom set up, they were prepared to be wound onto the back beams of the loom. Figure 4.17 explains the warp set up process.

Figure 4.17 The warp set up process

First the warps are attached to the allocated beam stick, then raddled – a process that counts out the warp threads into ¼ or ½ inch sections, (depending on raddle type) while the warps are tensioned and wound onto the beam. Cross sticks are inserted into the cross once the warps have been fully wound on; this is to ensure the order of the threads is sequential when threading process begins. The loop ends are cut to separate the threads and the cross sticks are suspended to begin threading. The process begins at the front of the loom, where the required heddles per shaft are first calculated according to the warp draft. These are counted out and balanced equally on each shaft. The warp draft is followed to thread the loom; this indicates which thread is allocated to which heddle in its sequential order. This is a time consuming process as each thread needs to be pulled through a single heddle; any errors in this part would result in mistakes in the weaving.

Once the complete warp is threaded, the reeding process begins – this enables the warp to be spread equally across the warp at an even consistency. Depending on the warp epi sett, a compatible reed is selected. Each reed gap/ slot is referred to as a dent. Using the warp epi sett and the reed number, the threads per dent is calculated. For example, a warp set at 30epi, using a 15s reed (15 dents per inch) would mean two threads per dent are pulled through. For EWs, as these are not calculated as part of the ground warp, the EW threads are bought into the reed where the EW threads appear in the ground warp sequence. Thus, they are pulled into the same dent as their ground warp neighbouring thread. Once reeding is complete, the reed is positioned and clamped onto the beating bar; the warp is tensioned and tied onto the front beam. Several picks of plain weave are taken to ensure the warp is correctly set up and to spot any errors. This also tensions and stabilises the warp. Sample weaving can commence from here.

4.2.6 Cut off process

The cut off process is simpler than the set up process. The warp set up enables cutting off samples multiple times if needed. However, for every time the warp is cut off, it needs to be tied on again, which incurs wastage and requires the warp to be re-tensioned. Before a sample is ready to cut, 1-2cm of plain weave (or equivalent structure) is woven to stop the sample from fraying. The cut off process is illustrated in Figure 4.18.

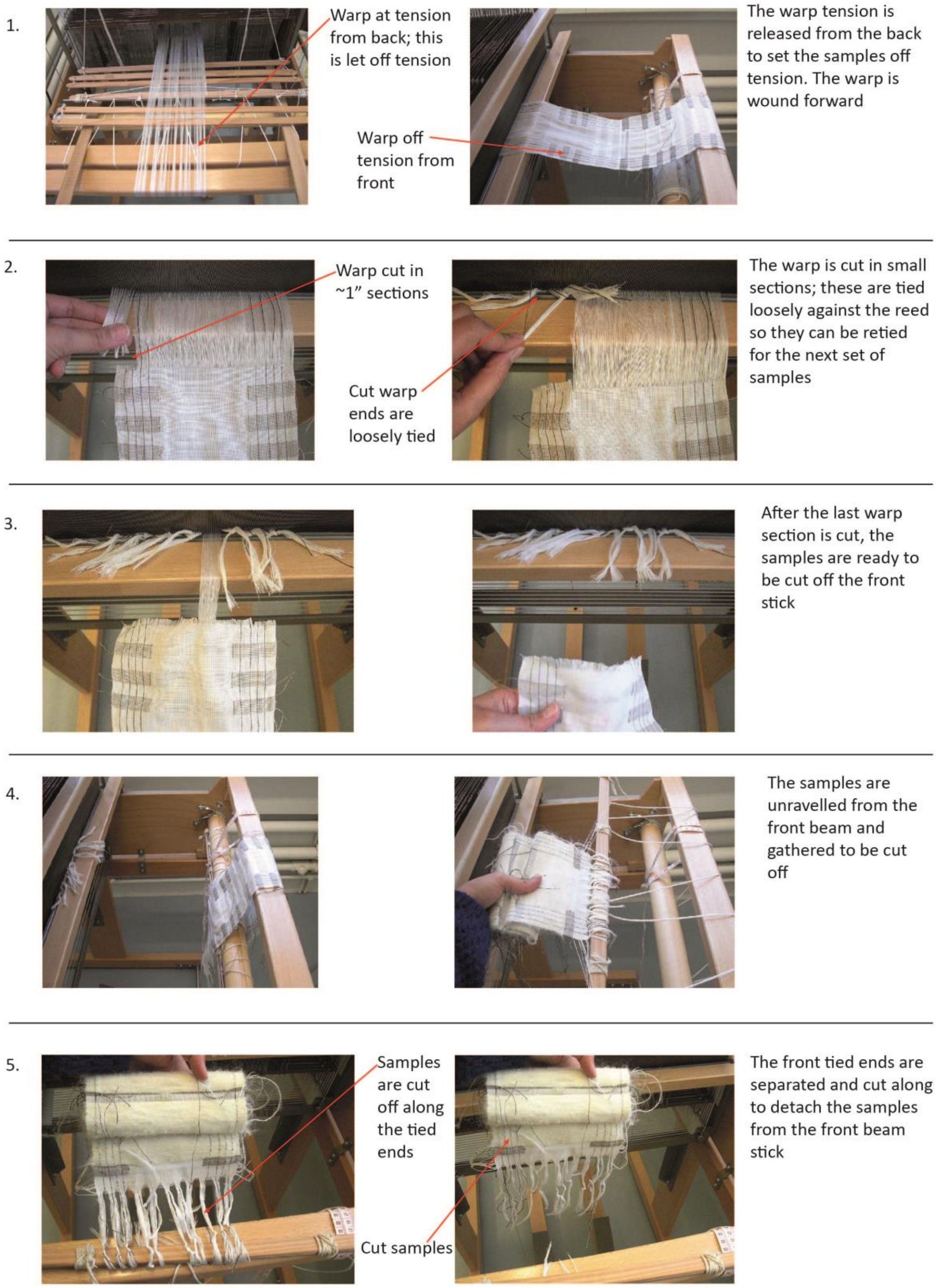
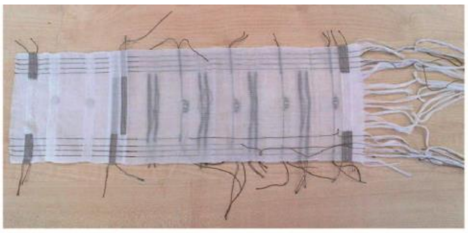


Figure 4.18 Sample cut off process

4.2.7 Finishing process

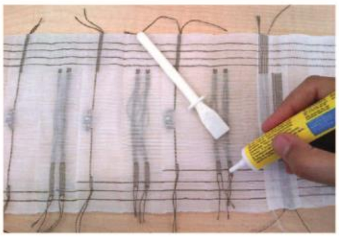
Once the woven samples are cut off the loom, they are ready for finishing to be applied. Basic finishing includes preparing the sample as a presentable piece and includes gluing, taping or cutting selvedge edges, trimming all excess yarn, gluing tips of conductive yarn (especially where positioned as an inlay weft), gluing battery holder slot and broken connections. The basic finishing process is illustrated in Figure 4.19.

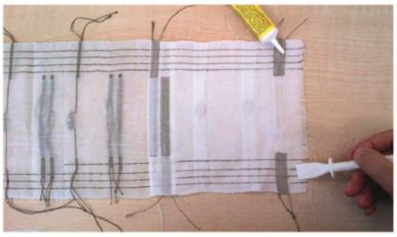
1.



A woven sample cut off from the loom and ready to have finishing applied

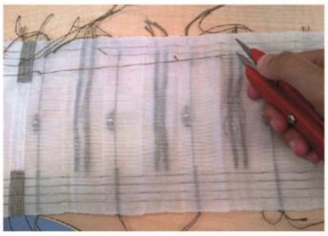
2.

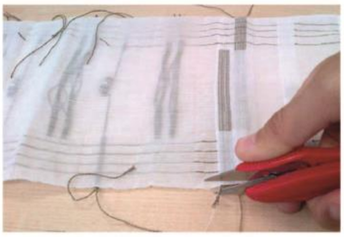




Using fabric glue or fray-check, the tips of excess thread are glued lightly to stop them from fraying. The top and bottom selvedges is also glued

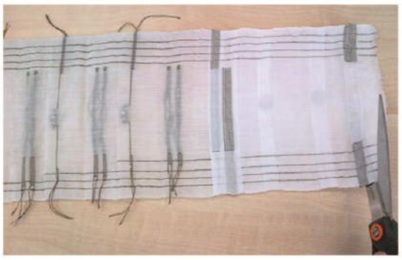
3.





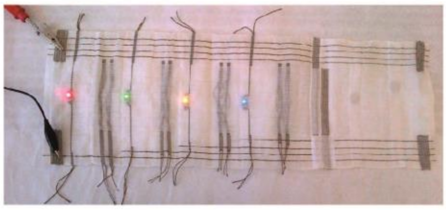
Once the glue is dried, the excess threads are cut off or trimmed back. Any broken connection floats and also cut

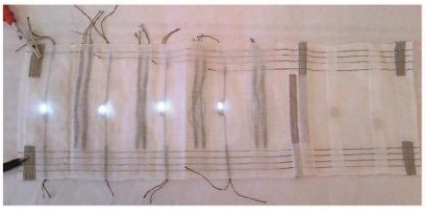
4.



The top and bottom selvedges are trimmed

5.

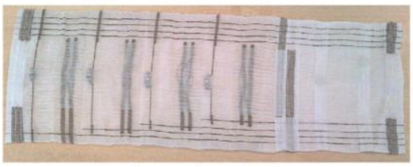




The circuit is tested with a power source

6.

Any additional floats and excess threads are cut



End sample

Waste material from one sample (3 grams)

Figure 4.19 Basic finishing process

Once all the excess yarns are trimmed along with the selvedges and the glue is dried, the circuit is tested to evaluate if it functions as required. If the circuit is working as needed, any remaining conductive yarn floats and excess is trimmed back. This would result in the end sample; however, additional finishing techniques could be applied to the sample at this stage such as pleating, heat setting or embellishments.

The amount of waste material from each sample differed depending on the sample length, number of conductive yarn wefts, excess wefts and warp threads and complexity of the sample. Often the samples were cut off in batches to avoid wastage, tying the warp back on and cutting off the top and bottom selvedges. If the excess cut conductive yarns were longer lengths, these would be re-used for other sampling, but other waste material was not re-used.

4.3 Woven e-textiles

For this e-textile research woven e-textiles were investigated; therefore, electronic properties were integrated *into* the textile construction (as discussed in chapter 1). The following subsections will discuss the fundamental aspects that contributed to the investigation and formation of this woven e-textiles research.

4.3.1 Electronic and weaving compatibility

As mentioned in the introduction chapter, the common architectural features between weaving and electronic circuits make them ideal to combine for integrated woven e-textiles. Both woven structures and electronic circuit matrices have common compatible structural parallels – i.e. they both operate in orthogonal matrices that are structurally well-matched. Thus, there is an opportunity to develop designs that have simultaneous integration of electronics into woven design, to combine the physical structures of electronics and textile weave design. Investigations of common compatible structural parallels of woven textiles and electrical circuits through a design process are required to enable progression towards fully integrated e-textile materials. Woven constructed e-textiles were specifically focused on in this research because:

- Woven textiles enable control of specific parts of a textile via structural manipulations and with combinations of multiple yarns that present opportunities for e-textile investigations

- Woven textiles can be manipulated to be static and stable, or introduce stretch qualities via weft yarns and woven structures, i.e. they can possess the same qualities as knitted textiles with the additional benefits of woven textiles
- Woven textiles can have areas of controlled isolation that can be constructed independently and simultaneously in the same piece (e.g. multilayer weaving)
- Woven textiles work on an orthogonal matrix making this an ideal and compatible architecture to work with electronic circuit configurations

To enable this integration and fully utilise woven construction, in-depth woven textiles knowledge was combined with electronic circuit knowledge. Although the electronics were simpler than the woven construction due to the researcher's expertise in woven textiles, the outcomes for woven e-textiles resulted in complex woven pieces (as will be described in chapter 5, 6 and 7).

This design process as described in the methodology chapter (3) was applied to develop the woven e-textiles in this research, where it helped synthesise the common compatible structural parallels between the electronic circuits and woven construction.

Component integration into PCB (plastic circuit board) circuits commonly use soldering or conductive epoxy to make electrical contacts and fix components. Stable contact between the component and conductive tracks ensures consistent power delivery and electrical function; weak connections result in circuit malfunctions. Attaching components to a woven textile required designing methods to integrate and adapt this to fit the textile construction. The established connections between the components, conductive warp and weft tracks, used conductive yarn to interweave between these points of connection. This differed depending on the component type and circuit design, however, the weave needed to remain tight to ensure contact consistency. As the samples developed, improvements for component integration were realised through analysis of previous woven e-textiles. For example, using double cloth pockets (sections 4.2.3 and 4.3.6.8) to house and position the components into the e-textiles were found to be more effective integration methods, as opposed to sitting loose above the cloth. In addition, using in-lay techniques (section 4.3.6.9) to make several contacts with crossing conductive yarn tracks helped establish better connectivity.

Arranging and building electronic circuits is a systematic process, i.e. the circuit is designed, exposed and etched onto PCBs. Holes can be drilled into the PCBs for components that are positioned and soldered into place. For this woven e-textiles research the order of making the soft circuits was quite different, as the complete soft circuit was built simultaneously and vertically constructed on the loom. This meant the e-textile was woven from the bottom to the top of the circuit. Alongside this, the e-textile components were required to be prepared ready for integration. Therefore, the design process establishing the order of weave became an integral part of constructing the woven e-textiles.

Resistance was another factor identified as compatible with woven e-textiles, particularly as conductive yarns are available in different resistance values. Thus, a soft circuit design could be integrated with resistance built into the textile via conductive yarns as opposed to additional resistor components. This was only possible if the resistance values were available in a specific length of conductive yarns. For example, if a conductive yarn was specified as 50Ω per meter, a 100Ω woven resistor could be achieved by weaving two isolated meters of this conductive yarn (further discussed in section 4.3.7.3).

On analysis of some initial woven e-textiles, these outcomes were used as inspiration for further iterations. E-textiles developed thereafter progressed, as the success and failures of the previous findings were catalysts for more advanced and complex e-textile designs. The progression of the e-textiles was based on both the complexity of weaving and extended electronics knowledge. A summary of samples can be viewed in Figure 4.34 (full details of all samples can be viewed in Appendix A and Appendix D).

4.3.2 Weaving materials and yarn counts

Previous discussions in section 4.2.1 have mentioned yarn counts; this will be explained in-depth in this section. Weaving materials usually have common attributes, including a yarn count (quantified measure of yarn), fibre composition, spun or unspun filament, short fibres or continuous threads, appear in a linear form and can be woven as a textile.

Yarn counts are calculated depending on their fibre type, i.e. filament yarns or staple fibres. Traditional systems that quantify yarn sizing have defined these calculations by weight and linear length; Table 4.1 lists a summary of selected key yarn counts. The systems are complex, particularly where counts (mainly for staple yarns) were historically established in different geographical locations. During that time, there was no communication between locations for what had already been developed. Thus, multiple systems performing the same measure in different units occurred in several methods. The direct system is predominantly for filament yarns, where the fixed length determines a specific weight. The same linear measure will equal in different weights; therefore, the higher the count, the thicker and heavier the yarn. The indirect system is predominantly for staple fibres, where a fixed weight determines a specific linear yardage. Consequently, the numbers of hanks required for a specific length equates to a heavier yarn and a lower yarn count. The Tex count (a direct yarn count system) was introduced as a universal system, this is not always been accepted by all manufacturers, particularly where traditional systems are familiar and successfully operate. However, conversion systems can be applied to find an equivalent count.

	Yarn Count System	*Abbreviation*	*Definition*	*Examples*
Direct System (fixed length)	Tex	TEX	Weight in grams per 1000 meters length	120tex = 120g per 1000m
	Decitex	DTEX	Weight in grams per 10,000 meters length	50DTEX = 50g per 10,000m
	Denier	DEN	Weight in grams per 9000 meters length	250DEN = 250g per 9000m
Indirect System (fixed weight)	Cotton Count	Ne / CC	Number of hanks of 840 yards per lb. pound	1CC = 1 hank of 840 yards
	Metric	Nm	Number of hanks of 1000 meters per kg	1Nm = 1 hank of 1000 meters
	Worsted (wool)	WC	Number of hanks of 560 yards per lb. pound	1WC = 1 hank of 560 yards
	Linen	LEA	Number of hanks of300 yards per lb. pound	1LEA = 1 hank of 300 yards

Table 4.1 Yarn counts and standard numbers (Yarns-and.com, 2010; Miller, 1984 pp.83-84; Lloyds Bank Chambers, 1975)

Often, an independent number appears alongside the yarn count separated by a forward slash (/). This represents the number of ply present in a specific yarn count, and is taken into consideration for multiple ply counts (e.g. 2/20s cc cotton would mean this is a 2 ply cotton yarn, where each ply is 20cc each).

In this research, base yarn counts were defined where possible. Some materials used in the e-textiles samples were non-traditional weaving materials and so did not have a defined yarn count. Substitute measures were indicated instead. A mixture of natural and synthetic yarn types were used in the e-textile samples, including some alternative materials such as wires, paper and plastics. The materials were an assortment of spun, unspun and filament yarns. Complete yarn types and compositions are listed in the e-textiles samples index in Appendix A.

4.3.3 Conductive yarns

Hard metal wires have always been an option for conductive tracks, but never truly gave the soft tactility that textiles possess. In addition, wire's brittle nature and the need for insulation do not make them an ideal option for e-textiles. Conductive yarn developments have been a significant influence on the movement and progression of e-textiles. They are electro conductor yarns due to their part or full composition made of conducting materials (mainly consisting of metals, but carbon fibre, or conductive polymers are also possible composition options). They differ to wires as they are commonly spun with softer fibres, coated in conductive materials, or if made with wires, these tend to be very fine and easily pliable.

Conductive yarns are still being developed to make them more efficient (addressing cost, physical form, resistivity and conductivity), but currently they do work in yarn and fibre form for e-textiles. In woven e-textiles, it is vital the warp yarns can sustain high endurance levels, particularly in in the weaving process where yarns are exposed to excessive stress and tension. Conductive yarns have been successfully used in woven e-textiles, however still requires improvements for better conductivity at the connection points, where the warp and weft meet in a woven e-textile. Once the woven fabric is constructed, the application of the e-textiles needs to withstand motion, strain and general wearing.

The level of conductivity is dependent on the conducting material type, amount of conductive material and resistance level. Commonly used metals in conductive yarns include silver (and silver coated yarns), copper and steel. Conductive yarns have a count that refers to the thickness and density of the yarn and the number of ply. The composition of conductive yarn can be in any manufacturable combination, where a percentage is specifically conductive material and the remaining composition is made of non-conductive material (e.g. polyester, wool, cotton, etc.).

For this research a number of conductive yarn suppliers were contacted and researched to obtain yarn specifications and samples to assess yarn quality. For the weaving process, the warp and weft yarn needed to sustain the stresses of loom motion, tension of yarn when weaving and needed to be physically durable; therefore, these qualities were also required for conductive yarns used. Spun continuous yarns were favourable over short fibres as they have higher tolerance to withstand the weaving process. A wide range of conductive yarns and materials were collected and analysed – these are summarised in Appendix B with specifications and vendor details.

The resistance level of a conductive yarn determined if it was used in the e-textiles for this research. Although resistance was also a quality used to integrate into the design of the e-textile. If specific conductive tracks of a soft circuit required higher or lower resistance, these were allocated using respective conductive yarns with high or low resistance counts. On occasions where e-textile circuit resistor values could be substituted with equivalent values in conductive yarns, these were integrated as part of the woven design, reducing hard components and utilising the woven construction.

The conductive yarns used for the main soft circuits were of low resistance, to reduce any additional resistance to the soft circuit (i.e. not to increase resistance unless intentional). A spun nylon silver coated yarn was chosen to weave the majority of the soft circuits as it had strong tensile strength, is tightly spun (good for weave handling), is highly conductive, has soft tactility, is washable and available in a range of resistance levels. Specifications used included Shieldex 235/34dtex 4-ply HC silver plated 50Ω/m (± 10Ω/m) and Shieldex 235/34dtex 2-ply HC silver plated 100Ω/m (± 30Ω/m) (Shieldtex Statex, 2011; Shieldextrading.net, 2011). Other conductive yarns were used where a different conductive quality was required. Initial woven tests were performed to assess if these yarns operated as required for the woven e-textiles – these are discussed in next section 4.3.4.

4.3.4 Initial e-textile sampling

Initial e-textile samples were woven to integrate conductive yarns into the weft, to analyse the reaction of weaving and the level of resistance in relation to woven structures. The warp and weft yarns are subjected to high levels of tension when weaving on the loom, particularly at the points of interlacing between the yarns. When the sample is cut from the loom, the tension is released. At this point, the woven warp and weft yarns position into a relaxed state, but need to adjust to their new woven structural form. If a warp or weft yarn is consistently interwoven (for example, as per plain weave), these woven threads have been exposed to a lot more movement in this interaction compared to a structure where there is less movement (e.g. satin weave). Therefore, the woven structure can affect how extreme and how many contours there are in each pick, and in the overall woven fabric. For this reason, conductive yarns exposed to a lot of undulating movement in the woven process can affect the position they sit in once the textile is off the loom. Subsequently, any extreme contours or relaxed tension will affect the level of resistance.

To assess if the difference in resistance in woven structures was significant, a series of test strips were woven with the two main selected conductive yarns used in this research (Shiledtex 235/34dtex 4-ply and Shieldtex 235/34dtex 2-ply). Three woven structures were tested with each of the conductive yarns. Each woven structure was woven as an insulated test (i.e. 1:1 pick ration with a polyester thread to keep the conductive yarn separated), and non-insulated (i.e. consecutive picks of the conductive yarn weft making contact with each pick). Therefore, a total of twelve test strips were woven on sample W003ET001. The woven structures included 2/2 twill, 1/3 twill and a honeycomb (Figure 4.20).

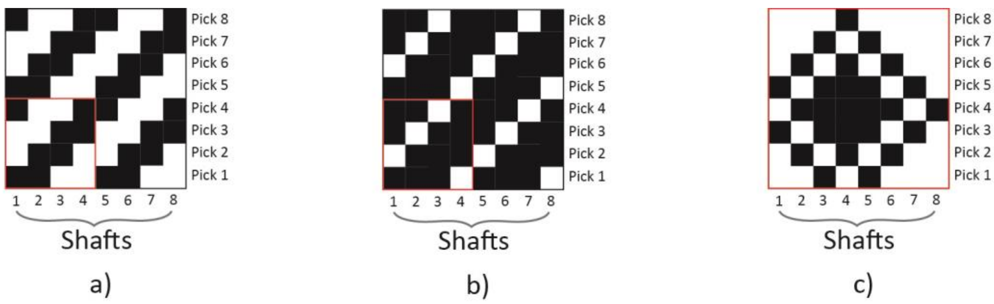
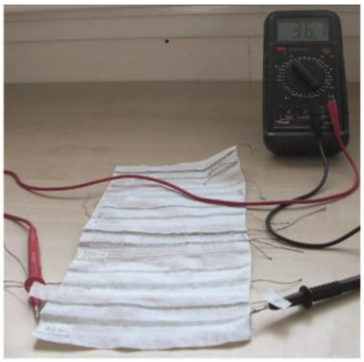
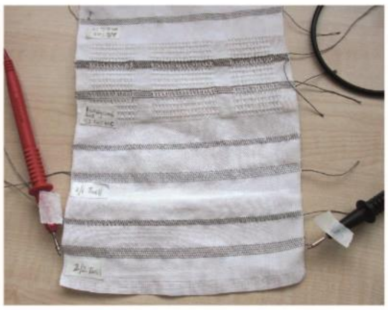


Figure 4.20 Woven structures applied to conductive yarn test strips: a) 2/2 twill, b) 3/1 twill and c) honeycomb

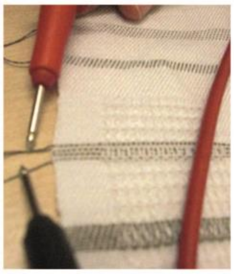
A Rapid 318DMM multi-meter was used to read resistance of the interwoven conductive yarn. The multi-meter's positive and negative probes are designed for testing hard electrical circuits; hence, why methods were designed to use this apparatus for conductive yarn measurements. As conductive yarn's conductivity is in and around the cylindrical shape of the yarn, pin pointing the multi-meter probe to only one point may not have taken an accurate reading of the resistance. Four different methods were applied to test each of the twelve test strips; the four methods were repeated five times on all twelve test strips. The methods are explained in Figure 4.21. Averages of the five readings were calculated after obtaining results.

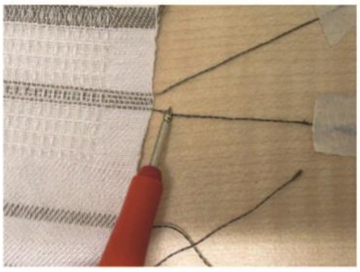


E-textile resistance testing set up; the sample was positioned at a relaxed state when measurements were taken. Each woven test strip corresponded with one of the two specified conductive yarns and a different woven structure. Four different methods of testing each woven strip was used; this was repeated five times for each test strip. A total of twelve test strips were woven.

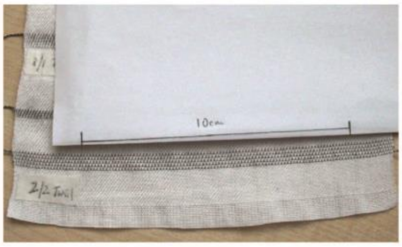


METHOD 1: the start and end of the conductive yarn ends were wrapped twice around each probe. Masking tape was used to help keep conductive yarn held into place

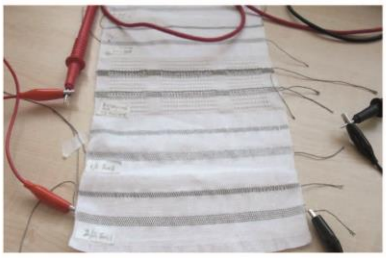




METHOD 2: test probe tips were positioned at the start and end of each of the conductive yarn to measure resistance across the complete track



METHOD 3: test probes tips were positioned at the start and end of a 10cm distance across the same conductive yarn pick



METHOD 4: test probes clamped to one end of croc clips, where the other clip is attached to the start and end of the conductive yarn weft across the complete distance of the test strip

Figure 4.21 Initial e-textile resistance testing. Two different specifications of conductive yarns were woven in a total of twelve tests strips. Four methods of resistance testing repeated five times per test strip.

Using a standard multi-meter did prove to be difficult but possible, as the probes needed to be completely stable to obtain a reading that did not fluctuate. On analysis of these results, it was found the methods used to measure the resistance differed slightly in their readings. However, this was not a significant difference, particularly when taking into consideration the resistance deviation tolerance specified by the yarn manufacturer. The readings between the tighter woven structures (2/2 twill and 3/1 twill) compared to the looser honeycomb structure did not show a significant difference in the insulated weft combination; nevertheless, there was a significant difference in the non-insulated readings. The honeycomb structure's resistance measured a lot higher than the twills in the non-insulated tests. This is likely to have been due to the twill structure picks forming a regular pattern in the weft, consequently making consistent contact with neighbouring picks, and hence a lower resistance. In a honeycomb structure, although the picks are woven looser than the twills, their contacts against neighbouring picks are far more irregular and spaced, and hence result in a higher resistance. These conclusions were considerably insightful for the research project, as structures could also be utilised to affect the resistivity in an e-textile, particularly for non-insulated woven configurations of conductive yarn. The results of the resistance testing can be viewed in Appendix C.

A few other experimental technical and pilot samples were also initially woven to trial specific ideas. This included testing conductive yarn through attaching the woven tracks in the warp and weft to a simple LED circuit – further explained in section 4.3.6.7.

Additional woven tests were conducted to explore resistivity combining elasticised yarn with conductive yarn, and an elasticised conductive yarn sampled by Bekaert Bekilast BK50/1 T/M 1200 Lycra (samples W003ET002, W003ET011, W004ET001 and W004ET002). The objective of these tests was to use the stretch quality as a variable resistor when the e-textile was under strain. A number of woven structures were investigated, integrating a combination of picks using elasticised yarn and conductive yarn, and also with the elasticised conductive yarn by Bekaert. Although the handle and integration of these experiments were successful as woven constructions, the resistance could not be accurately read as it fluctuated inconsistently. This was particularly true of the elasticised conductive yarn, which required an overnight wait to revert back to its relaxed resistant state if strained at maximum tension. This yarn's manufacture technical specification also stated a ±150Ω per cm tolerance, which is a considerable difference over longer lengths. Therefore, from the tests woven it was concluded that the elasticised woven e-textile would only be effective for variable resistance in future sampling, where the time period for relaxation of stable resistance would need to be considered as part of the design.

These initial e-textiles samples were a starting point leading to further investigations. Although the resistance reading of conductive yarns perhaps seems obvious, the insights were not, as these findings were applied to complex e-textile weaving in subsequent work. Building a comprehensive knowledge of fundamental electronic properties enabled application of these principles, which in turn formed new explorations, findings and inspiration for e-textiles.

4.3.5 Woven e-textiles components list

The e-textiles woven for this research integrated a number of different electronic and woven components, where each sample used a different combination. In order to organise the e-textile samples and classify the integrated components, this information was categorised and arranged into a database list – the 'woven e-textiles components list' (Appendix D).

The list includes two main columns defining the component type; these fell into the categories of electronic integration or woven constructions, and were further subdivided into specific component types, woven techniques or function. The samples were listed in a separate column and denoted against each sub-component that it correlated with. Therefore, the woven e-textiles components list provides an overview of what each sample is comprised of, and where specific components and features have repeated in other samples. Generally, where more components were integrated into a sample, the sample became more complex. The e-textiles' details and reference code are also listed to cross reference in the e-textiles sample index (Appendix A). To help summarise the component types used in the woven e-textiles developed, the complete list has been summarised in Table 4. 2.

	Component category	Component name	Section reference
Component type	Electronic integration	Weft tracks	Section 4.2.1 Section 4.3.2 Section 4.3.3 Appendix A Appendix B
		Warp tracks	Section 4.2.1 Section 4.3.2 Section 4.3.3 Appendix A Appendix B
		Woven resistor	Section 4.3.7.3
		Integrated battery holder	Section 4.3.6.2 Chapter 7
		Woven conductive connectors	Section 4.3.7.1 Chapter 7
		Integrated components (Non-LED, Lilypad, own made LED)	Section 4.3.6.4 Section 4.3.7.2 Chapter 5 and 6 Appendices E i) – E vii)
		Complete circuit	Section 4.3.6.5 Chapters 5 and 6
		Modular piece	Section 4.3.6.6 Chapter 7
		Pilot test piece	Section 4.3.4
		Heated element	Appendix A
	Woven construction	Single cloth	Section 4.2.2
		Double cloth	Section 4.2.3 Section 4.3.6.8 Chapters 5, 6 and 7
		Pocket/ housing	Section 4.3.6.8
		Conductive inlay weft	Section 4.3.6.9
		Broken tracks: cut	Section 4.3.6.10
		Broken tracks: woven design	Section 4.3.6.11
		Woven pleat	Section 4.3.6.12 Chapter 5
		Elasticised weft	Section 4.3.4
		Malleable	Section 4.3.6.13
		Floats	Section 4.3.6.15
		Finishing process	Section 4.2.6

Table 4. 2 Woven e-textiles components summary list

The electronic integration category considered any aspect of the e-textile where a woven feature or an integration of a physical component enabled an electronic behaviour. The component types listed under the electronic integration category were warp and/ or weft tracks, woven resistors, woven switches, integrated battery holder with or without magnetic clamps and whether they had single or double sided conductive contacts, LED and non-LED integrated components, with type and quantity, whether the circuit was a complete circuit, modular piece, a pilot or technical test piece and if heated elements were integrated.

The woven construction category considered any woven construction technique that enabled the electronic feature to be formed. The woven methods listed in this category included single cloths double cloths in vertical and/ or horizontal sections, if pockets were woven and what their use was, weft inlay techniques with conductive yarn, if any tracks were broken as part of the circuit via being cut or woven in broken paths, woven pleats and quantity, elasticised wefts, malleable qualities woven into the samples (i.e. with wires), heat setting samples, floated threads either in warp or weft, if any finishing process was applied to the sample and any additional details of this.

4.3.6 Weaving techniques and woven manipulations

As mentioned in the previous section 4.3.5, the e-textiles samples were constructed using a combination of woven techniques and woven manipulations. Some of these were specific to an e-textile design to enable the electronic circuit to function.

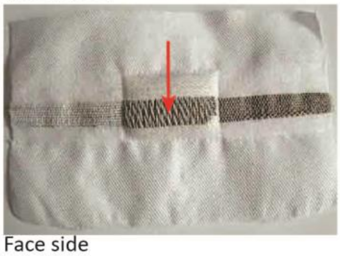
Woven techniques applied in commercial woven textiles for applications such as fashion and interiors, were the same types of techniques used for the e-textiles in this research. These were often adapted or manipulated to facilitate a specific e-textile feature. The main techniques and methods used in this research are listed in the woven e-textiles components list (Appendix D), as summarised in Table 4.2. As some of these were common to multiple samples, they will be further explained in this section, with the exception for those that have already been/ will be defined in other sections.

4.3.6.1 Woven switches

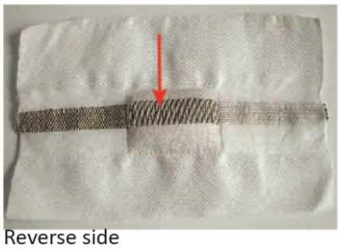
Integrated switches woven into e-textiles where the function is a result of a woven method can be applied using several techniques. The main principle is to include a break in the circuit (open switch) that can in some way be re-engaged to connect the circuit (closed switch). The main switch type explored in this research was a touch switch, where the circuit is closed for as long as the contact is held pressed; on release the circuit is opened (i.e. disconnected). Three other samples were explored with a constant on 'toggle' switch, where one action would actuate a closed circuit, and another action would disengage the switch to an open circuit. These three samples included 'Pin cushion contact' W003ET004, 'Tilt switch sample' W003ET010 and 'Ball bearing tilt switch sample1' W003ET012. Another switch type applied to two samples ('Fold fringe switch LED' W004ET12 and 'Corrugated pop LED angled sample' W004ET014), used cut or frayed conductive yarns that connected the tracks if the cut/ frayed tracks positioned to make contact. This would result in an inconsistent connected circuit, e.g. in the aforementioned samples this caused flickers of light.

Woven pleats were the main technique applied to make switches; a method where a pleat was woven on the loom to act as a tab with an interwoven conductive area to close the switch. Woven pleated switch designs were adapted on reflection of previous versions throughout the sampling process, where improvements could be made or adjusted to better suit an e-textile design specification. Figure 4.22 illustrates some examples of woven switches.

Pin cushion contact switch
W003ET004



Face side



Reverse side

Insert pin through the inlayed tracks woven above and below insulated stuffed double cloth pocket to connect the circuit

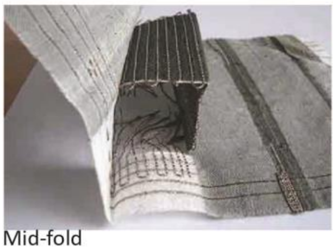
Modular kit2 switch module (pleated switch)
W005ET002

Press down pleated flap to connect to woven broken tracks

Fold fringe switch
W004ET012

Face side

Reverse side



Mid-fold

Folded flat - disconnected

Fringed and looped conductive yarn weft make contact to connect the circuit when the folded circuit is opened

Figure 4.22 Examples of woven switches

4.3.6.2 Integrated battery holder

A power source was required for all samples to operate. Initial samples had a power supply attached via crocodile clips or a hard button battery holder. However, on analysis of this approach, a design for an integrated woven battery holder for button batteries was realised. Subsequently, a pilot sample was developed and woven for this. It was developed to weave into the samples or be woven as an independent module that could be attached via magnetic connectors. The integrated battery holder's main conductive contacts were designed to be positioned against the positive and negative sides of a button battery, providing they were kept separated (i.e. not to short circuit). Therefore, double cloth structures were employed to weave this feature, using block draft design to help interact double cloth layers between blocks and help separate the battery contacts (in-depth description in section 7.3.1.1). The positive and negative contacts were woven on each side of a double cloth pocket i.e. positive on the top cloth and negative on the bottom cloth (or vice versa). To ensure the battery contact tracks did not touch, they were woven sequentially. In later design iterations this was further developed using several picks of non-conductive yarn to separate and ensure the contacts did not meet. The contacts were woven into the battery holder using inlay techniques (section 4.3.6.9), and manually intercepting yarns at specific points across the warp to control exactly where the conductive weft was positioned.

The entire battery holder was woven as a continuous piece of weaving; therefore, the design also considered access for the battery and attachment to circuits. There were several design iterations of battery holders, where each iteration was adapted and improved on the previous version, including better conductive contact woven structures, pocket size for the battery, magnetic clamp to keep the battery in position and magnetic connectors.

The independent battery holder modules were designed as cross or T shapes; therefore these were cut as required when they were off the loom as part of the finishing process. Access for the battery was also cut at this point. Woven battery holder modules are discussed in-depth in chapter 7.

4.3.6.3 Woven conductive connectors

Connectors were integral to many of the woven e-textiles designs (methods of connectors are discussed in section 4.3.7.1). Magnetic connectors were the chosen method integrated into the e-textile samples woven, to act as contacts for attachments of modular pieces and woven battery holders. They were made by constructing a double cloth pocket to hold a 10mm diameter circular disc neodymium magnet, where a conductive yarn contact was interwoven on one or both sides of the pocket to function as a contact pad. This connector would contact and clamp onto another woven magnetic connector to make a conductive connection.

4.3.6.4 Integrated components

Components were integrated into the woven e-textiles depending on the circuit specification. LEDs were key components integrated into the e-textiles as output indicators of the circuit functioning as required. LEDs were both Lilypad components that later developed into own made LEDs to better integrate with the woven method (section 4.3.7.2). Other components included buzzer modules, vibration modules, flashing module, velostat (pressure sensitive material), tilt switches, RGB LEDs and attached connector components. The integration method was specific to each sample type, where applying woven double cloth pockets to house the component proved effective for all LEDs and most components. This approach was adapted and developed through the course of making the samples and reflection of previous versions. This included improvement to stabilise warp and weft contacts for conductive connections, as illustrated in Figure 4.23.

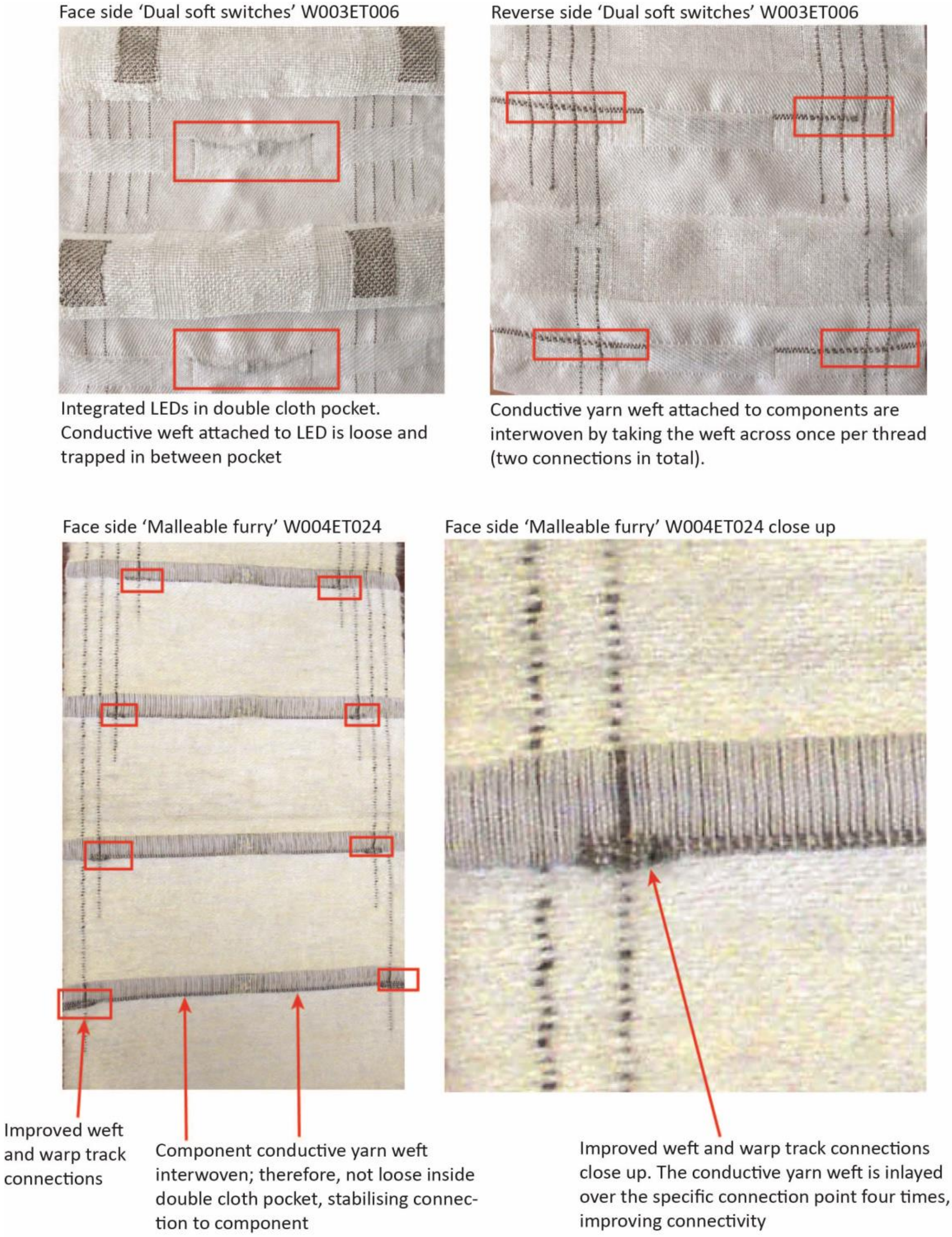


Figure 4.23 Integrated components and improved design integration

4.3.6.5 Complete circuit

E-textile samples that were woven as a single piece of weaving with the entire circuit were categorised as a complete circuit. Several of the samples were woven as complete circuits, but some of these required attached power or operated with the addition of detachable battery modules; in these instances, the samples were classed as both complete circuits and modular.

4.3.6.6 Modular Piece

Samples that were reliant on succession of modular connections to activate the circuit were classed as modular pieces. Modular e-textiles were an intentional part of the design specification, to investigate how e-textiles could function in different interchangeable configurations. This was a theme previously explored by the researcher in past work and adapted to fit e-textiles. The modular pieces were interactive with the user, who made choices in terms of how the e-textile 'Lego' could be assembled into a circuit and what modules to apply via a plug and play approach. The full complete circuits operated as static functions, whereas the modular pieces allowed for transformability and interaction with the e-textiles – an approach applied to a lot of current wearable technology.

4.3.6.7 Pilot and technical test samples

As some of the initial samples were trialling concepts of woven e-textiles, these samples were classed as pilot tests. They were integral to the research as starting points to lead further investigations of e-textiles. The analysis and reflection of the pilot samples was used as a foundation to build further knowledge of woven e-textiles. The iterations of these test pieces led to further samples and re-iterations to develop more complex and advanced samples.

Technical samples were similar to pilot tests, although were more concerned with evaluating the technical aspects that were required to be woven. This included resistance tests, trials for connectors and sampling the different qualities of conductive yarns. Technical and pilot samples have been categorised and indicated in the e-textiles components list Appendix D.

4.3.6.8 *Pockets/ housing*

Woven pockets were constructed via weaving using multi-cloth structures – mainly double cloths in this research (as discussed in section 4.2.3). This was applied by using the block draft widths for vertical tubular double cloths or across the width of the sample as horizontal double cloths. Vertical tube double cloths can be made across multiple blocks, where neighbouring blocks can be combined to make larger pockets. Once the double cloth pocket was woven to specification, this could be used to house a component. If a component was integrated on the loom, the double cloth was opened on the loom using a plain weave structure to separate the layers and insert the component into. To seal the pocket, the cloth was either woven as a single cloth or a double cloth with interacting layers to form a woven seam (as per Figure 4.14).

4.3.6.9 *Conductive inlay weft*

Inlaying weft yarn is similar to tapestry weaving techniques. For the samples in this research, inlaying conductive yarn allowed for control and placement of where the yarn could be allocated to specific points. This method was especially effective in making contact with pre-selected warp tracks for specific interconnections. Inlayed weft could be placed and pulled out at any point across the warp width. This resulted in only a small section of the warp being woven with the inlayed weft over a given section determined by the weaver. Therefore, the rest of the warp would need to be tied in with a regular yarn (non-conductive) in the same pick opening, to ensure the inlayed weft pick was securely positioned. This was done by taking the weft right across the width of the warp during the same pick of inlayed weft. Examples of inlayed conductive yarn weft can be seen highlighted in Figure 4.24.

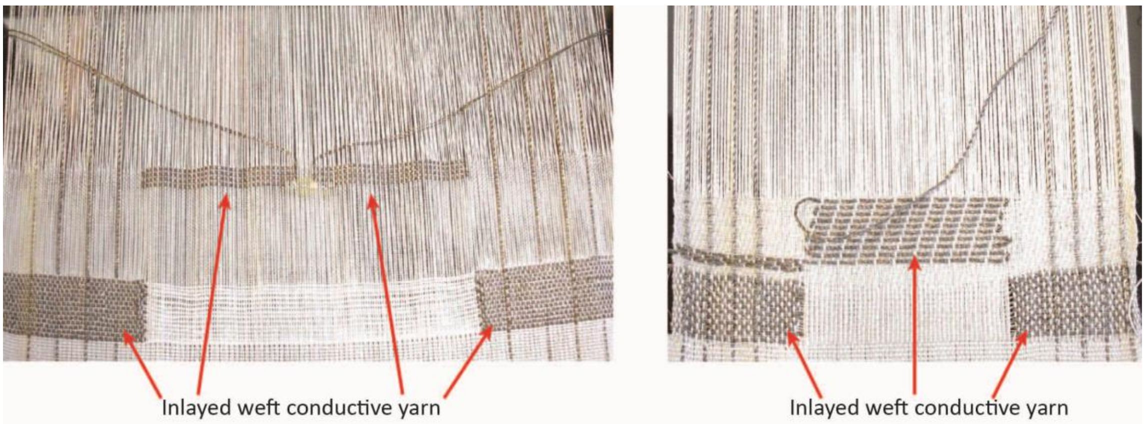


Figure 4.24 Examples of inlay techniques using conductive yarn weft

4.3.6.10 Broken tracks – cut

Broken tracks in this woven e-textiles research were used for two main purposes; switches and placement specific circuit tracks. To enable a track to be cut, it had to be designed with a float or space to enable an incision to take place. Once the conductive yarn track was cut, it became independent from the remainder of the same track. Cuts were only made once the sample was complete and cut off from the loom.

4.3.6.11 Broken tracks – woven design

Woven broken tracks served the same purpose as cut broken tracks; however, these could only be made using the weft via inlay techniques. Therefore, instead of taking weft yarn across the whole warp width for a pick, it would be positioned as per inlay techniques. Multiple consecutive conductive weft picks could be built up to make one consistent broken track.

4.3.6.12 Woven pleat

As mentioned in woven switches section 4.3.6.1, woven pleats were predominantly used for switch applications in this research. This technique required the warp draft to be set on two beams. The woven pleat structure would enable half of the warp (every other warp end) to be woven, while the remainder of the warp was unwoven and rested loose under the woven pleated section. The pleat warp (i.e. woven pleated section) would then be pulled forward into a pleated position and sealed with a woven single cloth. Once the switch was woven with non-conductive yarn and inlayed conductive yarn, it was made into a pleat as per Figure 4.25. Tunnel pleats were also possible to weave; this would weave double cloth for the diameter length of the pleat tunnel, and then proceed to complete the pleat as per Figure 4.25.

1.

Initial magnetic contacts woven at base of sample

2.

Woven broken tracks positioned into sample using inlay technique. Pleat conductive contact woven on half of warp. Non-conductive yarn woven to complete the pleat flat section

3.

Pleat warp bean released off tension and reed bought forward

4.

Reed is bought completely forward to meet the woven sample

5.

Side perspective of how pleat should look

6.

Reed is held forward while adjusting the back pleat warp beam into tension, but still allowing for some slack

7.

Pleated woven section is held in place and while pinning it down against woven section

8.

Pin right the way across, matching the pleated section to the unwoven warp, Re-adjust the warp tension, gradually tight-ening after the initial joining pick is woven to match the tension of the complete warp

9.

Continue weaving the rest of the sample at same tension on both beams

10.

Pins can be removed once sample is cut off. Pleat is permanently positioned in place. Final pleated switch sample off the loom

Figure 4.25 Woven pleat construction process

4.3.6.13 Malleable

A malleable quality in a woven sample enabled the sample to be physically transformed by manually moulding it into any shape. This was a technique explored by the researcher in previous work and then adapted to fit e-textiles. Combined warp faced and weft faced structures were designed to help integrate malleable qualities into some of the samples. This was achieved by using fine enamelled wires that were interwoven with other thicker tactile yarns. Once the samples were transformed into a shape, they could revert back to a flat textile by physically moulding them. This technique was applied to many of the woven e-textiles with integrated LEDs, resulting in malleable lighting as textile substrates.

4.3.6.14 Heat set pleat

Samples designed to integrate pleats via a finish process, were woven with a thermoplastic base yarn (e.g. polyester, nylon, monofilament, etc.), as polymer based synthetic yarns can be permanently heat set into shape. Depending on the design specification and the thermoplastic yarn used, the pleats could be heat set using an iron, steam or an industrial heat press machine, with regulated temperature not to damage or burn other fibres in the sample. Before heat setting, the sample is tacked or pinned into position and then exposed to heat. Once cooled, the pins/ tacked threads are removed, leaving the sample in its heat set form. Figure 4.26 illustrates the heat process using ‘Corrugated pleat LED v1’ sample. In this sample, steam has been applied to heat set the pleats into position.

Figure 4.26 Heat set process with 'Corrugated pleat LED v1' sample

4.3.6.15 Floats

Floats are threads that are not woven into the woven fabric; they can be designed to appear in pre-allocated positions in a woven design in either the warp or weft. In woven e-textiles, this technique is particularly useful in controlling conductive yarn extra warps, as each end is allocated to a specific shaft that can be floated over or under a woven section for as long as required. Weft floats work more effectively on block draft, as the block width determines the size of the float over one block, which is then woven into the adjacent block securing the floated weft. Examples of woven structures for floats are illustrated in Figure 4.27.

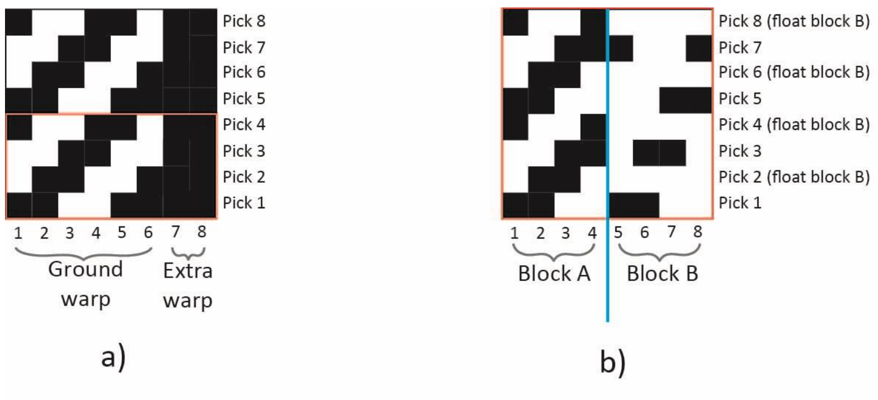


Figure 4.27 Example structures for woven floats: a) illustrates extra warp floats on shafts 7 and 8 where the ground cloth is woven with 2/2 twill, b) illustrates weft floats across block B in every other pick while weaving 2/2 twill across the cloth

4.3.7 Connectors, components and resistance

Other areas that were explored to build on the initial e-textiles sampling included exploration of connectors, components and resistance; these are discussed in the following subsections 4.3.7.1 – 4.3.7.3.

4.3.7.1 Connectors

A number of the woven e-textiles constructed operated in modular configurations, including some other complete circuit samples requiring attachment of soft woven battery holders. Thus methods of attachment were explored via several options. An important aspect to investigate connectors was to establish an approach that could be integrated as part of the connectors' design, and possibly construct this on the loom. The attachment's function was to act as a link between the modules and/ or circuit;

therefore, the connectors would have a direct connection with the circuit function. As a result, a fixed conductive connection was required to enable the circuit to work.

Several options were considered feasible for e-textile connectors, but only four methods were sampled to assess their effectiveness. The selected sampling methods were based on the researcher's previous working experience with modular connections, where more feasible and reliable methods were taken forward to trial in this research. These included conductive Velcro, metal press studs, magnets and metal sew on studs. A pilot test sample was woven where magnets were integrated into double cloth pockets on the loom; therefore, testing this method had already been constructed. Six additional woven test strips were constructed using a 2/2 twill structure and three further test strips with integrated LEDs. These test strips had conductive Velcro, sew on studs and press studs attached after they were woven, where each connector type had two connecting strips and one LED test strip. The connector test strips and constructions can be seen in Figure 4.28.

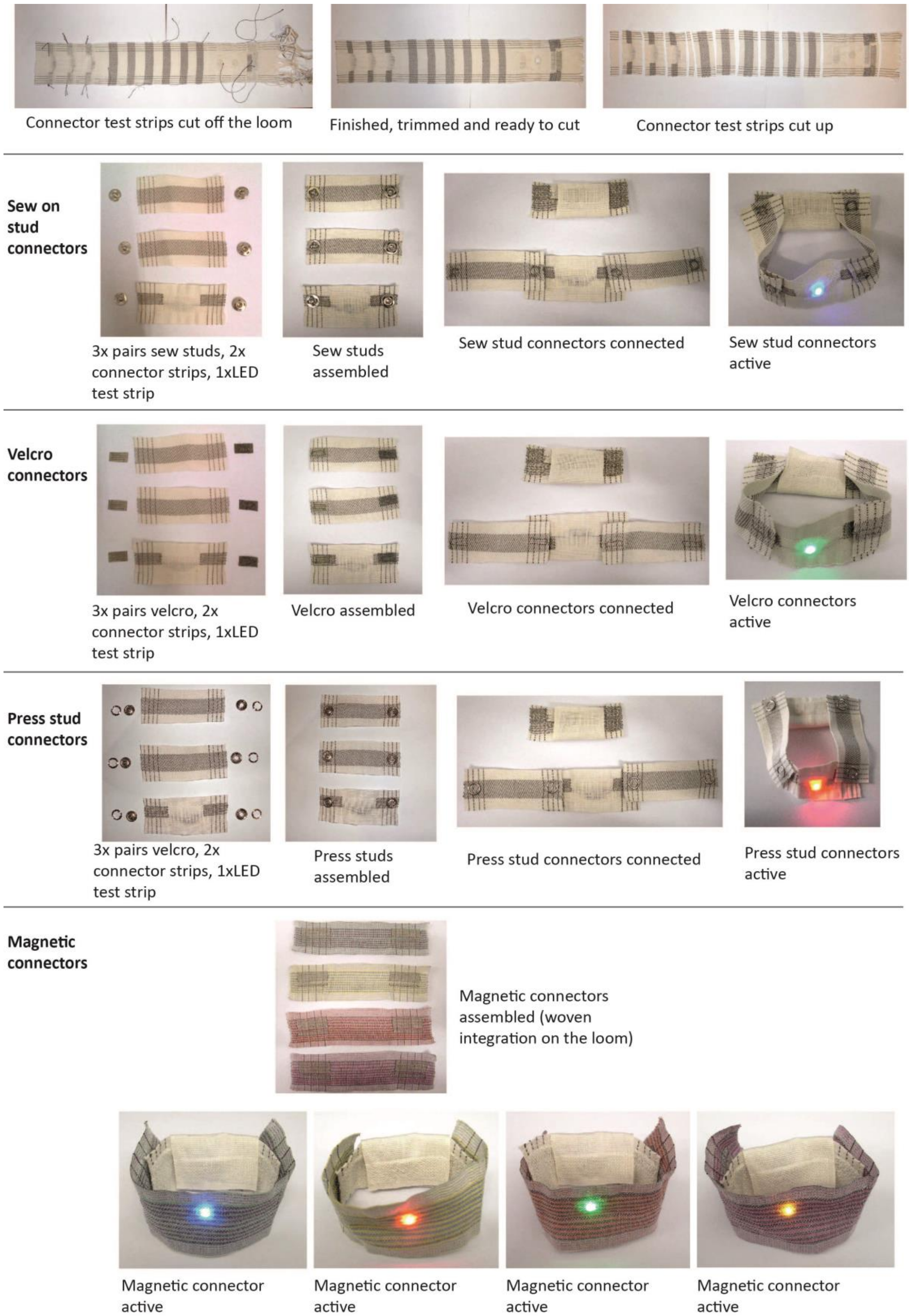


Figure 4.28 Connector woven test strips

The sew on studs and conductive Velcro were the most time consuming to construct, where comparatively the press studs were easier to assemble, although did move position when pressure was applied via the press tool. The magnets needed to be planned for in the design of the e-textile (i.e. integrated in double cloth pockets on the loom), but were comparatively unproblematic once specified.

On analysis of the connectors it was found all four methods worked successfully in connecting the circuit. The sew on and press studs had swivel articulation on the connecting components. These two sets of connectors were in constant motion, but this did not affect the conductivity as the metal connectors were securely fixed. Due to the small surface area of the conductive Velcro, this required more pressure to connect. Although the conductive Velcro connector did function effectively, it was not as secure as the sew on stud and press stud connections. However, this would not have been an issue for larger swatches of Velcro.

The magnetic connector functioned via attracting to another magnetic connector to connect the circuit. On the connection side, conductive yarn was woven in the areas where the magnets would make contact. Although the magnets connected through the cloth were insulated in the weave, they required conductive surfaces to make a connection. The magnets were held securely in the woven pockets; this also helped to keep the magnets intact when they were prized apart to disconnect. The magnetic connectors held the connection in a fixed contact, i.e. the connection did not articulate unless forced. As the woven fabrics in the samples were of different densities, strong but slim magnets were sourced. Rare earth magnets (neodymium) in 1mm thickness were used in 10mm diameter, which resulted in strong connections where the conductivity was not disturbed when the samples were physically handled. If the magnets repelled instead of attracted due to wrong side of polarity, this could be adapted by manually overturning the magnet in the woven pocket; this was possible as the magnets were loosely held in the pocket.

Comparing the four methods of connectors, the magnetic connectors were most efficient for strong conductive connection, minimal disturbance, secure fixing and were the easiest to assemble. Therefore, this method was applied in the majority of the woven e-textiles that required conductive connectors. On further iterations of this method, the conductive yarn contact was woven on both sides of the pocket holding the magnet. This was to enable conductive contact on either side of the magnetic pocket, if this feature was required.

4.3.7.2 Components

As mentioned in the literature review, components for e-textiles have stemmed from traditional electronic components that have been, and often still are adapted to fit the construction of e-textiles. More recent developments of specific e-textile components have seen examples such as Lilypad Arduino kits (Buechley and Eisenberg, 2008) and Aniomagic kits (Aniomagic, 2011), which have specifically designed electronic components and computer programmable microprocessors to work with methods of e-textile construction. E-textile specific components are slim in design as the integrated outputs are predominantly intended for soft textile products and wearable garments.

The method of construction intended for e-textiles components is hand stitch; however, Lilypad components were used in this e-textiles research as they were found to be compatible with woven integration. This was due to the Lilypad components possessing small, slim and discreet physical form that could be easily integrated into the weaving process. Some of the components also had surface mounted resistors that were also very subtle and did not appear bulky. The Lilypad components were applied using an adapted approach in comparison to when used via hand stitching, but this did not alter the component's function. The components were pre-prepared with conductive yarn weft and used the component's existing stitch holes to securely tie the conductive yarn to. Using a doubled conductive weft yarn (i.e. a single length folded in half), this was pulled through the Lilypad component's sewing hole using a needle threader. The conductive yarn was then pulled through itself via the folded loop, and then double knotted to keep in place. Figure 4.29 shows a prepared Lilypad LED with conductive yarn weft.

Figure 4.29 Lilypad LEDs: above – prepared with conductive weft yarn, below – Lilypad LED component with surface mount resistor

Once the component was prepared, it was ready to be integrated into a woven e-textile. This was designed to sit inside a double cloth pocket. The woven pocket would first need to be constructed to the specified size (i.e. minimum of the component height), to position and place inside the pocket when the double cloth was opened on the loom. The component weft was then positioned to make contact with the appropriate warp conductive tracks and interwoven into place.

On occasions where doubled LED components were applied to an e-textile sample, these were prepared similarly to the single LED component, however, this time two Lilypad LED components were required to make as one and integrate them as a single process. Lilypad LED component preparation is illustrated in Figure 4.30.

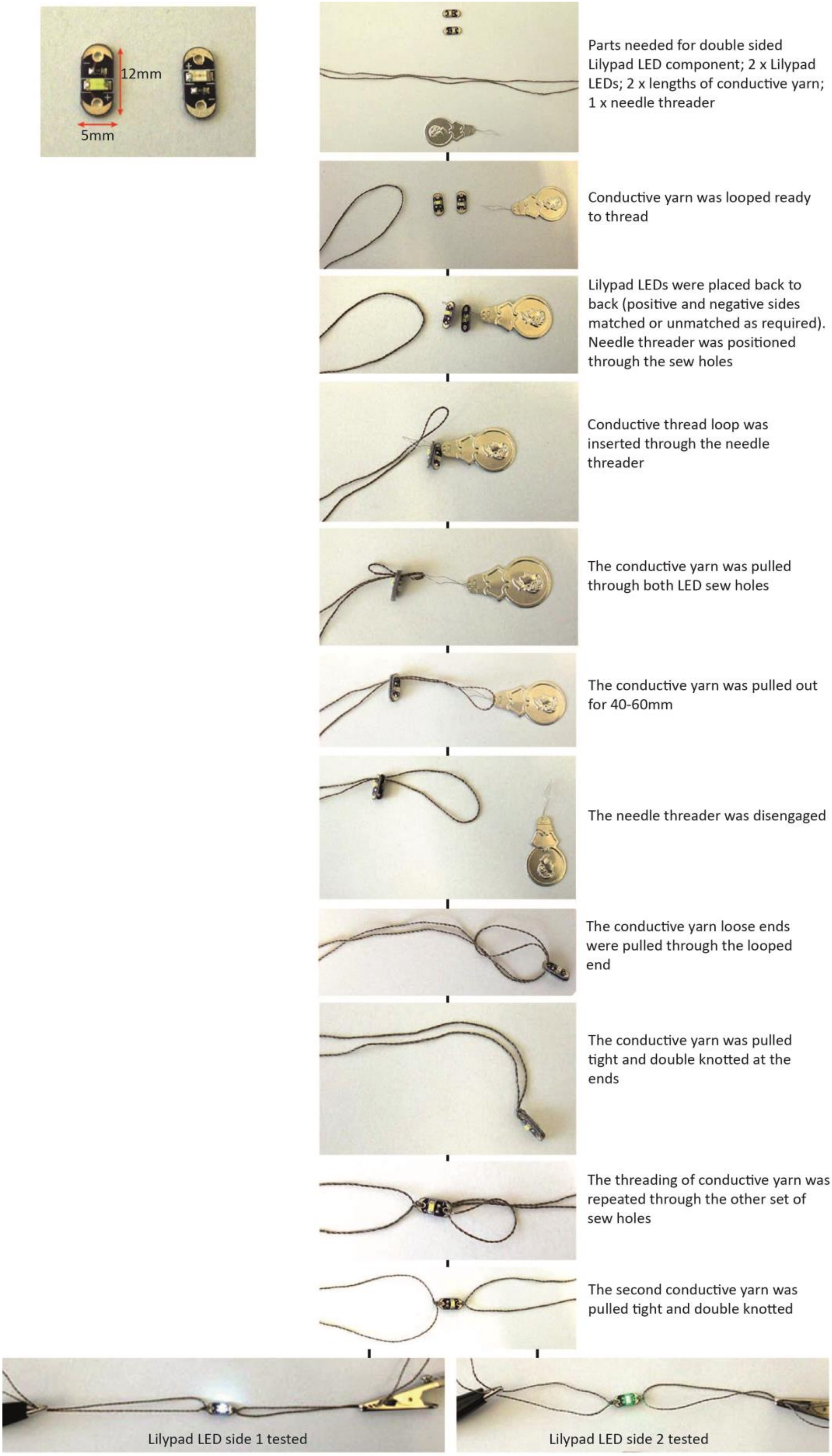


Figure 4.30 Lilypad double LED component preparation

Although Lilypad components were adequate for some woven e-textile circuits, for other soft circuits, e-textile specific components were not available or not compatible. On these instances, standard electronic components were sought and evaluated to assess if they could be adapted to fit the constraints of weaving. In a number of e-textiles in this research, standard electronic components were adapted and applied. The main adaptation was to enable a feature to tie and grip the conductive yarn to. On most standard components this was possible by bending the legs into coils using needle-nose pliers to create eyelet structures for the conductive yarn to thread through. An example of an RGB standard LED component being changed into a woven e-textile compatible component is shown in Figure 4.31. Although this method was successful for integration into a woven e-textile, the component still possessed some bulk (i.e. the spherical plastic lens). As this component was not originally intended for use in e-textiles, the design form was re-appropriated to suit woven integration. In the case of the 5mm RGB LED, this involved integration of the component sideways (as opposed to vertical) and bending the legs outwards.

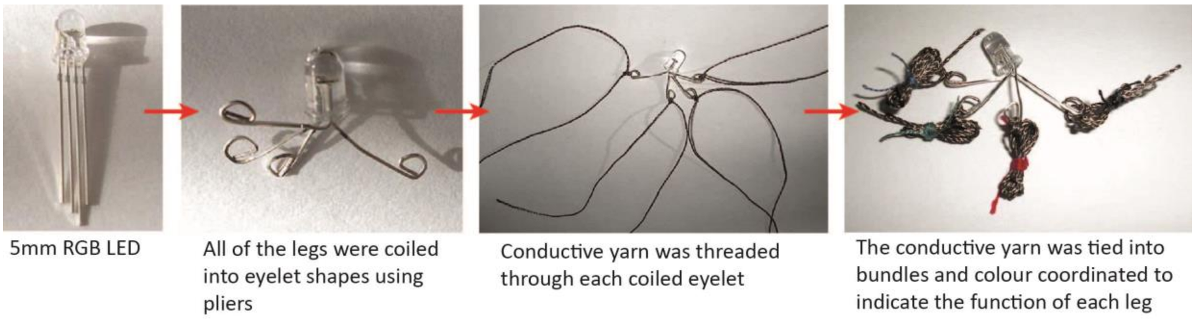


Figure 4.31 Standard 5mm RGB LED changed into an e-textile component

Other standard components were adapted to suit specific designs of woven e-textiles. Although the bulk of some standard component was the main disadvantage, this did not affect the function of the soft circuit. There is a need for more variety and better designed e-textile components.

Lilypad LEDs worked effectively in the woven circuits. However, when vigorously handled the knotted ends could slip and loosen due to the part nylon fibre composition of the conductive yarn. Therefore, the conductivity would be affected in the circuit if the knotted connection slipped. It was also noticed when applying doubled Lilypad LEDs this would double the surface mount boards, when this could be applied effectively on a single board by using both sides. The sew holes were also quite big, causing the conductive yarn to slip around the hole. Through analysing a Lilypad LED, it was found that this consisted of three subcomponents; a printed PCB, a surface mount LED and a surface mount resistor. An ideal woven e-textile integrate-able LED component would be smaller. This could be achieved by designing circuits on a PCB that would utilise one or both sides (for single or double sided LED). In addition, using two smaller holes on either side of the component to thread the conductive yarn weft through would enable better grip without knots. Seeking further advice from an electronic engineering expert and researcher, it was thought possible to design and print own made mounted LEDs. Following this idea, the researcher worked with the electronics expert to develop e-textile components for weaving. Figure 4.32 illustrates a range of own made components and the design iterations for the different versions developed. Appendices E i) – E vii) illustrates the complete making process for each of these components.

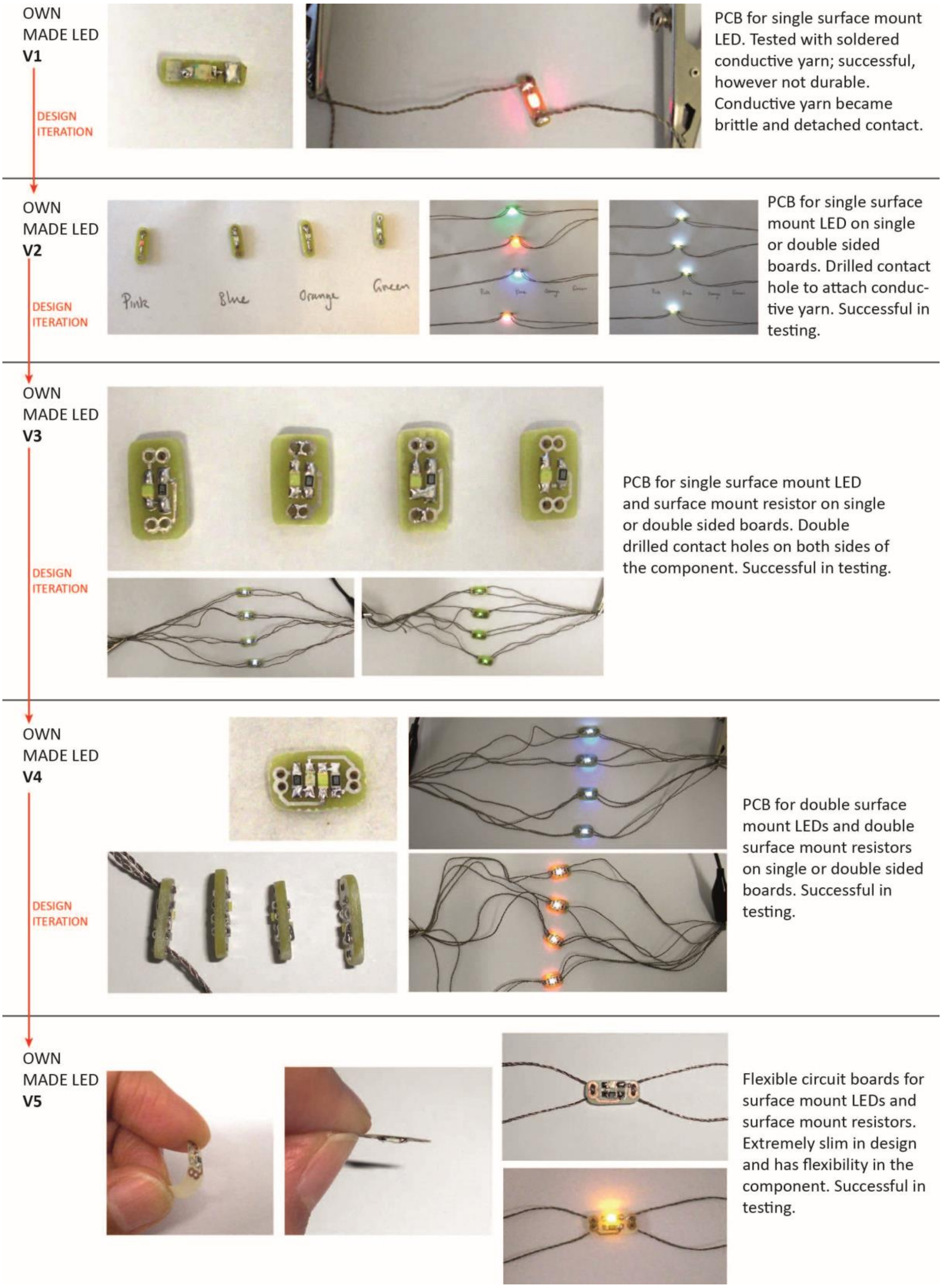


Figure 4.32 Own made components for woven e-textiles

Throughout this research project, own made woven e-textile components were developed as previous ones were analysed, reflected upon and re-designed to adapt and improve features. The design iteration from previous versions of own made LEDs are summarised in Table 4.3.

Component Type and version	*Function*	*Design improvement for new version*
Own made LED V1	PCB with single surface mount LED	Attachment for conductive yarn required drilled hole and track printed position onto component
Own made LED V2	PCBs – single or double sided for single surface mount LEDs	Attachment for conductive yarn required double drilled holes on either side of component to help grip tighter without knotting and consistent conductive contact. Resistor track needed integrated into PCB design
Own made LED V3	PCBs – single or double sided for single surface mount LEDs	Double LEDs on both single or both sides as an alternative option
Own made LED V4	PCBs – single or double sided for double surface mount LEDs	Potential to use this design V4 or V3 to apply to flexible circuit boards to make component slimmer with flexibility. Drilling of holes and filing of components would not be required, as flexible surface could be hand cut and needle pierced.
Own made LED V5	Flexible circuit boards – single or double sided for single or double surface mount LEDs. Also developed flexible circuit board for RGB surface mount LED with resistors.	

Table 4.3 Own made components design iterations summary

Although the components were mainly LEDs, the process and application to weaving could be applied for any surface mountable component. The main criterion was to help the component integrate better into the woven e-textile, function effectively in a woven construction and reduce bulk to keep the aesthetics and tactility focused on textiles. Version 5 was the most resolved option, although there is still opportunity to define the design further by investigating other component types.

4.3.7.3 Woven resistors

Resistance has been discussed in conductive yarn section 4.3.3 and initial e-textile sampling section 4.3.4. This section will discuss how this electrical property can be utilised in the designs of e-textiles.

Conductive yarns are specified with a level of resistance by the manufacturer. As this resistance is quantified, this property can be used to integrate as part of an e-textile design. A similar approach was used in a study by Li Li *et al.,* where conductive materials were applied to areas of a resistive conductive network for a wearable technology garment with a TENS (transcultaneous electrical nerve stimulation) system (Li *et al.*, 2014). In woven e-textiles, specific structures could also be applied to add intentional force and flex to make variable resistors using elastic yarn with conductive yarn, or with elasticised conductive yarns.

One approach, as applied in this research, is to use the resistance of the conductive yarn as woven resistors. This was designed by using the specified resistance along a fixed length and weaving the conductive yarn in isolation, i.e. insulating each pick of conductive yarn with non-conductive yarn to stop this from shorting and reducing the resistance value. An undulating weaving configuration was developed to help integrate the conductive yarn as woven resistors, and to ensure a consistent single length was used to quantify the resistance. For example, a 120Ω resistor could be woven using 1.2meters of Shieldex 235/34dtex 2-ply 100Ω/m (with tolerance of ± 30Ω/m) as a continuous piece of weft. Examples of woven resistors are shown in Figure 4.33.

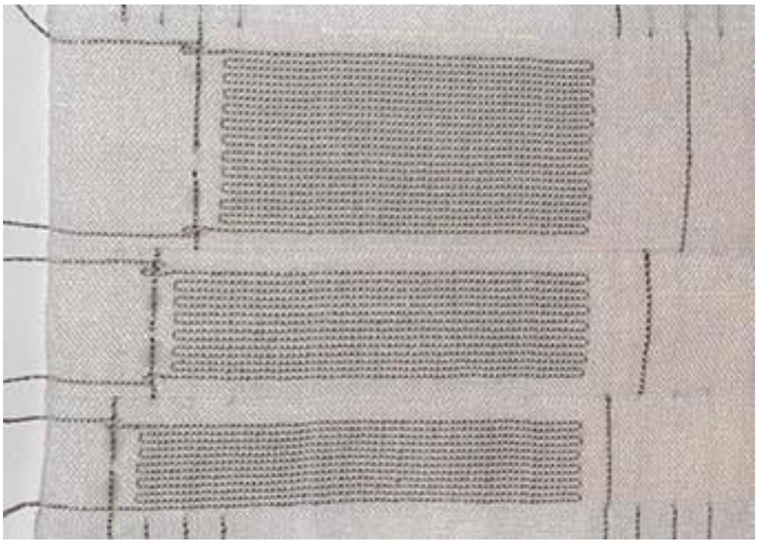


Figure 4.33 Three woven resistors of different values in a single soft circuit

Subject to the resistance value of the conductive yarn, this would determine the value of a woven resistor at a fixed length. For elasticised conductive yarn such as Bekaert Bekilast BK50/1 T/M 1200 Lycra, resistivity fluctuated depending on the stretch strain exposed, and therefore, was effectively used as a woven variable resistor. If the conductive yarn was woven consistently, this would reduce the resistance level and increase the conductivity; hence, each conductive yarn pick would be in contact increasing the conductive surface area.

Weaving resistors into woven e-textiles helped to reduce a hard resistor component and utilised the structure of the woven cloth. The space required to situate a woven resistor was dependent on the resistor value; thus, a large resistance value would require a longer length of conductive yarn or a higher conductive yarn resistance specification. The woven resistor required a particular amount of the woven cloth's surface area to integrate into and build in the resistor as part of the e-textile's construction. In samples where it was possible to weave in resistors, these functioned effectively when the circuits were activated. The points of connection at the beginning and end of a woven resistor's conductive yarn needed secure contact points when woven with warp conductive tracks, as loose connection would impact the circuit. Therefore, the woven resistor's beginning and end were interwoven over the warp track at least three times to ensure a securer contact.

4.3.8 Section summary

This chapter has provided an informed summary of the practical methods and techniques involved in the woven e-textiles of this research. The design specification indicated where these methods were applied to specific samples. These techniques were central to the development of this research; however, are not exhaustive woven methods as there are numerous techniques and approaches in woven textiles that have not been explored. The researcher selected the methods implemented in this research using prior weaving expertise through assessing which techniques could be utilised for weaving, and combining this with electronics for woven e-textiles. The design process was vital to enable the choices of woven structures selected for each design.

4.4 Mapping woven e-textiles and navigating the design process

As proposed in the methodology chapter, the design process was integral to the development of the woven e-textiles in this research. The following chapters 5, 6 and 7 will dissect woven e-textile samples developed in this research, to focus on how their designs evolved and what contributing factors affected these choices. Before moving on to the next chapter, this section will explain how the samples were organised, coded and mapped onto the design process.

As shown in the e-textiles samples index (Appendix A) and in the woven e-textiles components list (Appendix D), there were a number of factors that contributed to each sample. In relation to the design process, the pilot test samples were initial insights into woven e-textiles that led to iterations of other samples. Overall, there were three main categories of samples; these included actuators, circuits and modules.

Actuators included samples that were able react to an action; in the e-textile samples developed, these were switches. Circuits included samples that were woven as a continuous piece of weaving where the complete circuit was constructed as an integrated simultaneous sample (with exception of a battery holder in some samples). In the circuits category the e-textile samples were in two sub-groups, where the focus was on ‘integrated components’ and ‘malleables’. The final category was modules; this included e-textile samples that were designed to function when in a sequence of modular units. The modular category was further divided into two sub-groups where the sample focus was on ‘modular components’ or ‘battery holders’. Although some of the samples could have been classified in more than one category, the e-textiles were only associated with a single group. This was related to the development of that specific e-textile in relation to its main objective and how it developed in response to the design process. Figure 4.34 helps to summarise and visualise the samples in their categories with coded labels; this will relate to subsequent chapters when referencing specific categories.

The following chapters, 5, 6 and 7, will explain how the woven e-textile samples relate to the design process as described in chapter 3.

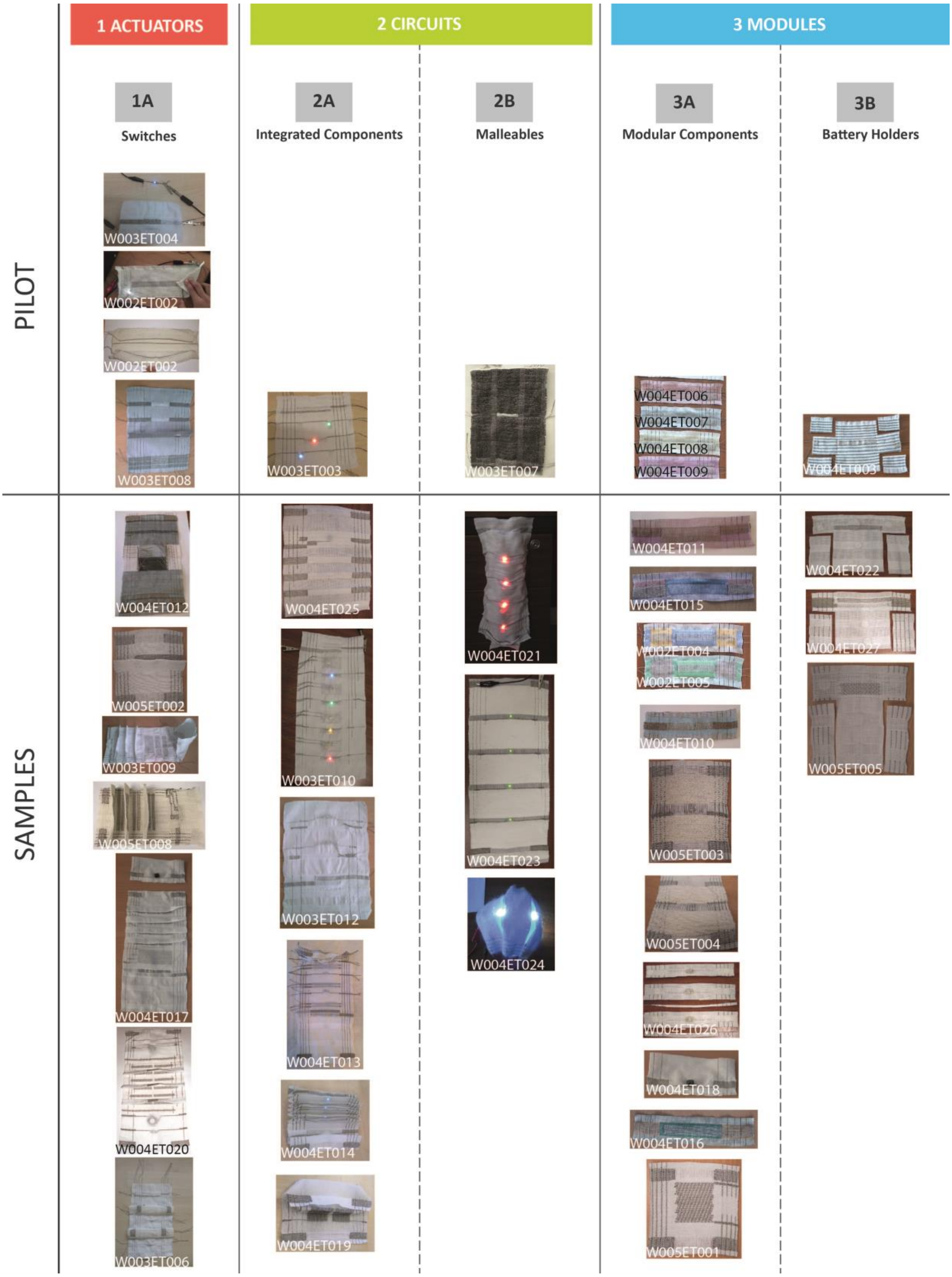


Figure 4.34 Woven e-textile sample categories and category codes

To help explain how the design process is applied through design iterations to the developed e-textiles, the design process is re-represented in a vertical visual order, as shown in Figure 4.35. However, the process remains the same as described in chapter 3.

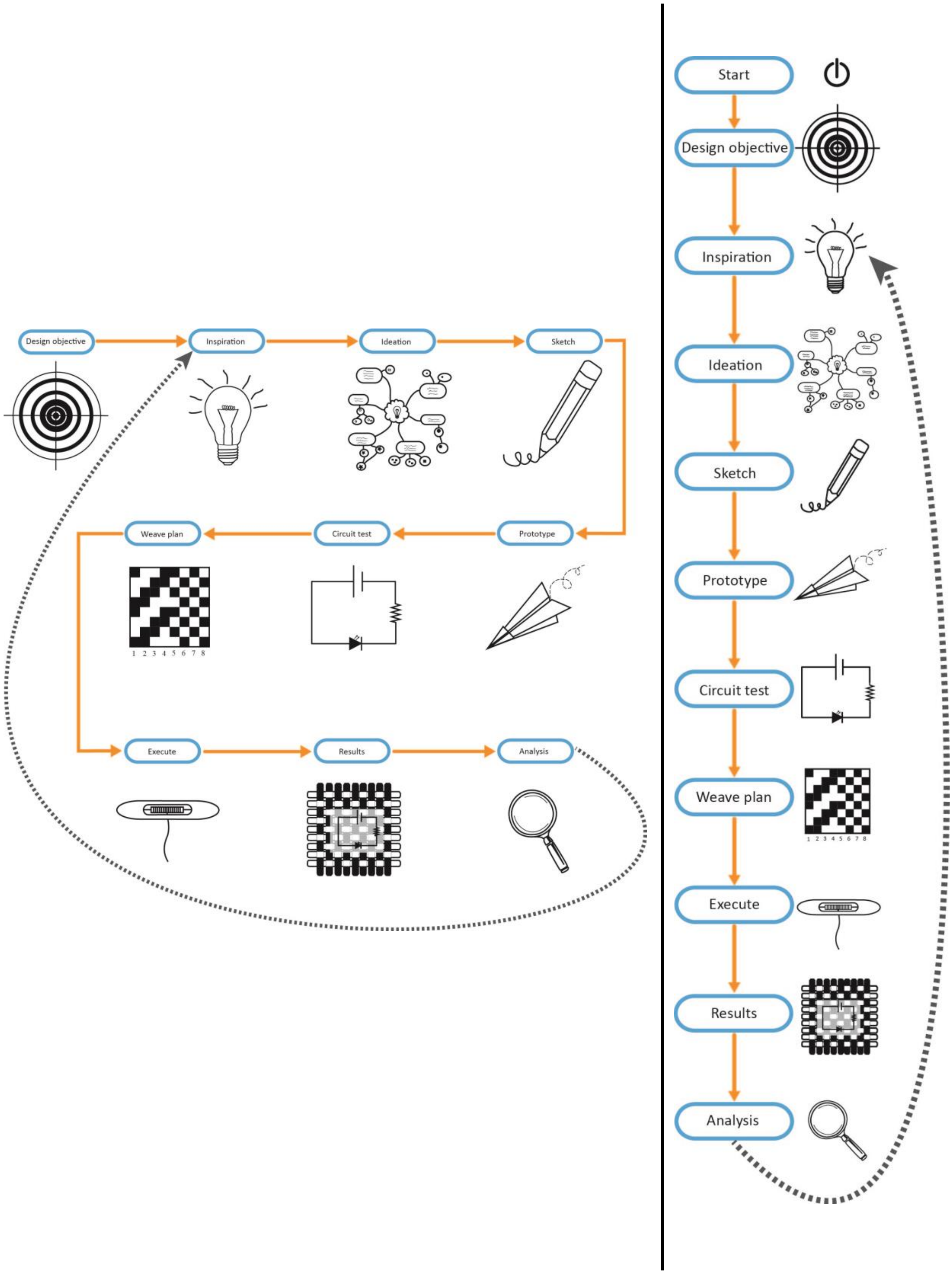


Figure 4.35 Woven e-textile design process (left) re-represented vertically (right)

This re-representation of the design process is to only help visualise it against the e-textile samples and their relationships to each development stage. This does not change any of the design process stages or sequence.

Chapters 5, 6 and 7 will map and navigate through the design process, to discuss three woven e-textile samples (one sample per chapter) in relation to the three categories they have been coded against. In each category/ or sub-group one specific sample is dissected to explain the complete design process and evolution, including the woven execution that led to the final e-textile outcome.

5 Actuators

This chapter will discuss the first category of actuators, as shown in woven e-textiles Figure 4.34. This category relates to samples that were able to react to an action, predominantly switches. Pilot samples in this category explored touch on/ off 'toggle' switch concepts using different woven methods of construction (as described in section 4.3.6.1). These initial samples were catalysts for further design iterations. In this category, two groups of samples were developed; however, these iterations were not ultimate studies of this category, as design iterations are continuous processes that have no definitive end. To summarise the findings from the woven e-textiles in this investigation, the samples have been mapped against the design process according to their category. The following subsections will guide through the design map of sample category actuators. This chapter will then focus on a specific sample in this group and discuss in-depth its design process development.

5.1 Map navigation: Actuators – 1A switches

Figure 5.1 illustrates actuators category 1A switches design process map. In this category, there are three groups of samples that relate to three levels of design iteration. Although the samples have been grouped together, they did not develop sequentially in these groups. The initial prototypes could have led to the development of one or more samples in the following design iteration; this may have been used as inspiration to reiterate into a second design iteration for a different sample.

To overview the flow of the design process, first the original design objective that related to the pilot samples was focused on, as this was linked to subsequent developments in the following iterations. In this category it was the concept of toggle on/ off switches that could control an output. Combining the design objective and external inspiration sources (which could be related to form and/ or function) led to ideating possible options for the function and form/ structures of the pilot samples. Using sketching to move chosen ideas forward from the ideation stage, (where the ideas were noted but not developed) enabled visualisation in two dimensional forms by working through potential options visually. Synthesising focused ideas, allowed them to progress. These ideas were translated into physical models during the prototyping stage, where the representations were used to work through practical design issues. Circuit testing and weave planning were the next design process stages, where the prototype models were used to map the circuit and weave designs onto. Refined weave structures, confirmed circuits and the physical form of the sample led to a design specification; this was used as instructions for weaving execution to make the woven e-textiles. The resulting e-textile sample was analysed, where the findings are applied back into a stage of the design process to develop further iterations – in category 1A actuators, the design iteration developed from inception of the inspiration stage. However, iterative design developments may intercept the design process at any stage where findings from the analysis of previous samples prompt new ideas. Therefore, the design process is intercepted at the inspiration stage in category 1A, where the findings from the initial design process sample are used to develop design iteration 1. Thus, the design process for design iteration 1 begins at the intercepting stage (i.e. inspiration for category 1A), and then continues to follow through the remaining design process.

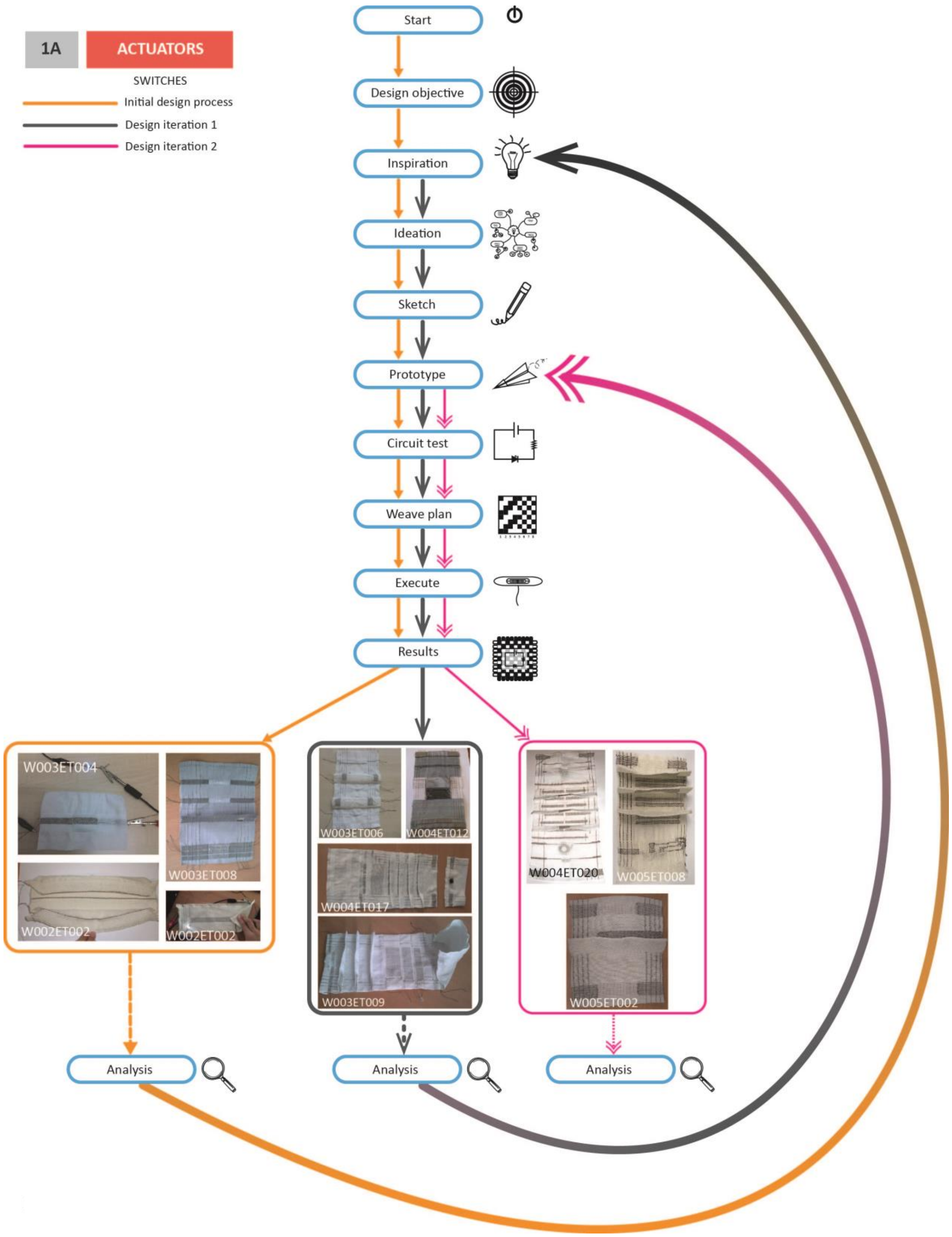


Figure 5.1 Actuators 1A switches design process map

The outcomes of design iteration 1 were analysed and the findings were used to intercept the design process for new design iteration, which followed through the design process for iteration 2. Any subsequent iterations are progressed back into the design process using the same method. Thus, outcomes developed after the initial design process result in direct relationships with previous samples due, to the iterative nature of the design process.

In relation to Figure 5.1, the initial design process (orange path) began at the design objective and followed through the stages, which resulted in four pilot samples. These outcomes were used for analysis (broken orange arrow), to create the inspiration for design iteration 1 (orange-grey arrow). The design process was followed from the inspiration stage (grey path) through to the results for design iteration 1 results (broken grey arrow), to inform prototype forms for design iteration 2 (grey-pink arrow). The design process was then followed from the prototyping stage (pink path) to the results stage, where the outcomes were used for analysis. However, a third design iteration was not performed for this category. For design iteration 2, the design process began from the prototyping stage, as new ideas were closely related to previous outcomes. Thus, at this stage the design development was progressed into prototyping as this version was slightly amended from a previous one.

The rest of this chapter will discuss the design process for a specific sample in this actuators category – RGB colour mixer.

5.2 RGB colour mixer

The sample RGB (red, green, blue) colour mixer (sample code W003ET009) was designed in the actuator switches category 1A in design iteration 1. The sample's objective was to integrate a standard RGB LED that could be operated using three independent switches in the same woven circuit, to independently address each colour or for a combined colour output. RGB colour mixer was designed by using the analysis of sample Duo pleat switch (sample code W003ET008) as inspiration to feed into the design process. The following sub-section will explain this design development process for the RGB colour mixer sample.

5.2.1 RGB colour mixer: design process

RGB colour mixer's design process is illustrated in Figure 5.2. As shown, the design process for this sample begins at the interception of the inspiration stage, using the findings from a previous sample's analysis (Duo pleat switch) to feed into the design process. Hence, the development of RGB colour mixer is an outcome of design iteration 1, but is inspired from sample Duo pleat switch developed in the initial design process of actuators 1A category.

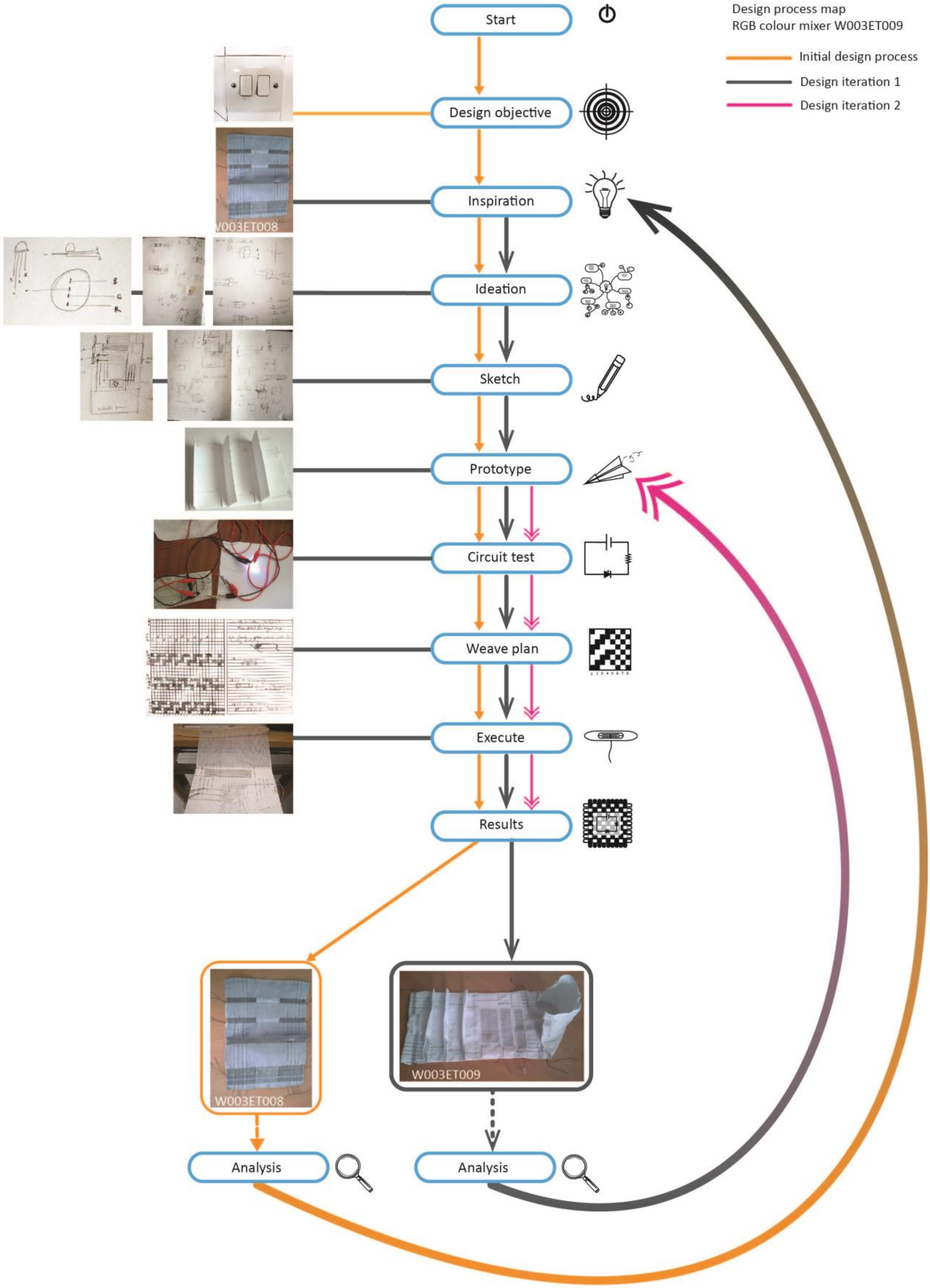


Figure 5.2 Sample RGB colour mixer design process

RGB colour mixer is an outcome of design group iteration 1 group; therefore, it is developed on this level as per other samples also classed in this level's group. It does not necessarily have a relationship with other samples in this group, as they are all developed independently. Samples developed as an outcome of design iterations are related to prior samples in a previous design process level. For example, RGB colour mixer (outcome of design iteration 1) is directly linked to Duo pleat switch (outcome of initial design process). This was because Duo pleat switch's analysis was fed back into the design process.

5.2.1.1 Inspiration: RGB colour mixer

The initial inspiration (on/ off switches) of the actuators category were still relevant to RGB colour mixer's design objective, as it related to independent or combined switches to control outputs (i.e. RGB LED colours). The inspiration for RGB colour mixer was drawn from Duo pleat switch (from the initial design process). Analysis of this sample presented opportunity to further develop and investigate woven pleats for switch applications via reflection and abductive thinking, i.e. knowledge gained from previous sample developments were central to inspire and progress RGB colour mixer. In addition, the findings of Duo pleat switch where a single pleat enabled a single output presented the possibility of using multiple pleated switches in a single sample, each to independently control different outputs. This idea synthesised implicit and explicit knowledge via reflections of a previous sample for a new potential sample – i.e. RGB colour mixer. It was this idea that was used for inspiration to develop RGB colour mixer, to enable independent switches to control independent or combined LED colour outputs.

A battery holder was also woven into Duo pleat switch sample. On analysis, although this was effective, the positive and negative woven contacts were woven too close together; therefore, occasionally caused a short circuit if the two tracks accidentally made contact. Thus, this was an aspect for improvement in the development of RGB colour mixer e-textile.

5.2.1.2 Ideation: RGB colour mixer

In this stage, the design objective of switches was viewed as an initial specification – i.e. integration of multiple switches into a single e-textile sample. The inspiration source was considered for RGB colour mixer's design development after reflecting *on* this (i.e. Duo pleat switch sample).The inspiration of pleated switches was used to ideate concepts through reflection *in* the ideation stage. This used tacit knowledge, as the translation of inspirational object to possible design ideas is an internal, implicit process that occurs using silent and subconscious decisions to creatively synthesise ideas and make them explicit.

On reflection of the inspiration source (Duo pleat switch sample) along with the design objective (on/off toggle switch), several switches could activate multiple outputs (i.e. RGB LED colours). A single standard 5mm RGB LED is a component with three colour outputs – red, green and blue. The RGB component was discovered during the researcher's development of initial pilot samples. On inspection of an RGB component, initial sketches ideated how it could be used and what potential adaptation could be made (Figure 5.3). The idea of using each of the colours as individual outputs was possible by bending and coiling the component's legs. This technique was previously trialled to attach conductive weft yarn to the coiled legs of the adapted standard LED component; this idea was progressed to the sketch phase for the RGB LED.

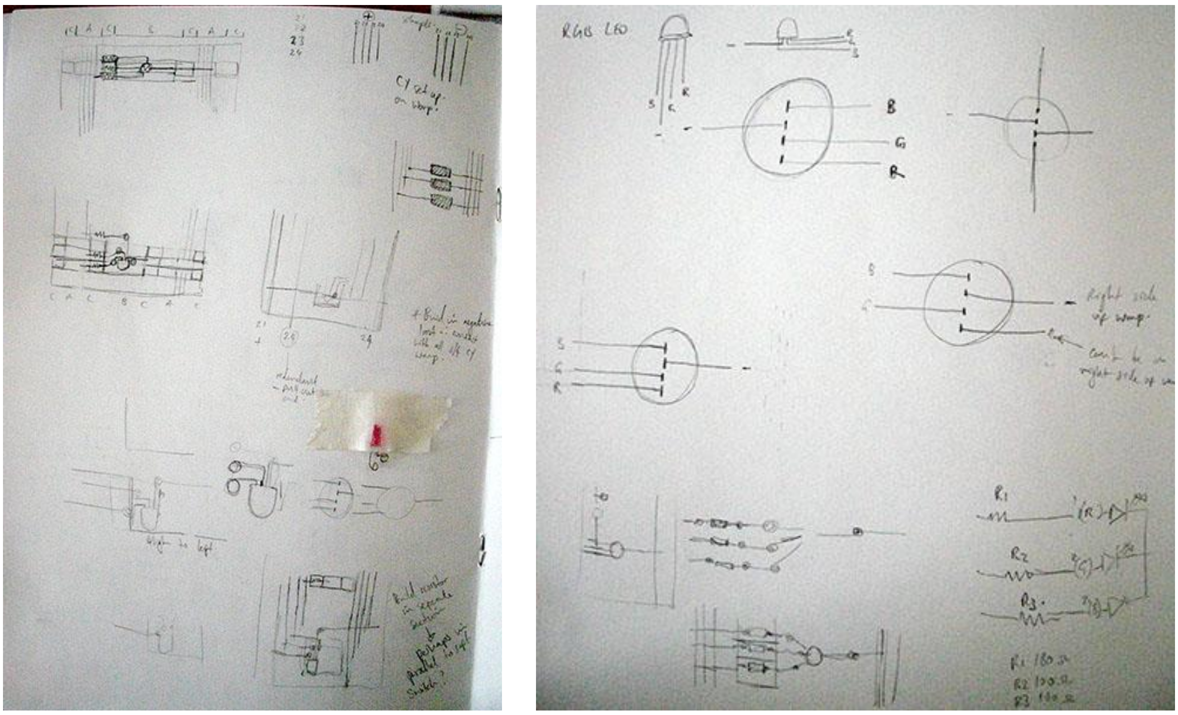


Figure 5.3 Ideation sketches for RGB colour mixer sample

As the circuit would require a power source, the idea of a woven battery holder (as per Duo pleat switch) was implemented. Options to improve the woven positive and negative contacts were considered, including weaving them further apart to ensure they would not short circuit. The battery contact would still need to be woven across a 20mm height, as this was the surface height of a 3v button battery. The option to improve the battery holder was taken forward to the sketching phase to visually translate improvements to its design.

5.2.1.3 Sketch: RGB colour mixer

Taking forward the idea of an adapted RGB LED component (i.e. legs coiled and separated in specific directions), sketches of potential forms and circuit layout were drafted by reflecting *on* and reflecting *in* the ideas generated in the previous ideation stage. Options for pleats were considered as this was the inspiration derived from the analysis of Duo pleat switch sample's form. Layouts for tracks were also thought about at this stage (Figure 5.4), as this required the creative synthesis of both form and function.

The RGB LED component specification was also referred to at this stage to integrate circuit requirements as advised by the component's manufacturer. A focused idea sketch was specified to lead into the prototype stage; this involved three independent pleats to function as three switches, each controlling one of the three colours of the RGB LED. Pleats would function effectively for switches as this was previously successful in the inspiration sample Duo pleat switch. In addition, resistors required to be integrated into the circuit, as per the component and circuit requirement. However, their position in the sample would be located after circuit testing and weave planning stages, as this would be affected by the woven structures.

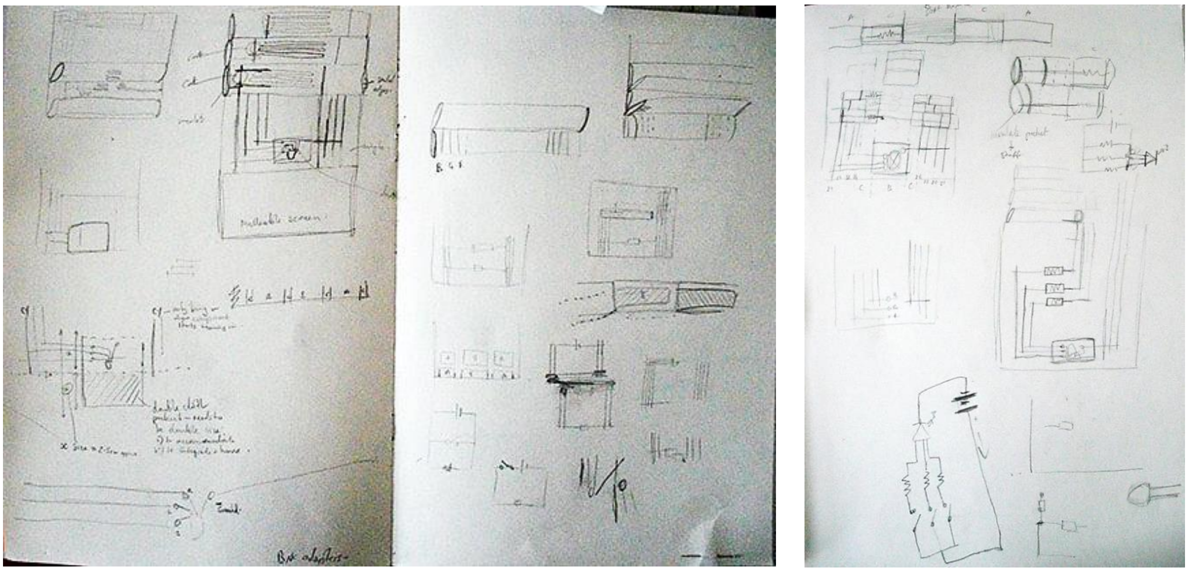


Figure 5.4 Sketches of RGB colour mixer

5.2.1.4 Prototype: RGB colour mixer

Paper prototype models for the form of the sample were creatively approached and constructed, synthesising the selected final sketched design. Reflecting *on* the sketches, three independent pleats would need to be positioned along the sample to act as independent switches, and would determine part of the form of the sample. Making paper prototypes helped to consider factors including the height of the pleated switches, spacing between switches and potential position in relation to the REG LED. This stage is praxis, as it applied woven theory to design making actions, visualising consequences of the design thus far in the prototype model outcome. This stage involved abductive theory, as it evolved ideas from what might be possible through previous findings and intuition into new ideas. As ideas evolved by working through the making process of the prototype model, this stage referred to reflection *in* the design process. The final prototype physically visualised the structure and positioning of the pleated switches. This stage used tacit thinking to first implicitly make decisions regarding actions, and then translate these explicitly through making the prototype model.

The final prototype design outcome of this phase was progressed as a physical map of the design form, where the following design stages referenced this model to guide the design and combine with the circuit and woven structures. The prototype could be adapted depending on the outcomes of the subsequent stages.

5.2.1.5 Circuit test: RGB colour mixer

The RGB LED was tested independently on a breadboard. Referring to the component's manufacturer specification, the known forward voltage for each of the colours was used to calculate the resistor values when applying 5v in parallel circuit. The known required current for the RGB component was 20mA, and the known required voltage for the red light was 1.8v, green light was 3v and blue light was 3v. Therefore, to run this component in a parallel circuit from 5v (source voltage), the resistor values were calculated using Ohm's law V = IR voltage (volts) = current (milliamps) x resistance (ohms). The voltage drop value calculated for each colour light was applied to Ohms law to calculate the resistance for each light (Table 5.1).

Colour light	Known Voltage	Voltage drop (from 5v source voltage)	V = IR	∴ R =
Red	1.8v	5 - 1.8 = 3.2v	3.2 = 0.02 x R 3.2/0.02 = R	160Ω
Green	3v	5 - 3 = 2v	2 = 0.02 x R 2/0.02 = R	100Ω
Blue	3v	5 - 3 = 2v	2 = 0.02 x R 2/0.02 = R	100Ω

Table 5.1 Resistor value calculations for RGB component

As shown in Table 5.1, the circuit would require three resistors of 160Ω for red, and 100Ω for blue and green lights. As these resistor values translated in conductive yarn lengths (using Shiledtex 235/34dtex 2-ply 100Ω/m), it was decided to integrate these as woven resistors in three lengths of 160cm, 100cm and 100cm for 160Ω, 100Ω and 100Ω respectively. The integration of the woven resistors would use the same method as discussed in section 4.3.7.3, but adapted to fit the form design of RGB colour mixer sample.

As the RGB component shared a common cathode (negative) connection, each colour diode would need independent interconnections for the separate anode (positive) connecting legs. The difference between the component's cathode and anode connections would need to be carefully considered when integrated into the weave plan. The circuit would need to be designed to run in parallel to address each colour independently, whereby three woven pleats could act as switches for each of the colours. The final circuit design is shown in Figure 5.5.

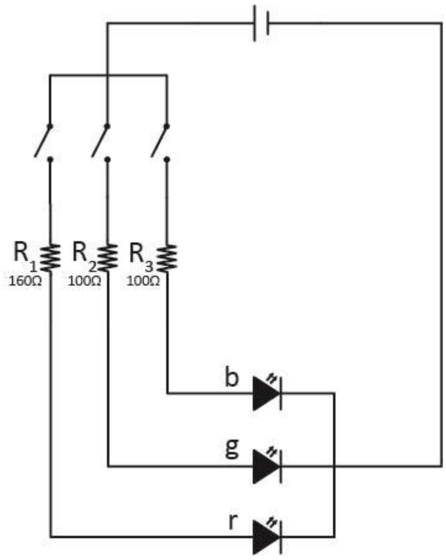


Figure 5.5 RGB colour mixer circuit schematic

During testing of the RGB LED component, it was observed the emitted light was bright enough to be further amplified when against a white or shiny surface. On reflection of this observation, it was deliberated in terms of the e-textile design and how this quality could be integrated as part of the sample's design. A separate reflective screen area was considered to help amplify the light emission; however, to make this an attached woven screen would enable the e-textile to be kept as a continuous piece of textile. Although this would be an experimental approach, the screen could be cut off if it did not suit or work with the sample. The screen was integrated into the weave planning stage.

When testing the component, an independent power source was applied. For the woven RGB colour mixer sample, the same power source could be applied. An integrated battery holder was also specified for this sample, as per the original inspiration source sample (Duo pleat switch), with a single magnetic clamp.

Although the circuit testing was conducted pragmatically and referenced a circuit schematic, this still required praxis of electronics knowledge into the planning and testing phase. In addition, knowing how to test the circuit needed to be translated from implicit knowledge into explicit actions. Some of the decisions to make progression from implicit to explicit thinking were connected to tacit knowledge, as these decisions were subconscious and intuitive behaviours. Abductive thinking was also a key design principle in this circuit testing phase of RGB colour mixer sample, as actions related to testing this circuit were related to knowledge based on theory, intuition from previous experiential learning and reflections. Synthesis of the RGB LED circuit into woven design required synchronisation of how this could be translated into woven structures. This was partially resolved through the circuit's layout position when tested, as parts of the circuit needed to make specific connections at fixed points. For example, connections to positive and negative power tracks, connections to corresponding switches for each RGB colour. The next phase (weave planning) would enable each part of the circuit as it appeared in the circuit test to be converted into woven structures. This transformation required creativity to fuse the function of the circuit into woven structures, relate this to the design objective, and to the prototyped form design. Reflective practice was also engaged at this stage, as reflecting *in* the process consistently checked if each part of the circuit functioned; reflection *on* the successful circuit test would allow the translation through to weave planning.

5.2.1.6 Weave plan: RGB colour mixer

In preparation for weaving, a design specification is drafted to help guide each section of the woven execution and specify woven structures. The draft specification synthesised and reflected on information from the design process thus far; this becomes complete after the weave planning stage. By compiling the design concept features from the sketching, prototyping and circuit testing stages, a physical plan of the sample evolved into a design specification draft. This became a set of instructions to guide the woven execution for RGB colour mixer sample (Figure 5.6).

The design specification needed to refer to the warp set up, as the sample design would be dependent on this. If the warp had not previously been set up, the specification would also be used as an instruction to help draft this. For RGB colour mixer sample, an existing warp had been set up using 2/74s spun polyester and Shieldtex 235/34dtex 4-

ply; therefore, the design specification referenced this set up when designing and specifying the sample.

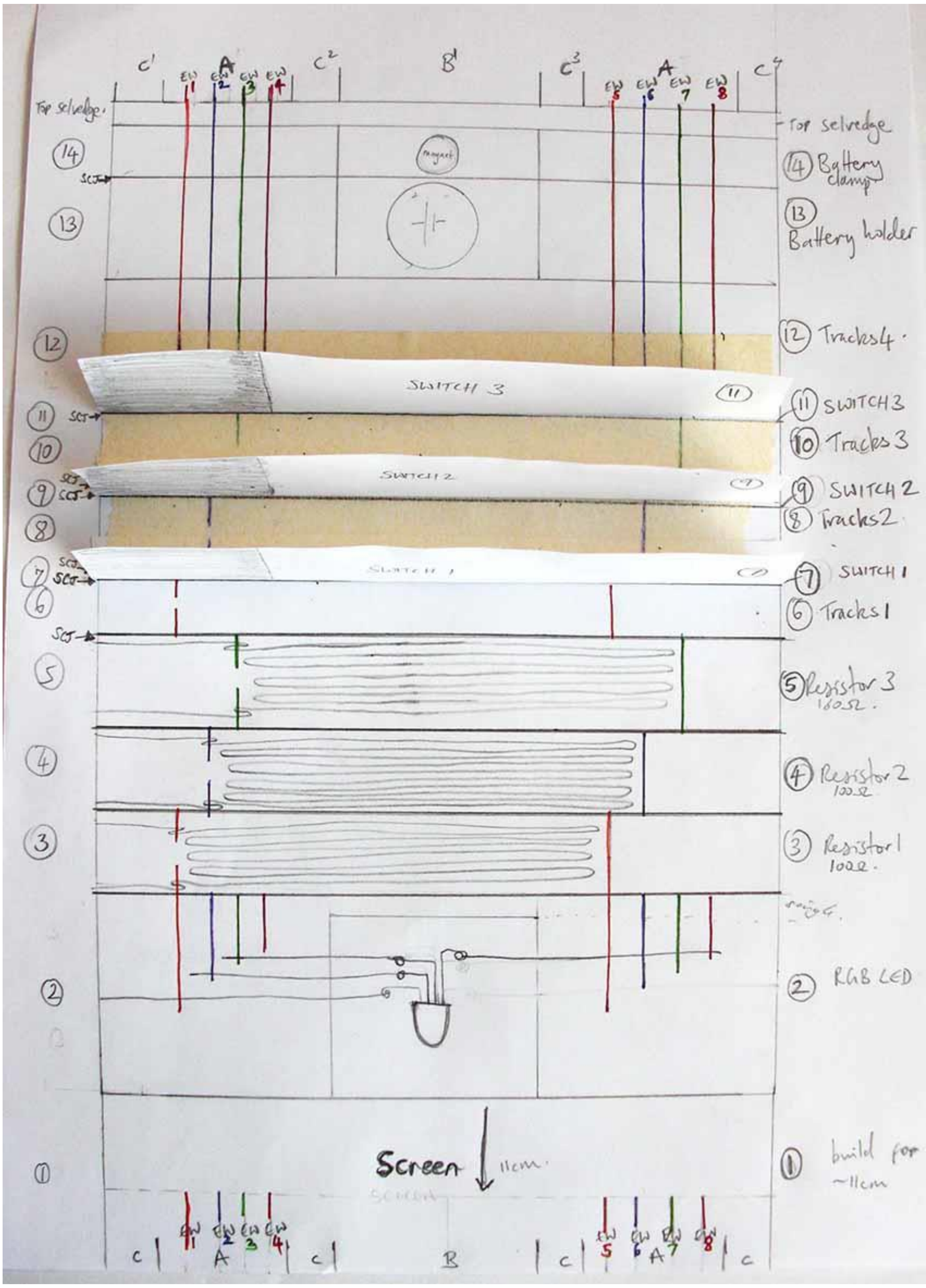


Figure 5.6 Design specification for RGB colour mixer

The final design specification for RGB colour mixer comprised of a malleable reflective screen, an integrated RGB LED, three woven resistors connected to each light output (red, green and blue) which were independently addressable via three woven switches, an integrated woven battery holder connecting power to the complete circuit and a battery clamp. The complete circuit was specified to be woven as a single simultaneous piece of weaving to integrate all the required soft circuit design components.

Woven structures were designed according to each section of the design specification in relation to the warp design. This needed to be creatively synthesised to integrate the function of the circuit with the woven structures, by using existing qualities of the weaves and adapting them for the design of RGB colour mixer. The form and function of RGB colour mixer's sections had been conceptually designed and specified. These required translation into woven structures to allow the physical translation from specification into tangible sample. To enable this interpretation, the researcher reflected on previous woven knowledge, both implicitly and explicitly to draw out structures that correlated with the required form and function of the design. In addition, some of the translated woven structures were intuitive to the researcher from previous experience and were referred to tacitly.

The warp design for this sample was arranged in block draft consisting of three blocks; A, B and C with an extra warp for conductive yarn. The warp draft block proportions can be seen in Figure 5.7. Therefore, the draft predetermined some of the design specification details, such as conductive yarn warp tracks, block widths and warp yarns. The warp draft also predetermined how the extra warp threads would be controlled; in this warp draft they were dually controlled on the left and right side. Therefore, extra warp threads 1 and 5 were controlled together as they were threaded on the same shaft. Other pairs of extra warp threads that were controlled together included 2 and 6, 3 and 7, and 4 and 8.

Although three blocks were integrated in this warp draft, RGB colour mixer sample's design only required two blocks. The warp draft did not hinder the design as it was originally designed as a multifunctional warp for multiple samples. The complete warp draft plan applied to RGB colour mixer sample can be seen in Appendix F.

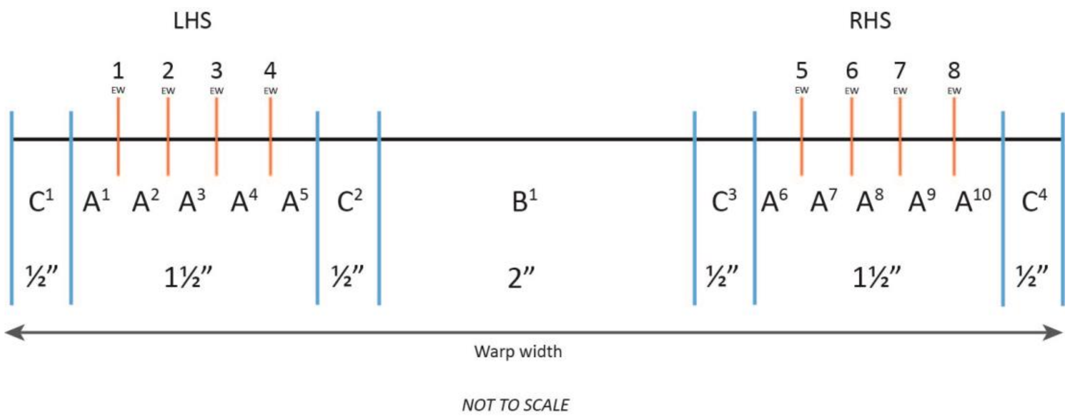


Figure 5.7 Warp draft block proportions used for RGB colour mixer (warp 003)

Woven structures designed for each section of the sample were required to enable specific functions. Therefore, it was imperative the correct structures were woven in the specific designed areas to synthesise with the allocated sections. RGB colour mixer's complete woven structures and weft yarns applied can be viewed in Appendix G. The choices and designs for each of the woven structures are discussed in section 5.3.

During the design speciation drafting, some details of the design also become clearer (i.e. from implicit knowledge to explicit information; reflection *in* and *on* the design). For example, breaks in warp tracks would need to appear at points where the switches made contact with the circuit. This meant options considered to make these sections would require either a different woven structure (e.g. floating extra warp threads), or the tracks could be picked and cut out of a regular weave in the finishing process. As the extra warp in this circuit dually controlled extra warp threads on the left and right side, the option to pick and cut these threads after the circuit was woven was chosen, as this would ensure the unbroken track on the right side would remain securely woven in.

Other technical issues that were resolved while drafting the specification included the size, spacing and clamp of battery holder, size of screen and spacing between the switches to ensure these did not short circuit. Although the resistors were specified, the exact heights of these sections were not known until woven. This was because the length of conductive yarn would need to be woven insulated between a non-conductive yarn and woven compression would also impact the height of these sections across different widths. Another detail that became apparent when drafting the design specification was the need to insulate the resistor double cloth sections to stop any short circuiting. This was required for RGB colour mixer as the warp draft had already positioned the extra warp threads onto specific shafts/ heddles that would intercept resistor woven weft tracks, potentially causing a short circuit. Thus, to avoid a short circuit calico (woven cotton) fabric strips were designed to insulate the three resistors double cloth sections, by trapping these in between the double cloth pockets.

5.2.1.7 Execute: RGB colour mixer

Yarns were selected to weave the sample; 2/74s spun polyester (same as the warp) was chosen to weave the complete sample. This was to enable a balanced weight of cloth in relation to the warp, and to assess how the switches reacted in a textile tactile consistency. The exception was with the conductive tracks that were woven with Shieldtex 235/34dtex 4-ply and 235/34dtex 2-ply conductive yarn. The screen section of the sample was designed with a shiny surface to reflect and amplify the light emitted; for this reason, a thin cellophane yarn (90Nm Lurex cellophane NR3720 clear) was woven in this area. An additional quality specified for the screen included malleability – this was particularly inspired by the malleable sample woven in category 2B circuits. Thus, the screen was woven using a satin and sateen structure, and with a thin 0.2mm enamelled copper wire on the reverse of the structure (i.e. not visible on the face side). Due to the integration of the RGB LED and order of extra warp threads integration, the sample was woven starting from the screen; this was section 1. In preparation for weaving, all woven structures were manually programmed into the Selectron system on the loom and the electronic component was prepared with conductive yarn (as discussed in section 4.3.7.2). The weaving process of RGB colour mixer sample can be seen in Figure 5.8.

Once the sample was complete, it was cut off the loom and finishing was applied. This involved trimming all excess ends, gluing selvedges and the button access slot, cutting the button access slot and cutting broken warp tracks.

1.

RGB component preparation; each of the conductive yarn wefts were bundled and tied with colour coordinated threads to help identify component legs

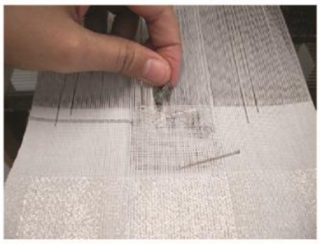
2.

The malleable screen was woven first. A double cloth pocket was constructed next; once the required height of the pocket was woven, the component was integrated

3.

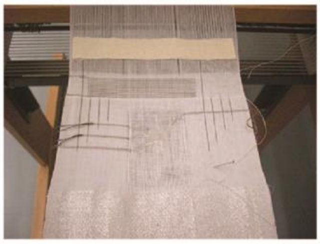
The conductive yarn weft attached to the first leg of the component was untied and interwoven across the allocated warp tracks

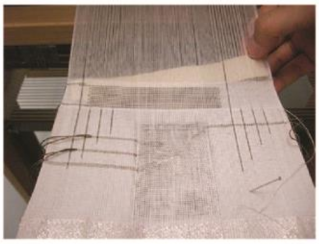
4.

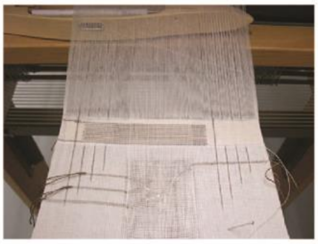


The subsequent conductive yarn wefts were also interwoven as per step 3 above

5.

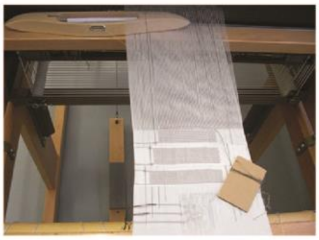






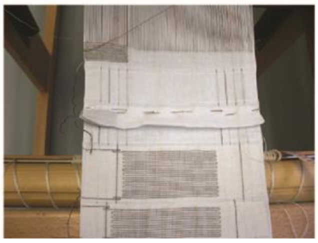
Woven resistors were constructed next. Calico fabric strips were interwoven to insulate against other tracks

6.



In total, three resistors were woven before commencing to weave the pleated switch tabs

7.



Second woven pleated switch being woven on the loom. A total of three woven switches were woven in this sample

Figure 5.8 Woven process for RGB colour mixer sample

5.3 Sample dissections: RGB colour mixer

To further explain the complete make up of RGB colour mixer sample, each of the sections has been dissected to indicate specific allocation as seen in Figure 5.9.

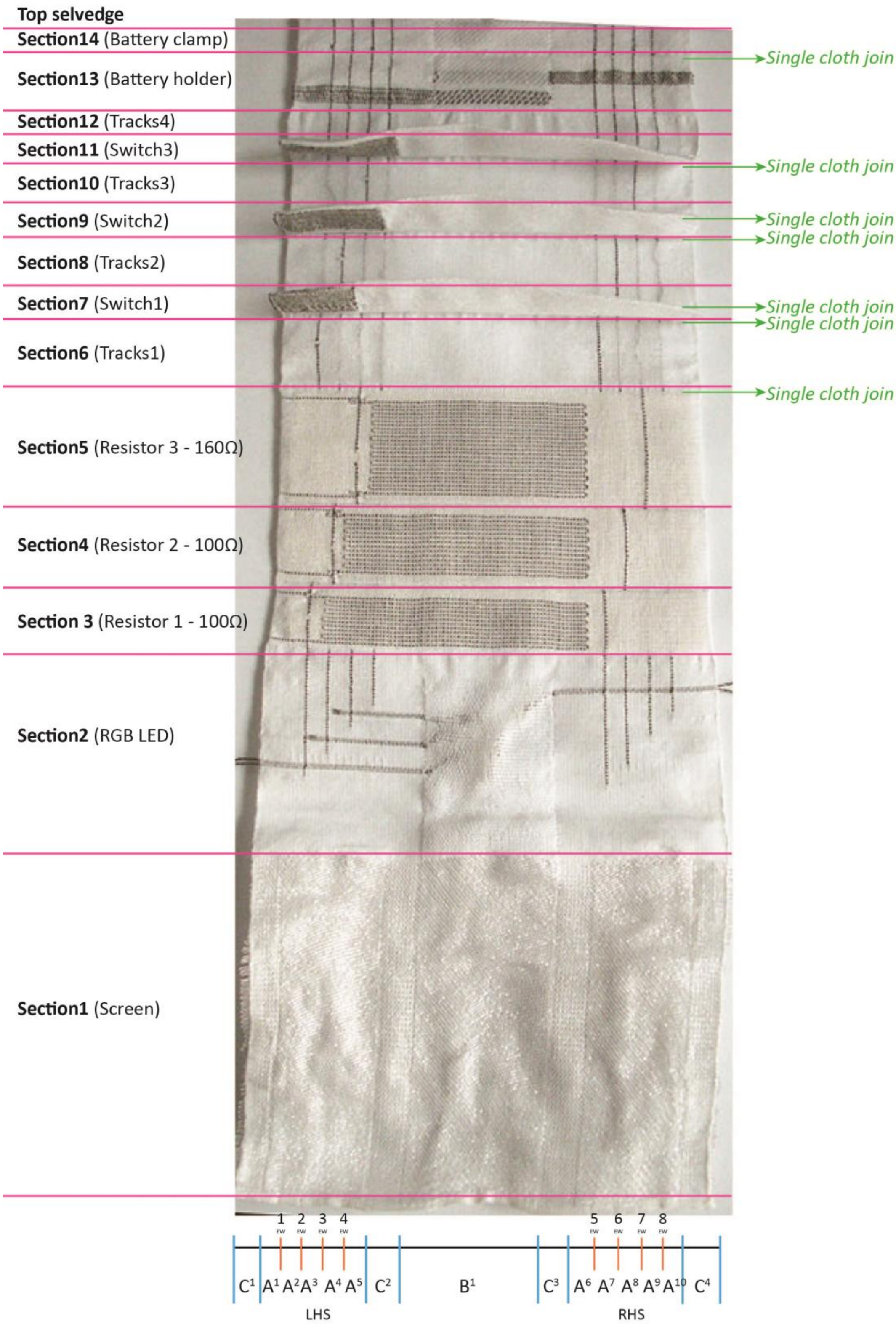


Figure 5.9 Dissected section labels for RGB colour mixer

Each section is represented between pink lines. Single cloth picks (plain weave) were inserted as joining picks between some of the sections (green arrows); these were to seal areas of double cloth or to complete a pleated section. The warp draft plan has been mapped onto the sample to help indicate the blocks and extra warp threads.

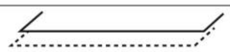
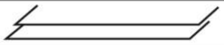
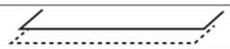
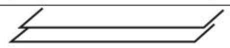
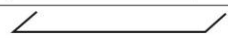
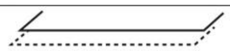
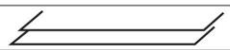
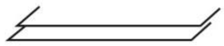
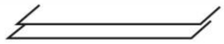
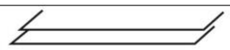
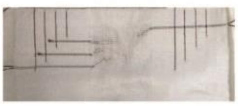
The following subsections explain the weaving execution of each woven section of RGB colour mixer sample.

5.3.1 Woven section descriptions: RGB colour mixer

A total of 14 sections (minus selvedges) were woven to complete the RGB colour mixer sample. To help visualise the complete sample and some of the complexities involved, the sample sections have been dissected and inserted into a table (Table 5.2), indicating section number, section function, section image, cloth structure applied to form each section, extra warp threads woven in, extra warp threads woven in as single cloth or on the top or bottom of double cloth, and a cross section schematic to illustrate the specific section.

As is illustrated in Table 5.2, the sample is comprised of many specific qualities that required woven integration. The circuit was woven as a complete simultaneous piece of weaving. Therefore, specific functions and details were required to be integrated sequentially, especially as circuit functions were fixed to these allocated areas, i.e. there was limited range for adaptation and errors due to the warp set up and adjacent sections. To avoid errors in woven structures and woven execution, these were checked and executed cautiously.

Each section of the sample is discussed in order of construction (i.e. from the base of the sample to the top), grouping discussions with the same or similar woven structures applied across the sample.

Section	Section function	Section image	Blocks & cloth structure A	B	C	Extra warp threads woven LHS 1 2 3 4	RHS 5 6 7 8	Cross section schematic
Top selvedge	Selvedge		SC	SC	SC	⚫⚫⚫⚫	⚫⚫⚫⚫	
14	Battery clamp		DC1	DC2	DC1	🔴🔴🔴🔴	🔴🔴🔴🔴	
	Single cloth join		SC	SC	SC	⚫⚫⚫⚫	⚫⚫⚫⚫	
13	Battery holder		DC1	DC2	DC1	🔴🔴🔴🔴	🔴🔴🔴🔴	
12	Tracks4		SC	SC	SC	⚫⚫⚫⚫	⚫⚫⚫⚫	
11	Switch3		DC1	DC1	DC1			
	Single cloth join		SC	SC	SC	⚫⚫⚫⚫	⚫⚫⚫⚫	
10	Tracks3		DC1	DC1	DC1	🟢🟢🔴🟢	🟢🟢🔴🟢	
	Single cloth join		SC	SC	SC	⚫⚫⚫⚫	⚫⚫⚫⚫	
9	Switch2		DC1	DC1	DC1			
	Single cloth join		SC	SC	SC	⚫⚫⚫⚫	⚫⚫⚫⚫	
8	Tracks2		DC1	DC1	DC1	🟢🔴🟢🟢	🟢🔴🟢🟢	
	Single cloth join		SC	SC	SC	⚫⚫⚫⚫	⚫⚫⚫⚫	
7	Switch1		DC1	DC1	DC1			
	Single cloth join		SC	SC	SC	⚫⚫⚫⚫	⚫⚫⚫⚫	
6	Tracks1		DC1	DC1	DC1	🔴🟢🟢🟢	🔴🟢🟢🟢	
	Single cloth join		SC	SC	SC	⚫⚫⚫⚫	⚫⚫⚫⚫	
5	Resistor3 (160Ω)		DC1	DC1	DC1	🟢🟢🔴🟢	🟢🟢🔴🟢	
4	Resistor2 (100Ω)		DC2	DC2	DC2	🟢🔴🟢🟢	🟢🔴🟢🟢	
3	Resistor1 (100Ω)		DC1	DC1	DC1	🔴🟢🟢🟢	🔴🟢🟢🟢	
2	RGB LED		SC	SC	SC	⚫⚫⚫⚫	⚫⚫⚫⚫	
			SC	DC1	SC	⚫⚫⚫⚫	⚫⚫⚫⚫	
			SC	DC1	SC	⚫⚫⚫	⚫⚫⚫	
			SC	DC1	SC	⚫⚫	⚫⚫	
			SC	DC1	SC	⚫	⚫	
			SC	DC1	SC			
1	Screen		SC	SC	SC			

SC = single cloth
DC1 = double cloth 1
DC2 = double cloth 2
⚫ *= Extra warp thread woven in as single cloth*
🔴 *= Extra warp thread woven in as double cloth on TOP cloth*
🟢 *= Extra warp thread woven in as double cloth on BOTTOM cloth*

Table 5.2 RGB colour mixer dissected sections

5.3.1.1 Section 1: Screen

The screen section was designed as a single cloth with pre-selected weft yarns (thin cellophane and enamelled wires). The woven structure applied to this section combined sateen and satin weaves, whereby every alternate weft pick was a sateen structure and every weft pick in between was a satin structure. Across blocks A and B, an 8 shaft structure fitted exactly; however, as block C was across 4 shafts, this used a 4 end sateen and satin structure. The sateen-satin structures were specifically designed for this section. In this structure one of the yarns would be highly visible on the face side and not very visible on the reverse side (i.e. cellophane); while the other alternative weft is highly visible on the reverse side and not very visible on the face side (i.e. the enamelled wire). The two wefts were required to be woven alternatively to match the structure and desired cloth visibility. As the screen section was designed to attain a shiny reflective and malleable quality, the sateen-satin structure designed would provide this result. This knowledge was identified by the researcher through previous weaving experience by reflecting on the required quality. Figure 5.10 helps illustrate the sateen-structure applied to the screen section. The structure did not lift shafts 21 – 24 as these were the extra warp threads that were not required to be woven in this section; thus, these were left floating on the back of the sample. The screen section was woven for 11cm in height.

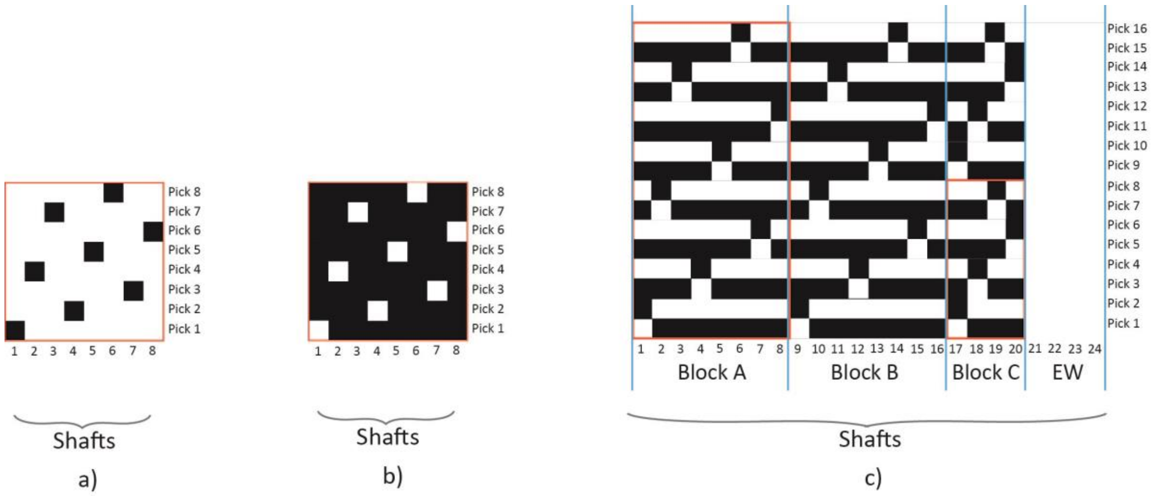


Figure 5.10 Sateen-satin structure a) 8 shaft 3-step satin structure; b) 8 shaft 3-step sateen structure; c) 3-step sateen-satin structure in blocks A and B, and block C has a 4 shaft sateen-satin structure applied. Red outlines indicate the repetition of the structure

5.3.1.2 Section 2: RGB LED

The second section of the sample required the prepared RGB LED component to be integrated on the loom. The weft conductive yarns were attached to the component when it was prepared; therefore, at point of integration, the required weft was inserted as needed. This complete section was woven with 2/74s spun polyester (same as warp).

This section was the most complex of the sample, as there were several variables that were being controlled and needed close attention to specifically integrate allocated tracks. Although this was one section, there were two fundamental woven structures applied; a single cloth and a double cloth section combined with single cloth. The complete section height is 7cm, where the first 5.5cm was woven in a single cloth structure in blocks A and C and double cloth structure in block B – this part of the section was constructed to house the RGB LED and interweave the weft conductive track. The upper part of this section (remaining 1.5cm) was woven in single cloth across blocks A, B and C with all conductive extra warp threads interwoven in to close the block B double cloth and stabilise the cloth – Figure 5.11 helps to illustrate this.

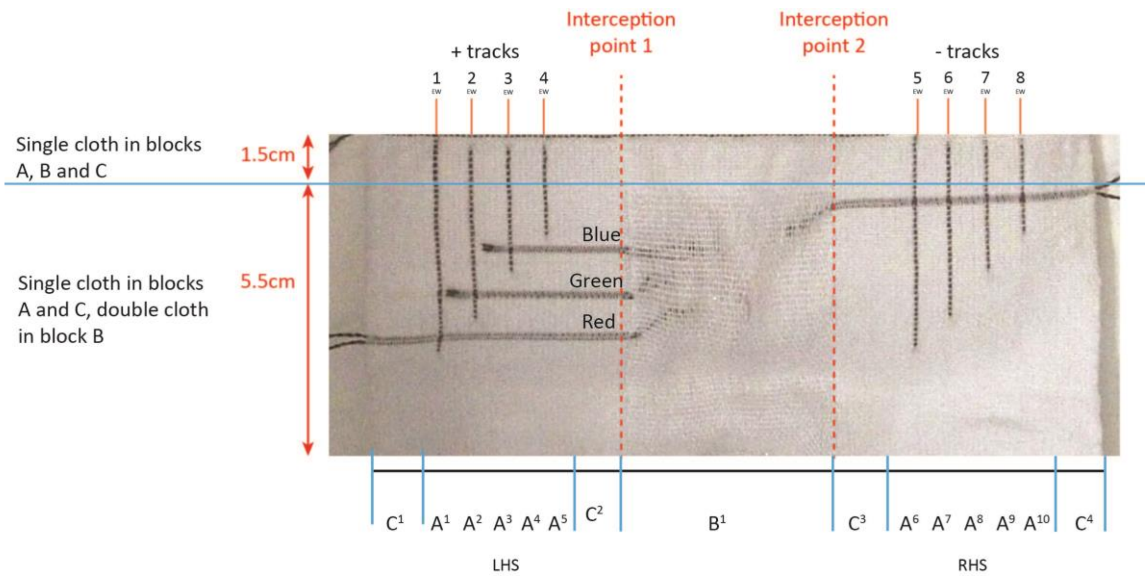


Figure 5.11 Section 2 of RGB colour mixer sample

First the lower part of section two was woven for 2.7cm before the double cloth pocket in block B was opened (using a plain weave structure) to place the RGB LED inside. Once positioned, the attached conductive yarn weft of the RGB component's red positive leg was taken out of the cloth at interception point 1 (as indicated in Figure 5.11) and placed on top of the warp. The remaining conductive wefts were positioned inside the double cloth pocket. The weave structure (single cloth in blocks A and C, double cloth in block B) continued to be woven, with the introduction of extra warp threads 1 and 5 controlled by shaft 21 for 0.3cm. At this point, the red positive leg's conductive weft was taken back into the warp and woven in to interact with extra warp thread 1. A polyester weft was woven across the complete sample in the same pick opening to weave in all other warp ends. This was repeated in the next pick as the conductive yarn weft attached to the component legs was double; therefore, each strand was woven in as an independent pick to ensure two interconnections with the extra warp to help improve connectivity and surface contact.

The same woven structure in this section was woven for another 0.5cm before extra warp threads 2 and 6 were introduced into the structure (controlled via shaft 22). The same process was applied to weave in the RGB LED green positive leg's conductive yarn weft. However, this time the conductive yarn weft was taken out of the warp soon after it had interconnected with extra warp thread 2 to prevent it from making contact with other conductive tracks. Two picks were also woven for this section. After an additional 0.5cm, extra warp threads 3 and 7 were included in the structure (controlled via shaft 23). This integrated RGB LED blue positive leg's conductive yarn weft, woven in as per the previous process for red and green positive legs. The same structure was woven for 0.4cm before introducing extra warp threads 4 and 8 (controlled via shaft 24) and was woven for 0.5cm. The last remaining conductive yarn weft was attached to the negative leg of the RGB LED. This was taken out of the double cloth pocket at interception point 2 and then woven into the right hand side, interweaving with extra warp threads 5, 6, 7 and 8. A polyester pick was woven right the way across (as previously) to tie in all warp ends. The structure was woven for an additional 0.6cm before the structure was changed to plain weave (i.e. upper part of section 2), which sealed close the double cloth block B.

The order of extra warp threads introduced into the woven structure was determined by the design specification. This had to ensure the RGB LED component was positioned in the correct arrangement in the double cloth pocket, to access the relevant conductive yarn wefts at the required points in the woven design. Hence, managing this section was the most difficult part of the sample.

5.3.1.3 Sections 3, 4 and 5: Resistors

The three resistor sections were constructed using the same method, with the exception of different extra warp thread interactions. Sections 3 and 4 integrated 100Ω resistors and section 5 integrated a 160Ω resistor. The resistors were woven using Shiledtex 235/34dtex 2-ply 100Ω/m; therefore, three lengths of 2x100cm (for 100Ω) and 1x160cm (for 160Ω) were prepared before starting to weave these sections. Each pick of the conductive weft yarn was insulated between a pick of 2/74s spun polyester. The construction of the resistor was as described in section 4.3.7.3 using inlay technique.

The woven structure applied to the resistor sections was a horizontal double cloth based on plain weave, where the resistor inlay was only applied to the top cloth. Each resistor required specific extra warp threads to be woven either on the top cloth or bottom cloth; therefore, the structures for the three resistors differed slightly depending on which extra warp threads were active on each cloth. Resistor1 was connected to extra warp thread 1; resistor2 connected to extra warp thread 2 and resistor3 connected to extra warp thread 3. The extra warp threads that were not used were woven onto the back of the fabric.

The resistors were only required to interact with specific extra warp threads on the left side for the first and last pick; this was interwoven three times to ensure a connection for both these picks. The remainder of the inlayed resistor track was woven on the top cloth without any other interaction with extra warp threads. The remainder length was built into this space in isolation to securely position and function as a resistor. The interacting extra warp thread with the resistor track required breaking in the finishing process to enable the current to flow through the resistor – areas of break are illustrated in Figure 5.12.

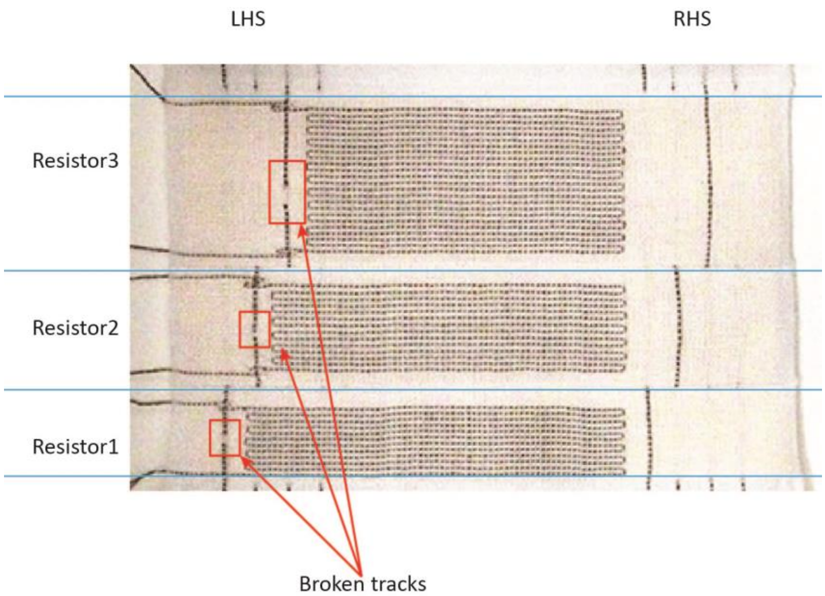


Figure 5.12 RGB colour mixer resistors' broken extra warp tracks

Once the complete resistor conductive yarn length was woven in, several picks of polyester yarn were woven to extend the double cloth. Once this section was completed, the double cloth was opened to place a strip of calico (cotton fabric) into the pocket to avoid short circuits between the extra warp threads and the resistor. The next structure was then woven to seal the double cloth pocket and trapping the calico.

5.3.1.4 Sections 6, 8, 10 and 12: Tracks

The main purpose of the track sections was to integrate the warp conductive threads into the woven fabric securely through to the next section. The track sections were woven in 2/74s spun polyester. Section 12 was constructed with a single cloth, where all extra warp threads were woven in as plain weave. Sections 6, 8 and 10, differed to section 12, as they were constructed as horizontal double cloths. A selected extra warp thread was allocated to be woven on the top cloth, while the remaining extra warp threads were woven on the bottom cloth of sections 6, 8 and 10. The single extra warp thread was allocated on the top cloth of these sections as this track was broken in the finishing process to act as part of the switch. Therefore, each extra warp thread broken corresponded with either the red, green or blue positive legs of the RGB LED component. The break in the track was designed to match the switch pleated tabs, which were broken in the upper half to ensure contact would be made with the switch contact.

5.3.1.5 Sections 7, 9 and 11: Switches

RGB colour mixer has three switches to independently control the three different colour lights; red, green and blue, which could be activated separately, in pairs or all three simultaneously. Sections 7, 9 and 11 correspond with switch1, switch2 and switch3 respectively. All three switches were constructed using the same techniques – woven pleats with inlay of conductive yarn for the switch tab. The pleats are based on a plain weave structure and woven with 2/74s spun polyester.

The woven structure applied to the switches is based on double cloth, as only half of the warp is woven to then construct the pleated form. During the weaving of the pleats, all extra warp threads are not woven, as once the pleated form was gathered, the complete cloth was then re-engaged to re-introduce the extra warp threads back into the cloth. The pleated form is positioned upright in relation to the rest of the cloth; thus, this form does not contribute to the length of the fabric. Plain weave was applied as a cloth join to seal and form the pleated section.

The pleated section was constructed to the size specified. For this sample, each pleated switch was required to be 2cm high. Each pleated section was woven for 4cm, with the inlayed conductive yarn tab woven into the first 2cm on the left side, as this section was required to make contact with the broken track also positioned on this side. The pleats were constructed as described in section 4.3.6.12. Once the pleats were formed, they would be pressed over to connect the corresponding broken track to connect the circuit.

5.3.1.6 Section 13: Battery holder

This section of the circuit had a specific function – to hold the battery and act as connectors to deliver power from the battery source to the complete circuit. The section was woven using vertical tube double cloths, where blocks A and C were treated equally (i.e. the same double cloth structure applied – DC1), and block B had the alternative double cloth applied – DC2. The double cloth layers interchange between the top and bottom cloths to interact at the seams of block B, i.e. where it started and ended. Across this section, a total of three double cloth subsections were formed (as illustrated in Figure 5.13).

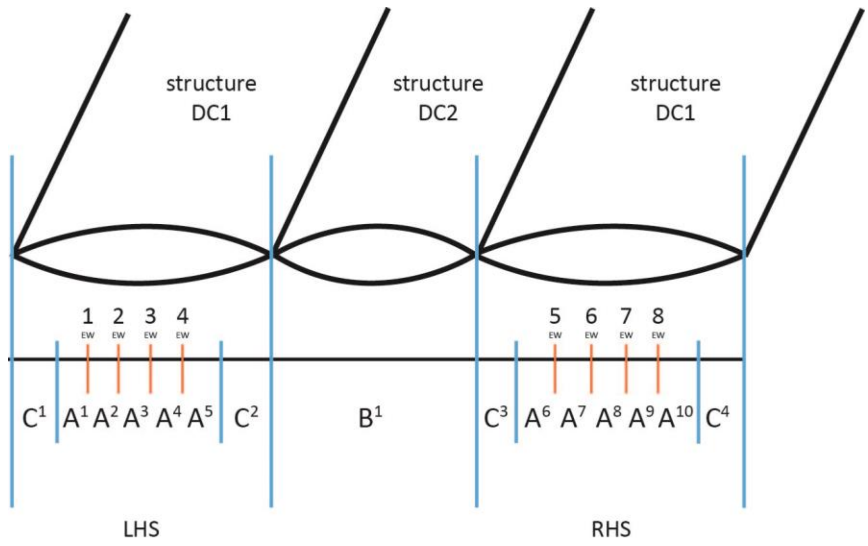


Figure 5.13 Vertical double cloth subsections in relation to warp 003

The design of this section required inlay technique with conductive yarn (Shieldtex 235/34dtex 4-ply) and was also woven with 2/74s spun polyester for the complete section. The position and placement of the conductive yarn determined where the positive and negative track would be built and make contact with the battery. Block B's double cloth was designed to house the battery; therefore, one side would make contact with the positive anode and the reverse with the negative cathode. The design specified block B's top cloth as the positive contact and the bottom cloth as the negative contact. As RGB colour mixer's design positioned the positive tracks on the left and negative on the right, the battery contact also needed to interweave with the respective tracks.

The entire battery holder section was constructed in double cloth, where all extra warp threads were woven on the top cloth. The section was constructed with 0.3cm polyester before the first battery contact was woven on the left side (the positive contact). This was interwoven with extra warp threads 1 – 4 by weaving conductive yarn weft only on LHS of the top cloth picks of block A and C. This was achieved by inserting the conductive yarn from the left side across blocks A and C, and picking the conductive yarn out of the top of the warp at interception point 1 (Figure 5.11). A polyester yarn was woven across the complete sample to tie in all warp yarns. The next pick wove the top cloth of block B and bottom cloth of blocks A and C. The conductive yarn weft was reinserted into interception point 1 and taken out at interception point 2, while another polyester pick was woven across the complete sample to tie in all ends. These two steps completed the first pick of the positive battery contact. For the next pick, only polyester yarn was woven across the sample, as this wove the bottom cloth of block B and top cloth of blocks A and C. At the third pick the conductive yarn weft was inserted into interception point 2 and taken out at interception point 1, while weaving polyester yarn across the samples. This pick wove the top cloth of block B and bottom cloth of blocks A and C. The fourth pick inserted the conductive yarn into interception point 1 and wove through to the left side and also wove a polyester yarn across the sample. This completed the second pick of the positive battery contact. There were a total of six positive contacts woven using the same process.

On completion of the positive battery contact, 0.3cm of polyester was woven using the same woven structure. This was the separating space between the positive and negative battery contacts to avoid short circuits and cross contact over the battery. The negative contact was woven next, using a similar approach to the positive contact. However, this time the conductive yarn weft was inserted from the right side of the warp, to interweave with extra warp tracks 5 – 8 (negative tracks). The conductive yarn was woven on the top cloth of blocks A and C and on the bottom cloth of block B, where this arrangement followed the sequence of the vertical tube double cloth structure. The conductive yarn was taken out at interception point 1 and a polyester yarn was woven across the complete section to tie in all warp ends. The next pick woven used only polyester yarn, as this wove the top cloth of block B and bottom cloth of blocks A and C. The third pick reinserted the conductive yarn at interception point 1, through to the right side of the warp. A polyester yarn was woven across in the same pick; this wove the bottom cloth of block B and top cloth of blocks A and C. Six picks of conductive yarn were woven for the complete negative battery contact. To complete the battery holder section, a further 0.7cm was woven in polyester yarn to build the height of this section to house 20mm wide 3v button battery. This part of the section was deliberately designed with a larger portion of polyester yarn, as the reverse of the sample was to be slit for access for the battery. Four picks of plain weave were woven to seal the section.

5.3.1.7 Section 14: Battery clamp

The final section of the sample was intended to hold a small (1cm diameter x 0.1cm thickness) disc neodymium magnet double cloth pocket in block B. The same vertical tubes double cloth woven structure was applied to this section, as the central block was required to hold the magnet to enable it to make contact with the below parallel section where the battery would be held. The magnet section was designed to flap over or under the battery section to help clamp this into position for stable contact with the positive and negative woven contacts.

The battery clamp section was woven with polyester yarn for the complete section of 1.2cm, where the extra warp threads were woven in on the top cloth. However, the extra warp did not serve any purpose in this section, as it was woven in to securely position it from the previous section. Once the battery clamp section was complete, the double cloth was opened on the loom using plain weave structure and the magnet was placed inside block B pocket. Plain weave was woven to seal the double cloth and weave a selvedge to the complete sample.

5.3.1.8 Finishing RGB colour mixer

Once the sample was cut off the loom, finishing was applied. The broken tracks needed to be cut accurately where the design specified, as this could potentially affect the circuit function. The circuit was tested as finishing was applied. The completed woven e-textile circuit can be viewed in Figure 5.14.

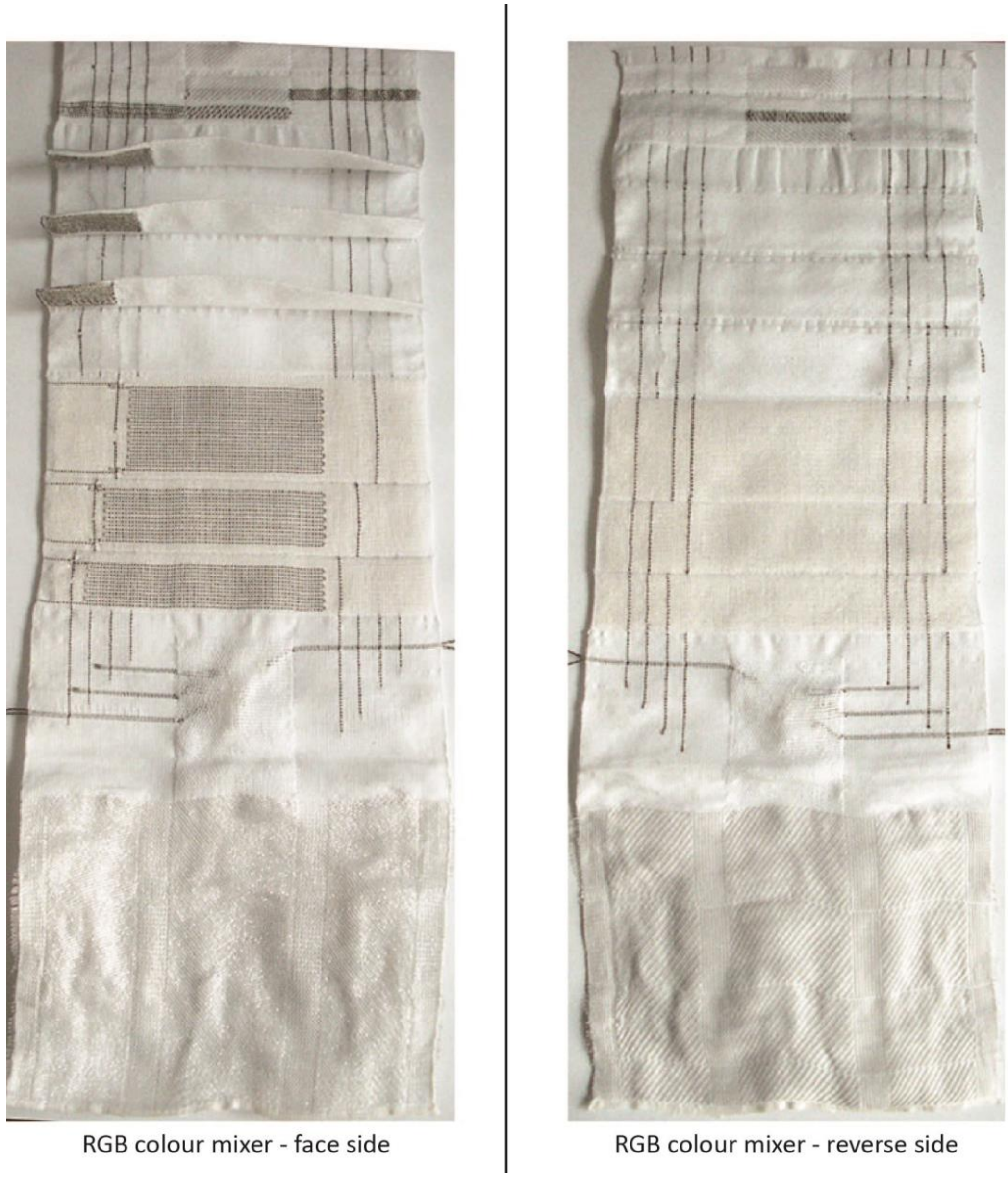


Figure 5.14 Completed RGB colour mixer woven e-textile sample (14.5 x 41.5cm)

5.4 Results : RGB colour mixer

The design process applied to the development of RGB colour mixer aimed to combine woven textile form and electronic function, into a simultaneous process for a specific woven soft circuit. In addition, the circuit aimed to independently control three outputs from an RGB LED – this was successfully achieved by implementing a design led process where the languages of weaving and electronics were amalgamated. The woven execution reflected on the researcher's weaving expertise to integrate electronic function into the design to attain the desired outcome. The methodical execution process enabled the woven architecture to form while simultaneously integrating electronic functionality, harnessing existing woven textile qualities.

The function and form of RGB colour mixer were integrated into the final samples. As illustrated in Figure 5.15 and Figure 5.16, the circuit design is mapped onto the design specification, which is then translated into the final sample design. The colour arrows in these images indicate specific parts of the circuit that interpreted into the design specification and then the e-textile.

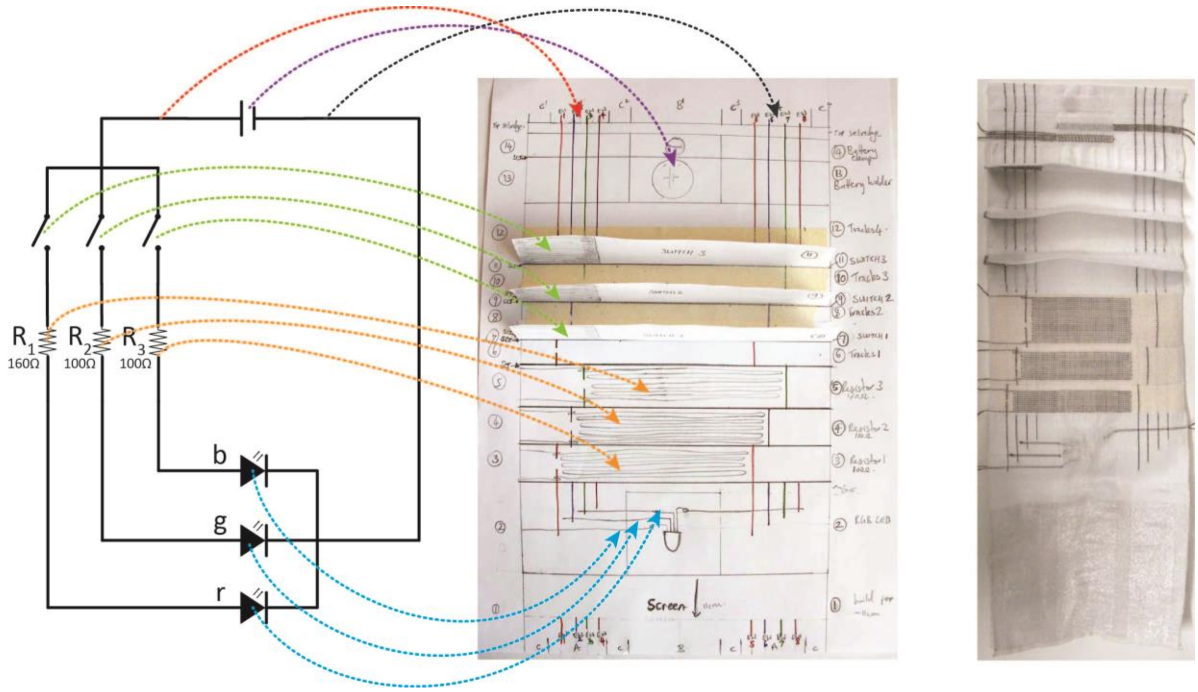


Figure 5.15 RGB colour mixer sample circuit design mapped onto the design specification

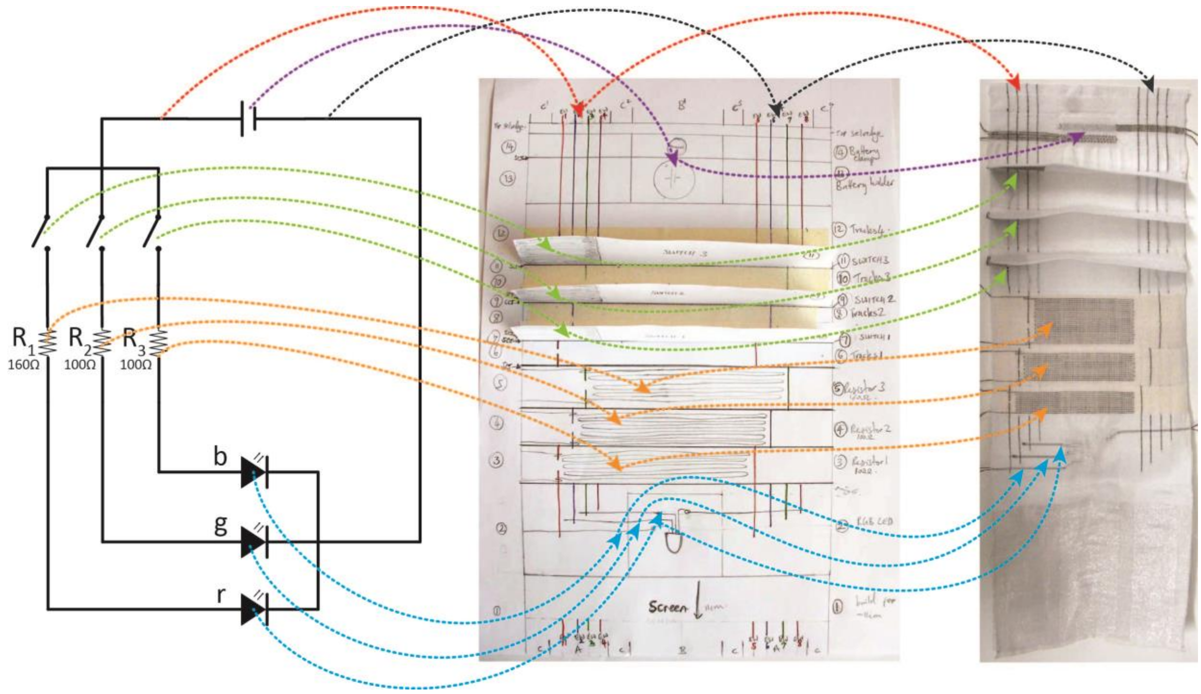
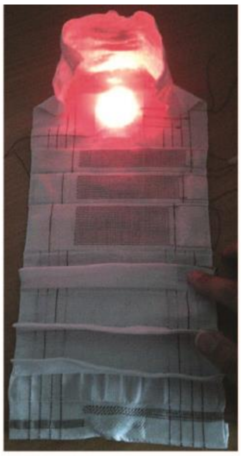


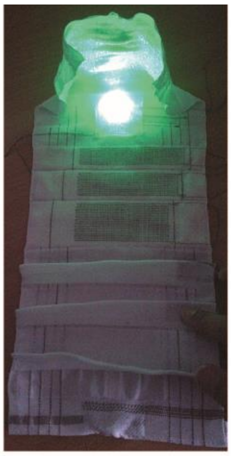
Figure 5.16 RGB colour mixer sample circuit design mapped onto the design specification and final sample

On completion, two button batteries were inserted into the battery holder and the output voltage was measured at 5v (as required by circuit). The screen was moulded to shape and the switches were tested first independently, then in pairs and finally simultaneously, testing all possible output options. The results can be viewed in Figure 5.17.

Pressing the switch for each colour activated the corresponding colour light. If held simultaneously with another colour, the colours would mix for an alternative output to the single colour. On activating all three switches, white light appeared. For the switch to activate a colour light, the tab needed to be held over the exact spot where the corresponding track was broken; this was possible as the switch conductive tab was woven far bigger than the broken track area. The malleable screen proved effective to amplify the effect of the emitted light, particularly in darker environments.



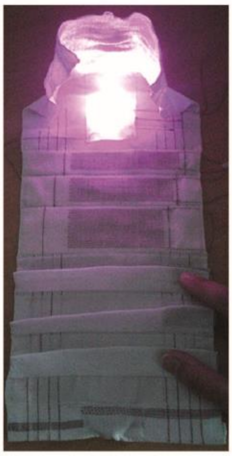
Red light



Green light

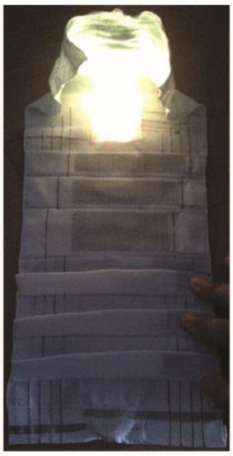
Blue light

Single colour activated



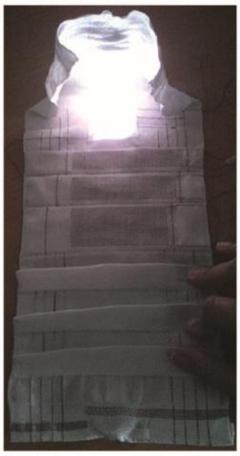
red+blue=
Purple light

blue+green=
Turquoise light



red+green=
Yellow/Orange light

Two colours activated



red+green+blue =
White light

Three colours activated

Figure 5.17 RGB colour mixer sample results with all options for active lights

The circuit outcome matched the design specification for this sample, where the switch forms and circuit layout were translated into weave. The weaving process methodically followed the design specification where all details were executed and translated as required.

On inspection of the final sample, some woven mistakes were noted on extra warp threads that were inconsistent; these were loom errors. Possible reasons could have been the shaft may not have lifted, warp threads may have been tangled for unclear shed, or tension may have been unbalanced). These lifting errors did not affect the function of the circuit. In addition, the first interconnection point of resistor1 across extra warp thread 1 was only interwoven once as opposed to three times, as per all other resistor interconnections. This was due to a weaving error, but did not hinder the e-textile function.

Although overall the circuit was successful, there were still opportunities for aspects of the design to be developed further. The next section will analyse the executed design, drawing particular focus on areas were possible objectives presented opportunities for refinement in subsequent design iterations.

5.5 Analysis: RGB colour mixer

The combinations of design principles (tacit thinking/ knowledge, implicit and explicit knowledge, praxis, abductive theory, synthesis, reflective practice and creativity) were all significant contributors to the design process that led to the final outcome of RGB colour mixer sample. Reflections *on* the results of RGB colour mixer enabled analysis of this sample, which were later used for inspiration and design development for actuators design iteration 2.

The integration of a standard 5mm RGB LED functioned successfully and proved it was possible to integrate in a woven e-textile. However; the preparation for integration (i.e. bending of legs), three dimensional form and overall size made this clearly visible and protruding from the final e-textile sample. Although the positions of the legs were separable, the extent to which this could be applied was limited; thus, the placement of the weft conductive yarn was determined by the leg positions. The size of the RGB LED component required a large enough pocket to house this in, taking up valuable surface area of the sample. In a later iteration for sample RGB colour mixer v2 module (W005ET008), the standard 5mm RGB component inspired an own made flexible RGB component of smaller dimension (2cm x 0.8cm), and with engineered placement of weft track connections. This enabled a better position of the component to fit the woven architecture for e-textile construction. The development of the flexible RGB component (inspired by the RGB colour mixer sample) allowed for easier integration with the woven component.

The double cloth section housing the RGB LED component was found to be too loose when the sample was off the loom, particularly as the three dimensional form of the component would alter the weft/ warp threads when off tension. This issue had partly occurred as the adjacent blocks were woven as single cloths; therefore, the weft compression across the complete sample was looser on double cloth and tighter on the single cloth. The design iteration of RGB colour mixer v2 module (W005ET008) altered this design feature to use double cloth structure throughout this section to avoid this problem.

The warp draft for RGB colour mixer was constructed on an existing warp, which meant the positions of the extra warp threads were already predetermined. In this warp draft, pairs of extra warp threads were lifted simultaneously on both the left and right side. As a consequence of simultaneous lifting of pairs of extra warp threads, they could not be independently addressable via woven structures. Therefore, cutting breaks in the circuit in the finishing process was difficult to isolate specific integrated woven threads. This would have been easier if the broken tracks could have been floated over the warp, and was a design consideration applied to subsequent warp draft designs as it enabled far more control over extra warp conductive threads.

The resistor sections had insulation layers of calico that were placed between double cloth layers to avoid short circuits. It is possible to design a warp draft that would negate the need for this calico insulation, or even weave this section as a triple cloth that would integrate an intermediate layer of cloth. Although the calico worked for this sample, future samples integrated this feature via the weaving where possible.

The switches functioned particularly well, as the light weight of the polyester woven pleats made these easy to manoeuvre. As previously noted, the breaks in the extra warp tracks for the switches were very small and required mapping of the conductive switch tab to activate the switch. For future development, multiple warp tracks could control the same switch, hence, enabling a larger area to make switch connection.

The battery clamp was effective during its use; however, as this was a single clamp, it only helped to securely contact one side. Future developments of this concept investigated double battery clamps that helped keep contact with both positive and negative tracks – this is further discussed in chapter 7.

The findings from the analysis of RGB colour mixer were used to inspire new ideas for further e-textile design iterations across the three categories of actuators, circuits and modules, as some findings were applicable to a cross range of e-textile designs. It was imperative to scrutinise the design of this sample, as gaining a deeper understanding of how this design's features could be improved were initialised in future iterations. The design process cycle would in turn help to refine details even further. In doing so, this helped to build further knowledge by gaining an in-depth insight into how woven e-textiles could be designed through creative practice led processes.

Although the making execution was a manual process where multiple manipulation techniques have been applied to achieve RGB colour mixer sample, these processes have opportunities to be adapted for commercial applications. This example has highlighted some methods applicable to woven e-textiles. The next chapter will discuss the category circuits and relate the woven e-textiles developed to the design process, investigating different woven e-textile concepts.

6 Circuits

This chapter will discuss the circuits category of woven e-textiles as indicated in Figure 4.34. The circuits category was divided into two groups; 2A integrated components and 2B malleables. Category 2A focused on complete circuits with integrated components in different combinations, while category 2B focused specifically on malleable e-textile circuits with integrated components. All of the samples developed in this category were designed as complete circuits; however, in group 2B malleables, the initial pilot sample inspired three further iterative samples. Here, each iterative sample design was developed in three individual design cycles, all based on the malleables concept. Category 2B malleables' design process map can be viewed in Appendix H.

This chapter will focus specifically on the circuits category 2A integrated components. In this category an initial pilot sample led to the development of three iterative design cycles, where each design was inspired by previous findings. As per the actuators category in chapter 5, the samples developed in category 2 circuits were not the ultimate findings as the design process is able to continue for further iterative outcomes. This chapter discusses circuits category 2A's pilot sample and subsequent design iterations. The iterative outcomes are mapped against the design process to explain their evolution. This chapter will also concentrate specifically on one sample to describe its design development. This will be a concise narrative in comparison to chapter 5's in-depth design development description of RGB colour mixer sample, as the same design flow applies between stages applies.

6.1 Map navigation: Circuits – 2A integrated components

Figure 6.1 illustrates the circuits category 2A integrated components design process map. The map has grouped the samples of this category onto four levels according to where they were developed in relation to the design process and the outcome of an iterative cycle. The samples in each group/ level did not necessarily have a relationship within the same design iteration, but did affect subsequent outcomes in following design iterations. The original design objective in this category aimed to integrate a complete circuit simultaneously through methods of weaving.

As per chapter 5, the design process was applied using the same approach. The pilot sample's development followed through from the design objective to inspiration of textile form, via applying explicit knowledge gained from previous samples in other categories. These elements were synthesised to develop potential ideas in the ideation stage. The idea and concept of weaving three independent LEDs into a circuit was chosen to progress into the sketching stage, particularly as multiple LEDs in a woven e-textiles had not been investigated previously in this research. Prototyping the sample helped position the components and initiated a circuit design to configure weave planning and a design specification.

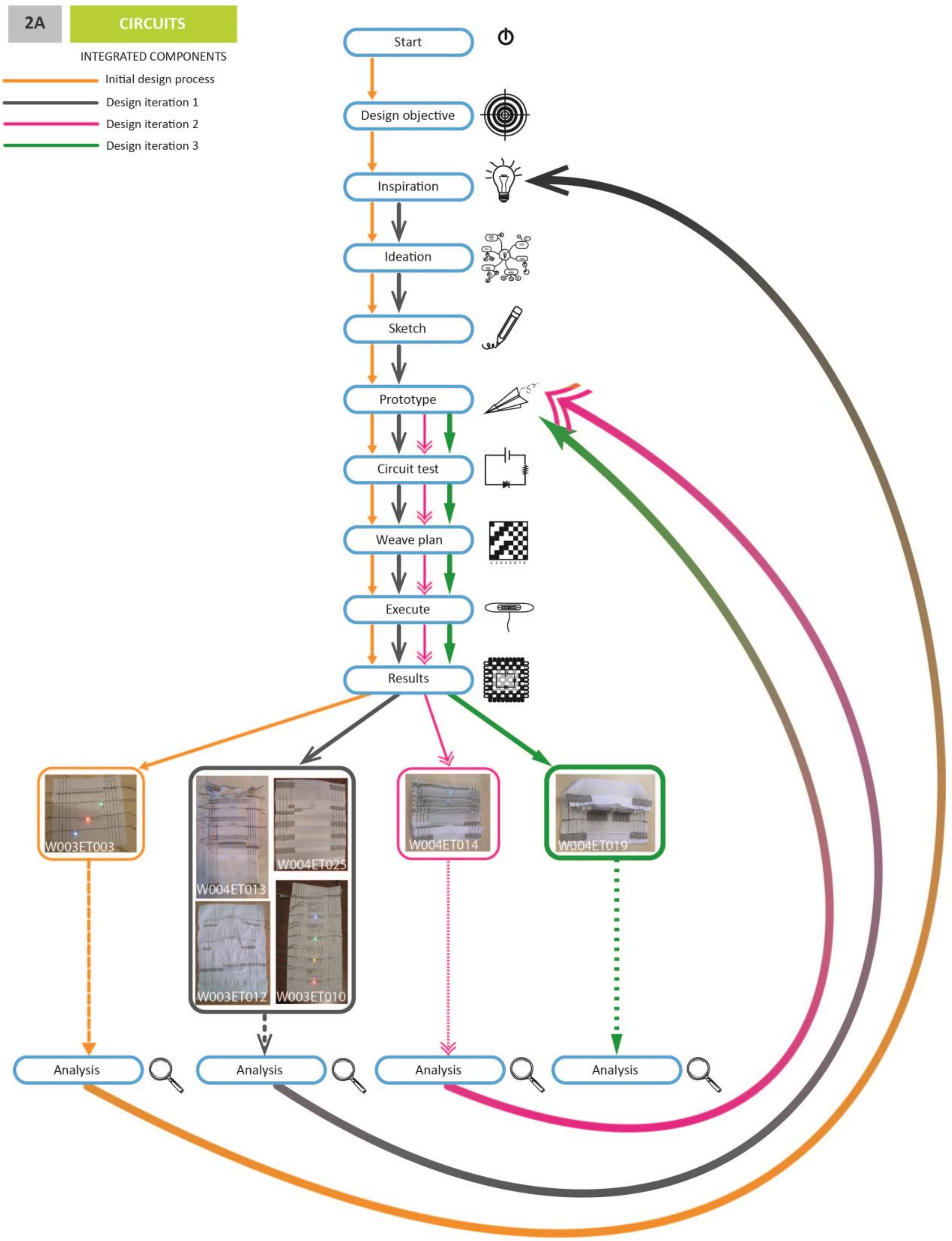


Figure 6.1 Circuits 2A integrated components design process map

A design specification was prepared, defining the combination of circuit and weave structures; this was applied to the woven execution stage. The outcome of this initial design process was a pilot sample Trio RGB (sample code W003ET003) – a parallel integrated circuit comprising of three independent LEDs with an integrated battery holder.

The development of the initial sample followed the orange path in the design process (Figure 6.1). Analysis of Trio RGB sample (broken orange arrow) was used in the design process at the inspiration stage. The findings from Trio RGB were used to inspire and develop the results of design iteration 1 (orange-grey arrow). This intercepted the design process at the inspiration stage and followed through the remainder of the design process (grey path). The results of design iteration 1 were analysed to feedback on the design process (grey-pink arrow), intercepting at the prototype stage for design iteration 2. The findings from design iteration 1 triggered specific ideas (tacit thinking) for prototyping. This was closely related to previous work of a specific sample/ collection of ideas that needed resolving from the prototyping stage onwards. Therefore, design iteration 2 (pink path) followed the design process from the prototyping stage through to the results, where the outcomes were analysed (broken pink arrow) and used to instigate design iteration 3 (pink-green arrow). The findings from design iteration 2 also intercepted the design process at the prototyping stage, as the outcomes inspired a new idea closely related to the concept of design iteration 3. This led to design iteration 3 (green path) which followed the design process from the prototyping stage through to the results, which were analysed for future iterations.

This section has overviewed the design process for circuits category 2A integrated components. The following sub sections in this chapter will specifically focus on one sample within this category – corrugated pleat LED v2 (sample code W004ET019).

6.2 Corrugated pleat LED v2

The sample corrugated pleat LED v2 (abbreviated to CPLEDv2) was an outcome of design iteration 3 in category 2B integrated components. The design development for CPLEDv2 was initiated from the prototyping stage in category 2B design process map. Thus, CPLEDv2's design objective matched the category's original design objective (to integrate a complete circuit into the woven design). The following section 6.2.1 will explain the design process related specifically to CPLEDv2.

6.2.1 CPLEDv2: design process

Figure 6.2 illustrates the design process for sample CPLEDv2. Although this sample was arrived at via design iteration 3, the findings from initial design process (pilot sample), design iteration 1 and design iteration 2 contributed significantly to the development of CPLEDv2. As CPLEDv2's development was instigated at the prototyping stage, from here forward the development in the design process is exclusively related to this outcome. Prior to this stage in the design process, previous stages were related to earlier iterations (as indicated with respective horizontal lines in Figure 6.2), where a direct link impacted the development of CPLEDv2.

As design iteration 1 in category 2A integrated components had several samples developed on this level, one specific sample, corrugated pleat LED angled[1] (W004ET013) led to the output of corrugated pleat LED v1[2] (W004ET014) in design iteration 2. Therefore, inclusive of the initial pilot sample, a total of three samples were directly linked to the development of CPLEDv2. The following subsections will explain how each stage of the design process impacted and helped progress CPLEDv2.

[1] *Corrugated pleat LED angled will be abbreviated to CPLED-A*

[2] *Corrugated pleat LED v1 will be abbreviated to CPLEDv1*

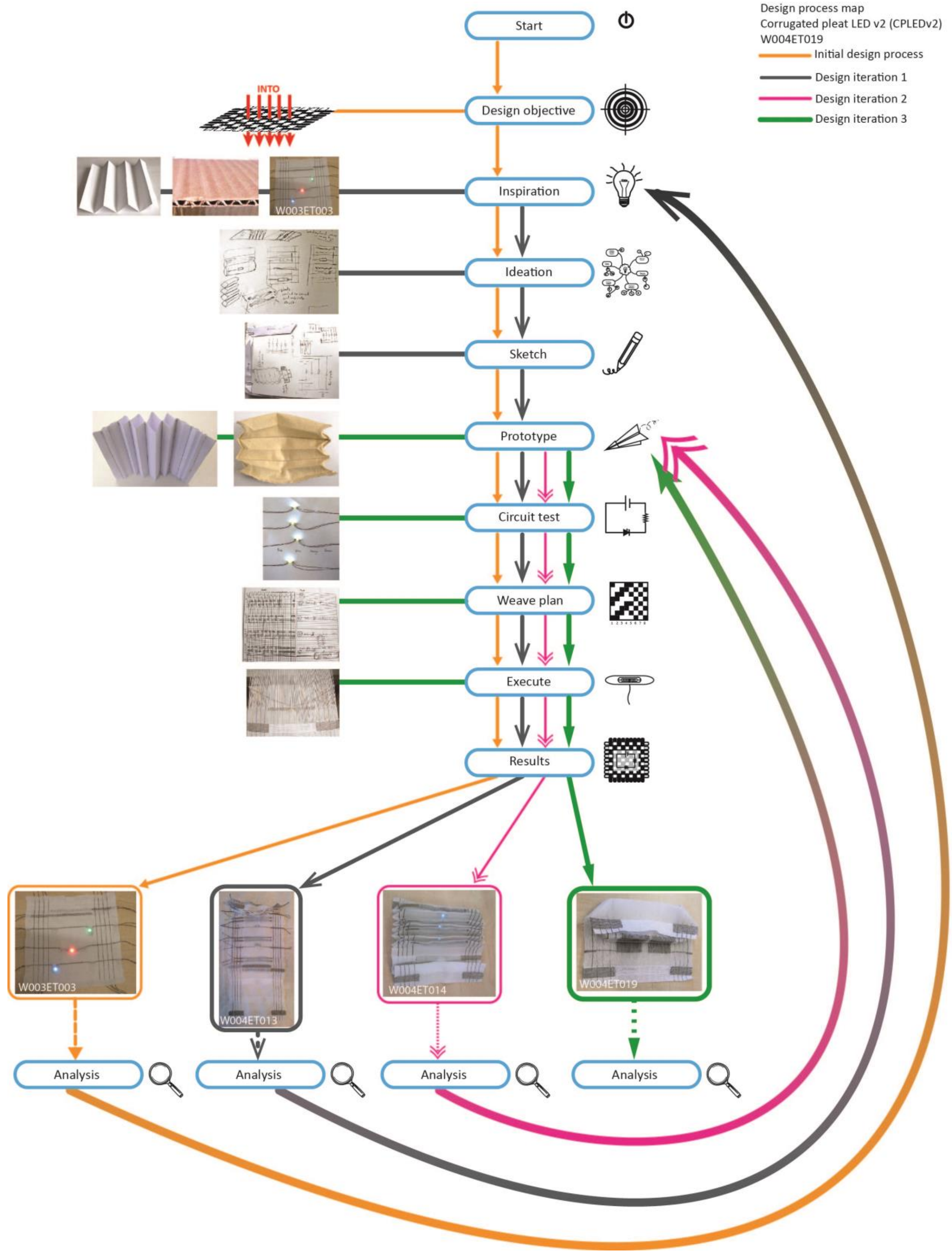


Figure 6.2 CPLEDv2 design process

6.2.1.1 Inspiration: CPLEDv2

The inspiration source relates to the development of CPLED-A, as this was one of the direct outcomes of design iteration 1. Trio RGB sample was also an inspiration source that led to the development of CPLED-A, as this was the initial design process outcome. Trio RGB sample had been analysed and reflected back into design iteration 1 to develop the outputs of this cycle (engaged praxis). The analysis of Trio RGB confirmed three LEDs placed in a parallel circuit can be successfully integrated into a single piece of weaving; this was an idea for further investigation. This inspiration input subsequently impacted the outcomes of design iterations 2 and 3 as they were directly linked to CPLED-A. The original design objective was still relevant to CPLED-A, CPLEDv1 and CPLEDv2, as Trio RGB sample was the initial output of the design objective and is subsequently connected to all following outputs. Therefore, the design objective to construct integrated circuits into woven textiles via different methods still applies to all iterations in this category.

The physical form of CPLED-A was inspired by a piece of paper folded like a fan and the cross section of corrugated card. These structures were of interest to the researcher as their forms related to woven structures (implicit knowledge), particularly three dimensional forms that are related to previous work developed by the researcher (Hemmings, 2012 pp.42-45; Quinn, 2013 pp.290-297). On analysis of the inspirational forms, the researcher was able to reflect on these (tacit thinking) and thought it was possible to translate them into physical woven structures. This sequence of events involves implicit and explicit thinking, reflective practice, abductive thinking, creativity and synthesis. The articulation of the fan folded paper was a quality that was potentially adaptable to woven textiles due to its flexibility. The corrugated card cross section was a structure studied by the researcher, where the isolated meandering central card was identified to translate into possible weaving structures using multilayer cloths. These were preliminary thoughts that were followed through to the ideation stage.

6.2.1.2 Ideation: CPLEDv2

The ideation stage sought to combine and synthesise the design objective (integrated circuits) and the inspiration source (Trio RGB findings, fan pleat and corrugated card structures). Through reflecting *on* and *in* the ideation stage, potential concepts to develop further were established (engaged praxis and abductive thinking) – this included concepts for CPLED-A. As CPLED-A led to the developments of CPLEDv1 and CPLEDv2, these original ideation concepts were common to all outputs from design iteration 1 (i.e. to CPLED-A, CPLEDv1 and CPLEDv2). The ideation stage recorded initial thoughts as notes and provisional sketches to collect an overview of all considered ideas, engaging tacit thinking into explicit knowledge and applying creative thinking. In this stage, ideas for woven forms were also being considered, as the inspiration for physical forms were drawing direct links with potential three dimensional structures (Figure 6.3). In addition, the findings from Trio RGB were significant factors in the ideation stage that led to thoughts on component and circuit placements.

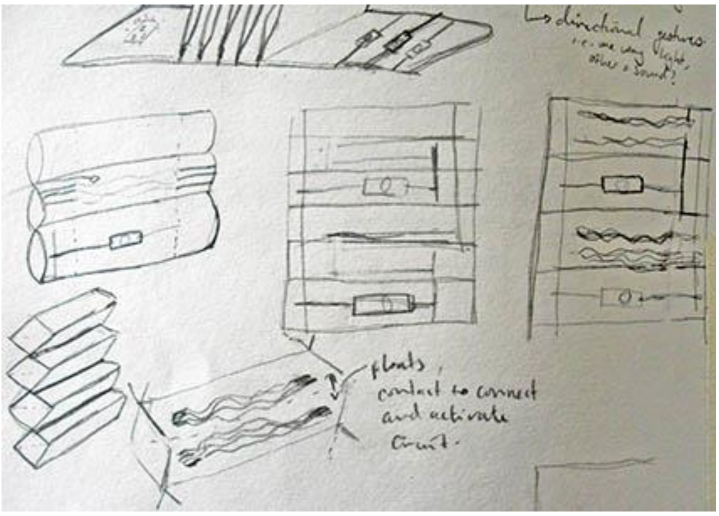


Figure 6.3 CPLEDv2 ideation notes and initial sketches

6.2.1.3 Sketch: CPLEDv2

The sketch phase selected a focused idea to develop; this was related to CPLED-A. The sketches investigated pleated structures, visualising these as three dimensional textiles inspired by the fan pleat and corrugated card. Working through sketching began to reveal ideas of combing independent LEDs in a three dimensional structure through the reflection and synthesising of selected ideas (tacit knowledge, implicit, explicit and abductive thinking). The sketches resembled a pleated structure in three dimensional sections, where LEDs could be placed in a parallel circuit (Figure 6.4).

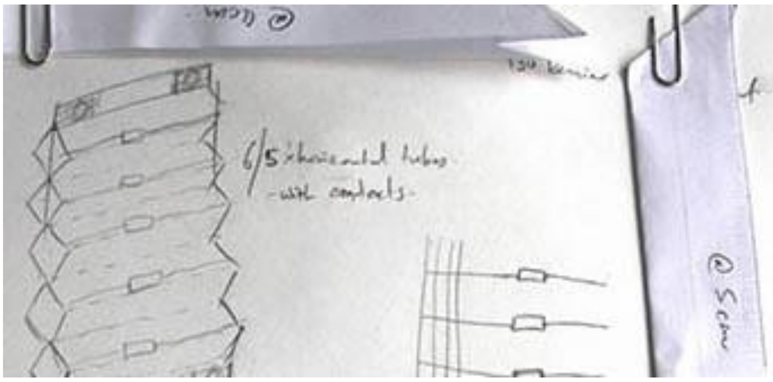


Figure 6.4 Sketches for CPLED-A development

An integrated battery holder was also considered. In this stage, weaving knowledge was being implicitly considered and explicitly recorded via sketches. Three dimensional woven pleated forms is a technique familiar to the researcher from previous work. Final sketches were selected to focus on in the prototyping stage.

6.2.1.4 Prototype: CPLEDv2

The development for CPLEDv2 intercepted the design process at the prototyping stage. Therefore, the prototypes discussed in this section are specific to CPLEDv2. Although CPLEDv1 and CPLED-A also channelled through prototyping stages in their respective design iterations, the developments were specific to the corresponding samples. However, as the findings from previous iterations were relevant to the development of CPLEDv2, (i.e. via inspiration) the prototyping of this sample was partially developed by knowledge gained from the analysis of previous iterations, i.e. synthesising abductively all findings for the new sample.

The prototyping stage synthesised findings from previous design iterations that were relevant to the development of CPLEDv2. The objective of sample CPLEDv2 remained as per previous samples in this category, but with new insights to develop. This included a corrugated pleated structure with an integrated circuit based on three dimensional pleats without floating connectors as per CPLED-A and CPLEDv1.

The first prototypes for CPLEDv2 visualised the final sketches three dimensionally made from paper. The paper models determined the structure of the design and the points of articulation. However, on reflection of these prototypes, the final design was iterated to seal the edges (as per CPLED-A and CPLEDv1). The sealed edges proved difficult to form on the paper prototype models as the scale was too small to be manipulated and the paper became brittle; although, the paper did depict the general form, if not perfectly. The prototype structure was developed into calico fabric by pinning, machine sewing and ironing. The result enabled a clearer three dimensional visualisation expected of the complete form design (Figure 6.5). The fabric quality of calico reacted differently to paper, helping to visualise and confirm the articulation aspect. This structural form was moved to the circuit testing stage. The pleated hollow forms of CPLEDv2 would integrate and hold LEDs, as per CPLED-A and CPLEDv1; though in this iteration, the pleated sections would be of equal proportion for consistency in the collapsed structure.

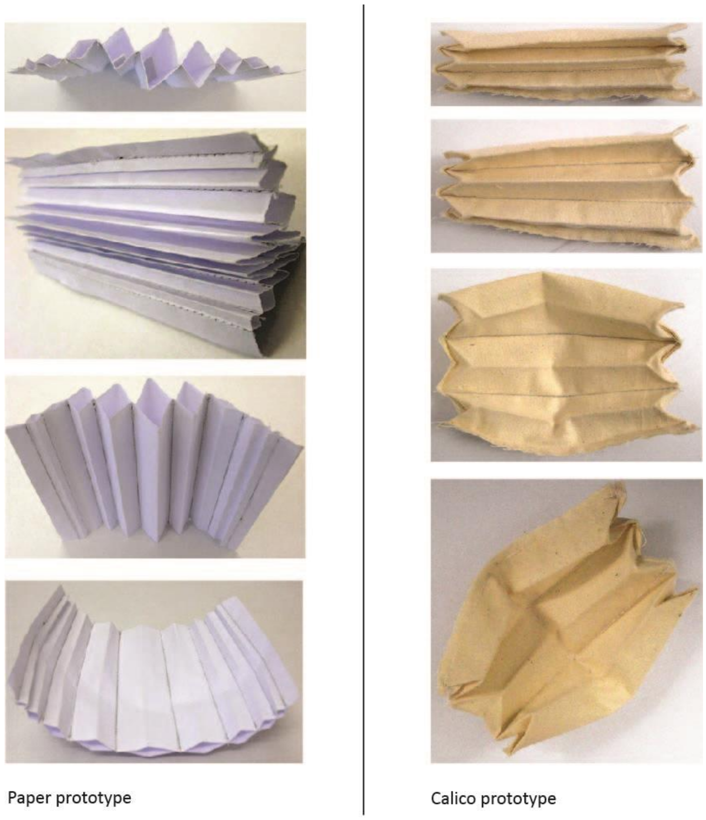


Figure 6.5 Images of paper and fabric prototype models for CPLEDv2.

6.2.1.5 Circuit test: CPLEDv2

The circuit layout for CPLEDv2 was partially inspired by the previous iterations of CPLED-A and CPLEDv1; however, these previous samples used Lilypad LEDs, included floating conductive yarn as connector switches and had integrated battery holders. On reflection of these previous samples and of the prototypes for CPLEDv2, it was decided to alter and to exclude an integrated battery holder (although, it was possible to design an integrated battery holder). Instead, a detachable battery holder would be woven separately that could be attached via magnetic connectors – a theme investigated in this research when exploring modular e-textiles and methods of connection (section 4.3.7.1). The simplicity of the prototype structure was the intended aim for CPLEDv2's e-textile design form.

During the design development of CPLEDv2, own made LEDs (as discussed in section 4.3.7.2, Figure 4.32) were also progressing concurrently. CPLEDv2 aimed to integrate double sided own made LEDs v2, where a single PCB had two surface mount LEDs (one on each side of the PCB) in a single component. As LEDs are directionally dependent on current flow, the surface mount LEDs were mounted in opposite directions. Hence, this aspect was built into the design for CPLEDv2, as this would enable two different LED light outputs depending on the direction of current flow. The components did not have resistors, so woven resistors were integrated into the circuit. Own made LEDs v2 were successful in proving this concept.

The warp draft for this sample was already set up. Although the warp could have been altered, it was acknowledged at this stage to help include of all the design components. A parallel circuit was designed to run in relation to the warp tracks with integration of own made LEDs v2. Resistors also required integration in the circuit (resistor values were calculated from the manufacturer's specification of the surface mount LEDs). Figure 6.6 illustrates the circuit schematic for CPLEDv2. This circuit plan was also used to test four own made LEDs v2 components.

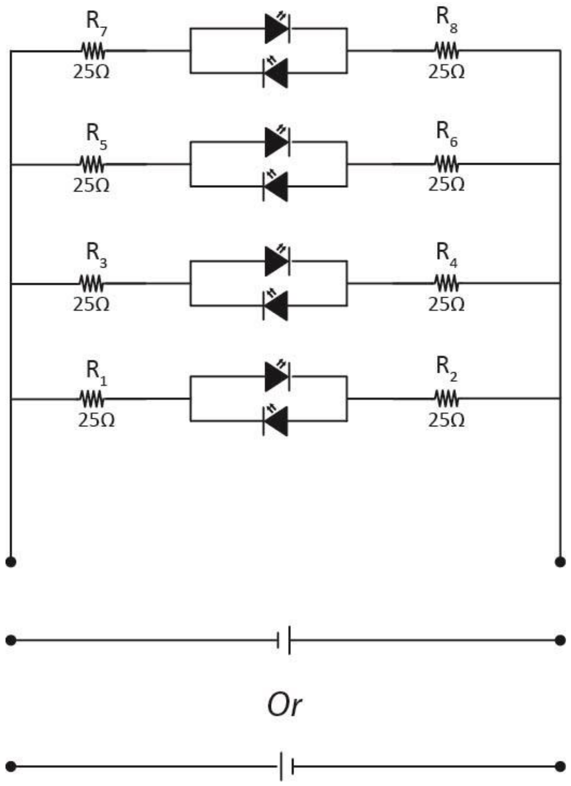


Figure 6.6 Circuit diagram for CPLEDv2

As the own made LED components were double mounted in opposite directions, the current had the option of flowing in one of two directions; therefore, a button battery could be inserted in either direction for a choice of outputs. The own made LED v2 components prepared for this circuit were a colour light on side one (pink, orange, blue or green) and white light on side two. The known current needed for the surface mount LEDs was 20mA and the known LED voltage was 2v. This meant running a parallel circuit from a 3v button battery (source voltage) required the calculation of resistance using Ohm's law V = IR (voltage = current x resistance). The voltage drop would be calculated as source voltage (3v) minus required voltage (2v), hence:

3 – 2 = 1v

Therefore, the resistance would be calculated on this value, using Ohm's law:

V (in volts) = I (in amps) x resistance (in ohms)

1 = 0.02 x R

1/0.02 = R

∴ R = 50 Ω

Based on these calculations, 50Ω would be required per LED component. For this design the resistors were integrated as woven resistors. The conductive yarn weft attached to the component would be used to construct the resistors as well as function as the circuit contact track between component and circuit. As the component had two lengths of conductive weft attached (left and right side), the 50Ω resistor value was split to 25Ω per side as each component's two resistors of 25Ω would run in series within the parallel circuit. Conductive weft attached to both sides of the component used Shiledtex 235/34dtex 2-ply 100Ω/m in doubled threads due the components double threading. This meant a minimum of 50cm would need to be woven on each side using 1:1 picks of conductive yarn (Shieldtex 235/34dtex 2-ply 100Ω/m) and insulated non-conductive yarn (as per woven technique discussed in section 4.3.7.3) to construct 25Ω resistors. The woven resistors were designed to be integrated either side of the component to utilise this space and to keep the weft equally distributed for a balanced cloth.

6.2.1.6 Weave plan: CPLEDv2

The weave plan for CPLEDv2 combined the finalised ideas in the circuit plan and the form of the textiles in the prototyping stage to prepare a design specification. This would be used for the woven execution.

The concept for CPLEDv2 was a succession of tubular sections that were pleated in the finishing process to enable the pleated structure to collapse and articulate. The circuit integrated four independent components of own made LEDs v2, which were woven into the hollow form of the pleated tubular sections as a parallel circuit. The LEDs were encased in the hollow pleated sections; therefore, when activated the light is contained and emitted in each pleated hollow tube.

The warp draft was an existing set up warp (warp 004), this was previously referenced when circuit testing for this sample. On assessment, the existing warp set up was found to be adequate to design CPLEDv2 on, and did not require altering. The warp was set on two main blocks (block A and block B) using 2/74s spun polyester for the ground warp sett at 84epi (42epi per cloth at double cloth), with an extra warp of conductive yarn (Shiledtex 235/34dtex 4-ply) intercepting block A. The warp was set across a 6" weaving width. Block A was set on shafts 1 – 8, block B was set on shafts 9 – 16, and 8 extra warp threads were set on shafts 17 – 24 (Figure 6.7). Each extra warp thread was allocated to a separate shaft and could therefore be controlled independently, despite intercepting the same block A. The complete draft plan for warp 004 can be viewed in Appendix I.

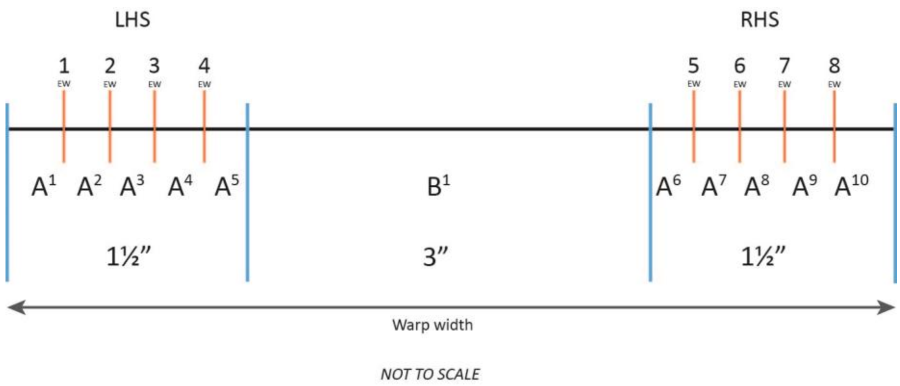


Figure 6.7 Warp draft block proportions used for CPLEDv2 (warp 004)

Referencing the warp draft enabled a clearer association with CPLEDv2's design requirements (i.e. integration of circuit plan and textile form), and resulted in the drafting of a design specification. The design specification tackled some technical issues with combining the design form and electronic function (reflection *in* and *on).* The specification positioned all elements considered and refined them into a single design via tacit thinking, reflection, making implicit thoughts explicit and creatively synthesising the design factors. Previous findings and weave planning from CPLED-A and CPLEDv1 were extremely beneficial at this stage of the design process, particularly as these two previous iterations were closely linked with CPLEDv2's design (function and form). This meant the outcomes of these previous samples influenced the development of this iteration (engaged abductive reasoning and praxis).

The final design specification for CPLEDv2 comprised of four own made LEDs in a parallel circuit, connecting to extra warp tracks on the left and right side across horizontal double cloth sections (Figure 6.8). Each of the four double cloth sections were specified as 5cm in height and designed to hold a LED. Each LED was allocated one extra warp thread on the right and one extra warp thread on the left. As the extra warp threads were independently controlled, the design specified pairs of conductive tracks allocated to each LED. The pairs of extra warp threads were allocated as threads 4 and 5 (shafts 20 and 21), threads 3 and 6 (shafts 19 and 22), threads 2 and 7 (shafts 18 and 23), and threads 1 and 8 (shafts 17 and 24); these were introduced into the circuit in this order.

The extra warp threads were connected to double-sided conductive magnetic connectors on the top and bottom of the sample. Therefore, the design enabled connection to an independent battery holder on either the front or back of the CPLEDv2, enabling four options to connect a power source. The conductive extra warp tracks were designed to weave on the front of cloth until interwoven with a LED component, at which stage the extra warp thread would be woven into the bottom layer of the double cloth structure.

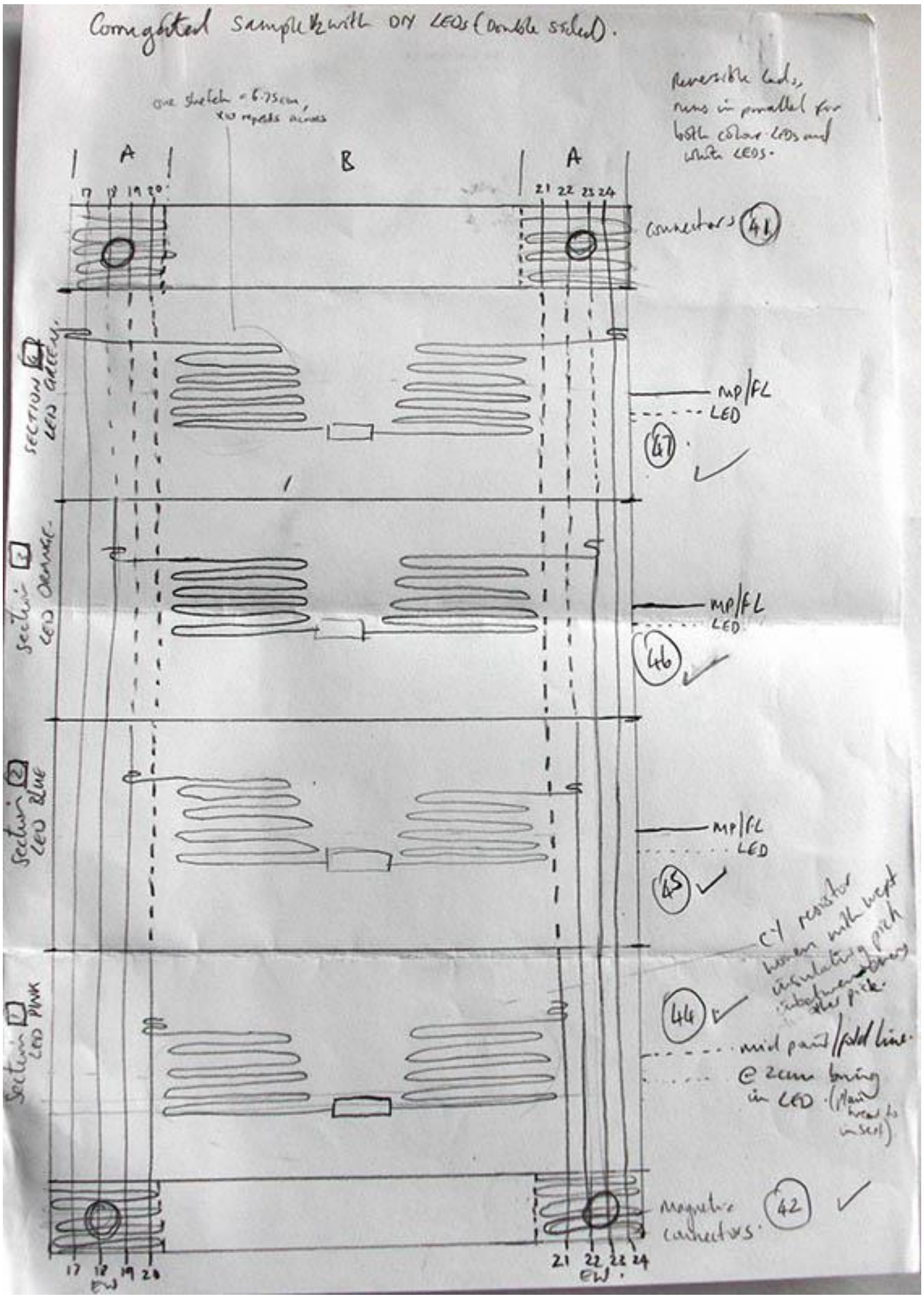


Figure 6.8 CPLEDv2 design specification drawing

Next, woven structures were designed against the design specification. Each structure required that section of the design to function as required, including double cloths, extra warp threads woven, interaction between double cloth layers and points of integration. Alongside the woven structure designs, weft yarns were selected for the entire sample. The ground warp was set up with 2/74s spun polyester. To enable the LED light to emit through the fabric and to remain visible when reflecting through the hollow pleated section, a translucent fine 80 denier monofilament yarn was selected for the weft yarn. In addition, the weft yarn was required to be a synthetic yarn to permanently heat set into the designed pleated structure in the finishing process. Finally, the monofilament yarn retained a spring like resistance when folded; this quality was required for the pleated articulation idea envisioned for this sample. This meant the monofilament yarn was able to comply with all of these requirements and was a yarn the researcher had experience working with. The complete woven structure for CPLEDv2 can be viewed in Appendix J. The design specification and woven structures were used to progress to the execution stage.

6.2.1.7 Execute: CPLEDv2

The woven structures were programmed into the loom Selectron module and weft yarns were prepared. In addition, the own made LED components were prepared with conductive yarn and were tested (Figure 6.9). The components were arranged in order and direction of integration, as error in these positions would result in the circuit not operating as specified due to the directional nature of the LEDs.

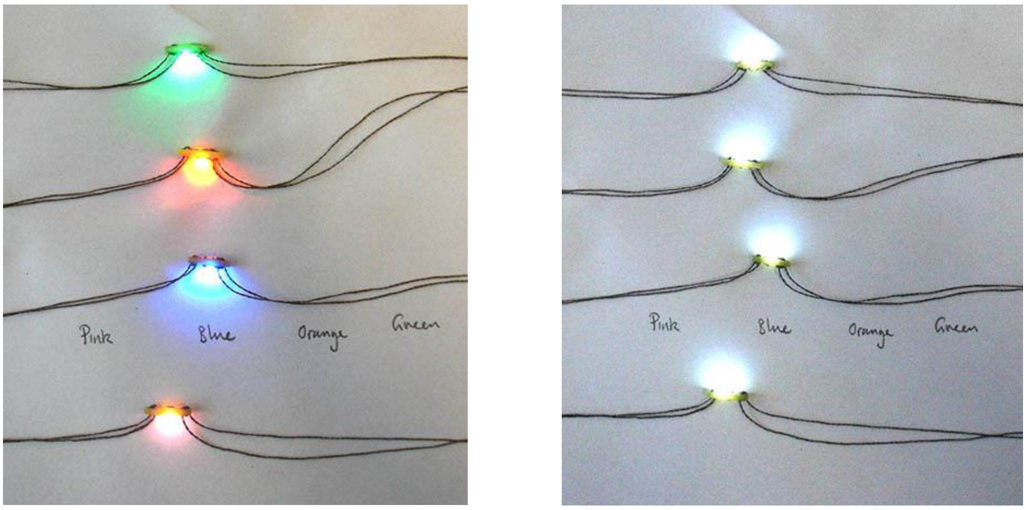


Figure 6.9 CPLEDv2's own made LEDs prepared and tested for woven execution

Sample CPLEDv2 was then woven using the design specification as a guide. The making process of CPLEDv2 is illustrated in Figure 6.10. The next section 6.3 will explain how CPLEDv2 was executed, guiding through each of the woven sections.

Figure 6.10 Making process of CPLEDv2 sample

6.3 Sample dissections: CPLEDv2

To help illustrate the woven process of CPLEDv2, the sample has been dissected into sections, as seen in Figure 6.11. Each section is represented between pink lines.

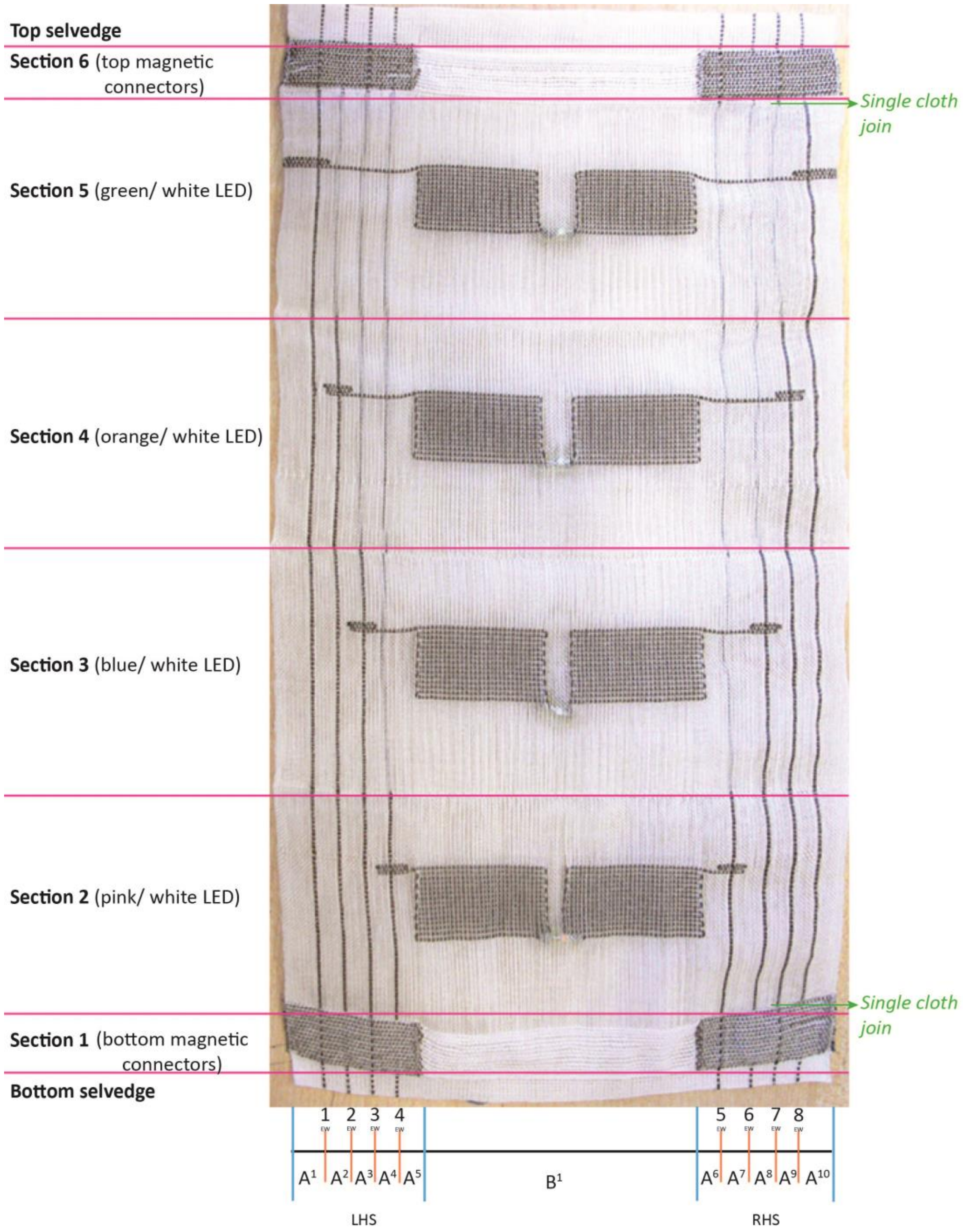
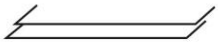
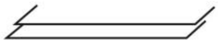
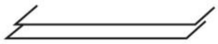
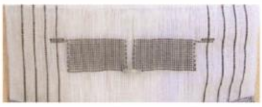
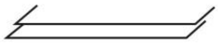
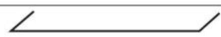


Figure 6.11 CPLEDv2 dissected section labels

The following subsection explains the weaving process for each of CPLEDv2's woven sections.

6.3.1 Woven section descriptions: CPLEDv2

A total of six sections were woven in sample CPLEDv2, with two selvedge edges (top and bottom) and two joining cloth sections in plain weave. As per sample RGB colour mixer in chapter 5, the complexity of CPLEDv2 has also been shown in a table (Table 6.1), illustrating the integrated woven qualities.

Section	Section function	Section image	Blocks & cloth structure A	B	Extra warp threads woven LHS 1 2 3 4	RHS 5 6 7 8	Cross section schematic
Top selvedge	Selvedge		SC	SC	⚫⚫⚫⚫	⚫⚫⚫⚫	
6	Top magnetic connectors		DC1	DC2	🔴🟢🔴🟢	🔴🟢🔴🟢	
	Single cloth join		SC	SC	⚫⚫⚫⚫	⚫⚫⚫⚫	
5	LED green/ white		DC2	DC2	🔴🟢🟢🟢	🟢🟢🟢🔴	
4	LED orange/ white		DC1	DC1	🔴🔴🟢🟢	🟢🟢🔴🔴	
3	LED blue/ white		DC2	DC2	🔴🔴🔴🟢	🟢🔴🔴🔴	
2	LED pink/ white		DC1	DC1	🔴🔴🔴🔴	🔴🔴🔴🔴	
	Single cloth join		SC	SC	⚫⚫⚫⚫	⚫⚫⚫⚫	
1	Bottom magnetic connectors		DC1	DC2	🔴🟢🔴🟢	🔴🟢🔴🟢	
Bottom selvedge	Selvedge		SC	SC	⚫⚫⚫⚫	⚫⚫⚫⚫	

SC = single cloth
DC1 = double cloth 1
DC2 = double cloth 2
⚫ *= Extra warp thread woven in as single cloth*
🔴 *= Extra warp thread woven in as double cloth on TOP cloth*
🟢 *= Extra warp thread woven in as double cloth on BOTTOM cloth*

Table 6.1 CPLEDv2 dissected sections

CPLEDv2 was woven as a single piece of simultaneous weaving, integrating components while being constructed on the loom. The sequence of weaving was essential to the order the sample formed. Thus, acknowledging it would be woven from the bottom up when designed would impact the function of the sample.

This sample was constructed predominantly using double cloth structures in different combinations (e.g. vertical and horizontal configurations). The extra warp threads required specific positioning in each section; this was imperative in order to introduce the correct threads at the right point of interaction to enable the circuit to function as designed. The construction of CPLEDv2 is discussed in the following subsections.

6.3.1.1 Sections 1 and 6: magnetic connectors

Sections 1 and 6 used the same woven structure and method to construct the magnetic connectors. The woven structure enabled the two warp blocks to be woven as vertical double cloth sections; hence, the double cloth layers interchanged at the start and end point of a block. Section 1 was woven after the bottom selvedge was constructed in plain weave, and a plain weave selvedge was woven on completion of the section 6.

Extra warp threads 1, 3, 5 and 7 (odds) were woven into the top cloth, and extra warp threads 2, 4, 6 and 8 (evens) were woven into the bottom cloth of block A double cloth. The extra warp threads were split in this arrangement to optimise the interconnection with conductive yarn weft to form pockets for the magnetic connectors. Conductive weft yarn was woven using inlay technique across block A on both the front and back of the double cloth. This enabled double sided magnetic connectors, interwoven with extra warp threads on both sides. As the magnetic connectors were parallel across the sample, these were woven simultaneously and required two separate shuttles of conductive wefts. In addition, a third weft of 2/74s spun polyester was also woven in these sections as the supporting weft in each inlayed pick.

The double cloth woven structure applied to the magnetic connector section 1 and 6 is illustrated in Figure 6.12.

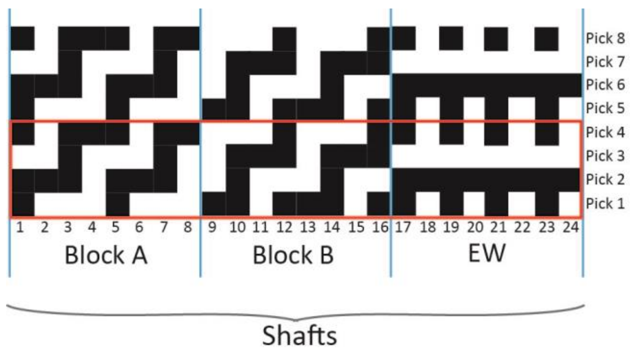


Figure 6.12 Woven structure applied to CPLEDv2 sections 1 and 6

Each pick wove the top cloth of block A and bottom cloth of block B or vice versa. This meant the two conductive yarn wefts were weaving the same pick independently on the two sides (i.e. left and right), simultaneously on the same side of woven cloth.

The left magnetic connector was woven from the left side, and right magnetic connector from the right side; therefore, the conductive yarns were being woven concurrently. The first pick wove the top cloth of block A, hence, conductive yarn was inserted from the left of the warp and taken out at interception point 1 (Figure 6.13). During the same pick, the second conductive yarn was inserted from the right side of the warp and taken out of the warp at interception point 2. The third weft (polyester) was woven right across the warp in the same pick to stabilise the complete cloth. The next pick wove the bottom cloth of block A and top cloth of block B. Here, the left conductive yarn weft was reinserted at interception point 1 and woven out on the left side of the warp. During the same pick, the right conductive yarn weft was reinserted at interception point 2 and woven out of the right side of the warp. A polyester pick was also woven across the complete sample in this same pick to stabilise the cloth. This sequence of inlaying two independent conductive yarn wefts simultaneously was woven for 1.1cm. At this point, the double cloth pockets were opened using a plain weave structure (not woven) to insert a 1cm diameter (0.1cm thickness) neodymium disc magnet into each side. The double cloths were joined with two picks of plain weave to seal the magnets, completing sections 1 and 6.

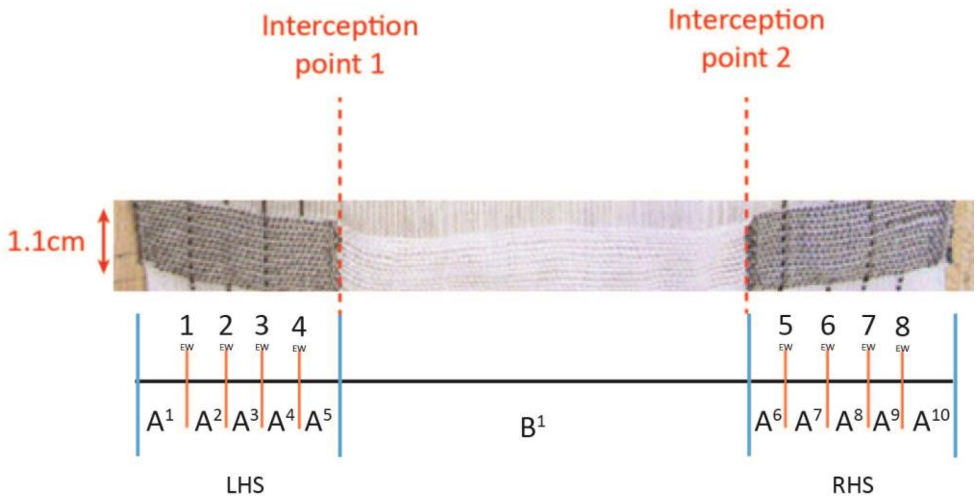


Figure 6.13 CPLEDv2 magnetic connector's interception points

6.3.1.2 Sections 2, 3, 4 and 5: LED integration and resistors

The next sections, 2, 3, 4 and 5, were woven using the same method and similar woven structures. These sections were constructed with horizontal double cloths. Each section had specific extra warp threads woven onto the top or bottom cloths (as indicated in Table 6.1). The four sections were woven consecutively, which meant the double cloth structures interchanged the sequence of layers to form an interaction between each section, as illustrated in Figure 6.14.

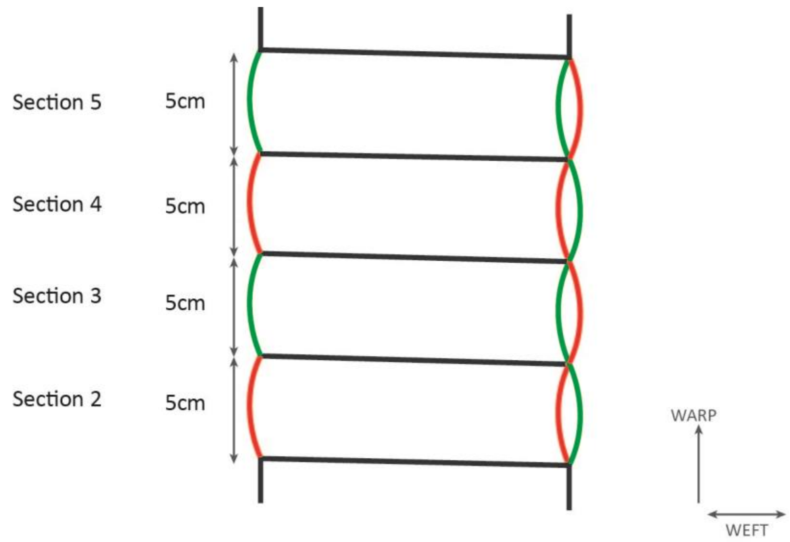


Figure 6.14 CPLEDv2's sections 2, 3, 4 and 5 horizontal double cloth schematic

Each section was woven for 5cm in height, as they were designed to be pleated in the finishing process at the centre of each section (i.e. at 2.5cm).

Monofilament weft was used to continuously weave sections 2, 3, 4 and 5 as a single weft to form a sealed edge along the vertical selvedges. Once the structure had been built for 2cm in height, the LED component was introduced into the weaving. The double cloth sections were opened using plain weave structure. The component was placed into the pocket and the attached conductive wefts were taken out from the top of the warp at interception point 3 for the left conductive weft track, and at interception point 4 for the right conductive weft track (Figure 6.15). At the next woven pick of the top cloth, the conductive wefts attached to the components were reinserted into the same interception point and taken out at interception point 1 for the left weft, and interception point 2 for the right weft. A monofilament weft was woven across the complete sample to tie all other warp ends. The next pick wove the bottom cloth. This was woven with monofilament, as the conductive yarn wefts were only woven into the top cloth of sections 2 – 5 to ensure the double cloths layers were kept separated.

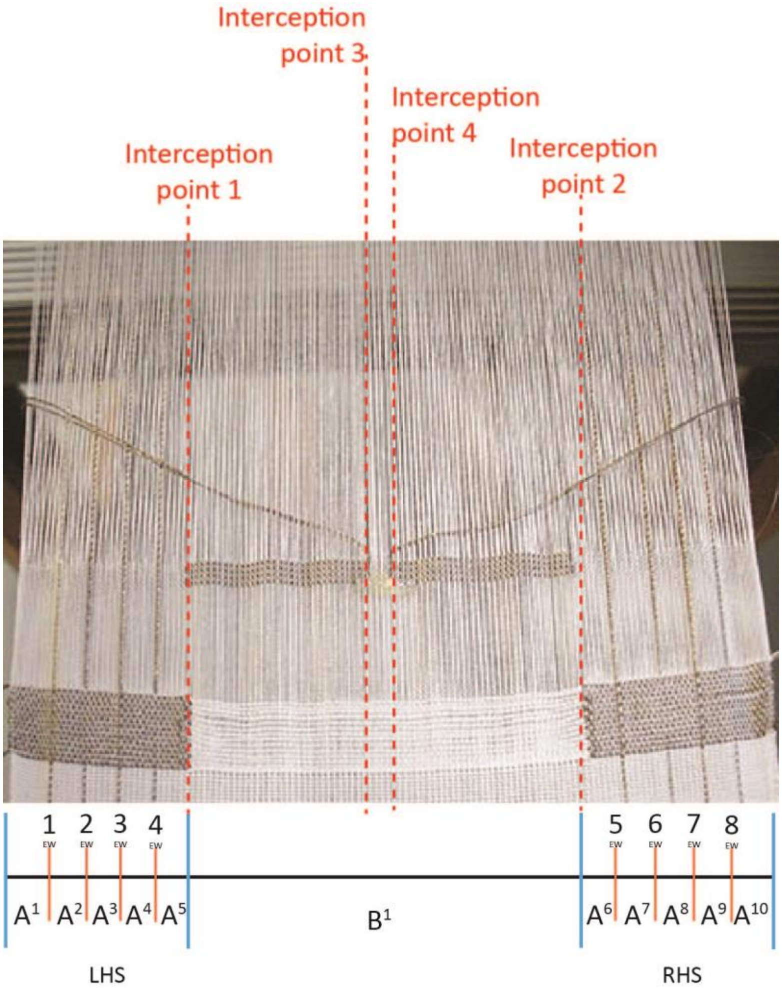


Figure 6.15 CPLEDv2 sections 2, 3, 4 and 5 interception points for LED integration

The double cloth structure applied to sections 2 – 5 was woven at alternate picks of top cloth between every pick of bottom cloth. Therefore, the next top cloth pick was woven with a monofilament weft, as the conductive yarn wefts attached to the component were also forming resistors that needed to be insulated. Hence, monofilament was woven in between every conductive weft pick. The subsequent top cloth pick reinserted the left conductive yarn into interception point 1 and this was taken out of the warp at interception point 3. The right conductive yarn weft was reinserted at interception point 4 and taken out of the warp at interception point 2.

The conductive yarn wefts attached to the component were prepared with 60cm length (50cm to weave, 10cm for weave handling/ connection), to weave 25Ω resistors on both sides – these were doubled lengths of Shieldtex 235/34dtex 2-ply 100Ω/m. Once the length of the conductive yarn was integrated into the weaving, the last pick of the conductive yarn weft needed to interweave with the corresponding extra warp track to connect the component to the circuit. At these points, the conductive wefts were inlayed and connected over the extra warp track three times to ensure a secure connection, without making contact with other conductive tracks. Once the extra warp tracks had been woven to a component's wefts, the allocated extra warp threads were woven to the bottom of the double cloth in the subsequent sections. Section 1 had extra warp threads 4 and 5 allocated, section 2 had extra warp threads 3 and 6 allocated, section 4 had extra warp threads 2 and 7, and section 5 had extra warp threads 1 and 8 allocated. On completion of section 5, two picks of plain weave were woven to seal this section.

6.3.1.3 Finishing CPLEDv2

Once the last section was woven, a plain weave selvedge completed the sample. The sample was cut off the loom, trimmed and then tested with a power source before beginning the pleating process (Figure 6.15).

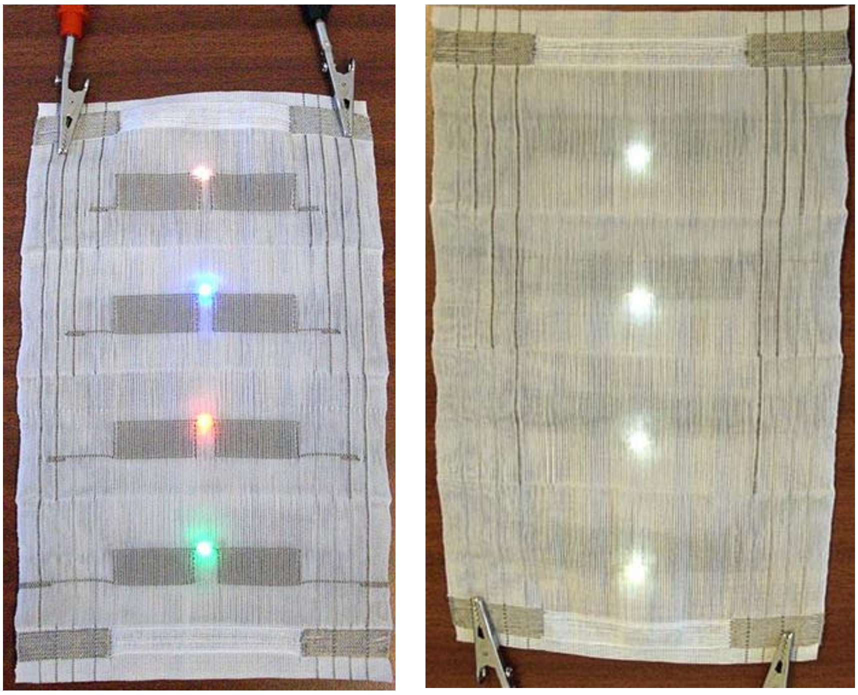


Figure 6.16 CPLEDv2 sample testing on completion (14.5 x 23cm)

The pleating process prepared the sample by manually folding section 2's vertical selvedges inwards, as per the fabric prototype. This was pinned into position before repeating at the opposite side. The centre of section 2 was pinched on the top cloth to bring this together to form a centre crease, and was then repeated on the reverse for the bottom cloth; this initially formed the centre pleats on both sides of the section. The pins were replaced with tailor tacks. Folding, pinning and tacking were repeated on sections 3 – 5 (as illustrated in Figure 6.10, step 6). The sample was then ready to be heat set.

Using a steam iron on medium heat and a piece of calico to place over the sample, it was gently ironed and steamed. Both sides of the sample were heat set before cooling down for a few minutes and removing tacked stitches (Figure 6.17). The sample was complete and tested with a power source.

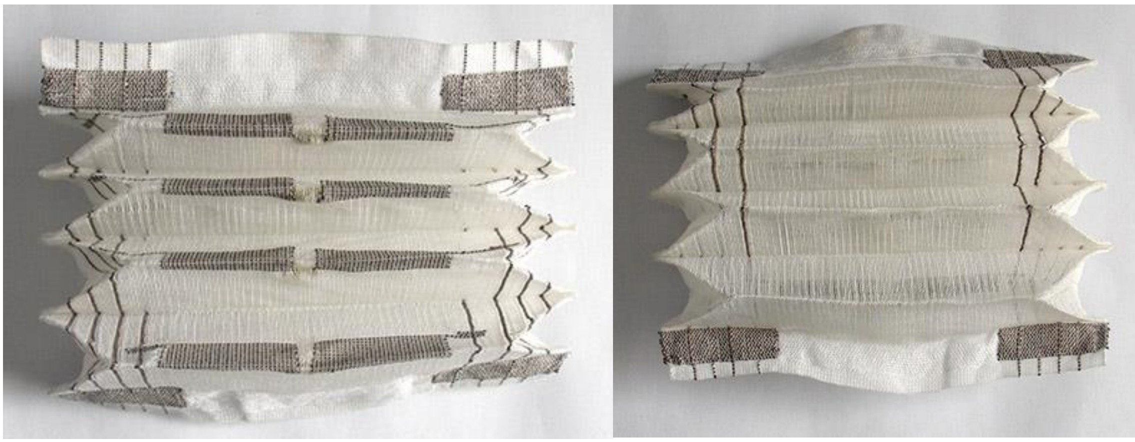


Figure 6.17 CPLEDv2 completed sample. Left: Face side, Right: reverse side

6.4 Results: CPLEDv2

The design process and woven execution for sample CPLEDv2 sought to combine textile form and electronic function for an integrated single piece of woven e-textiles. This was successfully achieved through a design led process. That used technical materials approach and creative craft methods. As per RGB colour mixer sample discussed in chapter 5, the development of CPLEDv2 applied the researcher's expertise in woven textiles combined with electronic properties for an integrated e-textile.

The findings from the previous iteration in the same category (2A circuits) from samples CPLED-A and CPLEDv1 were vital insights that enabled the development of CPLEDv2. This resulted in a sample with a parallel circuit consisting of four own made double sided LEDs integrated simultaneously during the woven process, whereby depending on the direction of current flow when a power source was attached, one of two combination of light outputs would be emitted. The results of CPLEDv2 when attached to a 3v power source are visible in Figure 6.18. The positive and negative power source contacts can be switched over to result in an alternative output.

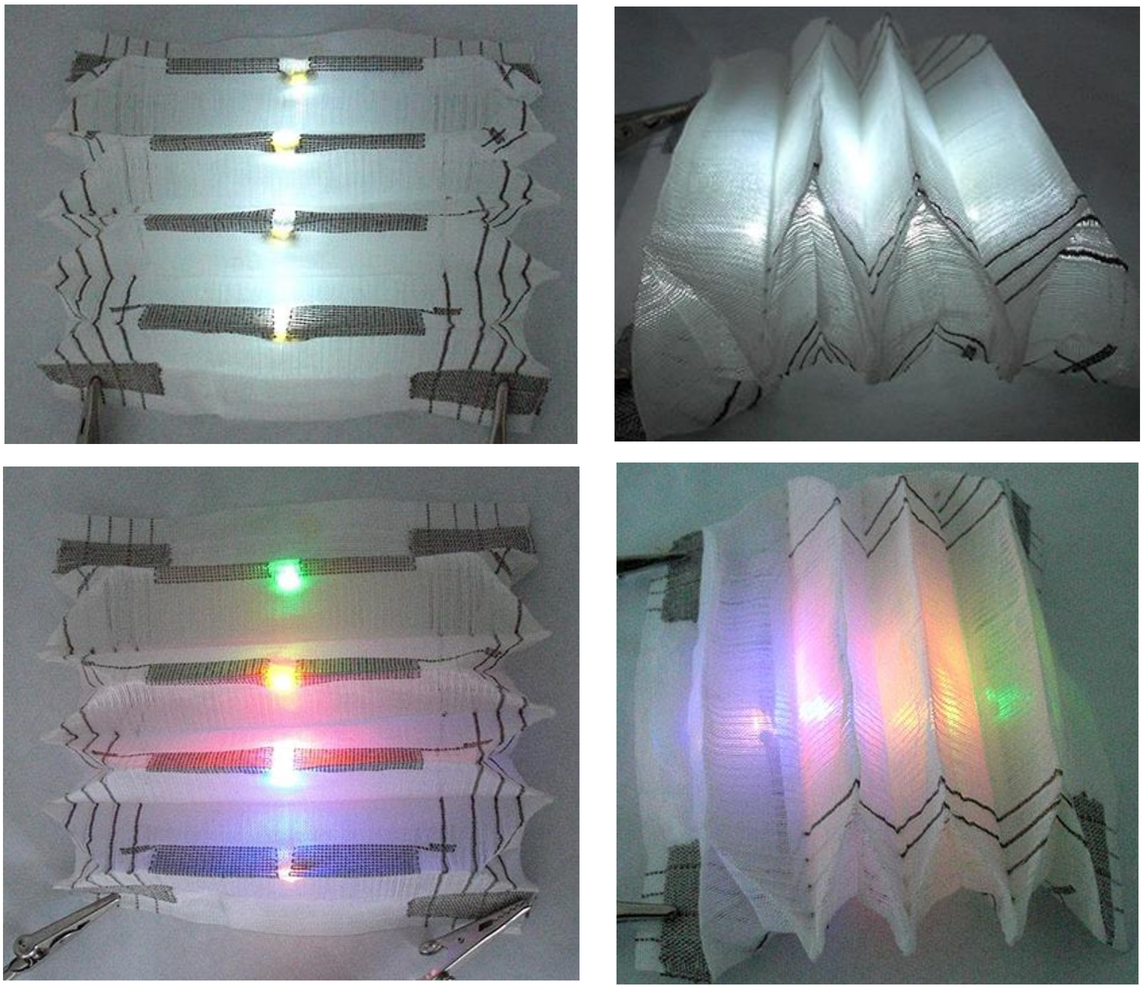


Figure 6.18 CPLEDv2 results; face side and reverse side with different light options activated

The light emission in the semi-translucent pleat hollow forms was very effective, particularly in darker environments. As per the design specification, the pleated form of CPLEDv2 was held in position by using synthetic yarns and applying heat set finishing. The final pleated form retained an articulated structure, as the heat set monofilament permanently set a memory for this physical form. The overall light weight sample allowed the structure to revert back to a collapsible two dimension shape, due to the monofilament's physical resistance pulling this back into the heat set structure. The same physical quality enabled the whole structure to be manually stretched into a three dimensional form by pulling it to a maximum stretch, causing a centre crease to hold a three dimensional shape. This formed shape was particularly effective when the lights were activated (Figure 6.19).

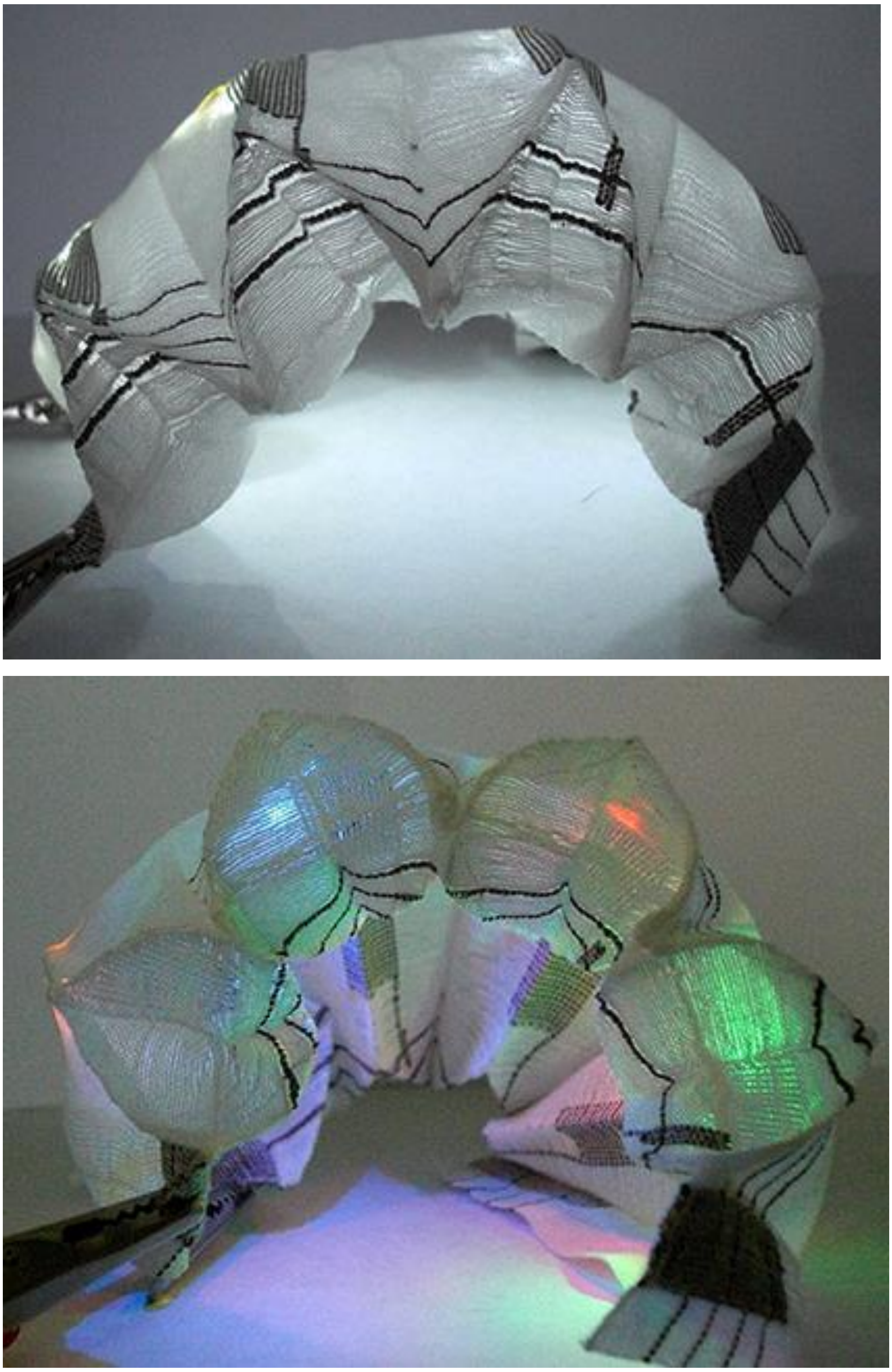


Figure 6.19 CPLEDv2 stretched to maximum capacity to self-hold in a three dimensional form (collapsed pleated dimensions 5 x 14.5cm)

On inspection of the sample, there was one lifting mistake in the top magnetic connectors, although this did not affect the circuit. Further analysis of the sample is discussed in the following section 6.5.

6.5 Analysis: CPLEDv2

CPLEDv2 successfully achieved its specified aims via the design process; hence, this was pivotal to the development of this sample. All the design approaches (i.e. tacit knowledge, implicit and explicit knowledge, praxis, abductive theory, synthesis, reflective practice and creativity) were influential in this process. CPLEDv2 was the outcome from analysis of previous iterations (Trio RGB, CPLED-A and CPLEDv1). Without these insights, the final design achieved in this sample would not have been developed. Although CPLEDv2 was the last outcome in design iteration 3 in category 2B integrated circuits, the findings are significant to potential application in future iterations and to build further knowledge of woven e-textiles. Some of these outcomes have also implicitly and/ or explicitly been applied to e-textiles across other categories.

The integration of own made LEDs and the success of their application was considerably influential to the development of further iterations of own made components (as discussed in section 4.3.7.2). The double sided LEDs were effective in function and were a key factor of this sample's design. The hollow pleats enabled the light emission to be contained in hollow vessels of space, resulting in effective use of three dimensional woven textiles. The woven resistors worked effectively; however, later iterations of own made LEDs integrated surface mount resistors, which could reduce the surface space of the e-textile and allow for a wider range of resistance values.

Reflection on of the warp design, it is possible to alter the set up to allocate one shaft to control any number of negative extra warp threads on the right. This would leave a minimum of seven shafts to control extra warp tracks on the right, and would have presented opportunity to control further extra warp threads. The design of this sample did not require the warp draft as presented, which could have been simplified to design the two blocks on fewer shafts leaving spare shafts available for extra warp threads. If this design was progressed for industrial weaving, it could be simplified further.

The interconnection of extra warp and weft conductive track proved effective, crossing over three times per connection. On reflection it was also thought multiple extra warp threads could have been designed into the warp (on the same shaft), to multiply and optimise circuit connections. However, when the sample was assertively handled with an attached battery pack, the LEDs would lose connection causing them to flicker. The same assertive approach with the sample when attached to a power source would result in less flickering, which was more stable than with the battery packs. This difference is due to the number of contacts between sample and power source; therefore, stable and consistent connection between sample and power source result in a more effective function.

The articulation and lightweight structure of sample CPLEDv2 was due to the scale at which this was woven. If the size of the sections were increased across a wider warp, the same structural articulation would need to be redesigned, as the weight of the sample would make the two dimensional to three dimensional transition react differently. However, this is thought to be possible after some initial investigations and prototypes on a larger scale.

The magnetic connectors worked effectively with an independent e-textile battery holder, but the weight of the holder and batteries affected the physical form of the CPLEDv2 due to the bulk of this additional attachment. This did not hinder the modular connection function.

CPLEDv2 has proved it is possible to weave an integrated circuit simultaneously on the loom, guided by a design led process. The findings from the e-textiles in this category (2B integrated circuits) and specifically CPLEDv2 have potential to be adapted for industrial manufacture. In addition, the soft circuits have provided deeper insights into how woven manipulations can be harnessed for woven e-textiles.

The next chapter will discuss an e-textile sample from the final category 3, modules.

7 Modules

This chapter will explore the final e-textiles category investigated for this research – modules (as per Figure 4.34). The modules category was split into two groups; 3A modular components and 3B battery holders. The overall category focused on developing modular e-textiles that could be configured into various combinations of circuits via connecting a series of modules. Category 3A modular components, focused on input and output components (e.g. LEDs, resistors, switches, buzzers, etc.). The methods used to integrate components were derived from findings across all categories and samples; however, in the modules category, the aim was to isolate single functions into independent modules. The modular e-textiles were developed concurrently to other e-textiles. Findings from other categories inspired developments in this category, but required adaptation to conform to modular formats. The design process map for category 3A, modular components, can be viewed in Appendix K.

As per chapters 6, this chapter will focus on a single category, providing a concise description of the design development in relation to the design process. This chapter will focus on 3B battery holder modules. In this group of e-textile modules, the initial pilot sample led to two further design iterations. The pilot sample had direct relationships influencing the outcomes in each design cycle, including the outcomes in design iteration 1 and design iteration 2. This chapter will explain the impact and development of one specific sample against the design process to explain its evolution.

7.1 Map navigation: Modules – 3B battery holders

The design process map for modules category 3B is illustrated in Figure 7.1. In this category there were three levels of design iterations, whereby the samples were placed on the level that reflects their design development. The design objective in this category was to develop integrated soft modular e-textiles, which could be connected via conductive magnetic connectors to form a functioning circuit. The modular e-textile objective was based on the idea of the connection and disconnection of independent modules that can be configured in various combinations, such as Lego.

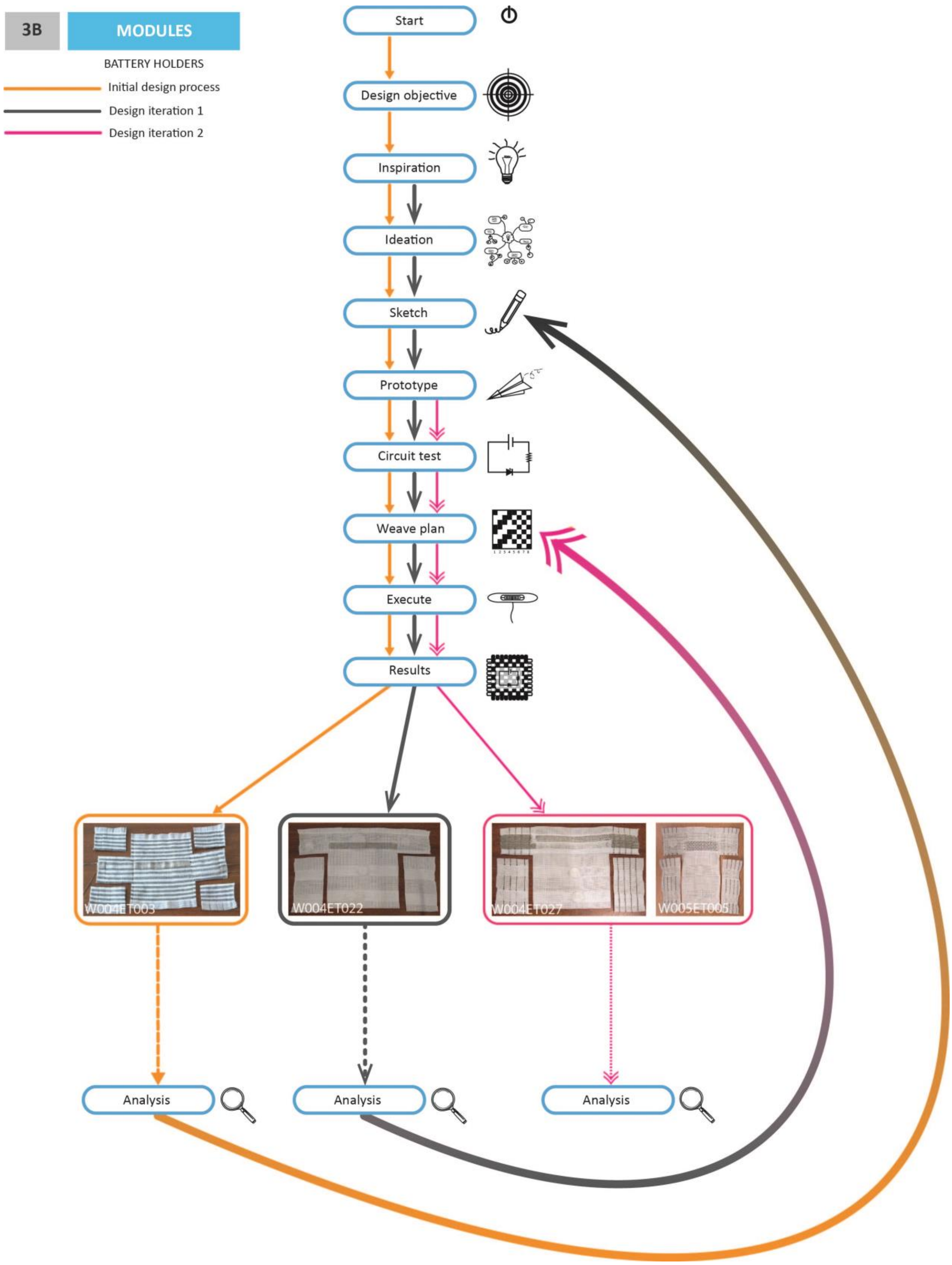


Figure 7.1 Modules 3B battery holders design process map

As with chapters 5 and 6, in category 3B battery holders, the initial design process developed a pilot sample that instigated two further design iterations for subsequent samples. The design objective of category 3 was to investigate modular e-textiles, where category 3B specifically focused on battery holder modules. The inspiration stage in this category sought form for the physical textile shape and function of a battery holder. Synthesising ideas extracted from the inspirational sources (using tacit thinking, implicit and explicit knowledge and reflective practice), the ideation stage considered options and ideas to develop specifically for woven e-textile battery holders. Selected ideas were guided into the sketching phase to refine and visually work through a modular battery holder concept. Focused ideas were translated as three dimensional battery holder prototypes; these were used to design the battery contacts and circuit contacts. The physical and functional forms were combined in the weave planning stage, which resulted in a design specification to help guide the woven execution of the battery holder module. The result was battery holder module v1 (W004ET003) – a cross shaped battery holder module with a double magnetic clamp. The design process for this sample can be viewed as the orange path in Figure 7.1.

The outcome of the initial design process (battery holder module v1) was analysed (broken orange arrow) and the findings were used to instigate design iteration 1 (orange-grey arrow); this intercepted the design process at the sketch phase. From here, the same idea was re-formed through sketching and then followed through the design process (grey path) for outcomes of design iteration 1. The findings, again, were analysed (broken grey arrow) and were fed back into the design process, this time intercepting at the weave planning stage (grey-pink arrow) for design iteration 2. Using the same design form and function as the previous finding (i.e. design iterations 1), the weave structures were adapted for the design iteration 2 (pink path). The design process was then continued through to the results stage for design iteration 2, where the results were analysed (broken pink arrow) and available for potential future iteration.

This section has outlined the design process for category 3B battery holders. The rest of this chapter will focus on one specific sample – battery holder module v4 (W005ET005), discussing its development in relation to the design process.

7.2 Battery holder module v4

Battery holder module v4 (BHMv4) was an outcome of design iteration 2. All the samples in this category followed the same design objective – modular e-textiles. This category specifically focused on modular battery holders, whereby one or two 2cm wide 3v button batteries could be held in an independent woven e-textile construction with magnetic conductive connectors. Although BHMv4 was not an ultimate outcome of the last iteration in this design group, this specific sample was developed from the sketch phase. The previous stages of the design process in category 3B battery holders were relevant to the development of BHMv4; the following subsection will explain how the design process was related to this sample's outcome.

7.2.1 BHMv4: design process

The specific design process for sample BHMv4 can be viewed in Figure 7.2. Sample BHMv4 was an outcome of design iteration 2, which developed after the initial design process and design iteration 1. As BHMv4 was initiated from the weave plan stage onwards, the previous stages are related to design iteration 1 and the initial design process. Thus, the design map for BHMv4 relates development prior to the weave plan stage to the relevant iterated design samples, as indicated via respective coloured horizontal connected paths. In category 3B battery holders, the initial design process and design iteration 1 resulted in one outcome in each of these levels. Therefore there were two previous samples that were directly associated with the development of BHMv4 – i.e. battery holder module v1 (BHMv1) sample code W004ET003, and battery holder module v2 (BHMv2) sample code W004ET022. Battery holder module v3 (BHMv3) sample code W004ET027 was developed on the same level as BHMv4 in design iteration 2; thus, there was no direct link with BHMv3 sample regarding the progression of BHMv4's design. The following sections will describe each stage of the design process in the development of BHMv4.

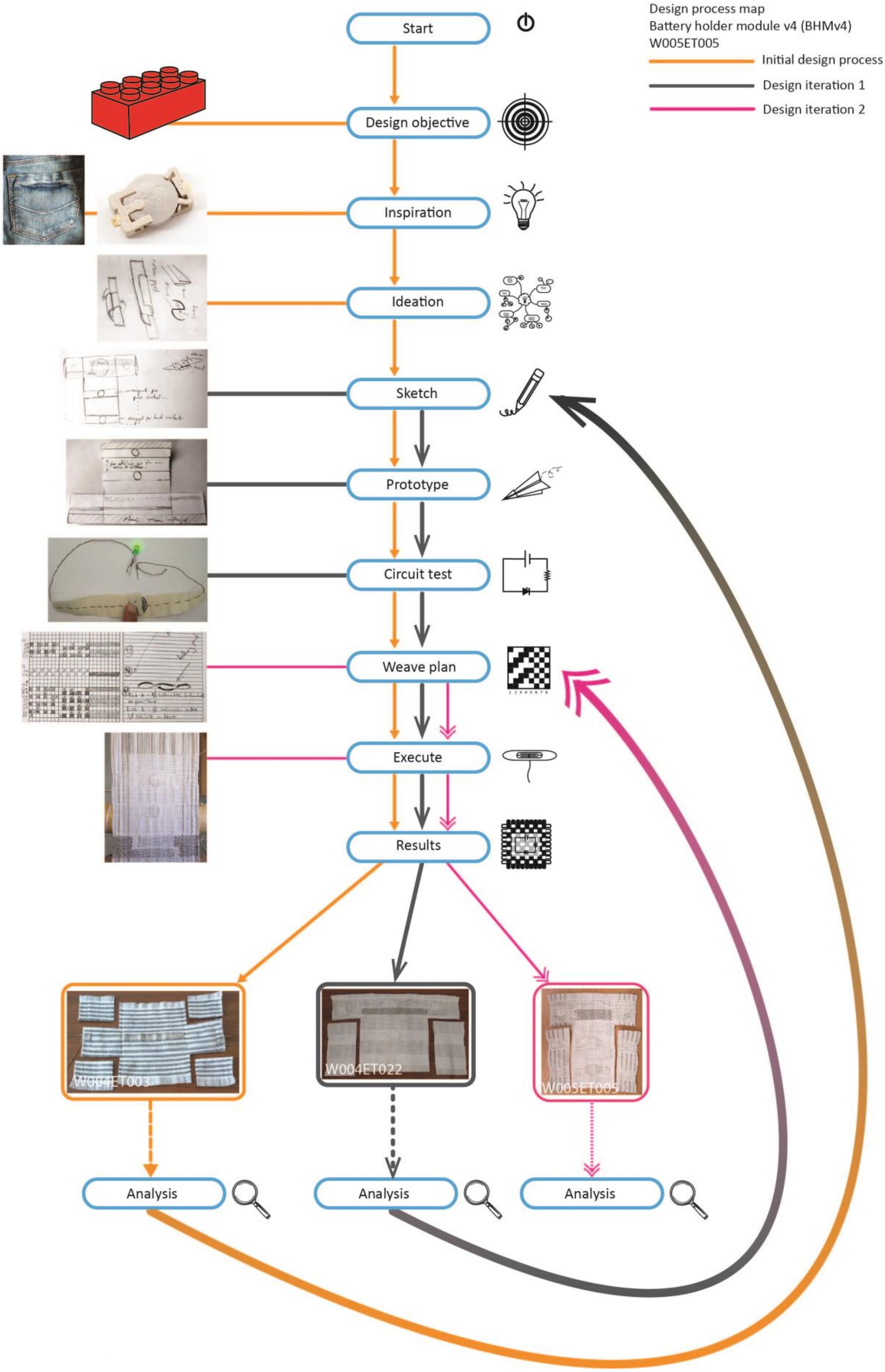


Figure 7.2 BHMv4 design process

7.2.1.1 Inspiration: BHMv4

The inspiration sources in this category were relevant to all the outcomes in this group including BHMv4, as they all had the same function – i.e. e-textiles battery holder. One of the inspiration sources was a conventional hard plastic 3v button battery holder; its function and form was specifically of interest as the battery size was compatible with the majority of the e-textiles developed in this research. Conventional electronic circuits, with 3v button batteries attached, require a hard external, sometimes bulky, battery holder. Although developments of e-textiles have established sew-on 3v button battery holders, they are principally the same hard plastic design with adapted conductive sew holes to connect to a soft circuit. The function of a 3v button battery holder was of interest to observe and analyse (reflection *in* and *on*) to gain an understanding of how it worked, and to draw inspiration from its design. The other inspiration source was the idea of a pocket, much like in clothing. Pockets were seen as related to the idea of a soft compartment or housing for a battery. This involved tacit and creative thinking implicitly and explicitly directed the potential of these inspiration sources to translate as a soft battery holder. Synthesising and combining the inspirational sources required creative thinking, reflection *on* and praxis to guide into the next design process stage of ideation.

7.2.1.2 Ideation: BHMv4

The ideation phase of the initial design process for the modules category 3B battery holders, combined the inspirational sources (including findings from the analysis of existing button battery holders) with the design objective of modularity. The initial design process' ideation phase was common to all sample development in this category, as subsequent iterations intercepted the design process after this stage. Ideas were recorded via sketches and notes reflecting *on* the design objective and inspiration and reflecting *in* this process. Collecting ideas to map an overview of possible options (engaged tacit thinking, implicit and explicit knowledge, praxis, abductive thinking and creativity) enabled synthesis of potential concepts.

Modular connection of the battery holder was a prerequisite determined by the category and design objective; therefore, connector options were also considered at this stage. Magnetic connectors were favourable after testing other connection methods (as discussed in section 4.3.7.1), and had already been integrated into previous samples.

However, other improved connection methods were also considered. Initial ideas contemplated how a 3v button battery could be housed securely into a textile structure. Key findings from the analysis of the existing battery holder demonstrated a tight fit between the battery and conductive contacts enabled the power source to function effectively. These attributes were considered at the ideation stage and led to concepts of gripping and clamping the battery source in a textile pocket (Figure 7.3).

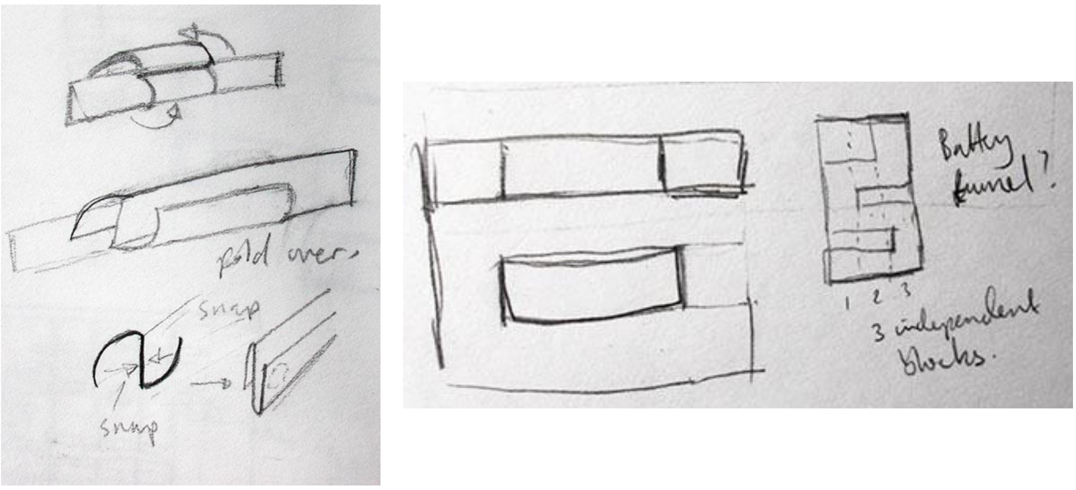


Figure 7.3 Ideation of initial battery holder modules

7.2.1.3 Sketch: BHMv4

The sketch phase relates to design iteration 1 (depicted as grey path in Figure 7.2), for specifically sample BHMv2. The analysis of findings from the BHMv1's (initial design process) prompted inspiration for a new design (abductive thinking); this intercepted the design process for iteration 1 from the sketch stage. BHMv1's design was a combination of double cloth to form a cross shaped soft battery holder, a double magnetic clamp (above and below), the battery, and two magnetic connections on the left and right to connect the positive and negative tracks to a soft circuit. Analysis of BHMv1 found the original cross form could be improved to assist a tighter clamp design and wider conductive paths to optimise connection via magnetic connectors (praxis). Reflecting *on* these findings and synthesising with the original design objective, creative thinking, implicit and explicit knowledge, sketching of new design forms were drafted (Figure 7.4). Reflecting *in* the sketching process led to refining one of the designs; this was a T-shaped form, where the double magnetic clamp could be wound around the entire button battery. This would help to tension and grip tighter, allowing for better connection with the positive and negative tracks. The form would still be in double cloth format. This idea was taken through to the prototyping stage.

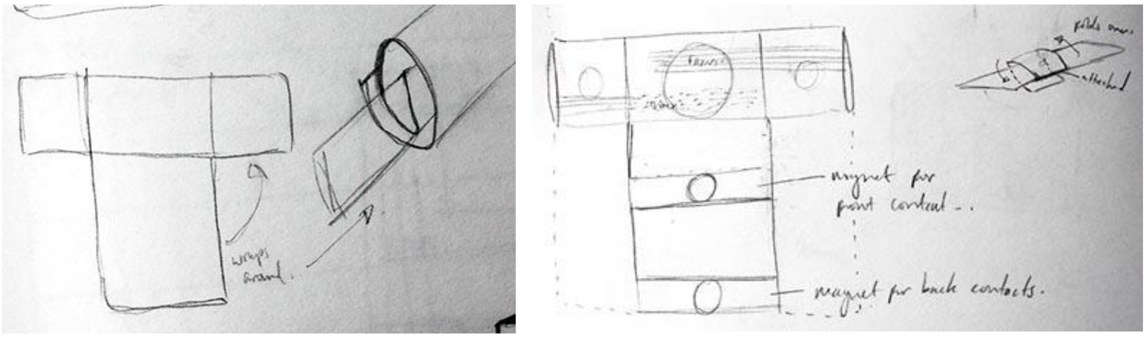


Figure 7.4 Sketches for BHMv4

7.2.1.4 Prototype: BHMv4

Synthesising the battery holder concept into a physical scale model helped to visualise and place the different elements of the design, i.e. magnets, button battery, conductive tracks. Folding the paper prototype as intended in the final piece helped to reflect *in* and reflect *on* to make any adjustments to the design. Knowledge gained from the development of BHMv1 was also useful when constructing the prototypes for BHMv2, as the previous iteration was of a similar physical structure (tacit thinking, implicit and explicit knowledge, praxis, abductive thinking). Once the final prototype was finalised (Figure 7.5), this was ready to progress into the circuit testing phase.

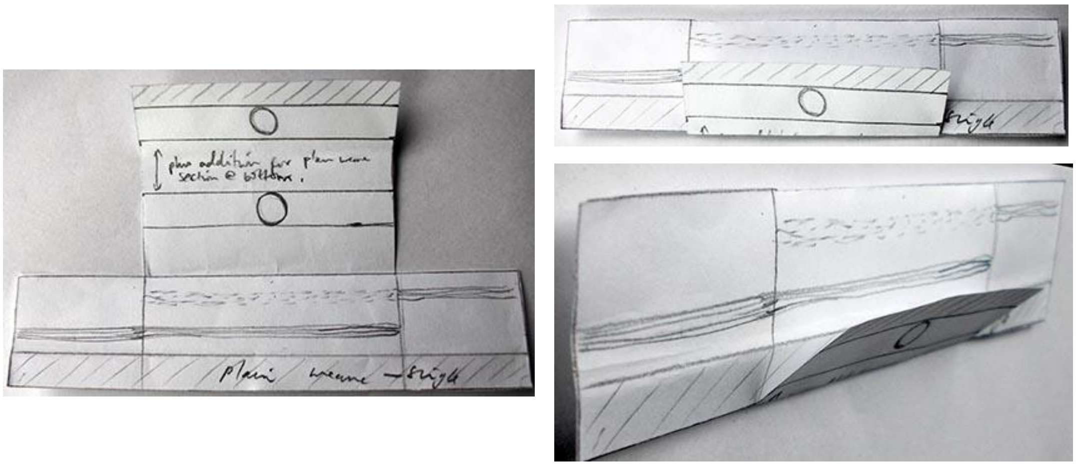


Figure 7.5 Prototype model of BHMv2

7.2.1.5 Circuit test: BHMv4

The circuit test for BHMv2 was the same as BHMv1; however, in this iteration the conductive tracks needed to be wider to optimise the battery connection (via reflection *on* and referring to explicit knowledge). As the woven construction for this design would be similar to BHMv1, some of the woven structures were known to the researcher at this point in the design process. The construction of the positive and negative conductive tracks required adaptation to weave each one wider for improved connectivity with more conductive surface area, and further apart to avoid any short circuits. In addition, the position of the magnets in relation to the battery shell (both positive and negative sides), needed to be placed in the centre of each side for a consistent grip. To test the circuit construction for the battery holder in the required design combination, a mock version was made using calico, conductive yarn, a standard LED and a 3v button battery (Figure 7.6). This functional prototype enabled the researcher to assess the pressure and placement of the positive and negative conductive tracks on the LED, and enabled reflection in the process of making.

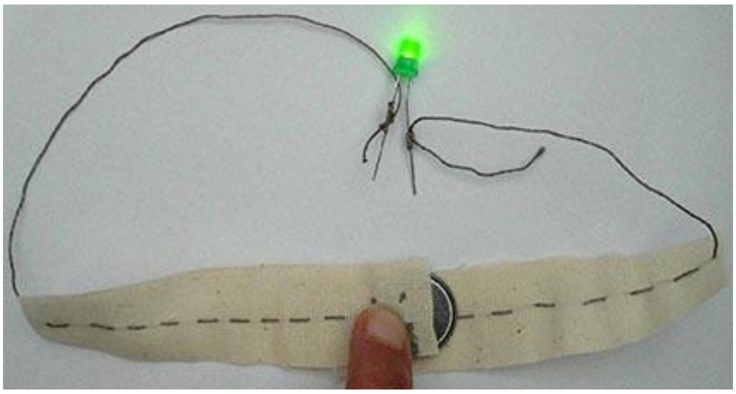


Figure 7.6 Circuit testing for BHMv2

The design of BHMv2 would enable one or two 3v button batteries to be positioned into the e-textile holder to connect to an e-textile circuit. The magnetic connectors would allow the module to be connected in either direction (Figure 7.7). These design elements for BHMv2 were synthesised for weave planning and led to a design specification for this sample.

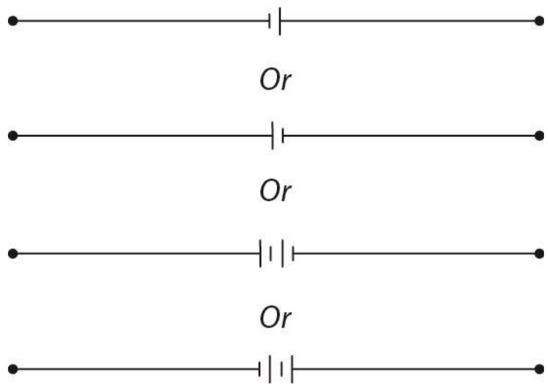


Figure 7.7 Battery holder module schematic (possible combinations)

7.2.1.6 Weave plan: BHMv4

Development of BHMv4 intercepted the design process at the weave planning stage, as the analysis of BHMv2 inspired design iteration 2 from this phase (reflection *on*). Although BHMv3 was also developed in design iteration 2, the design for BHMv4 will be specifically focused on in this iteration level. However, the analysis of BHMv2 also inspired BHMv3 using the same insight. The main difference between BHMv3 and BHMv4 was the sample width size as they were woven from different warps.

The analysis of BHMv2 from design iteration 1 found the T-shape form was effective for a soft battery holder module, where the position of the double magnetic clamp was also successful (Figure 7.8). Therefore, the form design was kept as per BHMv2 in design iteration 1 with amendments to the woven construction.

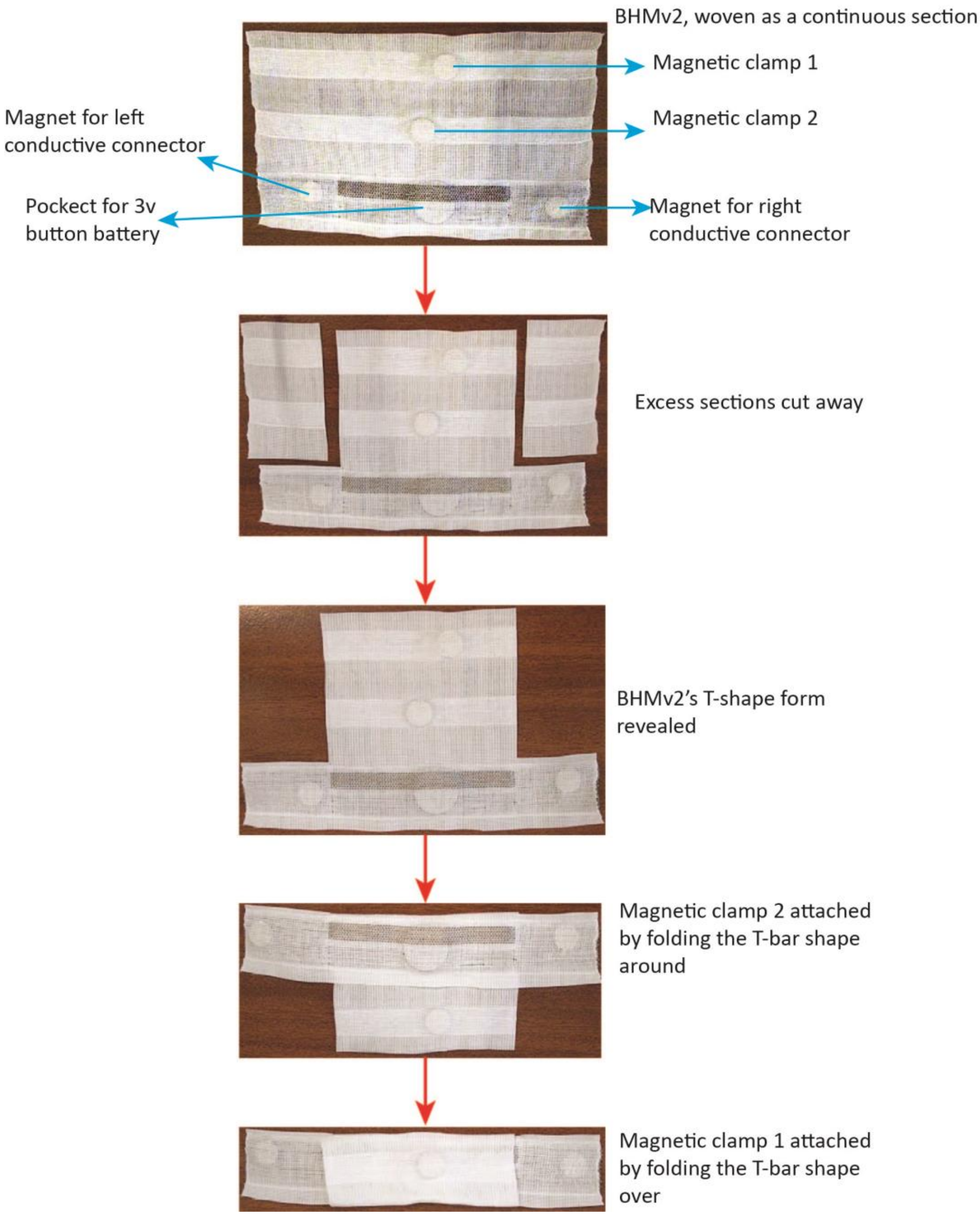


Figure 7.8 BHMv2 finished sample and activation assembly

BHMv2 was woven using plain weave in all sections, including the double cloths that were also based on this structure. Hence, BHMv2's function was also determined by the same plain weave construction that tied in the conductive contacts, including where the battery surfaces made contact with the woven conductive tracks. As plain weave is a balanced structure (i.e. equal number of threads up and down), where the conductive yarn weft picks are equally exposed as the warp threads. This meant increasing exposure of the conductive yarn could allow for more conductive surface area to make contact with the battery. This in turn would help secure better battery contact, improving connection with the battery source. Applying these findings to design alternative woven structures (i.e. weft faced for the side making contact with battery) would improve the design of BHMv4 (abductive thinking and praxis).

The warp for BHMv4 was an existing draft (warp 005); this was first referenced before designing the woven structures for BHMv4. The ground warp was set up on two blocks (block A and block B) on 2/20cc cotton, sett at 60epi (30epi per cloth at double cloth). Warp 005 also had an extra warp of conductive yarn (Shieldtex 235/34dtex 4-ply), which intercepted block A only. The complete warp was set across a 3½" weaving width, where block A was set on shafts 1 – 8, block B was set on shafts 9 -16, and 8 extra warp threads were set on shafts 17 – 24 (Figure 7.9). As per warp 004, each extra warp thread on warp 005 was also individually addressable as it was controlled via independent shafts. The full draft plan for warp 005 can be viewed in Appendix L.

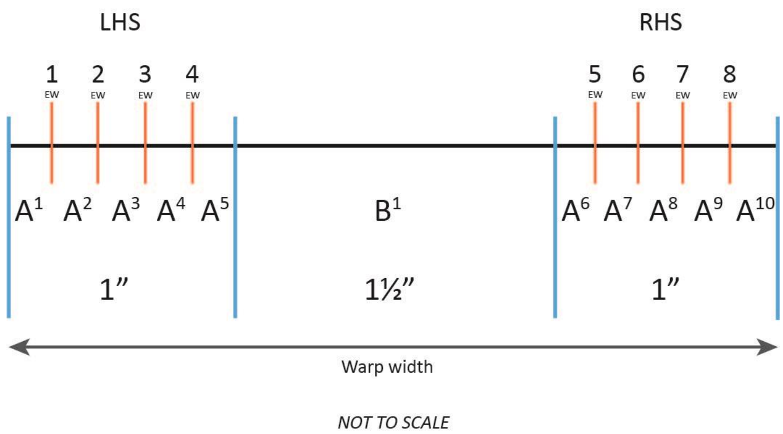


Figure 7.9 Warp 005 block proportions

Before planning the woven structures the warp draft was viewed, as this was beneficial to help design the woven structures referencing this set up. The envisaged design for BHMv4 was possible to make on this warp plan, therefore, it did not need adapting. Using the findings from the analysis of BHMv2 and synthesising this with the current warp draft, a design specification began to be prepared. The T-shape form was familiar from BHMv2's design, which meant it could be re-drafted and modelled on warp 005. The position of double cloth sections were as per BHMv2; however, the pocket to hold the button batteries was specified higher than BMHv2. This was because this section required additional space in the height as the width of warp 005 was much narrower, and was needed to gain access to the batteries.

The position of the magnetic conductive connectors were also as per BMHv2 (on the left and right sides), as well as the double magnetic clamp. The order and arrangement of the sections were based on BHMv2. Figure 7.10 illustrates the design specification for BHMv4.

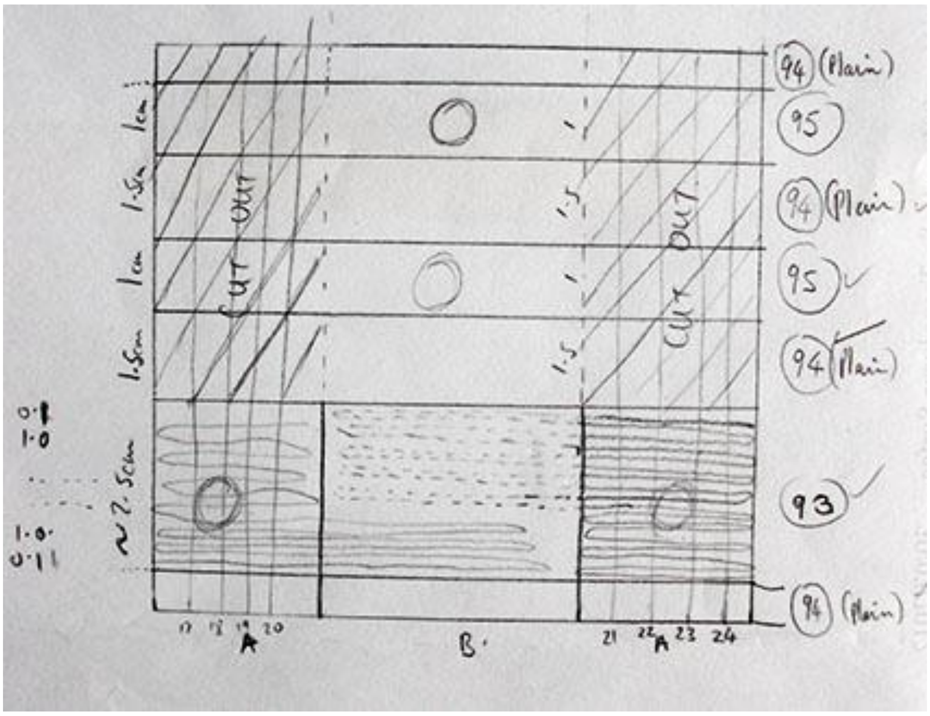


Figure 7.10 BHMv4 design specification

Woven structures for BHMv4's first section, where the battery is held, required re-designing to optimise conductive weft exposure. The button battery would be housed in the central block B's double cloth pocket (as per BHMv2). As the inner sides of this central pocket would have optimum contact with the battery faces, the conductive yarn required weaving on the inner sides of this central pocket. The inner conductive contacts would be woven one after the other consecutively with spacing in-between to ensure they would not cause a short circuit.

The magnetic connectors positioned on the left and right side pockets would need to make conductive contact on the external surface of these double cloths; this meant the conductive yarn weft needed to be woven weft faced. Figure 7.11 illustrates the positioning of the conductive weft for both the magnetic connectors and button battery housing.

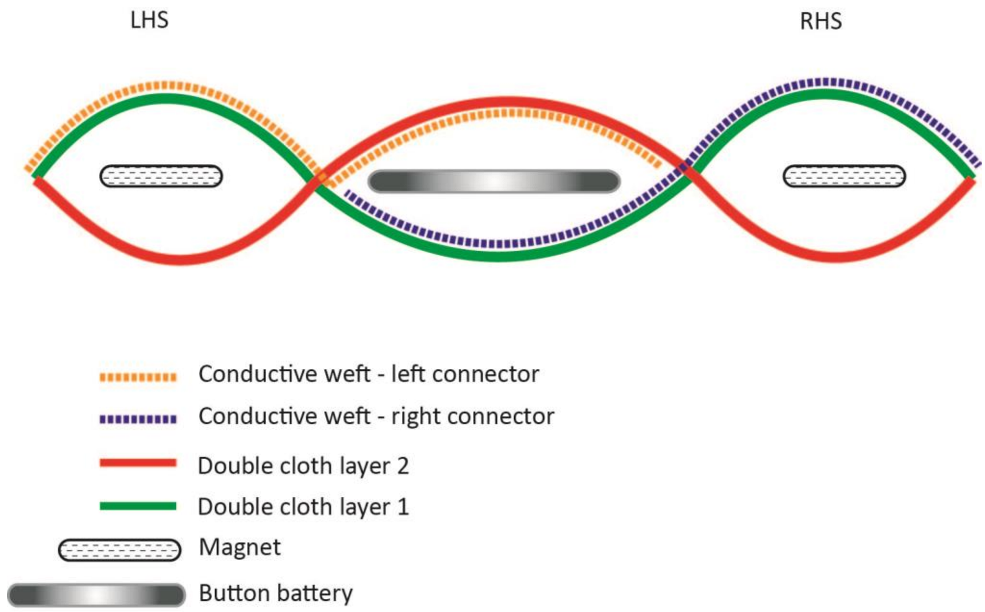


Figure 7.11 Cross view schematic of BHMv4 looking through all layers in battery holder section

The three double cloth sections (determined by warp draft blocks) in Figure 7.11 would be constructed simultaneously; thus, it was necessary to design the structures to correspond with the respective warp draft blocks and follow this sequence when being woven. The conductive weft for the left connector would be woven first, and only on completion, the right connector would then be woven to avoid short circuits. Therefore, the schematic in Figure 7.11 only illustrates a cross view including all woven layers through this section. The structures designed for this section still included double cloths; however, as blocks A and B would be split amongst two cloths, this would also split the number of shafts per cloth, i.e. 8 shafts per block would result in 4 shafts per cloth when applying double cloth structure. Woven structures using 4 shafts per cloth were designed, with either warp faced or weft faced weaves to optimise the conductive yarn weft exposure (Figure 7.12). Structures for BHMv4 are discussed in-depth in section 7.3. Essentially, warp or weft faced structures across 4 shafts would still result in securely woven cloths. The final design specification for BHMv4 was progressed to the woven execution stage. Complete woven structures for sample BHMv4 can be viewed in Appendix M.

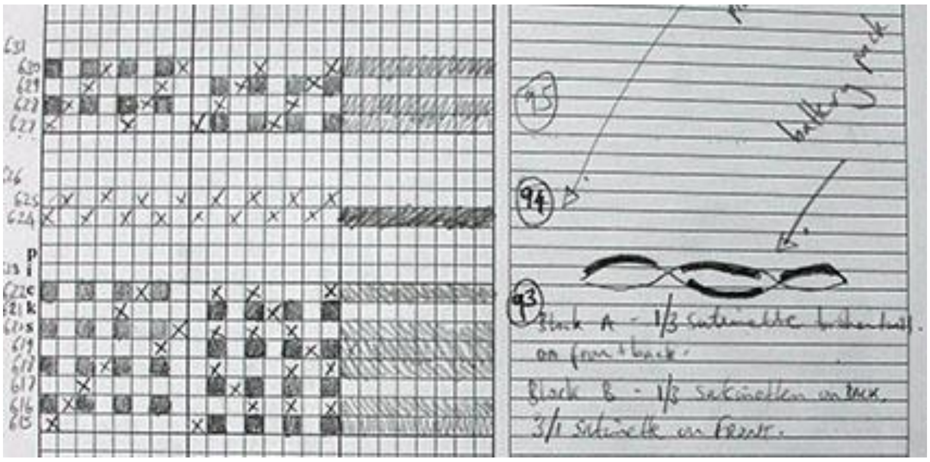


Figure 7.12 BHMv4 woven structure drafts

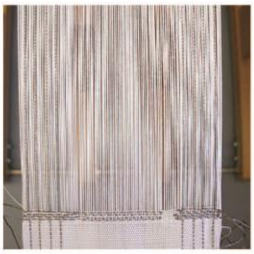
The following section will discuss the woven execution process for sample BHMv4.

7.2.1.7 Execute: BHMv4

The woven structures for BHMv4 were programmed into the Selectron loom system. The weft yarns were prepared and arranged ready to weave as per the design specification. For BHMv4, 2/20cc spun cotton was chosen to weave in the weft. This was the same yarn as in the warp and would weave a tight balanced density of cloth, with a flexible textile tactility to help the structure bend and wrap in function as a battery holder. From analysis of the physical textile quality of previous iterations (BHMv1, BHMv2 and BHMv3), there was more insight into how this structure would react to yarn types; therefore, a sturdy and robust cloth type was aimed for in this design in comparison to the previous versions. Four neodymium disc magnets (1cm diameter by 0.1cm thick) were allocated for this design. The making process for BHMv4 can be viewed in Figure 7.13.

The woven process for BHMv4 followed the design specification and related woven structures. Each section of BHMv4's construction will be explained in the following section.

1.



Bottom selvedge woven. Two independent conductive weft yarns begin to weave the battery and magnetic conductive contacts

2.

Battery and magnetic conductive contacts are completed

3.

Magnets are inserted into the double cloth pockets to form the conductive connectors

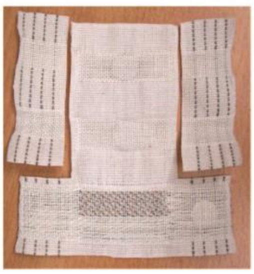
4.

Magnetic clamps and plain weave spacing sections woven

5.

Face and reverse of BHMv4 once cut off the loom

6.



Finishing process applied to BHMv4; exc
woven sections are glued and cut away.
Battery access slot glued and cut

Figure 7.13 Weaving process for BHMv4

7.3 Sample dissections: BHMv4

BHMv4 was woven in a series of sections as per previous samples. To illustrate this, the sections are displayed between the pink lines in Figure 7.14. Each section served a specific function; they will each be explained in-depth in the following subsections.

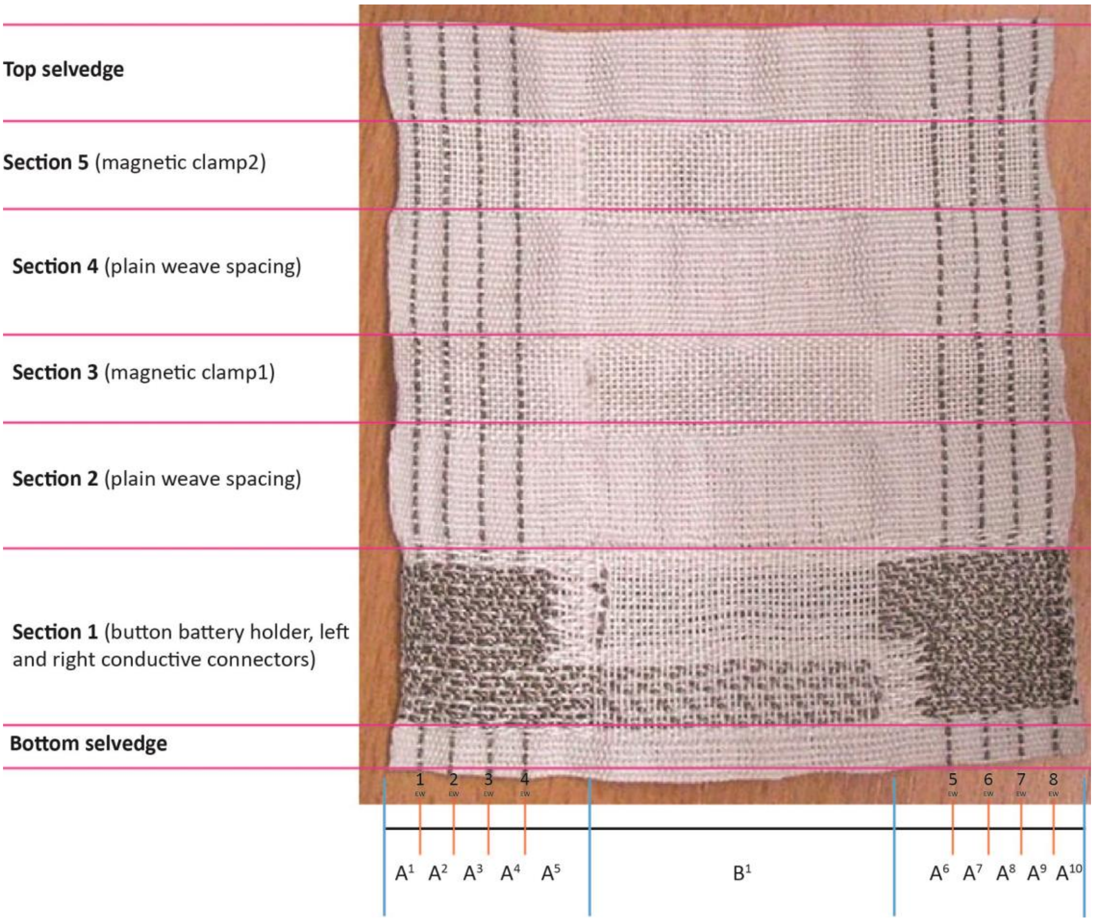


Figure 7.14 BHMv4 dissected section labels

7.3.1 Woven section descriptions: BHMv4

The complete sample BHMv4 comprised of five sections plus top and bottom selvedges. The extra warp was not specifically required for this sample. However, as the warp set up included an extra warp, it was utilised in the sample as it increased the interwoven mesh of the conductive connectors. The sample has been placed in Table 7.1 to distil the complexities involved in woven qualities.

Section	Section function	Section image	Blocks & cloth structure A	Blocks & cloth structure B	Extra warp threads woven LHS 1	2	3	4	RHS 5	6	7	8	Cross section schematic
Top selvedge	Selvedge		SC	SC	●	●	●	●	●	●	●	●	
5	Magnetic clamp2		DC1	DC2	🔴	🔴	🔴	🔴	🔴	🔴	🔴	🔴	
4	Plain weave spacing		SC	SC	●	●	●	●	●	●	●	●	
3	Magnetic clamp1		DC1	DC2	🔴	🔴	🔴	🔴	🔴	🔴	🔴	🔴	
2	Plain weave spacing		SC	SC	●	●	●	●	●	●	●	●	
1	Button battery holder, left and right conductive connectors		DC1	DC2	🔴	🔴	🔴	🔴	🔴	🔴	🔴	🔴	
Bottom selvedge	Selvedge		SC	SC	●	●	●	●	●	●	●	●	

SC = single cloth
DC1 = double cloth 1
DC2 = double cloth 2
● *= Extra warp thread woven in as single cloth*
🔴 *= Extra warp thread woven in as double cloth on TOP cloth*

Table 7.1 BHMv4 dissected sections

BHMv4 was woven from the bottom selvedge up, as a single piece of weaving; this was mapped from the design specification. The magnetic connectors, magnetic clamps and conductive wefts were simultaneously integrated during the weaving process.

The sample was constructed using single cloth plain weave and double cloth vertical tubes, where the extra warp was woven into the top cloth of double cloth sections, and integrated into the single cloths. The sample started and finished with plain weave single cloth, and with all extra warp conductive yarns woven into the structure to form the top and bottom selvedges. Each section of BHMv4's woven construction will be specifically discussed in sections 7.3.1.1 – 7.3.1.4.

7.3.1.1 Section 1: battery holder, conductive contacts and magnetic connectors

On completion of the bottom selvedge, section 1 was woven next. This was the most complex section of this sample as there were three functions to serve – a battery holder pocket, two battery conductive contacts and two conductive magnetic connectors. The different parts of BHMv4 section 1 are illustrated in Figure 7.15. Each of the conductive contacts and conductive magnetic connectors were joined – i.e. magnetic connector1 was linked to battery contact1, and magnetic connector2 was linked to battery contact2.

Two pieces of conductive yarn weft were woven for these parts, and a third cotton weft was woven simultaneously to these.

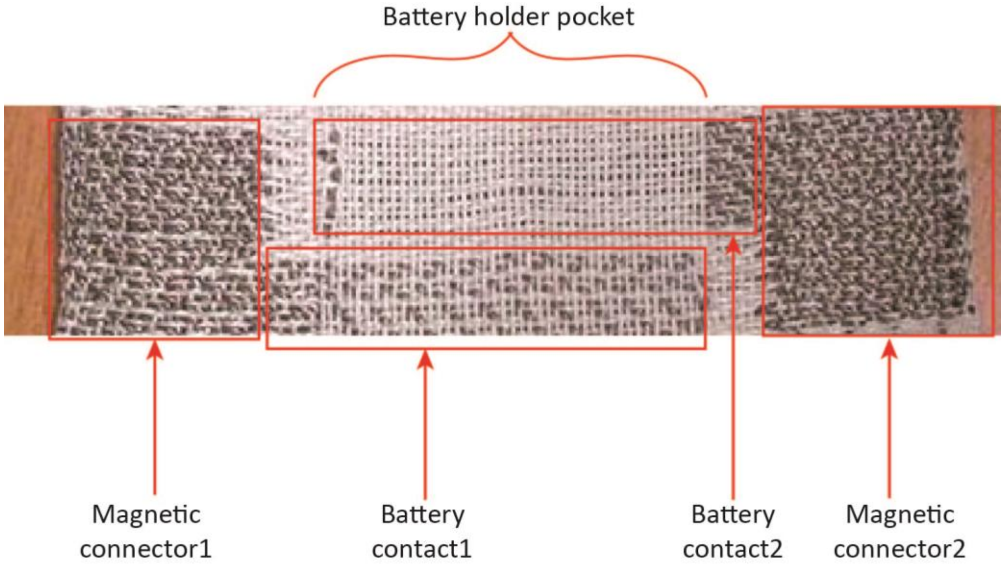


Figure 7.15 BHMv4 section 1 illustrated parts

Section 1 was woven in vertical tubular double cloths, as per the cross section schematic illustrated in Table 7.1. Thus, the sequence of conductive yarn weft order was crucial to forming the correct parts within this structure. The double cloth structure applied in this section interacted between the seams of block A and B, where the extra warp conductive yarns were woven only on the top cloth as plain weave. This structure was similar to that woven in RGB colour mixer’s battery holder section 13 (as discussed in section 5.3.1.6). The two battery contacts for the positive and the negative sides of the button battery, needed to be separated to avoid short circuiting when the battery was inserted into this pocket. Therefore, battery contact1 and battery contact2 were separated with 0.2cm of cotton woven between the two contacts. Battery contact1 and contact2 were woven for 0.7cm and 0.9cm respectively, with 0.2cm of 2/20cc cotton weft at the start and end of the same structure.

Two independent conductive yarn wefts were woven to form the two different connector and contacts. The sequence and placement of these weft yarns needed to match the woven structure to form the correct order for this section, using an inlay technique. Four interception points were used for BHMv4, where the inlayed conductive wefts were woven into and out of the warp (Figure 7.16).

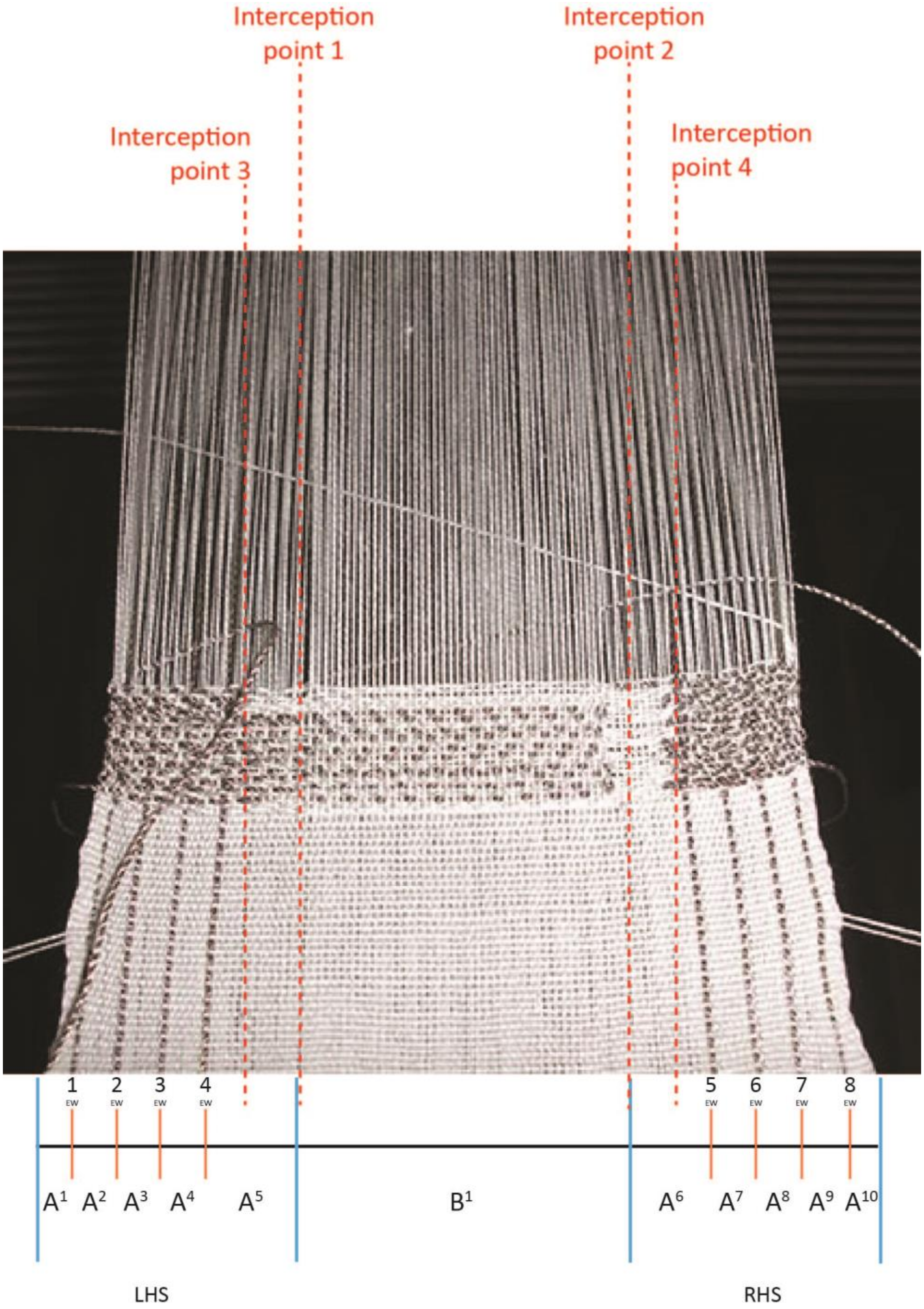


Figure 7.16 BHMv4's interception points

The interception points in this design were crucial to build section 1 of BHMv4. The order and management of three wefts woven simultaneously was challenging due to the narrow warp, scale and complexity of weft order in relation to the woven structure. However, after initial introduction of each weft, the sequence of integration became familiar to the researcher and consequently easier to construct. The integration of the three wefts in section 1 of BHMv4 can be viewed in Figure 7.17.

1.

Left conductive yarn weaves left magnetic connector and first battery contact. Right conductive yarn weaves right magnetic connector and second battery contact.

2.

Left conductive yarn woven in at interception point1 and taken out at interception point2 to weave top cloth of block B

3.

In the same pick, 2/20cc cotton pick woven across complete width of sample to tie in all warp ends

4.

The following pick (bottom cloth block B and top cloth block A), is woven with cotton across the complete sample

5.

The next pick weaves top cloth of block A with right conductive yarn; this is taken out at interception point4. A cotton pick is woven across complete sample in the same pick

6.

The left conductive yarn is woven in at interception point2 and taken out at interception point1 to weave the top cloth of block B. Cotton weft is woven across complete sample in the same pick

7.

The next pick weaves top cloth of block A; the left conductive yarn is reinserted at interception point1 and woven out on the left side of the warp. A cotton pick is woven across the complete sample

8.

The right conductive yarn is woven next from the right side of the warp to weave top cloth of block A and bottom cloth of block B; it is taken out of the warp at interception point1. A cotton weft is woven across the complete warp

9.

The following pick (top cloth block B and bottom cloth block A) is woven with cotton only across the complete sample - conductive yarn does not need to be woven in this pick

10.

The next pick weaves the left conductive yarn in from the left and is taken out at interception point3. The right conductive yarn is reinserted at interception point1 and woven out of the right side of the warp. Cotton weft is woven across the sample in same pick.

Figure 7.17 BHMv4 section 1 weft order integration

As mentioned in weave planning section 7.2.1.6, the woven structure applied to section 1 of BHMv4 was designed to expose optimum conductive weft on the top cloth external side of magnetic connector1 and connector2, and on the internal sides of block B (battery contacts). The woven structure for this section required double cloth across 8 shaft blocks, and resulted in 4 shafts per cloth, per block. Therefore, 4 shaft weft or warp faced structures were designed into a vertical tube double cloth (Figure 7.18).

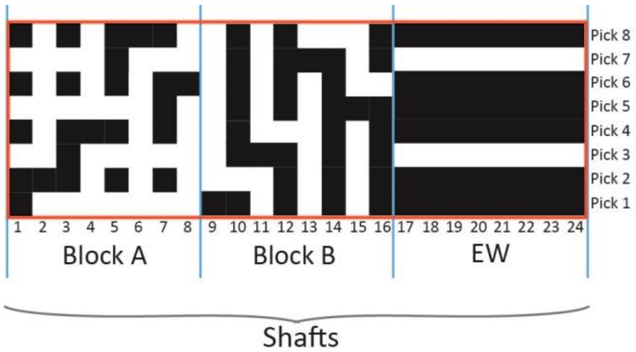


Figure 7.18 BHMv4's section 1 double cloth structure

The four shaft structures applied to each cloth were derivatives of satin and sateen – 1/3 and 3/1 satinettes. These structures were applied to this section as they would be stable across 4 shafts and would result in optimising weft exposure. To illustrate the specific applied structures to section 1 of BHMv4, Figure 7.19 shows the 4 shaft double cloth structure applied to the specific side of each block. Figure 7.19 is based on Figure 7.11.

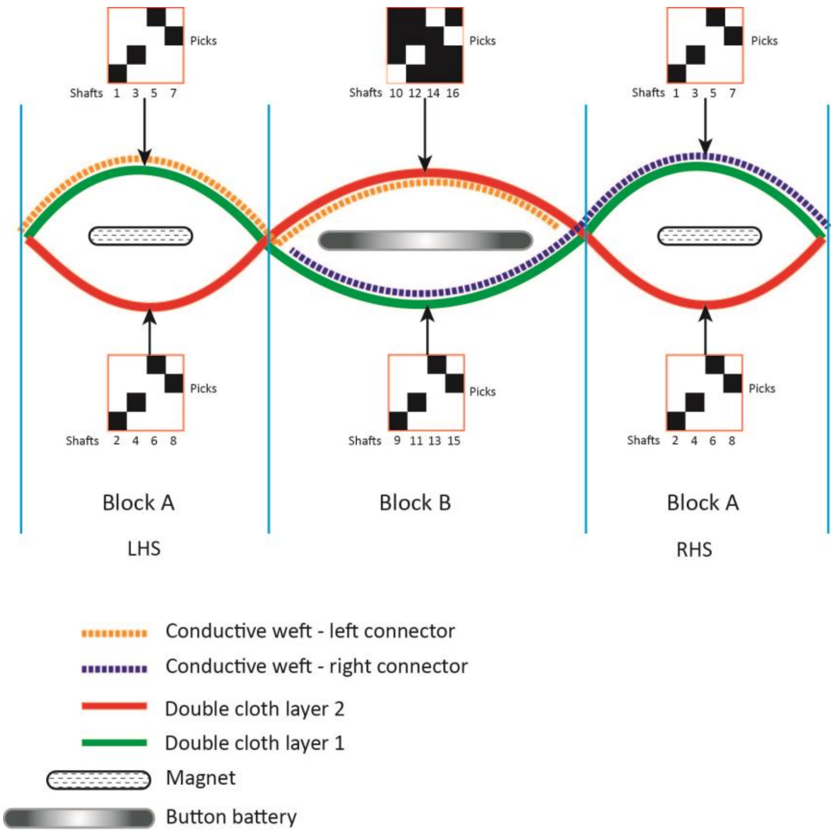


Figure 7.19 Cross view schematic of BHMv4 looking through all layers in the battery holder section with applied structures illustrated

Block B was designed to include the 1/3 satinette and the inverse of this – a 3/1 satinette, as this part housed the button battery. The top and bottom cloth's inner sides required optimum weft exposure for battery contacts. These structures were integrated into the double cloth structure as shown in Figure 7.18; however, to help view how the structures were integrated in relation to the double cloth layers, Figure 7.20 has separated the 4 shaft structures.

Once section 1 was complete (woven to 2.2cm height), a plain weave pick was treadled (not woven) to open the double cloth and insert the magnets into magnetic connector pockets in block A. This section was sealed by weaving plain weave that also began to form section 2.

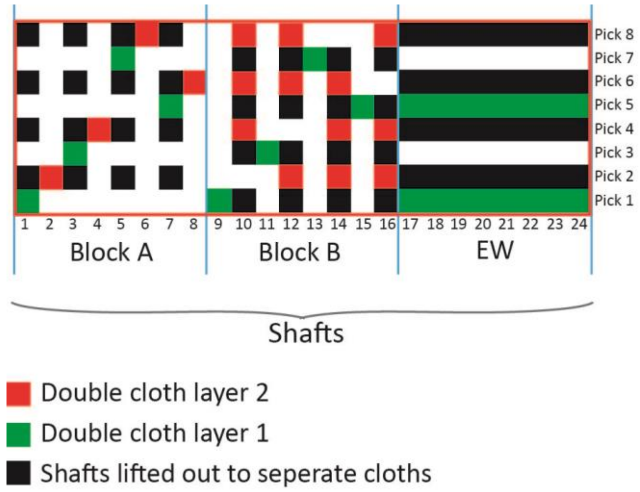


Figure 7.20 BHMv4's section 1 double cloth with separated 4 shaft structures

7.3.1.2 Sections 2 and 4: single cloths

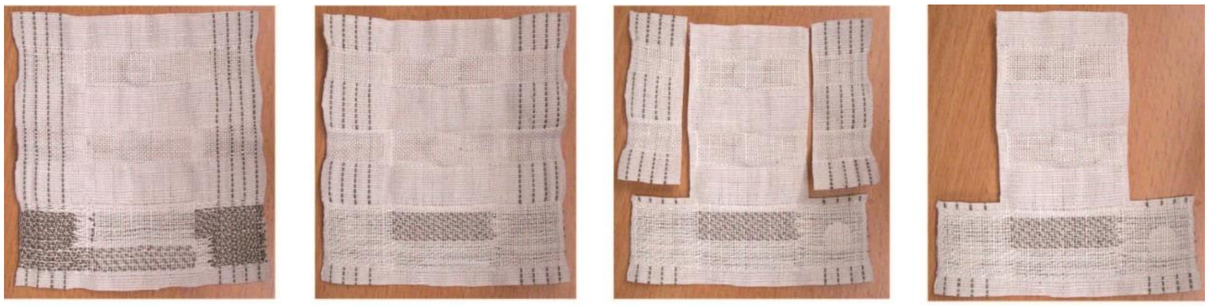
Sections 2 and 4 were single cloths using plain weave with the extra warp woven in, using 2/20cc cotton weft. The purpose of these sections was to weave a specific height between the magnetic clamps that would enable the sample to fold over and connect at allocated positions. The space required between the magnetic clamps was determined by how much fabric was needed to fold and wrap over for magnetic clamps 1 and 2; this would reach and connect to conductive battery contacts 1 and 2. There was sufficient flexibility designed into BHMv4 size for the clamp to be folded and wrapped in either direction. Sections 2 and 4 were woven for 1.3cm each.

7.3.1.3 Sections 3 and 5: magnetic clamps

Sections 3 and 5 were woven using a plain weave tubular double cloth structure, where the blocks A and B interacted as per section 1. The extra warp was woven into the top cloth of block A, although this was not required as part of the BHMv4's design. As most of the extra warp inter woven sections in the magnetic clamps would be cut away, they were retained and utilised for other work. The magnets were inserted into block B's woven pocket once woven to 1.1cm in height, and then sealed with plain weave. Although the magnets were tightly fitted into the pockets on the loom, once the sample was cut off, the magnets were more relaxed. The magnets could be easily manoeuvred inside the pocket to flip over to change magnetic polarity if required; the shiny magnets' surface helped to do this. The same manoeuvring principle applied to the magnets in the connector pocket in section 1.

7.3.1.4 Finishing BHMv4

Once BHMv4 was cut off the loom, the edges were trimmed of excess yarn. The sample needed to be cut into its T-shape design; therefore, the shape outline was determined by visible interactions of vertical double cloth joins. The cut incisions were first glued on both sides due to double cloths, as well as the battery access slot. Once dried, the excess fabric sections were cut off (Figure 7.21). The sample was then tested in a modular e-textile configuration.



BHMv4 face side | BHMv4 reverse side | BHMv4 excess fabric cut away | BHMv4 final sample

Figure 7.21 BHMv4 finishing process

7.4 Results: BHMv4

The results for BHMv4 sample were somewhat expected as this sample was closely related to the previous iterations BHMv1, BHMv2 and BMHv4. It was anticipated that the sample would be successful in function, particularly as the development for this sample was instigated from the weave planning stage. The outcomes were assessed on the objective set for this iteration – i.e. improved conductive contacts and smaller size holding for the battery. The final outcome and assembly process of BHMv4 can be seen in Figure 7.22.

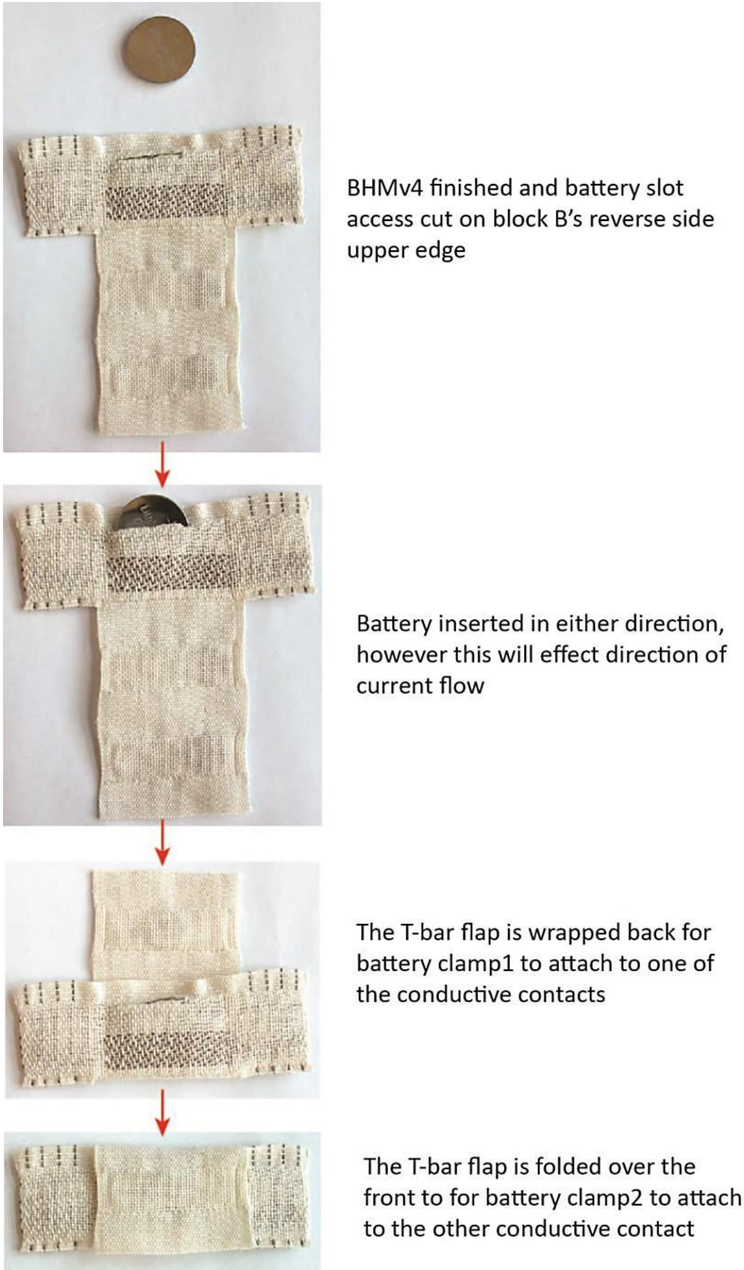


Figure 7.22 BHMv4 assembly

BHMv4's access slot was cut 2cm wide for a 3v button battery to fit into. The access slot was cut to the left of the sample to allow the battery to be pushed to the right hand side to hold and grip in the pocket. The narrow size of the battery holder pocket (block B) in this sample compared to previous iterations proved to be effective, as this helped grip and hold the battery in place. The cotton warp and weft yarns were thicker and sturdier than yarns used in previous iterations; this helped BHMv4's T-shape structure to fold into position and remain stable when active, supporting the battery and magnetic contacts.

Connecting BHMv4 to another output module via the magnetic connectors was effective (Figure 7.23). It was easily able to connect and attach to attracted magnetic connectors.

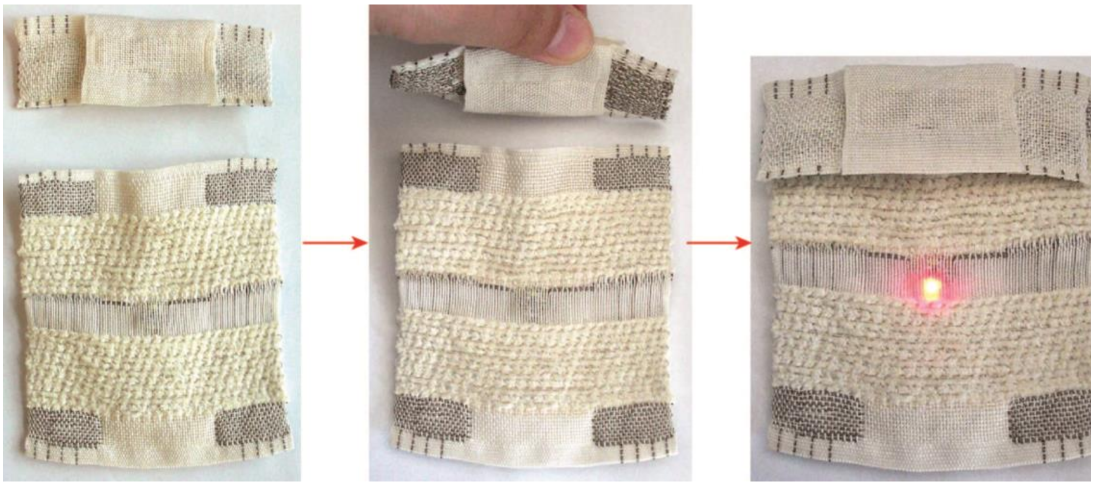


Figure 7.23 BHMv4 connected to a woven e-textile LED module

In this research BHMv4 was designed as part of e-textile modular kit2; therefore, it was able to function in a series of connected modules of the same width size and conductive magnetic connection method. Figure 7.24 shows BHMv4 connected to two other modules to form a circuit with a switch and LED output. Testing this circuit was effective and relates to the original concept of modular e-textiles, where the modules attached and detached into different configurations. The magnetic connectors proved to be effective for power delivery in a series of connections due to the quick and easy connecting forms.

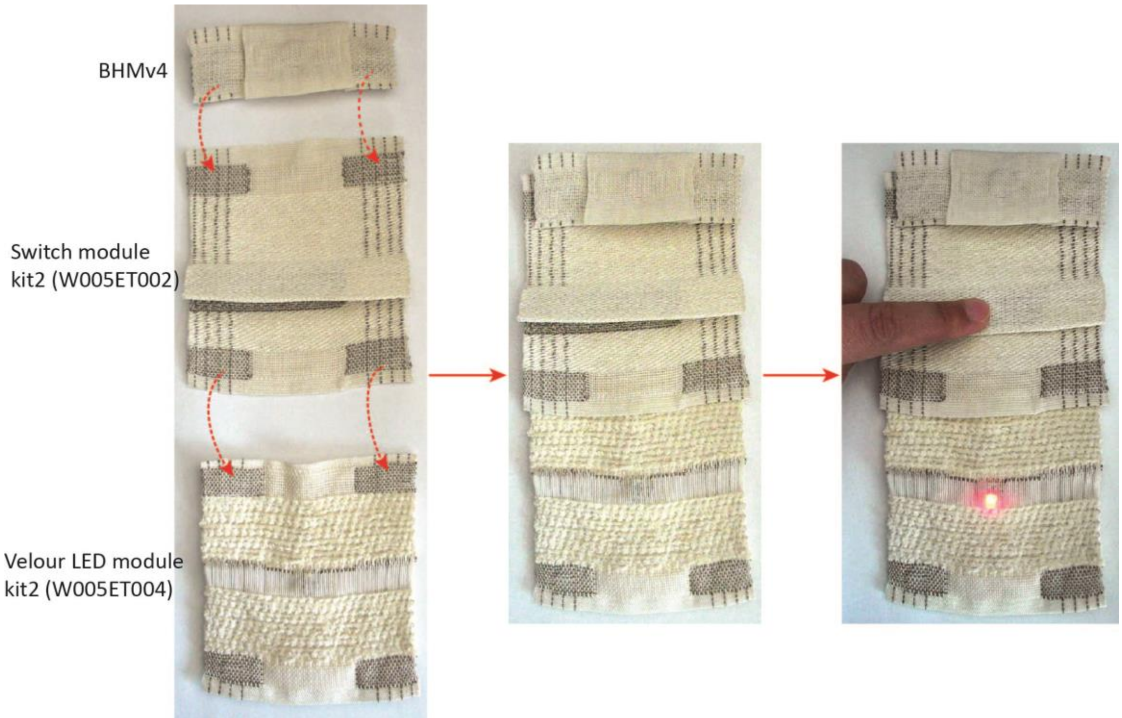


Figure 7.24 BHMv4 connected to a series of woven e-textiles modules

7.5 Analysis: BHMv4

The development of BHMv4 was an outcome of the modules category 3B battery holders in design iteration 2. Although BHMv4 was developed in the last iteration of its category, it is not necessarily a final solution as the analysis of this sample could still lead to further outcomes. However, as this category was specific to the output objective of modular battery holders, the deviation between iterations was subtle and closely related to previous samples. The design process to develop BHMv4 was essential to its outcomes and reliant on the reflective analysis of previous samples, especially as each of the samples in this category intercepted the design process at different stages.

In terms of the physical form of BHMv4, its smaller size improved handling and supported the form to connect with other modules. The scale and size of BHMv4 defined compatible modules, i.e. connecting modules needed to have the same width size to match magnetic connectors. When attached to a woven e-textile LED module, the connection was consistently held when static. With moderate movement, the LED would flicker, causing disruption to current flow. In comparison to previous battery holder modules, there was an improvement on consistent power delivery. The improved connection cannot be completely verified as being due to the change of woven structures without technical structural analysis, as other factors could have been influential (e.g. output modules connectors, LED component). Nevertheless, BHMv4 clearly showed the conductive yarn as more visible on the external sides of the magnetic connector, and in the internal sides of block B's battery holder pocket. Therefore, the function of BHMv4 from a woven structural construction perspective had been optimised to help expose the conductive yarn.

The central pocket housing the button battery (block B) was able to connect two 3v button batteries (2cm wide) in this single module – i.e. in series. They were positioned on top of one another and connected to an output source which proved successful. Although on analysis of this arrangement, it was found the slippage between the two batteries reduced grip impacting current flow; however, the tight fit of the pocket helped grip the batteries in the pocket. Applying pressure from the top of the battery pack helped to improve this issue.

The battery holders in this e-textiles category were designed specifically for 2cm wide button batteries. Different size button batteries would need size specific battery holders, much like conventional battery holders. Different forms of batteries would require adapted designs of holders. This research has highlighted central issues and principles of making e-textile battery holders when designing e-textile battery holders (e.g. battery contacts, connection points, stable connection between battery contact and output connectivity, and optimising exposure of connecting conductive surfaces).

Woven construction methods were applied in this e-textiles category, addressing the objective to make soft e-textile battery holders; however, other methods of e-textile construction are also applicable to this design objective. Advantages of woven e-textile include the integration of components, simultaneous making process and manipulation of woven structures as a single process. In addition, adaptation for industrial weaving (particularly jacquard weaving) has the potential to produce similar designs, where the layout across commercial weaving widths could be nested to avoid wastage of materials.

Although BHMv4 integrated the extra warp conductive yarns into the design, these were not specifically required. BHMv4's design was able to function without the extra warp and would not be required for future battery holder designs similar to this one.

Chapters 5, 6 and 7 have presented and discussed three specific examples of woven e-textiles constructed in this research. The next chapter will discuss the overall finding of this research project and relate this back to the research objectives.

8 Discussion of woven e-textiles design process and outcomes

This chapter discusses the research outcomes in relation to the research question, and compares this to the key gaps identified in the literature review. This research sought to inform an inquiry of woven e-textiles *through* a design led practice. The discussion will also analyse the position and dual role of the design practitioner-researcher. A questionnaire based on this e-textile research was also conducted and completed by experts in the field for peer feedback and insights of this research.

8.1 Outcomes of woven e-textiles design research

The samples discussed in chapters 5, 6 and 7 have demonstrated the impact of the design process on the outcomes and for future iterations. This research inquiry aimed to integrate and synthesise weaving and electronics through a design led approach, where the investigation intended to answer the research question as stated in chapter 1:

> *RQ1: How can the weaving process be manipulated to make woven e-textiles with integrated electronics?*

The woven e-textile design process illustrated and demonstrated the explicit approaches involved in the amalgamation of two subject areas – woven textiles and electronics. The research set to achieve the aims:

- To combine weaving and electronic design methods to develop e-textiles, through design led approaches
- To apply in-depth knowledge of weaving to make unobtrusive integrated woven e-textiles, utilising the full potential of woven structures.

The woven e-textile design process model was implemented through the practice of this research project. Woven textiles and electronic parallels were bought together via a series of design stages between the design objective and final outcome. This process enabled construction of design considered woven e-textiles to inform both form and function. The design process can be viewed again in Figure 8.1.

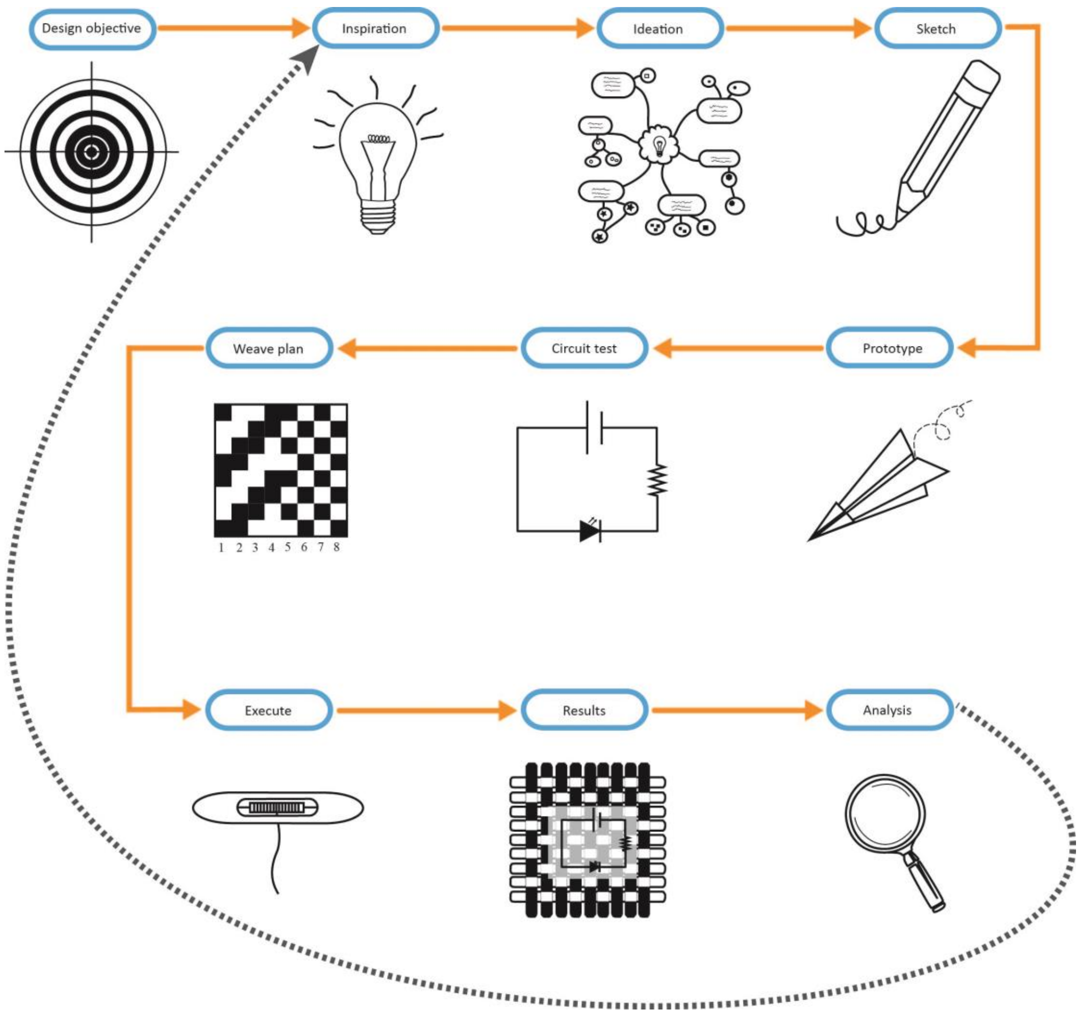


Figure 8.1 The woven e-textiles design process

The development of the design process was significant because it identified the key stages and underpinning design principles to produce woven e-textiles. This enabled the researcher to understand the relationship between the key methods applied in developing woven e-textiles, through both a technical materials approach and with creative craft methods. As a result, the discussions and examples presented in chapters 5, 6 and 7 have demonstrated the researcher's approach to meeting the research aims. The outcomes have been analysed to develop e-textiles, which are then used to inform the new design iterations.

The design process model explicitly documented all the activities that occur during the production of woven e-textiles. In particular, the cross-tabulation between the design process stages and identified key design principles is significant. This is because it helps to explain what occurs during the design process stages, to enable progression from one stage to the next, and how these stages are related (repeated to view in Table 8.1). In essence, the transition between design process stages allows for synthesis between the different phases for integrated woven e-textiles.

Design principles / **Design process**	Tacit knowledge	Implicit & explicit knowledge	Praxis	Abductive theory	Synthesis	Reflective practice: *Reflection -*		Creativity
						On	*In*	
Design objective	●	●		●		●		●
Inspiration	●	●	●	●	●	●	●	●
Ideation	●	●	●	●	●	●	●	●
Sketching	●	●	●	●	●	●	●	●
Prototyping	●	●	●	●	●	●	●	●
Circuit testing	●	●	●	●	●	●	●	●
Weave planning	●	●	●	●	●	●	●	●
Design specification		●	●	●	●	●		

Table 8.1 Relationship between woven e-textiles design process and design principles

The examples presented in chapters 5, 6 and 7 demonstrated an actuator, a complete integrated circuit and a modular woven e-textile, where these developments were led through the design process from initial design objectives through to final executions. Each of the presented samples was a result of the accumulated progression through each stage in the design process. Each sample had its own distinctive journey in relation to where it had developed from, i.e. from reflection on analysis of previous samples, experiential learning, reflections in the design stages, and as a result of previous design iterations. Thereby, the woven e-textile outcomes were a result of specific woven and electronic circuit design elements that were synthesised through the design process. Analysis of these led to further design iterated woven e-textiles that were also progressed via the design process.

8.1.1 E-textile sample outcomes comparison to existing work

The literature review identified a difference between woven e-textiles developed through technical materials approaches (predominantly focused on function), and woven e-textiles developed through creative craft methods (predominantly focused on form). Thus, this research sought to develop woven e-textiles through both technical materials approach *and* creative craft methods, to address both form and function. In addition, the research aimed to synthesis woven methods with electronic properties via a design led process using in-depth woven expertise, to fully utilise the woven construction. To help explain this approach, existing woven e-textiles developed through predominantly one of these approaches (i.e. technical materials or creative crafts methods), will be compared to sample RGB colour mixer (W003ET009) from chapter 5. The existing woven e-textile comparison samples will be examples that have already been referred to in the introduction and literature review.

ETH's technical materials development of a strip temperature sensor in a woven e-textile (Kinkeldei, Zysset et al. 2009), and SubTela's creative craft led development of a woven e-textile for their 'Black Wall Hanging' piece (Layne, Studio SubTela et al. 2006), will be compared with RGB colour mixer from chapter 5. Table 8.2 summarises the main differences between the three woven e-textile samples.

Woven e-textile image	Sample name/ reference	Development approach	Woven structural utilisation	Integrated woven function
	RGB Colour mixer (W003ET009) as described in chapter 5 in this thesis.	Development through both **technical materials approach and creative craft methods,** addressing both form and function, via a woven e-textiles design process	Woven structures have manipulated the textile on the loom to integrate multiple functions including woven switches, woven resistors, integrated battery holder and woven tracks. Integrated woven construction included single and double cloths, complex weaving techniques to attach	Three independent switches to control three output colours from a single standard RGB LED. One piece woven e-textile with integrated soft conductive yarns, malleable screen and battery holder to function as an interactive e-

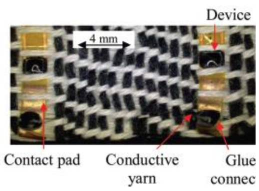
			component without soldering, inlay weft weaving and manipulation of floats.	textile colour mixer
	Barbara Layne & SubTela's woven e-textile for Black Wall Hanging (Layne, Studio Sub Tela et al. 2006)	Design led process through **creative crafts methods, addressing form and partial function as this is dependent on an external system**	Woven on a single cloth only using 2/2 twill structure, integrated multiple LEDs on the loom as a single piece of weaving (finishing processes possible applied – not fully documented)	Multiple standard LEDs integrated with hard conductive wire, independent power source and a complete computerised system to activate the e-textile as an interactive wall hanging
	ETH's woven e-fibre strip temperature sensor in a woven e-textile with conductive yarn tracks (Cherenack, Zysset et al. 2010 p.2)	**Technical materials approach** - focused on design of e-fibre strip temperature sensor component function	Woven on a single cloth only using a twill variation (specific structure not documented). Woven structure is only utilised to run two conductive yarns in the warp as tracks. Strip sensor placed into the weave to hold in position – these are glued into position to stabilise the contact.	Weave only integrated two woven conductive tracks. E-fibre temperature sensor is the focus of this project. Woven construction does not fully integrate the function as the e-fibre controls this.

Table 8.2 Woven e-textile samples summarised for comparison

RGB colour mixer has been developed with a specific objective (multiple switches controlling a RGB LED), through the woven e-textile design process. RGB colour mixer used all of the five identified woven methods in section 2.3, to make integrated woven e-textile by investigating these methods further. This included multiple functions (i.e. LED integration, switches, battery holder and resistors), complex weaving techniques for RGB LED integration, weft inlays for resistors, double cloths for switches and insulation, and manipulation of floats for conductive tracks. Although RGB colour mixer is specifically compared to the SubTela's wall hanging and ETH's temperature sensor, samples corrugated pleat LED v2 in chapter 6 and battery holder module v4 in chapter 7 also applied the identified woven methods. Sample corrugated pleat LED v2 applied all five of the identified woven methods. This included multiple functions (i.e. complete integrated circuit, lighting display and conductive contacts), complex techniques for LED integration, inlay of conductive weft attached to the LED component, double cloths for the pleated sections and integration of component, and manipulation of floats for conductive interconnections. Sample battery holder module v4 applied three of the identified woven methods. This included the integration of multiple functions (i.e. batter holder, battery clamp and conductive connectors), double cloths for pockets and inlay of conductive yarn.

The researcher developed RGB colour mixer with in-depth woven textile knowledge, and utilised the woven construction to integrate the complete circuit into the textile. This meant multiple woven structures were applied at specific points of the construction, with a combination of weft yarns. The design considered both form and function to synthesis the textile qualities, (e.g. soft tactile switches, malleable reflective screen, and flexible substrate), with a complete integrated independent circuit. This can function with an internal or external power source.

In comparison, SubTela's Black Wall Hanging piece was design led and developed with some contributed woven knowledge. Although the complete development process for Black Wall Hanging is not explicitly documented, the end application for this piece was for an interactive public art installation. Thus, the piece was largely dependent on an external computerised system. The integration of hard electronic wires with multiple standard LEDs would have made the integration difficult due to the rigidity of the wires. The woven structure was very basic (2/2 twill), where the LEDs were woven in as a single cloth with no additional woven manipulation. The woven structures were not further utilised; however, the design of this piece did function successfully in its application context. Use of soft conductive yarns in the warp and weft and multiple conductive interconnections using other woven structures, would have helped utilise the woven construction for this piece.

The third woven e-textile piece in the comparative Table 8.2, illustrates ETH's temperature sensor. The project was a technical materials development, where the e-fibre was the focus of the project. Nevertheless, the integration of the e-fibre strip temperature sensor was very basic, where the woven construction appears to be a twill variation (structure not fully documented). The emphasis is on the function of the sensor, where the woven structure is used as a frame to hold the strip sensor, although two conductive yarns were woven into the warp for circuit tracks. The sensor has been woven into the textile; however, no other woven method has been applied to help its function. Instead, glue had been applied to secure interconnects between the sensor and conductive yarn. This is an aspect that could have been improved via the weaving by integrating multiple conductive yarns in the warp and weft, applying a combination of woven structures to control interconnections and secure the integration of the e-fibre without glue.

In comparison to SubTela's Black Wall Hanging and ETH's temperature sensor, RGB colour mixer sample has utilised extensive woven construction to integrate a circuit into the weave. In addition, the woven e-textile process has enabled the investigation of common parallels between the design objective and the final outcome. It has considered both the form and function through a technical materials approach and using creative craft methods. Although SubTela's wall hanging piece was successful in its final application, the design and materials integration could have been developed further. In addition, it was not a complete circuit as it was part of a larger system. ETH's e-fibre temperature sensor woven e-textile only demonstrated very limited use of woven construction, although the e-fibre temperature sensor function was very sophisticated. Therefore, developing integrated woven e-textiles via a technical materials approach and creative craft methods can enable new perspectives to fully integrate the complete woven construction, as demonstrated by the samples discussed in chapters 5, 6 and 7.

8.2 Expertise in practice based research

The woven methods applied in this research project used the researcher's weaving expertise; thus, her previous textile design experience was invaluable in the development of this research. The researcher's expertise enabled advanced woven techniques and manipulation methods to develop simultaneously, shaping integration of electronics properties into the woven architecture. This established complex structures combining both woven structures and electronics properties simultaneously into the weaving process. The resultant woven e-textiles proved successful in meeting their individual objectives, and also displayed opportunities to be further investigated in progressive iterations.

The accumulation of woven e-textiles investigated in this research demonstrated the range of methods used to achieve complex and advanced woven e-textiles. The technical materials approach and creative craft methods have enabled a link between the two approaches. This research has only demonstrated a small proportion of potentially unlimited opportunities of design led woven e-textile developments. Thus, design led methods used to develop this research enabled woven e-textiles that may not have been realised through purely technical materials or creative craft approaches alone.

The nature of this practice based design research determines several factors that need to be considered when critically evaluating the methods applied. Carole Gray and Julian Malins have summarised these characteristics to help implement critical analysis on practice based methods (Gray, Malins 2004 pp.29-30):

- "*Experiencing/ exploring, gathering, documenting information and generating data/ evidence*
- *Reflecting on and evaluating information, selecting the most relevant information,*
- *Analysing, interpreting and making sense of information*
- *Synthesizing and communicating research findings, planning new research*"

Gray and Malins' reference points have been focused on in this research, where the synthesis between problem and solution has been a result of a constant *reflection on* and *reflection in* before, throughout and after the design process. The analysis of outcomes contributes to the cyclical nature of the design process, where new knowledge and ideas indicate insights and understandings for meaning making of the design task. However, the process of analysis is never truly complete due to the iterative nature of design activities, where this can only be considered an exhaustive process if no new ideas can be generated – this relates to the e-textiles design process that seeks to establish fully integrated e-textile material.

As Cobb *et al.* identified, in terms of learning and educational research, design experiments are multi-faceted, including prospective and reflective thoughts that lead to iterations of design (Cobb, Confrey et al. 2003). They further this idea by suggesting that emergence of new insights throughout the design process is beneficial to the researcher's methodological framework. Such insights enable questioning and/ or testing of additional ideas whilst applying the same systematic methods; thus reinforcing the initial design approach. Although Cobb *et al.* propose this position from an education and learning point of view, the design process in this e-textile research is largely dependent on experiential learning, as this is related to researcher's criteria for analysis. Learning is development, as "*learning is the process whereby knowledge is created through the transformation of experience. …to understand learning, we must understand the nature of knowledge, and vice versa*" (Kolb 1984 p.38). Therefore, the previous experiences of a practice based researcher impacts analytical skills, as the knowledge gained is used to add to an acquired repository of understanding that impacts thoughts, actions and subsequent outputs of work. Clive Dinlot (1998) implied, research findings related to design practice through reference and discussion alone are not stable enough insights to claim as new knowledge in research to a domain. However, when this is combined with analytical thinking for further investigation, it can be considered as new knowledge in research (cited in Swann 2002 p.60).

Similarly, Lucy Kimbell suggests, *"…in the practice approach design cannot be understood without people and their practices …In order to see the connections between design-as-practice* [practice/process] *and design-in-practice* [outputs/results]*, researcher must go and look for them*" (Kimbell 2009 p.12). Thus, the visual analysis of design work can be specific to the designer, as their expertise is central to warrant this integrity. The process of analysis is a 'creative construction' (Gray, Malins 2004 p.155) whereby decisions are made via reflections of actions. Synthesis of these observations in the design process leads to answers, questions, conclusions, effective/ ineffective outcomes, and/ or further enquiry. However, the systematic and in-depth analytical thinking applied in the analysis stage is related to the expertise of the designer. The next subsection will address this issue specifically.

8.2.1 The role of the design practitioner-researcher

The dual role of a design based practitioner-researcher means they are directly involved with the execution of the research (i.e. designing and making the object/s), and critically analysing the objects concerned. However, the researcher's integrated relationship with the practice sets challenges and questions the bias, credibility and trustworthiness of the research (Barab, Squire 2004). Although these themes are derived from and closely related to science based research, they should be able to hold equivalent credibility in practice based design research.

The designer-researcher positions themselves as an integral cog of practice research production, while concurrently acting as the external researcher to objectively evaluate and determine the validity of the research content. Therefore, "*…the advantages of the practitioner-researcher role are compelling: your 'insider' knowledge, experience and status usually lends your research credibility and trustworthiness in the eyes of your peers, that is, you are not an 'external' researcher*" (Gray, Malins 2004 p.23). Thus, the designer *becomes* the researcher who is actively involved in the empirical research, and assesses actions reflectively to provide expert level self-validation.

8.3 Expert feedback on novel woven e-textiles

Expert feedback was sought at the eTextile Summer Camp 2013, via a questionnaire to gain insights of the e-textile research conducted for this PhD project. Although the eTextile Summer Camp's name refers to a 'camp' style, this event was a professional event, with high profile participants from the e-textiles field. The event took place during the summer in an informal setting; however, the e-textiles activities were high level and in-depth quality.

An open-ended questionnaire was designed and presented to participants at the eTextiles Summer Camp, specifically to gain feedback from peers in the e-textiles field. The questions aimed to gain responses with reference to a presentation and the woven e-textiles samples demonstrated to the participants. The organisers of the summer camp were contacted prior to the event to request permission to conduct this questionnaire, whereby permission was granted. The participants attending the eTextiles Summer Camp were selected upon application by the event's organising committee. Participants were required to consent to their participation in workshop activities and related events for the duration of the camp. Therefore, the questionnaire did not need ethical approval as all participants attending provided consent to be subjects for such activities, including the questionnaire. All participants were given an information sheet outlining the purpose of the questionnaire, researcher's contact details and consent to use the data for this research (the questionnaire design and information sheet can be viewed in Appendix N).

All participants attending the summer camp provided an initial introduction of their own work; this was presented informally over a five minute pecha-kucha slide show. During the presentation, the researcher presented an overview of this woven e-textiles research, including the objectives, the design process model and examples of woven e-textiles to illustrate the integrated woven approach. Three examples were presented in the slide show to demonstrate executed results ('Malleable light1', 'Dual soft switches' and 'RGB colour mixer'). The last presentation slide requested voluntary participation for a questionnaire consisting of five open ended questions, to be completed during the summer camp.

The eTextiles Summer Camp's schedule was intensive with the majority of the day consisting of workshops, discussions and group activities. Participants were approached during and in-between activities when idle, and asked if they would like to take part in the questionnaire that would contribute towards a PhD research project. They were informed this was a voluntary activity taking up to 10 minutes, and that they were not obliged to take part and could withdraw at any time. Participants who agreed to participate were shown two physical samples of the woven e-textiles – 'Malleable light 1' (W003ET007) and 'Corrugated pleat LED v2' CPLEDv2 (W004ET019). An explanation of how the e-textile pieces had been made and demonstrations of the soft circuits functioning were shown. Participants were also given the opportunity to physically handle the samples and ask any questions.

A total of 27 e-textile practitioners attended the e-textiles summer camp 2013 (26 excluding the researcher); 17 questionnaires were given out to participants, all of whom were given the same explanation, demonstrations of woven e-textile samples and had viewed the researcher's presentation of this research. A total of 15 questionnaires were returned of which 14 were from e-textiles practitioners as one participant was an accompanying partner (a media artist). This data was withdrawn from the final results as the participant was not an e-textile expert.

The questionnaires were presented in printed form with five open ended questions, based on the samples demonstrated and the debriefed explanations about these. On completion of the questionnaire, participants returned the form to the researcher and were given a copy of the information sheet to take away in case they had any further queries. The five questions were:

Q1: *What do you think about the woven e-textiles samples shown? Do you think the overall designs are novel?*
Q2: *What do you think about using a design led approach to develop woven e-textiles?*
Q3: *What do you think about an integrated woven process to make one piece e-textiles?*
Q4: *What types of application do you think woven e-textiles could have?*
Q5: *Any other thoughts?*

The questionnaire probed insights into:

- novelty of design
- design and/ or aesthetics
- making process
- applications
- industry manufacture

The field experts were able to provide key insights from their professional experience and perspectives on whether they regarded the e-textiles as novel compared to what they know of in the field. It was important to ask the participants about design and/ or aesthetics of the woven e-textiles as this relates to the design of the overall e-textile. The making process similarly related to the design of the e-textile; however, this specific subject related to the woven construction and the design process as referred to in the researcher's presentation. The questionnaire sought to question the participants' recognition and/ or comprehension of the woven construction in relation to the e-textile design and integrated electronics. Types of applications for the e-textile were also probed, as the e-textiles were samples and not designed for a specific application. Any suggested applications may have been inspired by the demonstrated e-textiles, including existing, possible and conceptual applications of integrated woven e-textiles. The final subject was industry manufacture, and although a specific question was not designed for this subject, it was related to all of the questions.

8.3.1 Feedback of woven e-textiles questionnaires

The transcribed questionnaires can be viewed in Appendix O. Participant's names have been coded using a participant number to keep their identity anonymous. The transcribed questionnaire coding and results summary can be viewed in Appendix Q. The classifications of all the questionnaire answers can be viewed in Appendix P.

The participants' feedback with reference to the novelty of woven e-textile design was supportive. Examples of comments in this subject category included:

- "*The designs are novel and show a lot of potential for future products/ developments. It really exciting to see woven circuitry*" (Participant 04, Q1)
- "*The functionality is completely new*" (Participant 06, Q1)
- "Yes, [I] *think that the approach related to the quality of woven e-textile it is novel. It is a next step research in e-textiles"* (Participant 07, Q1)
- "*They are the most technically accomplished woven e-textiles samples I have seen*" (Participant 10, Q1)

With reference to the design led approach to develop the e-textiles and their aesthetic, the majority of feedback in this subject reported this to be affective in the sample's design. Comments in this subject included:

- "*I think an advantage of the e-textile making is that we can influence the look, it doesn't have to look like electronic components*" (Participant 09, Q5)
- "*I think a design led approach to combine the technical and go through that iterative process is essential to bring together textiles and electronics in an intelligent, meaningful and aesthetic way*" (Participant 10, Q2)
- "*I love the neatness and pleating combining the electronics without feeling/ looking 'e-textily'* " (Participant 13, Q1)

The making process was integral to the design of the woven e-textiles. The majority of participants agreed the integrated woven e-textiles making process was beneficial to the e-textile samples' design. Examples of comments for this subject included:

- "*Looks very simple but obviously a lot of thought has gone into it* [woven e-textile samples]" (Participant 01, Q5)
- "*It's really inspiring to see such a strong exploration of e-textiles where the textiles techniques and structures are the focus… its fantastic*" (Participant 04, Q5)
- "*I think that* [integrated woven process] *could be a good thing because you can have a completely integrated circuit*" (Participant 06, Q3)
- "*The woven process is one way to bring textiles and electronics together and keep the fabric qualities that are so important to a breadth of people*" (Participant 10, Q3)

The majority of comments regarding the applications of woven e-textiles (as per the samples demonstrated), visualised or conceptualised useful/ positive applications. Comments suggesting positive application types included:

- "*Because of how integrated the textiles and electronics are, it opens up more opportunities for how e-textiles can be used in our everyday environments such as interiors, garments, furnishing, etc., as well as in more specialised areas such as health care*" (Participant 04, Q4)
- "*Interactive interior textiles; automotive industry; furniture, healthcare area*" (Participant 11, Q4)
- "*Is it possible to include other electronics or parts than LEDs? I think link wind so the textile inflates hidden sound*" (Participant 14, Q5).

The last subject probed by the questionnaire related to industry manufacture. Four negative comments were attributed to sustainability issues, where two participants made 2 comments each on this subject. Examples of positive industry manufacture comments included:

- "*It's an interesting approach that would allow designers in companies to easily create stable and reliable LED e-textiles. Industrialisation requires reliable and fast processes such as this*" (Participant 03, Q3)

- "*This is the way forward for e-textiles if it needs to come into the production stage of e-textiles*" (Participant 04, Q3)
- "*I think this method has a lot of potential to be developed for production*" (Participant 08, Q3)
- "*You quit* [leave out] *some parts in the production, which means the production becomes less expensive*" (Participant 14, Q3)

Overall, the questionnaire responses provided positive and supportive feedback of the novel approach applied to develop the woven e-textiles in this research. The insights were determined by the participants' e-textile related background and involvement in the field, i.e. their level of expertise.

8.4 Chapter 8 summary

This chapter has presented a discussion based on the woven e-textiles design approach employed in this research project. The main outcomes of this research have been discussed against the research question, by positioning the outcomes against the objectives and gaps in knowledge identified in the literature review. This chapter has discussed the woven e-textile design process and methods applied in this project against other existing projects (i.e. technical materials approach and creative craft methods); this has helped explain how this PhD research approach differs from existing work and its advantages.

Expertise in practice based research and the dual role of the designer-researcher was discussed to position this against this practice based project and the implications of this, particularly research validity. Finally, expert feedback was sought and evaluated using a questionnaire applied to participants at the eTextiles Summer Camp 2013 event, devised to reflect peer insight of this e-textiles research.

The following and final chapter in this thesis will present the project conclusions.

9 Conclusions

This thesis has presented an in-depth account of the woven e-textiles research investigated via design led processes. This chapter will present the research conclusions. It will review the outcomes of the research in relation to the research aims and objectives

9.1 Meeting the research aims and objectives

The research aims set for this project are reiterated below:

- To combine weaving and electronic design methods to develop e-textiles, through design led approaches
- To apply in-depth knowledge of weaving to make unobtrusive integrated woven e-textiles, utilising the full potential of woven structures.

In order to pursue these aims, two objectives were set to specifically investigate:

Objective 1

- *Determine a design process model that can be applied to develop woven e-textiles*

Objective 2

- *Develop novel physical e-textile outputs using the design process developed in objective 1 and reflective practice*

The following subsections describe how these objectives were met.

9.1.1. Objective 1: *Determine a design process model that can be applied to develop woven e-textiles*

The researcher's previous woven design experience and processes, her knowledge of electronics design, and her reflection on initial woven e-textile pilot samples were combined to make explicit the key elements of her woven e-textile design process; this was presented as a design process model in chapter 3. In this model, both form and function are combined through reflective practice, praxis, synthesis, implicit and explicit knowledge, tacit thinking, creativity, abductive theory and experiential learning. To gain insights of what occurs in each of the design process stages, and how the stages are related, underpinning design principles were explained in detail in chapter 3 and supported by theoretical literature. Although every aspect of the design process cannot be explained due to some implicit qualities only being known to the designer (i.e. 'designerly ways of knowing' as suggested by Nigel Cross) (Cross, 2000 p.97), the main phases have been extracted. The design process is ultimately an iterative one, where each cycle evolves and produces new insights and progression for future woven e-textiles design.

The design process has brought together technical material approaches and creative craft methods to produce integrated woven e-textile design. Each stage of the design process stimulates design actions that serve as a catalyst for progressive stages. Woven e-textiles were produced as a result of the accumulated decisions of the design process, where technical approaches and craft methods were synthesised. This included designing electronic circuits and woven structures, to weave as integrated e-textiles.

9.1.2. Objective 2: Develop novel physical e-textile outputs using the design process developed in objective 1 and reflective practice

This objective was met by applying the design process model developed in chapter 3 to guide the combination of woven techniques and electronics design methods to develop advanced woven e-textiles.

The weaving techniques were explained in chapter 4, sections 4.2 and 4.3, as part of a technical repository of woven e-textile methods and techniques. The techniques were applied in a collection of e-textile samples, which are documented in the Appendix A and Appendix D. Building the technical repository enabled further woven methods to be designed through reflective practice. Minor amendments to some of these woven e-textile techniques improved function and helped to inspire new ideas for exploration.

Under objective 2, the research question of how the weaving process could be manipulated to make novel integrated e-textiles was addressed. The literature review had identified five methods for manipulating the weaving process which had been little used previously for integrating electronics into textiles. Through developing novel e-textiles using the design process developed in objective 1 and reflective practice, the application of these five methods was explored in depth.

The most significant methods applied were:

- **The use of double cloth** (seen in chapters 5, 6, and 7, in the samples RGB colour mixer, corrugated pleat LED v2, and battery holder module v4)

- **The integration of multiple functions into the textiles as part of the weaving process** (seen in chapters 5, 6, and 7, in the samples RGB colour mixer, corrugated pleat LED v2, and battery holder module v4)

- **The use of complex weaving techniques to attach and integrate components** (seen in chapters 5 and 6, in the samples RGB colour mixer and corrugated pleat LED v2)

- **The use of inlay weft weaving** (seen in chapters 5, 6, and 7, in the samples RGB colour mixer, corrugated pleat LED v2, and battery holder module v4)

- **The manipulation of floats** (seen in chapters 5 and 6, in the samples RGB colour mixer and corrugated pleat LED v2)

9.2 Contributions to knowledge

The thesis has presented a design process model to amalgamate two disparate processes into a single combined one, where the outcomes have been considered in terms of both form and function. Applying the researcher’s woven expertise to this design process, many woven e-textile outcomes were realised.

The collection of e-textiles investigated in this research demonstrated an accumulation of specific woven e-textile techniques. These methods were systematically documented throughout the thesis and were predominantly presented in chapter 4 (technical woven repository), and through the samples discussed in chapters 5, 6 and 7.

The following points summarise the contributions to knowledge made in this thesis:

- Identification of the key design stages involved in a design process model to create fully integrated woven e-textiles.

- The synthesis of design principles (i.e. tacit knowledge, implicit and explicit knowledge, praxis, abductive theory, synthesis, reflective practice and creativity), with woven textile methods within a design process model. This has enabled design led processes to integrate electronics and weaving in e-textiles.

- The manipulation of the weaving process to make novel integrated e-textiles. (Through the use of double cloth, integration of multiple functions, the use of complex weaving techniques to attach and integrate components, the use of inlay weft weaving, and the manipulation of floats).

- An e-textile technical woven repository, (presented in chapter 4), which documents a range of advanced weaving techniques which may be applied to create integrated woven e-textiles

Thus, the contributions make reference to the identification of key stages involved in the woven e-textile design process; this has introduced design led approaches to think about, design for and make woven e-textiles. The design process has also provided a deeper insight into the underlying design principles that influence the synthesis between woven design and electronics. Reflective practice and working through the design process developed a collection of woven e-textiles, where the methods and techniques were specifically manipulated, analysed and iterated to improve design features.

9.3 Other concluding insights

Parallels between other existing design process models such as in architecture, product, and industrial design, were analysed and compared to one of the only studies on textile design process by Rachel Studd (Studd, 2002). Similarities were identified between these design processes; however, there remain differences amongst subject specific practices and alternative sequence of events, between initial objective and final outcome. The design process model proposed in this research is specific to woven e-textiles. However, there are common features recognised within this model outline that would appeal to making processes and design practices across a number of design subjects. In particular is reference to the design principles, which are essential to any design practice involving design thinking, reflective practice and iterative design.

Woven e-textile materials development was the focus in this project, thus, a specific application was not intended for investigation. However, some of the woven samples did present instant product like qualities, for example textile lighting surfaces. The research has demonstrated the potential of woven e-textiles, where these methods could be applied to specific application contexts. The textile structure can be utilised to add value to the final e-textile without compromising form or function. In addition, advanced weaving methods are more advantageous to integrated woven e-textiles. This research has demonstrated that woven construction can be manipulated for different electronic properties, where these methods have the capability to be adapted for more complex woven circuitry.

Standard electronic components are often altered to better fit the weaving process. Linear like standard components have been popular and successfully integrated into woven e-textiles due to their yarn like form; however, this highlights the need for better woven e-textile components. In this research, own made components were developed to integrate into the woven e-textile samples. This produced improved integrated woven e-textiles, where the woven construction assisted the integration process and did not compromise the form or function.

The woven e-textiles questionnaire generated suggestions for potential application areas for woven e-textiles, such as the ones executed in this research. The suggested applications were from a number of sectors, including interiors, installation, transport and wearable garments. These responses revealed initial thoughts of specific context applications, where experts in the e-textile field were provisionally visualising these applications with physical active samples.

The methods and techniques applied to the e-textile outcomes in this research project have the ability to be appropriated and adapted for e-textile circuits. This has the potential to be applied for eventual applications in wearable technology and electronic soft product interfaces.

9.4 Limitations and improvements of the research

Time is inevitably a limiting factor in all projects including this research. Although a thorough investigation of woven e-textiles was conducted during this PhD project, the nature of this practice based research (particularly hand weaving), was time consuming. In addition, the design process' cyclical feature does not determine a definitive end; therefore, the process is still able to continue. The practical output of this research addressed several different themes of e-textiles, where some were not fully explored due to time constraints. However, there is opportunity to pursue this work in future investigations.

The researcher was an expert weaver; thus, the weaving process was an instinctive activity that did not require any additional training. In contrast, electronics was a new subject to the researcher that required additional time to familiarise with; this was an aspect that progressed simultaneously to the research. The researcher had basic electronic knowledge on commencement of this project, which was a motivating factor to progress the research and build further knowledge that enabled a fresh approach to electronics. As a result, simple aspects were valuable building blocks to initiate the project and to progress it to advanced latter phases. Incidentally, the basic electronic principles were sufficient to execute complex woven methods to demonstrate these functions, where the findings are applicable to more complex electronic configurations.

This project has demonstrated possibilities for woven e-textiles using the researcher's woven expertise and reflective based design practice. Multiple options to execute woven samples are possible, some of which have been highlighted through this research. The limitations of specific woven techniques were raised in chapter 4 (technical woven repository), and chapters 5, 6 and 7 when analysing specific referenced samples.

The dual role of the designer-researcher as per in this project, could be viewed as an influential bias through direct over involvement in the research. However, as previously discussed, this research project aimed to investigate woven e-textiles *through* design led practice. The nature of this project required the researcher's woven expertise to contribute as a central factor for the research output, where the research would be conducted via reflective practice. The researcher's tacit methods are also key aspects in the design process, which formed an integral part of the outputs. As a result, this research is directly related to, and exposes real world design practice, and a designer's usual work activity. The main difference between real world design and design research is the formalisation process of design practice using research methodologies, i.e. defined objectives and research questions, critical evaluation of the design process, justification of all methods, distilled and explicit documentation of the design process, methods and outcomes. In addition, design research seeks to uncover deeper insights of the subject that can contribute new understanding and knowledge to the field.

Some qualities of design research practice will not be able to be explained due to the tacit and implicit nature of design practice, whereby these thought processes are internally held by the designer who is unable to explicitly express these. Although, the researcher's expert knowledge in practice based design research provides credibility and warrants self-validation, they are not deemed 'external' in this capacity. This is due to reflective practice of this research that requires internal activity through subject specific practice (Gray, Malins 2004 p.23).

The samples discussed in chapters 5, 6 and 7 have explicitly demonstrated how the design process model is applied to the practice of woven e-textiles. However, the model has been developed through the researcher's own practice and applied to the research executed by the researcher for this project; thus, the model is verified by the researcher and from the outputs of this. To gain external verification, this design process model would need to be verified by other woven e-textile designers/ developers, by applying it to their practice and evaluating it. This could be an additional implication for future research, where the model could be used as a foundation tool and adapted for other designer's/ researcher's processes.

There was only a small sample size of experts who participated in the e-textile questionnaire. Although this was only to gain feedback on the woven e-textiles developed in this research, the environment and possible bias by the researcher are factors that could have affected their answers. However, given the expertise of the participants, the briefing for honest opinions and the detailed answers provided, there was sufficient opportunity for participants to openly express their views; nevertheless, the limitations are still applicable factors to consider.

Materials such as conductive yarns have the opportunity to be combined with softer materials and reduce large quantities of hard electronics and metal wires, reducing soldering and still integrating electronic function. Alternative product designs could also consider integration of e-textile parts. For example, modular systems whereby skeletal circuit tracks on garments or product chassis/ frames are constant, with the opportunity to adapt and attach soft interfaced technology modules of different functional abilities. If e-textile products are proven successful, there is a possibility of policies or systems to deconstruct re-use and recycle e-textile based products, as per existing technology in the current market, e.g. mobile phones, computers and household electronic goods.

Currently, cost is also a limiting factor to the development and uptake of e-textile products. Cost of e-textiles is likely to decrease with larger production quantities and improved manufacturing abilities. However, this is largely dependent on future efficiency, reliability, application, design and consumer acceptance of e-textile based products.

9.5 Future work and the research value to industry

The woven e-textile developments explored in this research were produced on a multi-shaft manual sampling ARM loom, which allowed the researcher to perform more complex manipulation techniques as opposed to an industrial loom. These methods and techniques have potential to be adapted and converted for industrial woven processes (e.g. jacquard and dobby looms), with some adaptation for manufacturability. The process of manual sample weaving for translation into industrial weaving is common with standard textile production. Previous specialist textile machinery has, in the past, been developed through experimental textile work. For example, loom technology has been modified for specific textile qualities such as velvet, tri-axial weaving and 3D fabrics. Similarly, textile machinery modifications for e-textiles have also been seen possible, such as adaptation of embroidery technology for e-textile lighting as shown by Forster Rohner (Zimmerman, 2011; Forster Rohner Textile Innovations, 2014). Thus, the future for woven e-textile developments could also see such loom adaptations, to enable automated processes such as positional inlay techniques for conductive tracks, or on loom component integration specific to a woven e-textile.

Industrial level weaving for e-textiles has opportunity to explore a wider range of textile qualities, aesthetics, scale, repetition and further complex structures. Although particular manipulation techniques would need to be modified for industrial looms, this would enable more control over woven variables for e-textiles. Thus, this would be an advantage for large reproducible lengths of e-textile fabric. More recent progression with e-yarns, such as developments by Tilak Dias (2011), Huang *et al.* (2008) and Gu *et al.* (2010), will enable easier integration of electronic capabilities into woven e-textiles, where electronic components and functionality will be pre-integrated into yarns. However, the circuit interconnections and woven structural architecture would still need to be considered via the design for optimum function; methods such as the ones demonstrated in this thesis could also apply here. Closer working relationships between designers, engineers, textile technologists and weaving mills would help industrial progress of e-textiles.

There is still considerable opportunity to take design led investigation of woven e-textiles research forward into the technical e-textiles domain, for function testing and technical measurables. This would present an ideal working platform for collaborative projects to develop woven e-textiles for specific application, or as in-depth technical materials investigations, while still retaining a design focus.

There is extensive potential for this e-textiles work in wearable technology and future soft digital product interfaces. Applications for e-textiles are broad and likely to grow considerably in the near future. Nevertheless, much of e-textiles' success will be determined by product application types, design, user acceptability, product reliability, cost and manufacturability. Further insight via e-textile user appropriation studies for types of application, user acceptance, usability, forms of integrated e-textiles products, and function would help developers and designers to cater for specific user needs. E-textile outcomes as a result of experimental processes without specific application/ objectives could also be applied to these markets.

9.6 Final concluding remarks

The practice based research sought to investigate woven e-textiles through design led processes and reflective practice. Developing an understanding of weaving and electronic integration was a central theme throughout the course of this research, as it presented the potential of woven e-textiles *through* design led processes.

The practical focus in this research aimed to extend the woven textile boundaries for integration of electronic design for e-textiles. The research has emphasised and demonstrated the potential to utilise existing woven structural architectures for electronic capabilities.

The extracted value of this research has been positioned in the contributions to knowledge section 9.2. These findings have drawn new attention to the profile of woven e-textiles. A deeper insight into woven e-textile practice, specific actions and underlying design principles were identified. This research has stressed the potential for future woven e-textile developments, as a direct consequence of the findings presented in this thesis.

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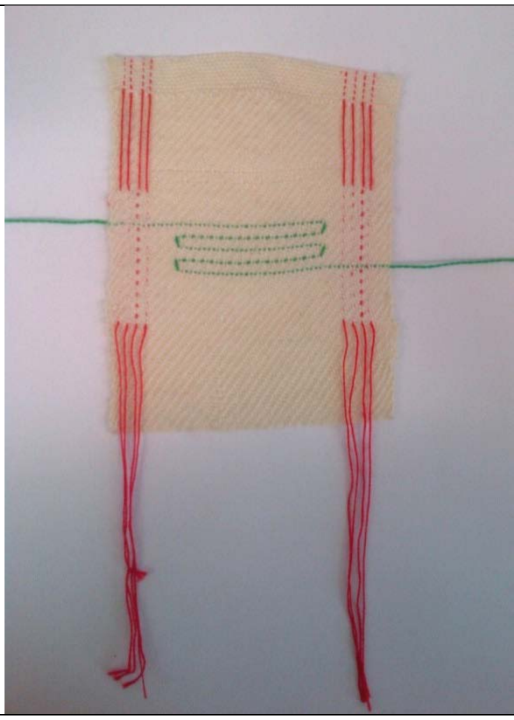
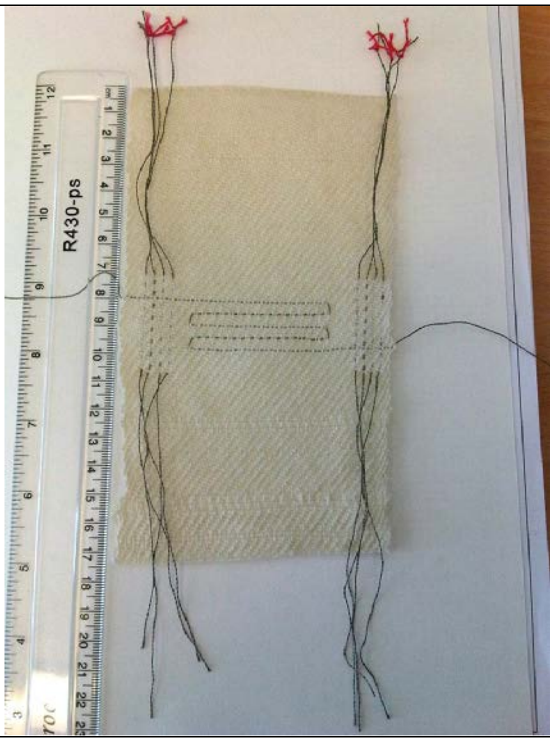
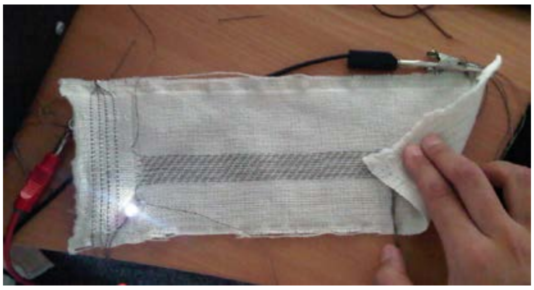
APPENDICES

Appendix A – Woven e-textiles sample index

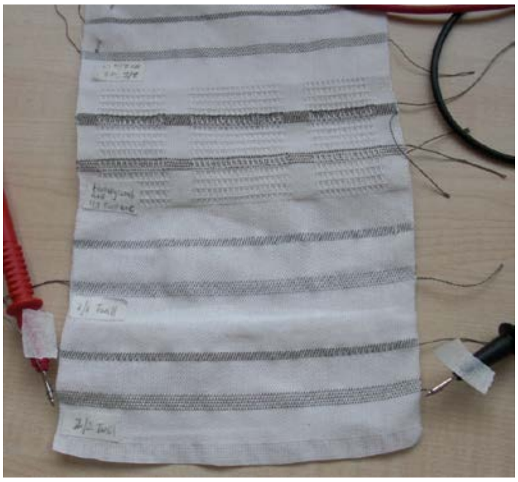
SAMPLE ID: **W001ET001**	
WARP: **001**	
SAMPLE NAME: Heatable textile wool test patch1	
WARP YARNS: 2/16s worsted wool	
WEFT YARNS: 2/16s worsted wool	
MAIN ATTRIBUTES: Sample prototype to prove woven construction, spacing between conductive yarn and length of conductive yarn for the heatable test patch.	

SAMPLE ID: **W001ET002**	
WARP: **001**	
SAMPLE NAME: Heatable textile wool test patch2	
WARP YARNS: 2/16s worsted wool 235f34dtex 4plyHC (50Ω/m)	
WEFT YARNS: 2/16s worsted wool 235f34dtex 2plyHC (100Ω/m)	
MAIN ATTRIBUTES: Heatable e-textiles patch – sample piece woven with one heating element to test and calculate input electrical variables and heat output.	

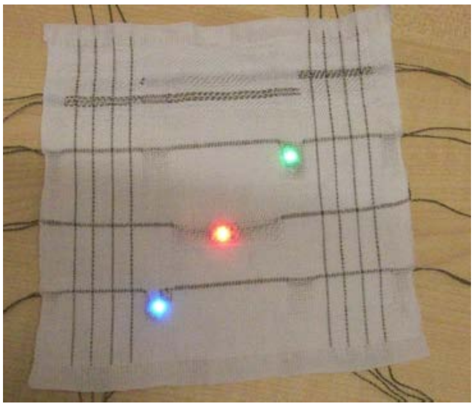
SAMPLE ID: **W002ET001**	
WARP: **002**	
SAMPLE NAME: Heatable textile mark II (large sample)	
WARP YARNS: 2/30Nm lambs wool 235f34dtex 2plyHC (100Ω/m)	
WEFT YARNS: 2/30Nm lambs wool 235f34dtex 4plyHC (50Ω/m)	
MAIN ATTRIBUTES: Large heating e-textiles – insulated onto fleece backing. Complete sample includes 19 heating elements. Produced for collaborative project with Applied Physiology for Sports, Medicine and Human Performance, Brunel University to investigate blood circulations via heating upper leg/ thigh area to measure core muscle temperature.	

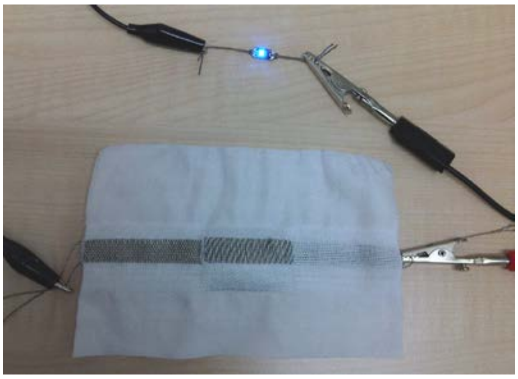
SAMPLE ID: **W002ET002**	
WARP: **002**	
SAMPLE NAME: LED wool test patch	
WARP YARNS: 2/30Nm lambs wool 235f34dtex 4plyHC (50Ω/m)	
WEFT YARNS: 2 x 2/20cc mercerised cotton 235f34dtex 2plyHC (100Ω/m)	
MAIN ATTRIBUTES: Test piece to investigate sensitivity and track layout of conductive yarn in woven construction. Also works as a switch demonstrator. Enabled to assess conductive yarn in weft as 1:1 ration pick in centre block.	

SAMPLE ID: **W002ET003**	
WARP: **002**	
SAMPLE NAME: Wool pleat switch	
WARP YARNS: 2/30Nm lambs wool 235f34dtex 4plyHC (50Ω/m)	
WEFT YARNS: 2 x 2/20cc mercerised cotton 235f34dtex 2plyHC (100Ω/m)	
MAIN ATTRIBUTES: Woven as three horizontal double cloths with isolated conductive yarn strips in each section. Double cloth upper and lower sections are pleated to match the conductive yarn section in central section (placement of conductive yarn pre-determined for weaving to match).	

SAMPLE ID: **W003ET001**	
WARP: **003**	
SAMPLE NAME: TEST STRIPS v1	
WARP YARNS: 2/74Nm spun matt polyester	
WEFT YARNS: 2/74Nm spun matt polyester 235f34dtex 4plyHC (50Ω/m) 235f34dtex 2plyHC (100Ω/m)	
MAIN ATTRIBUTES: Conductive yarn test strips in three different structures – 2/2 twill, 1/3 twill and honeycomb. Two tests in each construction – conductive yarn in consecutive picks and in 1:1 ration with polyester yarn. Three structures with two sets each repeated with two conductive yarn specs. 12 total tests woven. Investigates woven structural impact and resistivity.	

SAMPLE ID: **W003ET002**	
WARP: **003**	
SAMPLE NAME: TEST STRIPS v2 – elasticised conductive yarns	
WARP YARNS: 2/74Nm spun matt polyester	
WEFT YARNS: 2/74Nm spun matt polyester 1/80Nm Lycra and tencel Bekilast BK50/1 T/M lycra	
MAIN ATTRIBUTES: Test strips with plain weave and 2/2 twill using elasticised conductive yarn at tension and no tension, consecutive picks and 1:1 with polyester or tencel and lycra. 7 test strips woven	

SAMPLE ID: **W003ET003**	
WARP: **003**	
SAMPLE NAME: Trio RGB sample	
WARP YARNS: 2/74Nm spun matt polyester 235f34dtex 4plyHC (50Ω/m)	
WEFT YARNS: 2/74Nm spun matt polyester 235f34dtex 4plyHC (50Ω/m)	
MAIN ATTRIBUTES: Three lilypad LEDs woven in parallel circuit with integrated battery holder. Using the woven block set up to integrate the LEDs in double cloth pockets and making connection with tracks in same pick.	

SAMPLE ID: **W003ET004**	
WARP: **003**	
SAMPLE NAME: Pin cushion contact	
WARP YARNS: 2/74Nm spun matt polyester	
WEFT YARNS: 2/74Nm spun matt polyester 235f34dtex 4plyHC (50Ω/m)	
MAIN ATTRIBUTES: Double cloth stuffed pocked where conductive yarn track is broken between the front and back – using a pin to connect the two sides, the track is completed to activate the circuit.	

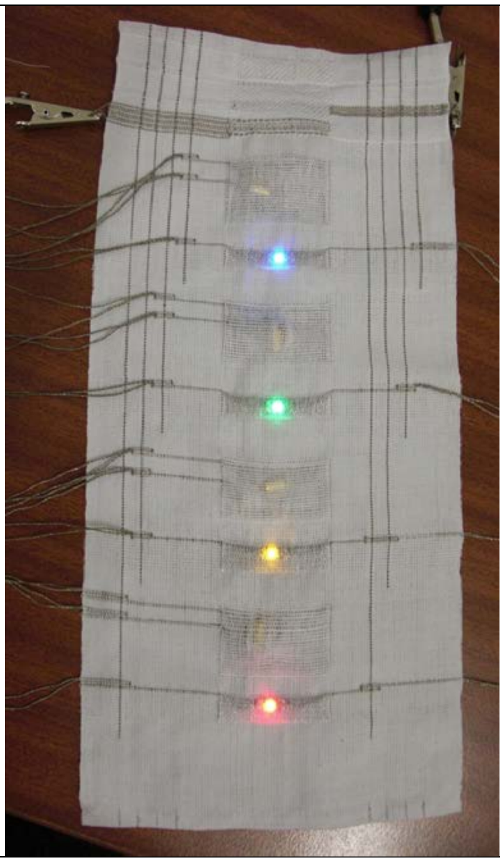
SAMPLE ID: **W003ET00**	
WARP: **003**	
SAMPLE NAME: Pull cord variable resistor	
WARP YARNS: 2/74Nm spun matt polyester 235f34dtex 4plyHC (50Ω/m)	
WEFT YARNS: 2/74Nm spun matt polyester 2/74Nm spun shiny polyester 235f34dtex 4plyHC (50Ω/m) 235f34dtex 2plyHC (100Ω/m)	
MAIN ATTRIBUTES: Integrated battery holder in matt polyester to help grip/position battery and integrated LED in double cloth pocket. Six double cloth section with floating conductive yarn warp track to use as pull cords to gather fabrics and shortening track length; hence, reducing resistivity for a brighter light omission in LED.	

SAMPLE ID: **W003ET006**	
WARP: **003**	
SAMPLE NAME: Dual Soft Switches	
WARP YARNS: 2/74Nm spun matt polyester 235f34dtex 4plyHC (50Ω/m)	
WEFT YARNS: 2/74Nm spun matt polyester 235f34dtex 4plyHC (50Ω/m) 90Nm Lurex cellophane NR3720 clear 4mm spun fine paper yarn (0.5mm spun diameter)	
MAIN ATTRIBUTES: Integrated battery holder, two integrated LEDs in double cloth pockets, two pairs of independent switches to control LEDs in parallel circuit.	

SAMPLE ID: **W003ET007**	
WARP: **003**	
SAMPLE NAME: Malleable light1	
WARP YARNS: 2/74Nm spun matt polyester 235f34dtex 4plyHC (50Ω/m)	
WEFT YARNS: 235f34dtex 4plyHC (50Ω/m) 5nm 'Antara' black polyurethane coated cotton & polyamide 'Gomina'3200: white coated material- 50% polyurethane; core material- 30% viscose 20% cotton 90Nm Lurex cellophane NR3720 clear 0.315mm enamelled copper wire 2/74Nm spun shiny polyester	
MAIN ATTRIBUTES: Integrated battery holder, integrated LED in centre block pocket, complete circuit with malleable quality to shape the sample or roll up. Sateen and satin structure applied for double sided fabric on single cloth.	

<table>
<tr><td>SAMPLE ID: W003ET008</td><td rowspan="6"></td></tr>
<tr><td>WARP: 003</td></tr>
<tr><td>SAMPLE NAME: Duo pleat switch</td></tr>
<tr><td>WARP YARNS: 2/74Nm spun matt polyester
235f34dtex 4plyHC (50Ω/m)</td></tr>
<tr><td>WEFT YARNS: 2/74Nm spun shiny polyester
235f34dtex 4plyHC (50Ω/m)
90Nm Lurex cellophane NR3720 clear</td></tr>
<tr><td>MAIN ATTRIBUTES: Integrated battery pocket with magnetic clamp. Woven pleat as switch to control two LEDs independently (not simultaneously).</td></tr>
</table>

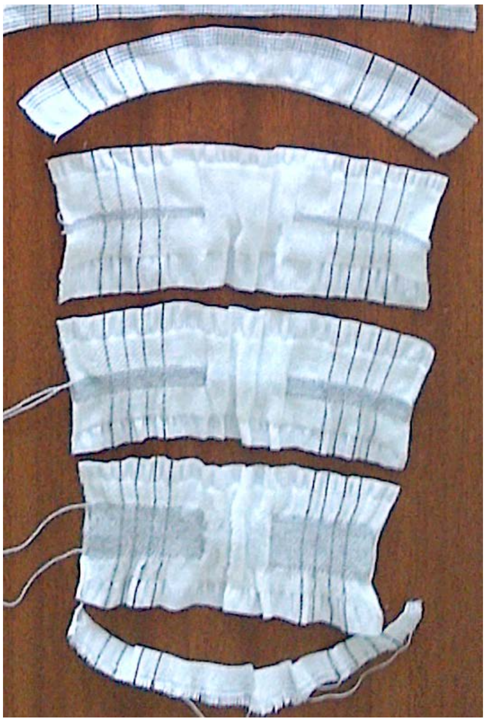
<table>
<tr><td>SAMPLE ID: W003ET009</td><td rowspan="6"></td></tr>
<tr><td>WARP: 003</td></tr>
<tr><td>SAMPLE NAME: RGB colour mixer</td></tr>
<tr><td>WARP YARNS: 2/74Nm spun matt polyester
235f34dtex 4plyHC (50Ω/m)</td></tr>
<tr><td>WEFT YARNS: 2/74Nm spun matt polyester
235f34dtex 4plyHC (50Ω/m)
235f34dtex 2ply (100Ω/m)
90Nm Lurex cellophane NR3720 clear
0.2mm enamelled copper wire</td></tr>
<tr><td>MAIN ATTRIBUTES: Integrated battery pocket with magnetic clamp. RGB LED integrated into central block pocket; each colour independently addressable via woven pleated switches to control red, green, blue, 2 colours or all three. Integrated woven resistors each to spec for the RGB LED. Woven malleable lurex screen to reflect light onto for greater illuminated effect. Complete woven circuit with resistor pockets insulated with calico fabric.</td></tr>
</table>

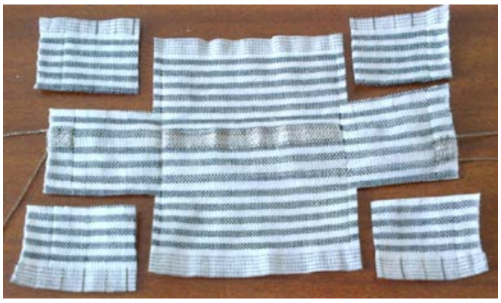
SAMPLE ID: **W003ET010**	
WARP: **003**	
SAMPLE NAME: Tilt switch sample	
WARP YARNS: 2/74Nm spun matt polyester 235f34dtex 4plyHC (50Ω/m)	
WEFT YARNS: 2/74Nm spun matt polyester 235f34dtex 4plyHC (50Ω/m) 90Nm Lurex cellophane NR3720 clear	
MAIN ATTRIBUTES: Integrated battery holder with magnetic clamp. Four LEDs in parallel circuit, each controlled via independent tilt sensors (each at 90°, 180°, 270° and 360°). Triple connection in weft connection to warp conductive yarn.	

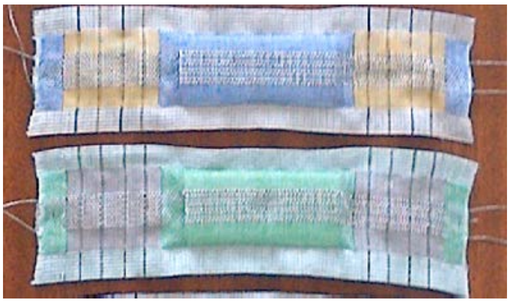
SAMPLE ID: **W003ET011**	
WARP: **003**	
SAMPLE NAME: Elasticised conductive yarn double cloth test strips	
WARP YARNS: 2/74Nm spun matt polyester	
WEFT YARNS: Bekilast BK50/1 T/M lycra Lycra and tencel	
MAIN ATTRIBUTES: Test strips with elasticised conductive yarn and elasticised lycra/tencel yarn. Double cloth structures in vertical tubes with weaving in and floating in between tubes/ double cloths for different range of resistivity in a stable cloth.	

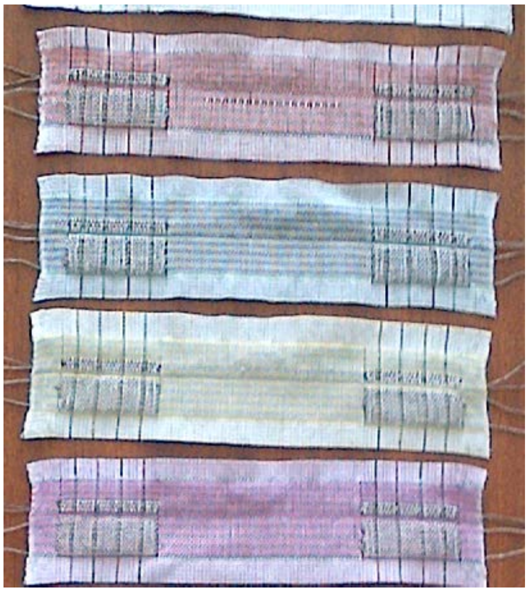
SAMPLE ID: **W003ET012**	
WARP: **003**	
SAMPLE NAME: Ball bearing tilt switch1	
WARP YARNS: 2/74Nm spun matt polyester 235f34dtex 4plyHC (50Ω/m)	
WEFT YARNS: 2/74Nm spun matt polyester 235f34dtex 4plyHC (50Ω/m) 90Nm Lurex cellophane NR3720 clear	
MAIN ATTRIBUTES: Integrated battery holder witch double magnetic clamp. Two independent LEDs controlled via independent ball bearing switches, consisting of weft inlay breaks to circuit.	

SAMPLE ID: **W004ET001**	
WARP: **004**	
SAMPLE NAME: Elasticised conductive yarn test strips – single cloth (satin/ sateen structures)	
WARP YARNS: 2/74Nm spun matt polyester 235f34dtex 4plyHC (50Ω/m)	
WEFT YARNS: 2/74Nm spun matt polyester Bekilast BK50/1 T/M lycra 1/80Nm Lycra and tencel	
MAIN ATTRIBUTES: Elasticised conductive yarn in sateen (weft faced) 12 consecutive picks in stretched and non-stretched tension, bordered with spun polyester or lycra and tencel to assess stability and resistivity/ conductivity.	

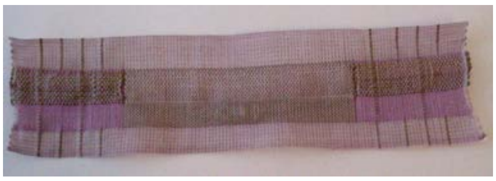
SAMPLE ID: **W004ET002**	
WARP: **004**	
SAMPLE NAME: Modular kit1 – stretch variable resistors	
WARP YARNS: 2/74Nm spun matt polyester 235f34dtex 4plyHC (50Ω/m)	
WEFT YARNS: 2/74Nm spun matt polyester Bekilast BK50/1 T/M lycra 1/80Nm Lycra and tencel	
MAIN ATTRIBUTES: Three modules with magnetic connectors. Elasticised conductive yarn woven into and floated in-between double cloth sections. Each module consists of different width of conductive yarns.	

SAMPLE ID: **W004ET003**	
WARP: **004**	
SAMPLE NAME: Battery holder module v1 (kit1)	
WARP YARNS: 2/74Nm spun matt polyester 235f34dtex 4plyHC (50Ω/m)	
WEFT YARNS: 2/74Nm spun matt polyester 235f34dtex 4plyHC (50Ω/m)	
MAIN ATTRIBUTES: Cross shaped battery holder with double magnetic clamp and magnetic connectors. Woven in double cloth interacting blocks to isolate pockets.	

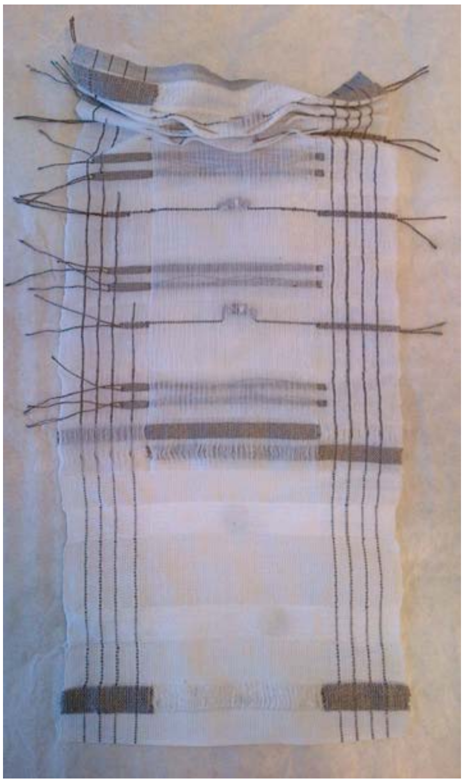
SAMPLE ID: **W002ET004** (blue) SAMPLE ID: **W004ET005** (green)	
WARP: **004**	
SAMPLE NAME: Modular kit1 – push buttons	
WARP YARNS: 2/74Nm spun matt polyester 235f34dtex 4plyHC (50Ω/m)	
WEFT YARNS: 2/74Nm spun matt polyester 235f34dtex 4plyHC (50Ω/m)	
MAIN ATTRIBUTES: Modules with magnetic connectors. Woven in double cloth interacting blocks to isolate pockets for button spacer sponge. Two different size holes in spacer sponge for each module. Conductive track broken via weft, connect face and back of track by pressing button.	

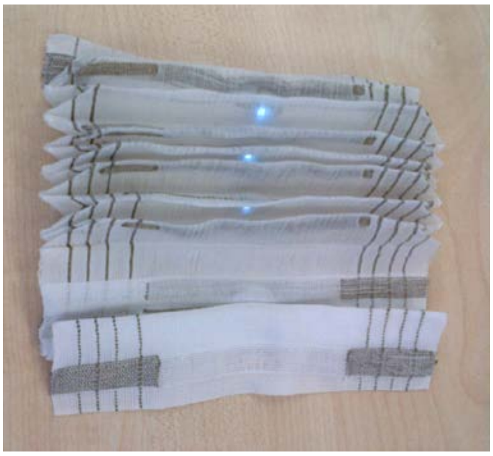
SAMPLE ID: **W004ET006** (orange) SAMPLE ID: **W004ET007** (green) SAMPLE ID: **W004ET008** (yellow) SAMPLE ID: **W004ET009** (pink)	
WARP: **004**	
SAMPLE NAME: Modular kit1 – single LED modules	
WARP YARNS: 2/74Nm spun matt polyester 235f34dtex 4plyHC (50Ω/m)	
WEFT YARNS: 2/74Nm spun matt polyester 235f34dtex 4plyHC (50Ω/m)	
MAIN ATTRIBUTES: Four modules, all with lilypad LEDs (single) integrated into double cloth pocket. Magnetic connectors on reverse side.	

SAMPLE ID: **W004ET010**	
WARP: **004**	
SAMPLE NAME: Modular kit1 – Slide switch module	
WARP YARNS: 2/74Nm spun matt polyester 235f34dtex 4plyHC (50Ω/m)	
WEFT YARNS: 2/74Nm spun matt polyester 235f34dtex 4plyHC (50Ω/m)	
MAIN ATTRIBUTES: Slide switch module – broken conductive track via inlay weft weaving. Metallic object inserted into pocket to slide across to complete the track. Double sided magnetic connectors.	

SAMPLE ID: **W004ET011**	
WARP: **004**	
SAMPLE NAME: Modular kit1 – Double LED reversible module	
WARP YARNS: 2/74Nm spun matt polyester 235f34dtex 4plyHC (50Ω/m)	
WEFT YARNS: 2/74Nm spun matt polyester 235f34dtex 4plyHC (50Ω/m)	
MAIN ATTRIBUTES: Two lilypad LEDs integrated (back to back) into double cloth centre black with double sided magnetic connectors.	

<table>
<tr><td>SAMPLE ID: W004ET012</td><td rowspan="6"></td></tr>
<tr><td>WARP: 004</td></tr>
<tr><td>SAMPLE NAME: Fold fringe switch LED</td></tr>
<tr><td>WARP YARNS: 2/74Nm spun matt polyester
235f34dtex 4plyHC (50Ω/m)</td></tr>
<tr><td>WEFT YARNS: 2/74Nm spun matt polyester
235f34dtex 4plyHC (50Ω/m)
139Nm SPRP252520 green lurex cellophane
90Nm Lurex cellophane NR3720 clear</td></tr>
<tr><td>MAIN ATTRIBUTES: Integrated battery holder. Part of sample woven as individual sections to create fringe connection effect. Central fold section woven with satin and sateen weave for easier crease set. Lilypad LED activated when fringe connects to central section. Magnetic connectors integrated as an option to work with modules.</td></tr>
</table>

<table>
<tr><td>SAMPLE ID: W004ET013</td><td rowspan="6"></td></tr>
<tr><td>WARP: 004</td></tr>
<tr><td>SAMPLE NAME: Corrugated pleat LED angled (CPLED-A)</td></tr>
<tr><td>WARP YARNS: 2/74Nm spun matt polyester
235f34dtex 4plyHC (50Ω/m)</td></tr>
<tr><td>WEFT YARNS: 2/74Nm spun matt polyester
235f34dtex 4plyHC (50Ω/m)
80 Denier monofilament</td></tr>
<tr><td>MAIN ATTRIBUTES: Integrated battery holder with roll over magnetic connectors. Four Lilypad LEDs in parallel circuit, each with floated conductive yarns in central double cloth pockets as switches that connect via movement. Double sided magnetic connectors. Heat set to preserve irregular pleat form. Blocks intersect as vertical double cloth tubes.</td></tr>
</table>

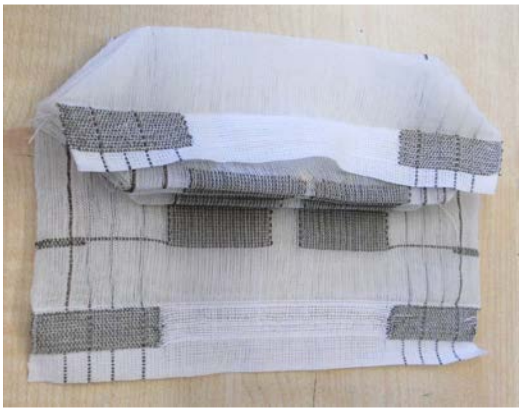
SAMPLE ID: **W004ET014**	
WARP: **004**	
SAMPLE NAME: Corrugated pleat LED v1 (CPLEDv1) (floating connections – uncut)	
WARP YARNS: 2/74Nm spun matt polyester 235f34dtex 4plyHC (50Ω/m)	
WEFT YARNS: 2/74Nm spun matt polyester 235f34dtex 4plyHC (50Ω/m) 80 Denier monofilament	
MAIN ATTRIBUTES: Integrated battery holder with roll over magnetic connectors. Four Lilypad LEDs in parallel circuit, each with floated conductive yarns in central double cloth pockets as additional connectivity. Double sided magnetic connectors. Heat set to preserve regular pleat form. Blocks do not intersect for horizontal double cloth tubes.	

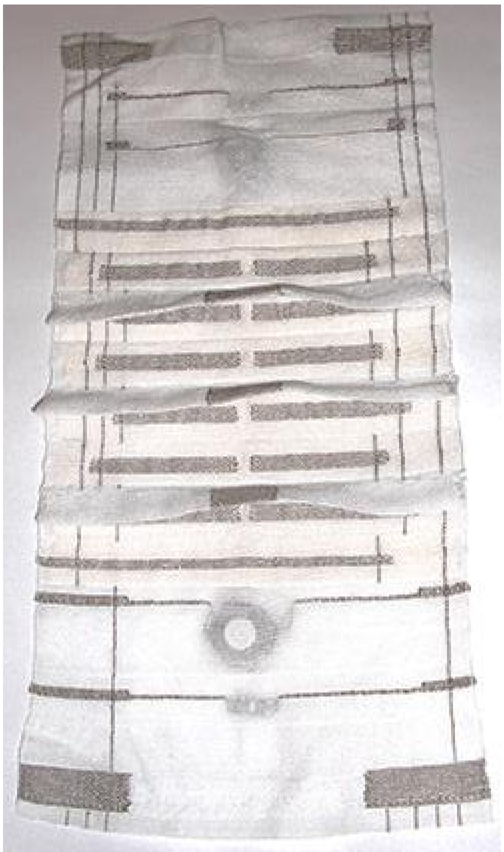
SAMPLE ID: **W004ET015**	
WARP: **004**	
SAMPLE NAME: Modular kit1 – DIY double LED module	
WARP YARNS: 2/74Nm spun matt polyester 235f34dtex 4plyHC (50Ω/m)	
WEFT YARNS: 2/74Nm spun matt polyester 235f34dtex 4plyHC (50Ω/m)	
MAIN ATTRIBUTES: Own made double sided single LED integrated into centre double cloth block, with double sided magnetic connectors.	

SAMPLE ID: **W004ET016**	
WARP: **004**	
SAMPLE NAME: Modular kit1 – Velostat module	
WARP YARNS: 2/74Nm spun matt polyester 235f34dtex 4plyHC (50Ω/m)	
WEFT YARNS: 2/74Nm spun matt polyester 235f34dtex 4plyHC (50Ω/m)	
MAIN ATTRIBUTES: Velostat strip integrated into centre block double cloth pocket. Weft inlay conductive yarn broken track that is connected via applied pressure on the centre block to reduce resistance. Double sided magnetic connectors.	

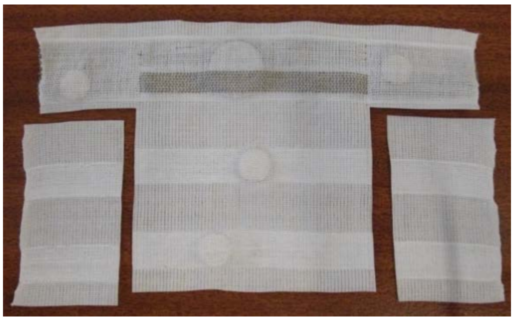
SAMPLE ID: **W004ET017**	
WARP: **004**	
SAMPLE NAME: Buzzer pleat sample – base	
WARP YARNS: 2/74Nm spun matt polyester 235f34dtex 4plyHC (50Ω/m)	
WEFT YARNS: 2/74Nm spun matt polyester 235f34dtex 4plyHC (50Ω/m)	
MAIN ATTRIBUTES: Integrated battery holder with double magnetic wrap around clamp. Four woven pleat switches to activate buzzer attachment connected via the circuit to three woven integrated resistors to vary pitch of buzzer sounds. Magnetic connectors to attach the buzzer module. Combination of single and double cloths.	

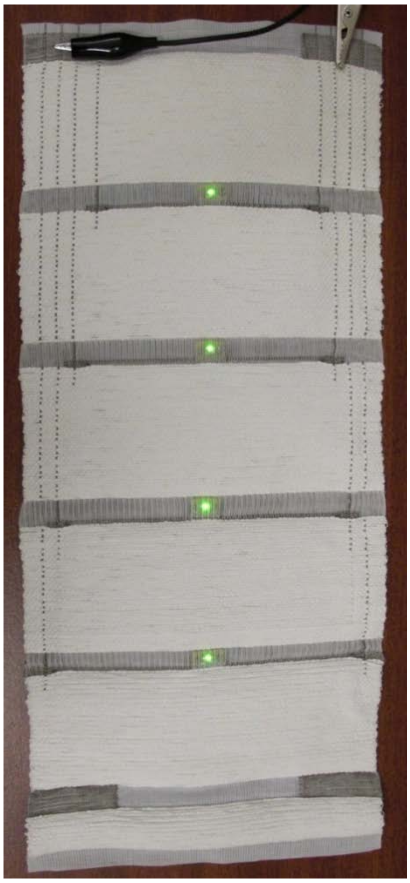
SAMPLE ID: **W004ET018**	
WARP: **004**	
SAMPLE NAME: Buzzer pleat sample – buzzer module	
WARP YARNS: 2/74Nm spun matt polyester 235f34dtex 4plyHC (50Ω/m)	
WEFT YARNS: 2/74Nm spun matt polyester 235f34dtex 4plyHC (50Ω/m)	
MAIN ATTRIBUTES: Buzzer module to attach to sample W004ET017. Magnetic connectors. Double cloth fold over pocket to conceal the buzzer component.	

SAMPLE ID: **W004ET019**	
WARP: **004**	
SAMPLE NAME: Corrugated pleat LED v2 (CPLEDv2)	
WARP YARNS: 2/74Nm spun matt polyester 235f34dtex 4plyHC (50Ω/m)	
WEFT YARNS: 2/74Nm spun matt polyester 235f34dtex 4plyHC (50Ω/m) 235f34dtex 2plyHC (100Ω/m) 80 Denier monofilament	
MAIN ATTRIBUTES: Four own made single LED double sided, integrated into double cloth pocket in a parallel circuit – improved integration of component for better stability. Woven in resistors. Double sided magnetic connectors for battery pack and to form cylindrical lighting piece.	

<table>
<tr><td>SAMPLE ID: W004ET020</td><td rowspan="6"></td></tr>
<tr><td>WARP: 004</td></tr>
<tr><td>SAMPLE NAME: Two way stroke sound and vibe sample</td></tr>
<tr><td>WARP YARNS: 2/74Nm spun matt polyester
235f34dtex 4plyHC (50Ω/m)</td></tr>
<tr><td>WEFT YARNS: 2/74Nm spun matt polyester
235f34dtex 4plyHC (50Ω/m)</td></tr>
<tr><td>MAIN ATTRIBUTES: Buzzer and vibration components integrated into a single complete circuit. Woven pleats as switches; double sided to activate each of the integrated components. Lilypad LED integrated in series to each of the components (i.e. independently for the buzzer and vibration module). Double sided magnetic connectors to power/ independent battery holder.</td></tr>
</table>

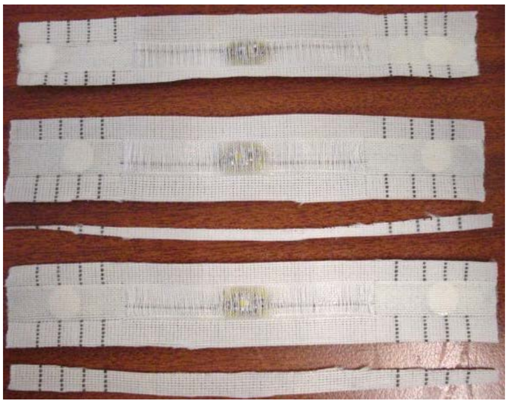
<table>
<tr><td>SAMPLE ID: W004ET021</td><td rowspan="6"></td></tr>
<tr><td>WARP: 004</td></tr>
<tr><td>SAMPLE NAME: Malleable roll and connect LED sample</td></tr>
<tr><td>WARP YARNS: 2/74Nm spun matt polyester
235f34dtex 4plyHC (50Ω/m)</td></tr>
<tr><td>WEFT YARNS: 2/74Nm spun matt polyester
235f34dtex 4plyHC (50Ω/m)
4mm spun fine paper yarn (0.5mm spun diameter)
0.315mm enamelled copper wire
80 Denier monofilament</td></tr>
<tr><td>MAIN ATTRIBUTES: Malleable lighting sample; four lilypad LEDs doubled (8 LEDs in total) in back to back arrangement for two colour lighting output (red or white). Double sided magnetic connectors for power/ battery holder module and to form cylindrical lighting piece.</td></tr>
</table>

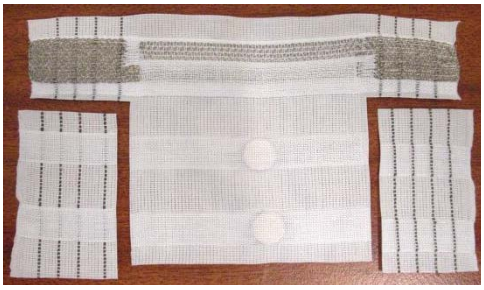
SAMPLE ID: **W004ET022**	
WARP: **004**	
SAMPLE NAME: Battery holder module v2 (BHMv2)	
WARP YARNS: 2/74Nm spun matt polyester 235f34dtex 4plyHC (50Ω/m)	
WEFT YARNS: 2/74Nm spun matt polyester 235f34dtex 4plyHC (50Ω/m)	
MAIN ATTRIBUTES: Battery holder module with magnetic wrap around clamp – v2. Improvement change of shape for the wrap around portion of the module as a single continuous piece, configuring a 'T' shape.	

SAMPLE ID: **W004ET023**	
WARP: **004**	
SAMPLE NAME: Malleable light v2- polyurethane single LEDs reverse	
WARP YARNS: 2/74Nm spun matt polyester	
WEFT YARNS: 2/74Nm spun matt polyester 'Gomina'3200: white coated material- 50% polyurethane; core material- 30% viscose 20% cotton 0.315mm enamelled copper wire	
MAIN ATTRIBUTES: Malleable lighting sample; four own made single LED double sided (8 LEDs in total) in a single component with resistors for two colour lighting output (green or white). Double sided magnetic connectors for power/ battery holder module and to form cylindrical lighting piece.	

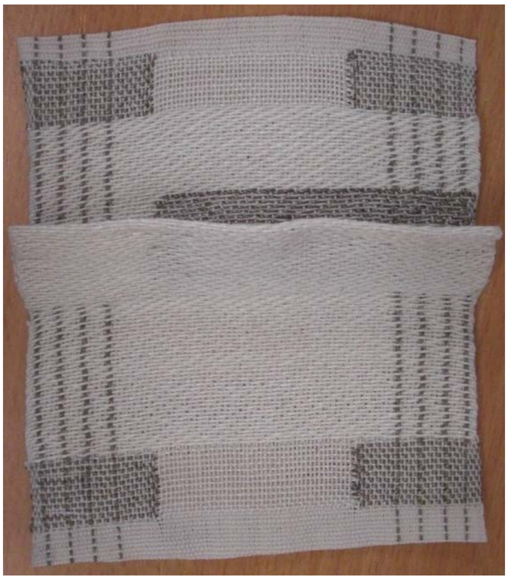
SAMPLE ID: **W004ET024**	
WARP: **004**	
SAMPLE NAME: Malleable furry - double reverse LEDs	
WARP YARNS: 2/74Nm spun matt polyester 235f34dtex 4plyHC (50Ω/m)	
WEFT YARNS: 2/74Nm spun matt polyester 235f34dtex 4plyHC (50Ω/m) 5Nm brushed mohair blend 80 Denier monofilament 0.315mm enamelled copper wire	
MAIN ATTRIBUTES: Malleable lighting sample; four own made double LED double sided (16 LEDs in total) in a single component with resistors for two colour lighting output at a time (i.e. blue and white **or** green orange and white). Double sided magnetic connectors for power/ battery holder module and to form cylindrical lighting piece.	

SAMPLE ID: **W004ET025**	
WARP: **004**	
SAMPLE NAME: Flashing LED connector base	
WARP YARNS: 2/74Nm spun matt polyester 235f34dtex 4plyHC (50Ω/m)	
WEFT YARNS: 2/74Nm spun matt polyester 235f34dtex 4plyHC (50Ω/m)	
MAIN ATTRIBUTES: Flashing module component integrated into a circuit base to attach up to three LED modules via magnetic connectors. Power attachment via magnetic double sided connectors.	

SAMPLE ID: **W004ET026**	
WARP: **004**	
SAMPLE NAME: Flashing LEDs modules x 3	
WARP YARNS: 2/74Nm spun matt polyester 235f34dtex 4plyHC (50Ω/m)	
WEFT YARNS: 2/74Nm spun matt polyester 235f34dtex 4plyHC (50Ω/m) 80 Denier monofilament	
MAIN ATTRIBUTES: To work with flashing module base sample W004ET025. Three modules with integrated own made double LEDs single sided components. Magnetics connectors (single sided).	

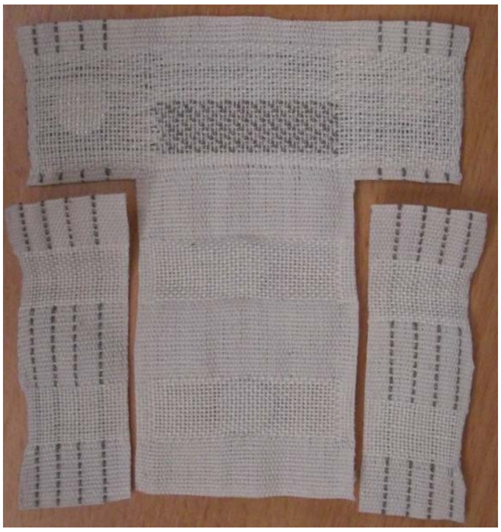
SAMPLE ID: **W004ET027**	
WARP: **004**	
SAMPLE NAME: Battery holder module v3 (BHMv3)	
WARP YARNS: 2/74Nm spun matt polyester 235f34dtex 4plyHC (50Ω/m)	
WEFT YARNS: 2/74Nm spun matt polyester 235f34dtex 4plyHC (50Ω/m)	
MAIN ATTRIBUTES: Batter holder v3 in 'T' shape. Improvements include structures with optimum conductivity connection to both the battery and connector source using weft faced or warp faced structures.	

<table>
<tr><td>SAMPLE ID: W005ET001</td><td rowspan="6"></td></tr>
<tr><td>WARP: 005</td></tr>
<tr><td>SAMPLE NAME: Resistor module kit2</td></tr>
<tr><td>WARP YARNS: 2/20cc spun cotton
235f34dtex 4plyHC (50Ω/m)</td></tr>
<tr><td>WEFT YARNS: 2/20cc spun cotton
235f34dtex 4plyHC (50Ω/m)
235f34dtex 2plyHC (100Ω/m)
Fine silk organza
80 Denier monofilament</td></tr>
<tr><td>MAIN ATTRIBUTES: 100Ω resistor module compatible with modular kit2. Double sided magnetic connectors; module can operate in any direction or flipped reversed.</td></tr>
</table>

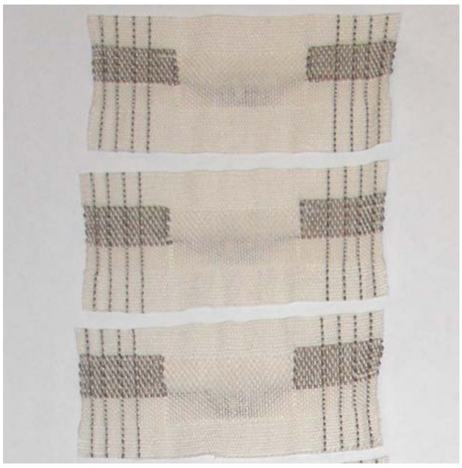
<table>
<tr><td>SAMPLE ID: W005ET002</td><td rowspan="6"></td></tr>
<tr><td>WARP: 005</td></tr>
<tr><td>SAMPLE NAME: Switch module kit2</td></tr>
<tr><td>WARP YARNS: 2/20cc spun cotton
235f34dtex 4plyHC (50Ω/m)</td></tr>
<tr><td>WEFT YARNS: 2/20cc spun cotton
235f34dtex 4plyHC (50Ω/m)
4mm spun fine paper yarn (0.5mm spun diameter)</td></tr>
<tr><td>MAIN ATTRIBUTES: Switch module compatible with modular kit2. Woven pleat operates as switch. Double sided magnetic connectors; module can operate either way up or connect via reverse side.</td></tr>
</table>

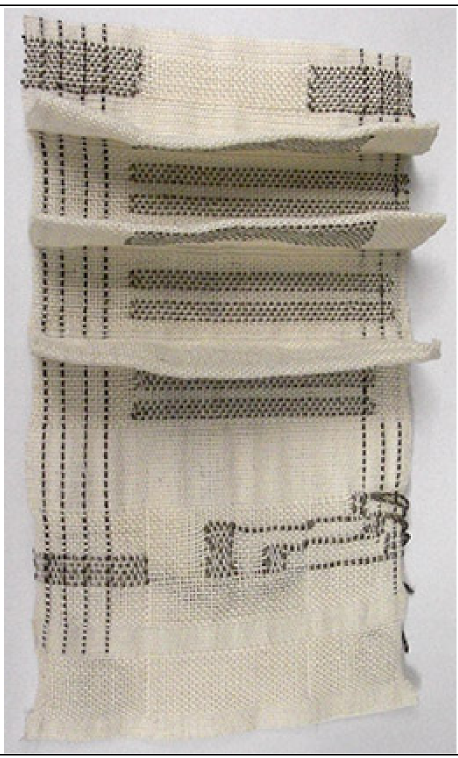
SAMPLE ID: **W005ET003**	
WARP: **005**	
SAMPLE NAME: Cotton crimp module kit2 - single LED reverse module	
WARP YARNS: 2/20cc spun cotton 235f34dtex 4plyHC (50Ω/m)	
WEFT YARNS: 2/20cc spun cotton 235f34dtex 4plyHC (50Ω/m) 0.315mm enamelled copper wire Cotton crepe	
MAIN ATTRIBUTES: Malleable lighting module with own made single LED double sided; compatible with modular kit2. Double sided magnetic connectors; module can operate in either direction or connect via reversed side.	

SAMPLE ID: **W005ET004**	
WARP: **005**	
SAMPLE NAME: Velour module kit2 – double reverse LED	
WARP YARNS: 2/20cc spun cotton 235f34dtex 4plyHC (50Ω/m)	
WEFT YARNS: 2/20cc spun cotton 235f34dtex 4plyHC (50Ω/m) 0.315mm enamelled copper wire 2Nm fine chenille	
MAIN ATTRIBUTES: Malleable lighting module with own made double LED double sided (i.e. 2 light active simultaneously); compatible with modular kit2. Double sided magnetic connectors; module can operate in either direction or connect via reversed side.	

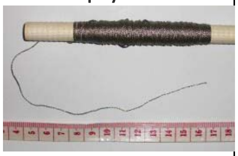
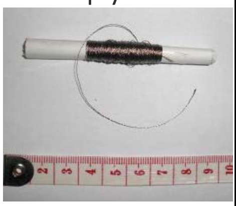
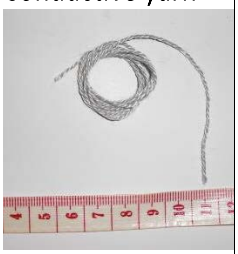
<table>
<tr><td>SAMPLE ID: W005ET005</td><td rowspan="6"></td></tr>
<tr><td>WARP: 005</td></tr>
<tr><td>SAMPLE NAME: Battery holder module v4 – kit2 (BHMv4)</td></tr>
<tr><td>WARP YARNS: 2/20cc spun cotton 235f34dtex 4plyHC (50Ω/m)</td></tr>
<tr><td>WEFT YARNS: 2/20cc spun cotton 235f34dtex 4plyHC (50Ω/m)</td></tr>
<tr><td>MAIN ATTRIBUTES: Batter holder for modular kit 2 based on sample W004ET027 v3 in ‘T’ shape with improvement for optimum conductivity connection to both the battery and connector source using weft faced or warp faced structures. Central battery pocket smaller than previous sample, helping fit and grip of batteries.</td></tr>
</table>

<table>
<tr><td>SAMPLE ID: W005ET006</td><td rowspan="6"></td></tr>
<tr><td>WARP: 005</td></tr>
<tr><td>SAMPLE NAME: Connectors - base strips x 6</td></tr>
<tr><td>WARP YARNS: 2/20cc spun cotton 235f34dtex 4plyHC (50Ω/m)</td></tr>
<tr><td>WEFT YARNS: 2/20cc spun cotton 235f34dtex 4plyHC (50Ω/m)</td></tr>
<tr><td>MAIN ATTRIBUTES: Connector base strips to attach different connector materials (e.g. press studs, stitched poppers, conductive Velcro) to assess conductivity via other methods.</td></tr>
</table>

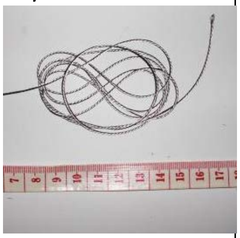
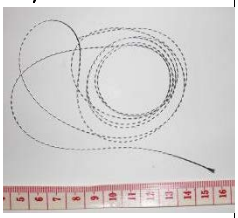
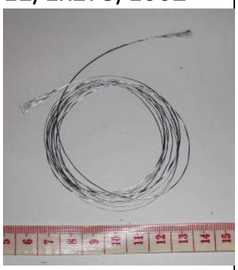
SAMPLE ID: **W005ET007**	
WARP: **005**	
SAMPLE NAME: Connectors – LED strip modules x 3	
WARP YARNS: 2/20cc spun cotton 235f34dtex 4plyHC (50Ω/m)	
WEFT YARNS: 2/20cc spun cotton 235f34dtex 4plyHC (50Ω/m)	
MAIN ATTRIBUTES: To work with the connector base strips as component output. Integrated lilypad LED in each module.	

SAMPLE ID: **W005ET008**	
WARP: **005**	
SAMPLE NAME: RGB colour mixer v2 module	
WARP YARNS: 2/20cc spun cotton 235f34dtex 4plyHC (50Ω/m)	
WEFT YARNS: 2/20cc spun cotton 235f34dtex 4plyHC (50Ω/m)	
MAIN ATTRIBUTES: Own made RGB component integrated into a complete circuit; pleated buttons independently control each colour, or can be used to mix the colours.	

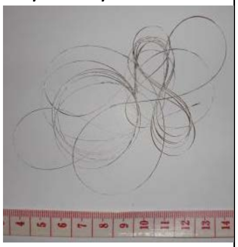
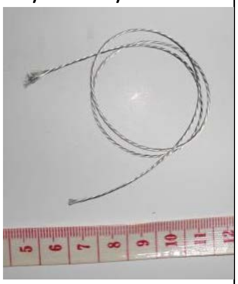
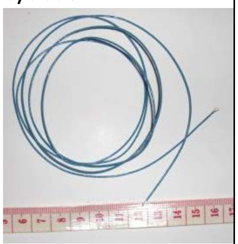
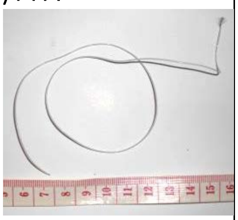
Appendix B – Conductive materials log

#	Conductive material & name	Material description	Vendor details	Other notes
	YARNS			
1	Shieldex 235/34 dtex 4-ply 	Shieldex 235/34 dtex 4-ply HC: Silver plated, 50 Ω/m ± 10 Ω/m	Statex Statex Produktions & Vertriebs GmbH, Kleiner Ort 11, 28357 Bremen, Germany Tel: +49 421 2575047 www.statex.de www.statex.biz	Silver coated polyamide yarn (99% pure silver). Yarn count silverised: ~dtex 1160. Elongation break ~27%.
2	Shieldex 235/34 dtex 2-ply 	Shieldex 235/34 dtex 2-ply Silver plated, HCB: 100 Ω/m ± 30 Ω/m	Statex Statex Produktions & Vertriebs GmbH, Kleiner Ort 11, 28357 Bremen, Germany Tel: +49 421 2575047 www.statex.de www.statex.biz	Silver coated polyamide yarn (99% pure silver). Yarn count silverised ~dtex 560. Elongation break ~ 15.5%
3	Shieldex 110/34 dtex 2-ply 	Shieldex 110/34 dtex Z-turns ht HCB: Silver plated, < 1 kΩ/m	Statex Statex Produktions & Vertriebs GmbH, Kleiner Ort 11, 28357 Bremen, Germany Tel: +49 421 2575047 www.statex.de www.statex.biz	Silver coated polyamide yarn (99% pure silver). Yarn count silverised ~ dtex ± 3. Elongation break ~ 15%
4	Shieldex 117/17 dtex 2-ply 	Shieldex 117/17 dtex 2-ply: Silver plated, average 185 Ω/m. Yarn count 35 Nm.	Statex Statex Produktions & Vertriebs GmbH, Kleiner Ort 11, 28357 Bremen, Germany Tel: +49 421 2575047 www.statex.de info@statex.de Also from Plug and Wear www.plugandwear.com	Silver coated polyamide yarn (99% pure silver). Yarn count silverised ~ dtex 140f17 x 2ply. Elongation break ~ 40% ± 5%. Good for sewing machine
5	Nm10/3 Conductive yarn 	Nm10/3 Conductive yarn 80% polyester 20% stainless steel. Surface resistance <10^4Ω. Combed PES/ stretched-broken stainless steel, Yarn count Nm10/3.	Plug and wear www.plugandwear.com	Breaking elongation 21.8%. RohS compliant. High resistivity. Good quality for knitting and weaving.

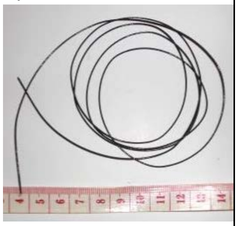
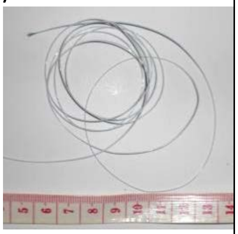
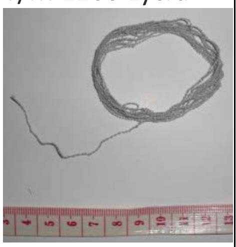
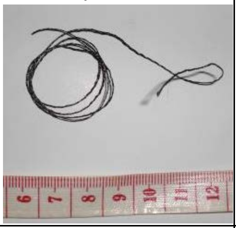
Appendix B – Conductive materials log

#	Conductive material & name	Material description	Vendor details	Other notes
6	Bekinox VN 12/6x275 	Spun filament yarn. Bekaert Bekinox VN 12/6x275. 100% stainless steel filament. 12 µm diameter filament, 6-ply, 275 filaments/ ply, 120 torsions/m S-twist. Linear resistivity 4.7Ω ± 7%.	Bekintex NV, Industriepark Kwatrecht, Neerhondered 16, BE-9230 Wettern, Belgium Tel: +32 9 365 71 02 www.bekaert.com	1500 Tex (g/1000m). 0.7Nm (m/g). Breaking load ~160N. 1% elongation. Good for heating textiles. Strong continuous filament.
7	Bekinox VN 12/3x275 	Spun filament yarn. Bekaert Bekinox VN 12/3x275. 100% stainless steel filament. 12 µm diameter filament, 3-ply, 275 filaments/ ply, 175 torsions/m, S-twist. Linear resistivity 9Ω/m ± 11%.	Bekintex NV, Industriepark Kwatrecht, Neerhondered 16, BE-9230 Wettern, Belgium Tel: +32 9 365 71 02 www.bekaert.com	760 Tex (g/1000m). 1.3Nm (m/g). Breaking load ~110N. 1% elongation. Good for heating textiles. Strong continuous filament.
8	Bekinox VN 12/2x275 	Spun filament yarn. Bekaert Bekinox VN 12/2x275. 100% stainless steel filament. 12 µm diameter filament, 2-ply, 275 filaments/ply, 175 torsions/m, S-twist. Linear resistivity 14Ω/m ±7%.	Bekintex NV, Industriepark Kwatrecht, Neerhondered 16, BE-9230 Wettern, Belgium Tel: +32 9 365 71 02 www.bekaert.com	505 Tex (g/1000m). 2 Nm (m/g). Breaking load ~75N. 1% elongation. Good for heating textiles. Strong continuous filament.
9	Bekinox VN 12/1x275/100Z 	Spun filament yarn. Bakaert Bekinox VN 12/1x275/100Z. 100% stainless steel. 12µm diameter, 1 ply. 275 filaments/ ply, 100 torsions/m, Z-twist. Linear resistivity 30 Ω/m ± 7%.	Bekintex NV, Industriepark Kwatrecht, Neerhondered 16, BE-9230 Wettern, Belgium Tel: +32 9 365 71 02 www.bekaert.com	235 Tex (g/1000m). 4Nm (m/g). Breaking load ~40N. 1% elongation. Good for heating textiles. Strong continuous filament.

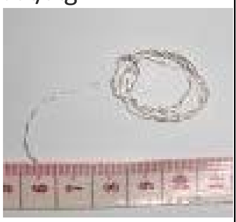
Appendix B – Conductive materials log

#	Conductive material & name	Material description	Vendor details	Other notes
10	Bekinox VN 14/1x90/200Z 	Spun filament yarn. Bakaert Bekinox VN 14/1x90. 100% stainless steel. 14µm diameter, 1ply. 90 filaments/ply, 200 torsions/m, Z-twist. Linear resistivity 70Ω/m ± 10%.	Bekintex NV, Industriepark Kwatrecht, Neerhonderd 16, BE-9230 Wettern, Belgium Tel: +32 9 365 71 02 www.bekaert.com	110 Tex (g/1000m). 9.1Nm (m/g). Breaking load ~20N. 1% elongation. Good for heating textiles. Strong continuous filament.
11	Bekinox VN 12/4x275/100S 	Spun filament yarn. Bakaert Bekinoz VN 12/4x275/100S. 100% stainless steel. 12µm diameter, 4 ply, 275 filaments/ply, 100 torsions/m, S-twist. Linear resistivity ~6.9Ω/m ± 10%	Bekintex NV, Industriepark Kwatrecht, Neerhonderd 16, BE-9230 Wettern, Belgium Tel: +32 9 365 71 02 www.bekaert.com	1010 Tex (g/1000m). 1Nm (m/g). Breaking load ~150N. 1% elongation. Good for heating textiles. Strong continuous. filament
12	Bekinox VN 12/4x275/175S/HT/PFA 	Insulated spun filament yarn. Bakaert Bekinox VN 12/4x275/175S/HT. PFA insulated 100% stainless steel. 4 ply, 275 filaments/ply, 175 torsions/m, S-twist. Linear resistivity ~6.9Ω/m ± 10%	Bekintex NV, Industriepark Kwatrecht, Neerhonderd 16, BE-9230 Wettern, Belgium Tel: +32 9 365 71 02 www.bekaert.com	1010 Tex (g/1000m). 1Nm (m/g). Breaking load ~150N. 1% elongation. Good for insulated heating textiles. Strong continuous. filament
13	Bekinox VN 14/2x90/175S/HT/PFA 	Insulated spun filament yarn. Bakaert Bekinox VN 14/2x90/175S/HT/ PFA insulated 100% stainless steel. 2 ply, 90 filaments/ply, 175 torsions/m, S-twist. Linear resistivity (based on twice that of 14/1x90) ~140Ω/m ±10%.	Bekintex NV, Industriepark Kwatrecht, Neerhonderd 16, BE-9230 Wettern, Belgium Tel: +32 9 365 71 02 www.bekaert.com	250 Tex (g/1000m). 4.5Nm (m/g). Breaking load ~ 25N. 1% elongation. Good for insulated heating textiles. Strong continuous. filament

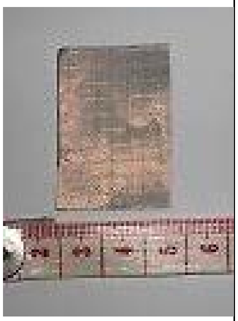
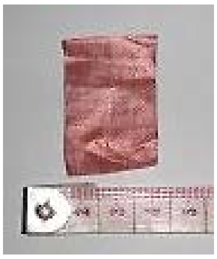
Appendix B – Conductive materials log

#	Conductive material & name	Material description	Vendor details	Other notes
14	Bekinox VN 12/2x275/175S/HT/PFA 	Insulated spun filament yarn. Bakaert Bekinox VN 12/2x275/175S/HT. PFA insulated 100% stainless steel. 2 ply, 275 filaments/ply, 175 torsions/m, S-twist. Linear resistivity ~ 14Ω/m ±7%.	Bekintex NV, Industriepark Kwatrecht, Neerhondered 16, BE-9230 Wettern, Belgium Tel: +32 9 365 71 02 www.bekaert.com	505 Tex (g/1000m). 2 Nm (m/g). Breaking load ~75N. 1% elongation. Good for insulated heating textiles. Strong continuous. filament
15	Bekinox VN 14/1x90/200Z/HT/PFA 	Insulated spun filament yarn. Bakaert Bekinox VN 14/1x90/200Z/HT. PFA insulated 100% stainless steel. Single ply, 200 torsions /m, Z-twist. Linear resistivity ~ 70Ω/m ±10%.	Bekintex NV, Industriepark Kwatrecht, Neerhondered 16, BE-9230 Wettern, Belgium Tel: +32 9 365 71 02 www.bekaert.com	110 Tex (g/1000m). 9.1Nm (m/g). Breaking load ~20N. 1% elongation. Good for insulated heating textiles. Strong continuous. filament
16	Bekilast BK50/1 T/M 1200 Lycra 	Elasticated conductive yarn. 91% Bekitex 50/1, 9% Lycra C1 56. Electrical conductivity ±150Ω/cm – extremely variable due to elasticity	Bekintex NV, Industriepark Kwatrecht, Neerhondered 16, BE-9230 Wettern, Belgium Tel: +32 9 365 71 02 www.bekaert.com	450 dtex, 22.5Nm. Average elongation 236%. Development yarn – no longer available.
17	Soieries Elite PES HT 1100 + VN 60 400 t S/Z 	PES HT 1100 + VN 60 400 t S/Z. 2ply PES 1100dtex with stainless steel VN 60 twisted with 400 s/z twists (60 micron filament with high twist).	Soieries Elite Stationsstraat 54 9660 Brakel Belgium Tel: +32 55 431 000 www.soierieselite.com	Central core/ main fibre PES with a double stainless steel yarn openly (i.e. not cont wrap) twisting around the outside. **sample*
18	Elinox PS130035 	Elinox PS130035. Polyester thread (gold colour) twisted filament yarn, 330dtex coated in silver	Soieries Elite Stationsstraat 54 9660 Brakel Belgium Tel: +32 55 431 000 www.soierieselite.com	Very conductive. **sample*

Appendix B – Conductive materials log

#	**Conductive material & name**	**Material description**	**Vendor details**	**Other notes**
19	High Flex 3981 7X1 Silver 14/000 	7 ply twisted into single yarn. Each ply is silver foil coated (complete wrap) around a central core yarn (possibly nylon base). Material composition and resistivity unknown.	Karl Grimm GmbH & Co. KG Fabrik Leonischer Waren Grimmsrabe, 75 91154 Roth, Eckersmühlen, Germany Tel: +49 9171 96 010 www.karl-grimm.com	High conductivity and solder-able. **sample*
20	Konstantan high flex 8394 7×1 	7 ply twisted into single yarn. Each ply is a conductive metal foil coated (complete wrap) around a central core yarn (possibly nylon base). Material composition and resistivity unknown.	Karl Grimm GmbH & Co. KG Fabrik Leonischer Waren Grimmsrabe, 75 91154 Roth, Eckersmühlen, Germany Tel: +49 9171 96 010 www.karl-grimm.com	'Konstantan' yarn name makes reference to constantan – a copper nickel alloy; however, inconclusive if this is used on this yarn. *sample
21	Elitex 235/34 PA/Ag 	'Elitex' silver coating over core polyamide thread.235 dtex/34 filaments. Final yarn count with silver 450dtex ±10dtex. Linear conductivity 20Ω/m ±10Ω/m.	Imbut GmbH Zeulenrodaer Srabe 4/2 07973 Greiz, Germany Tel: +49 366 1/611-214 www.imbut.de	Breaking extension 15-25%. Solder-able with low melting point <185°C. **sample*
	Conductive ribbons/ tape			
22	Lahnband 8057/15mm 	15mm wide, woven ribbon. Foil tape warp (~0.5mm width per foil end) woven with 2 picks of fine orange polyester (?) thread in plain weave. Material composition and resistivity unknown.	Karl Grimm GmbH & Co. KG Fabrik Leonischer Waren Grimmsrabe, 75 91154 Roth, Eckersmühlen, Germany Tel: +49 9171 96 010 www.karl-grimm.com	Conductive. (Manufacture intention for decorative application) **sample*

Appendix B – Conductive materials log

#	Conductive material & name	Material description	Vendor details	Other notes
23	High Flex 3981 29/2 	Flat braided ribbon ~ 5mm when relaxed, but expandable to ~20mm without contracting size. Constructed with 58 ends of metal foil coated (complete wrap) around a central core yarn (possibly nylon base).	Karl Grimm GmbH & Co. KG Fabrik Leonischer Waren Grimmsrabe, 75 91154 Roth, Eckersmühlen, Germany Tel: +49 9171 96 010 www.karl-grimm.com	Conductive and solder-able. (Manufacture intention for decorative application) **sample*
	Conductive fabrics			
24	Conductive riptop fabric 	Woven ripstop conductive fabric, Tin/Nickle over silver (Sn/Cu/Ag coated nylon fabric). ~0.1mm thickness. Roll width 1.3m. Weight 77g/sq.M. Surface resistance <0.02Ω/(?).	www.proto-pic.co.uk Statex product	Good handle, easy use for sewn constructions. Good conductivity.
25	Shieldex Bremen 	Woven conductive fabric with soft ripstop quality. Silver plated polyamide fabric (RS), Parachute silk with 99% pure silver, < 0.3 Ohms/cm2 surface resistivity.	Statex Statex Produktions & Vertriebs GmbH, Kleiner Ort 11, 28357 Bremen, Germany Tel: +49 421 2575047 www.statex.de www.statex.biz	**sample*
26	Shieldex Kassel 	Woven ripstop conductive fabric. Corrosion proof copper-silver plated polyamide ripstop fabric, < 0.03 Ω/cm2 surface resistivity.	Statex Statex Produktions & Vertriebs GmbH, Kleiner Ort 11, 28357 Bremen, Germany Tel: +49 421 2575047 www.statex.de www.statex.biz	**sample*

Appendix B – Conductive materials log

#	Conductive material & name	Material description	Vendor details	Other notes
27	Shieldex P130 	Knitted conductive jersey fabric. Surface resitance <5Ω/cm^2. Coating 99% pure silver. Thickness 0.45mm. Weight 140g/m^2. Roll width 135cm. Composition 78% nylon, 22% elastomer.	Statex Statex Produktions & Vertriebs GmbH, Kleiner Ort 11, 28357 Bremen, Germany Tel: +49 421 2575047 www.statex.de www.statex.biz Also available from www.proto-pic.co.uk	Face side more shiny than reverse. Also sued for wound care and antimicrobial products. **sample*
28	Eeonyx LR mm-2-84 (4-5KΩ) 	Knitted conductive jersey with two way stretch. Face side shiny, reverse side matt. High resistivity, useful for pressure sensing or bend sensors.	Eeonyx Corporation 750 Belmont Way Pinole, CA 94564, USA Tel:+01 510 7413632 *www.eeonyx.com*	**sample*
29	Eeonyx NW170-PI-10EY 	Non-woven, stiff quality. High resistivity, useful for pressure sensing or bend sensors.	Eeonyx Corporation 750 Belmont Way Pinole, CA 94564, USA Tel:+01 510 7413632 www.eeonyx.com	**sample*
30	Eeonyx MA-3-12 (20KΩ) 	Non-woven, stiff quality. High resistivity ~20kΩ, useful for pressure sensing or bend sensors.	Eeonyx Corporation 750 Belmont Way Pinole, CA 94564, USA Tel:+01 510 7413632 www.eeonyx.com	**sample*
40	Eeonyx KA-2-18 (50-70KΩ) 	Non-woven, stiff quality. High resistivity ~50-70kΩ, useful for pressure sensing or bend sensors.	Eeonyx Corporation 750 Belmont Way Pinole, CA 94564, USA Tel:+01 510 7413632 www.eeonyx.com	**sample*
41	Plug and wear textile push button	Knitted with conductive stainless steel fine wire and non-conductive nylon yarn.	Plug and wear www.plugandwear.com	Knitted construction with 'raschel' stitch-holes that separates the face and reverse conductive threads as one layer, but

Appendix B – Conductive materials log

#	Conductive material & name	Material description	Vendor details	Other notes
				with small separating areas; pressure connects the two sides. **sample*
	Conductive fibers/ tops			
42	Bekinox W12/18 	Wool with stainless steel loose fibre mix – used for felting conductive materials	Bekintex NV, Industriepark Kwatrecht, Neerhondered 16, BE-9230 Wettern, Belgium Tel: +32 9 365 71 02 www.bekaert.com	**sample*
43	Bekinox PES 12/50 	Polyester with stainless steel fibre – could be used to make synthetic c felt or non-woven.	Bekintex NV, Industriepark Kwatrecht, Neerhondered 16, BE-9230 Wettern, Belgium Tel: +32 9 365 71 02 www.bekaert.com	**sample*

**sample – this material was obtained from an event/ supplier. Some samples were obtained with limited technical information.*

Appendix C – Resistance readings from initial tests

Conductive yarns type, no. picks and woven structure	Reading no.	Resistance reading method			
		METHOD 1 Wrapped end x 2	**METHOD 2** Pointed probes – start to end	**METHOD 3** Across 10cm distance	**METHOD 4** Croc clips – start to end
TEST A1 – insulated 2/2 twill – 1pick Shieldex 235/34dtex 4-ply 50Ω/m (72.5cm length): 1pick polyester. 15.5cm weaving width	1	37.1Ω	36.3Ω	5.1Ω	36.5Ω
	2	36.6Ω	36.2Ω	5.5Ω	36.4Ω
	3	36.7Ω	35.9Ω	5.1Ω	36.4Ω
	4	37.0Ω	36.1Ω	5.1Ω	36.4Ω
	5	36.6Ω	36.2Ω	5.3Ω	36.5Ω
	Average reading	*36.8Ω*	*36.14Ω*	*5.22Ω*	*36.44Ω*
TEST A2 – insulated 3/1 twill - 1pick Shieldex 235/34dtex 4-ply 50Ω/m (72.5cm length): 1pick polyester. 15.5cm weaving width	1	36.4Ω	35.9Ω	6.0Ω	36.6Ω
	2	36.7Ω	36.0Ω	5.4Ω	36.4Ω
	3	36.9Ω	36.2Ω	7.2Ω	36.2Ω
	4	36.3Ω	35.9Ω	5.7Ω	36.4Ω
	5	36.4Ω	36.0Ω	6.3Ω	36.4Ω
	Average reading	*36.54Ω*	*36.0Ω*	*6.12Ω*	*36.4Ω*
TEST A3 – insulated Honeycomb on blocks A and B; 1/3 twill on block C – 4picks Shieldex 235/34dtex 4-ply 50Ω/m (57.6cm length): 4picks polyester. 14.4cm weaving width	1	29.9Ω	28.6Ω	4.6Ω	29.3Ω
	2	29.8Ω	29.2Ω	4.0Ω	29.2Ω
	3	29.7Ω	28.8Ω	4.5Ω	29.5Ω
	4	31.2Ω	28.6Ω	4.6Ω	29.0Ω
	5	30.7Ω	29.0Ω	4.7Ω	29.0Ω
	Average reading	*30.26Ω*	*28.84Ω*	*4.48Ω*	*29.2Ω*
TEST A4 – non-insulated 2/2 twill – 5 consistent picks Shieldex 235/34dtex 4-ply 50Ω/m (72.5cm length). 15.5cm weaving width	1	5.6Ω	4.1Ω	2.1Ω	4.6Ω
	2	6.1Ω	4.2Ω	2.2Ω	4.4Ω
	3	5.6Ω	4.2Ω	2.9Ω	4.5Ω
	4	5.5Ω	4.5Ω	1.9Ω	4.4Ω
	5	5.9Ω	4.4Ω	2.0Ω	4.8Ω
	Average reading	*5.74Ω*	*4.28Ω*	*2.22Ω*	*4.54Ω*
TEST A5 – non-insulated 3/1 twill – 5 consistent picks Shieldex 235/34dtex 4-ply 50Ω/m (72.5cm length). 15.5cm weaving width	1	6.6Ω	6.6Ω	4.3Ω	7.0Ω
	2	6.8Ω	7.1Ω	4.8Ω	7.5Ω
	3	6.7Ω	6.6Ω	3.2Ω	7.3Ω
	4	6.8Ω	7.0Ω	4.0Ω	6.8Ω
	5	7.1Ω	6.9Ω	4.8Ω	7.6Ω
	Average reading	*6.8Ω*	*6.84Ω*	*4.22Ω*	*7.24Ω*
TEST A6 – non-insulated Honeycomb on blocks A and B; 1/3 twill on block C – 8 consistent picks Shieldex 235/34dtex 4-ply 50Ω/m (115.2cm length). 14.4cm weaving width	1	39.5Ω	35.5Ω	4.4Ω	37.9Ω
	2	37.0Ω	34.2Ω	4.3Ω	35.1Ω
	3	36.5Ω	36.8Ω	5.0Ω	35.8Ω
	4	38.4Ω	36.6Ω	4.7Ω	34.8Ω
	5	37.1Ω	35.4Ω	4.4Ω	35.3Ω
	Average reading	*37.7Ω*	*35.7Ω*	*4.56Ω*	*35.78Ω*

Conductive yarns type, no. picks and woven structure	Reading no.	Resistance reading method			
		METHOD 1 Wrapped end x 2	**METHOD 2** Pointed probes – start to end	**METHOD 3** Across 10cm distance	**METHOD 4** Croc clips – start to end
TEST A7 – insulated 2/2 twill – 1pick Shieldex 235/34dtex 2-ply 100Ω/m (72.5cm length): 1pick polyester. 14.5cm weaving width	1	84.3Ω	82.5Ω	10.4Ω	84.4Ω
	2	84.1Ω	83.3Ω	12.9Ω	85.5Ω
	3	84.0Ω	83.4Ω	10.3Ω	85.0Ω
	4	84.2Ω	83.5Ω	9.6Ω	85.2Ω
	5	84.2Ω	84.1Ω	10.4Ω	85.3Ω
	Average reading	*84.16Ω*	*83.36Ω*	*10.72Ω*	*85.08Ω*
TEST A8 – insulated 3/1 twill - 1pick Shieldex 235/34dtex 2-ply 100Ω/m (72.5cm length): 1pick polyester. 14.5cm weaving width	1	80.4Ω	79.1Ω	10.2Ω	82.5Ω
	2	80.5Ω	80.3Ω	10.5Ω	83.1Ω
	3	81.0Ω	81.6Ω	11.6Ω	82.5Ω
	4	80.8Ω	80.4Ω	13.1Ω	82.0Ω
	5	81.1Ω	81.8Ω	13.4Ω	80.9Ω
	Average reading	*80.76Ω*	*80.64Ω*	*11.76Ω*	*82.2Ω*
TEST A9 – insulated Honeycomb on blocks A and B; 1/3 twill on block C – 4picks Shieldex 235/34dtex 2-ply 100Ω/m (57.2cm length): 4picks polyester. 14.3cm weaving width	1	63.9Ω	63.5Ω	12.3Ω	63.3Ω
	2	64.0Ω	63.7Ω	12.2Ω	63.5Ω
	3	64.2Ω	64.2Ω	13.4Ω	64.2Ω
	4	64.4Ω	63.9Ω	10.8Ω	65.0Ω
	5	64.1Ω	64.3Ω	11.3Ω	65.8Ω
	Average reading	*64.12Ω*	*63.92Ω*	*12.0Ω*	*64.36Ω*
TEST A10 – non-insulated 2/2 twill – 5 consistent picks Shieldex 235/34dtex 2-ply 100Ω/m (72.5cm length). 14.5cm weaving width	1	25.0Ω	22.5Ω	4.9Ω	29.5Ω
	2	24.5Ω	19.5Ω	4.6Ω	27.6Ω
	3	23.9Ω	18.1Ω	4.4Ω	27.9Ω
	4	34.6Ω	24.9Ω	4.8Ω	21.9Ω
	5	28.3Ω	23.9Ω	5.8Ω	22.1Ω
	Average reading	*29.26Ω*	*21.78Ω*	*4.9Ω*	*25.8Ω*
TEST A11 – non-insulated 3/1 twill – 5 consistent picks Shieldex 235/34dtex 2-ply 100Ω/m (72.5cm length). 15.5cm weaving width	1	31.2Ω	37.6Ω	6.5Ω	36.1Ω
	2	29.5Ω	33.8Ω	6.4Ω	35.9Ω
	3	22.2Ω	36.2Ω	6.5Ω	35.7Ω
	4	38.8Ω	41.0Ω	6.4Ω	31.1Ω
	5	43.0Ω	47.1Ω	7.8Ω	31.4Ω
	Average reading	*32.94Ω*	*39.14Ω*	*6.72Ω*	*34.04Ω*
TEST A12 – non-insulated Honeycomb on blocks A and B; 1/3 twill on block C – 8 consistent picks Shieldex 235/34dtex 2-ply 100Ω/m (114.4cm length). 14.3cm weaving width	1	73.6Ω	67.6Ω	8.7Ω	84.5Ω
	2	75.1Ω	70.1Ω	6.9Ω	75.5Ω
	3	74.6Ω	69.9Ω	9.1Ω	73.1Ω
	4	68.8Ω	70.4Ω	8.2Ω	70.2Ω
	5	67.1Ω	69.8Ω	8.4Ω	68.4Ω
	Average reading	*71.84Ω*	*69.56Ω*	*8.26Ω*	*73.34Ω*

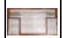
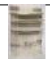
	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X	Y	Z	AA	AB	AC	AD
1	Appendix D WOVEN E-TEXTILES COMPONENTS LIST						Component Type																							
2							Electronic Integration																							
3							Warp Tracks	Weft Tracks	Woven resistor		Woven switch/es		Integrated battery holder			Woven conductive connectors			Integrated component								Complete circuit	Modular piece	Pilot test piece	Heated element
4	Group ID			Sample name	Image	Sample ID								Magnetic clamp			Single sided	Double sided	Non-LED			Lilypad		Own made LED						
5	Pilot	Sample	Technical						Yes	Qty.	Yes	Qty.	Yes	Single	Double	Yes	Qty.	Qty.	Yes	Type	Qty.	Yes	Qty.	Made LED	Type	Qty.				
6				LED wool test patch		W002ET002	•	•																					•	
7	1A			Wool pleat switch		W002ET003		•			•	1																	•	
8	2A			Trio RGB sample		W003ET003	•	•					•									•	3				•		•	
9	1A			Pin cushion contact switch		W003ET004		•			•	1																	•	
10		1A		Dual soft switches		W003ET006	•	•			•	4	•									•	2				•			
11	2B			Malleable light1		W003ET007	•	•					•									•	1				•			
12	1A			Duo pleat switch		W003ET008	•	•			•	2	•	•								•	2				•		•	
13		1A		RGB colour mixer		W003ET009	•	•	•	3	•	3	•	•					•	RGB LED (5mm standard electronic)	1						•			
14		2A		Tilt switch sample		W003ET010	•	•			•	4	•	•					•	Tilt switches	4	•	4				•		•	
15		2A		Ball bearing tilt switch1		W003ET012	•	•			•	2	•		•				•	Ball bearing switch connectors	2	•	2				•			
16	3B			Battery holder module v2 (kit1)		W004ET003	•	•					•		•	•	2											•	•	
17		3A		Modular kit1 – push buttons		W002ET004 (blue) W004ET005 (green)	•	•			•	2 (1per piece)				•	4 (2per piece)											•		
18	3A			Modular kit1 – single LED modules		W004ET006 (orange) W004ET007 (green) W004ET008 (yellow) W004ET009 (pink)	•	•								•	8 (2per piece)					•	4 (1per piece)					•		
19		3A		Modular kit1 – Slide switch module		W004ET010	•	•			•	1				•		2	•	Metal switch connector	1							•		
20		3A		Modular kit1 – Double LED reversible module		W004ET011	•	•								•		2				•	2					•		
21		1A		Fold fringe switch LED		W004ET012	•	•			•	1	•			•		4				•	1				•			
22		2A		Corrugated plead LED angled (CPLED-A)		W004ET013	•	•			•	4	•		•	•		4				•	4				•			
23		2A		Corrugated pleat LED V1 (CPLEDv1)		W004ET014	•	•					•		•	•		4				•	8				•			

F	AF	AG	AH	AI	AJ	AK	AL	AM	AN	AO	AP	AQ	AR	AS	AT	AU	AV
	Woven Construction																
Sample ID	Single Cloth	Double Cloth		Pockets/ housing		Conductive inlay weft	Broken tracks: Cut	Broken track: woven design	Woven pleat		Elasticised weft		Malleable	Heat set pleat	Floats		Finishing process
		Vertical	Horizontal	Yes	What for				Yes	Qty.	Conductive	Non-conductive			Warp floats	Weft floats	
W002ET002	Selvedge only	•				•											Tied in LED to test
W002ET003	Selvedge only		•											•			Set pleats
W003ET003	•	•		•	Battery holder, LEDs	•											Cut battery slot
W003ET004	•	•		•	Insulated wadding	•		•									
W003ET006	•	•	•	•	Battery, LEDs	•	•		•	2					•		Cut battery slot, cut tracks, cut warp floats
W003ET007	•	•		•	Battery, LED	•							•				Cut battery slot
W003ET008	•	•	•	•	Battery, magnetic clamp, LEDs	•	•		•	1					•		Cut battery slot, cut tracks, cut warp floats
W003ET009	•	•	•	•	RGB LED, calico insulation, battery, magnetic clamp	•	•		•	3			•		•		Cut battery slot, cut tracks, cut warp floats
W003ET010	•	•		•	Battery, LEDs, tilt switches, magnetic clamp	•	•								•		Cut battery slot, cut tracks, cut warp floats
W003ET012	•	•		•	Ball bearing switch connectors, LEDs, magnetic clamp	•		•							•		Cut battery slot, cut warp floats
W004ET003	Selvedge only	•		•	Battery, magnetic connectors, battery clamp	•											
W002ET004 (blue) W004ET005 (green)	Selvedge only	•		•	Magnetic connectors, sponge button insulation	•		•									
W004ET006 (orange) W004ET007 (green) W004ET008 (yellow) W004ET009 (pink)	Selvedge only	•		•	LED, magnetic connectors	•											
W004ET010	Selvedge only	•		•	Magnetic connectors, metal switch connector	•		•									
W004ET011	Selvedge only	•		•	LED, magnetic connectors	•											
W004ET012	•	•		•	Battery, LED, magnetic connectors	•	•							•	•	•	Cut battery slot, cut weft and warp floats
W004ET013	•	•		•	Battery holder, LEDs, magnetic connectors, magnetic clamp	•	•							•	•	•	Cut battery slot, cut warp floats
W004ET014	•	•	•	•	Battery holder, LEDs, magnetic connectors, magnetic clamp	•								•	•	•	Cut battery slot, cut warp floats

Appendix D WOVEN E-TEXTILES COMPONENTS LIST

Component Type

Electronic Integration

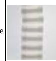
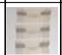
Row	Group ID: Pilot	Group ID: Sample	Group ID: Technical	Sample name	Image	Sample ID	Warp Tracks	Weft Tracks	Woven resistor: Yes	Woven resistor: Qty.	Woven switch/es: Yes	Woven switch/es: Qty.	Integrated battery holder: Yes	Magnetic clamp: Single	Magnetic clamp: Double	Woven conductive connectors: Yes	Single sided: Qty.	Double sided: Qty.	Non-LED: Yes	Non-LED: Type	Non-LED: Qty.	Lilypad: Yes	Lilypad: Qty.	Own made LED: Made LED	Own made LED: Type	Own made LED: Qty.	Complete circuit	Modular piece	Pilot test piece	Heated element
	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X	Y	Z	AA	AB	AC	AD
29		3A		Modular kit1 – DIY double LED module		W004ET015	•	•								•		2						•	Double sided, single LED (no component resistor)	1		•		
30		3A		Modular kit1 – Velostat module		W004ET016	•	•								•		2	•	Velostat variable resistor strip	1							•		
31		1A		Buzzer pleat sample – base		W004ET017	•	•	•	3	•	4	•		•	•		2									•	•		
32		3A		Buzzer pleat sample – buzzer module		W004ET018	•	•								•		2	•	Buzzer module	1							•		
33		2A		Corrugated pleat LED V2		W004ET019	•	•	•	4						•		4						•	Double sided, single LED (no component resistor)	4	• (excluding battery holder)	•		
34		1A		Two way stroke sound and vibe sample		W004ET020	•	•			•	6				•		4	•	Buzzer module x1; vibe module x1	2	•	2				• (excluding battery holder)	•		
35		2B		Malleable roll and connect LED sample		W004ET021	•	•								•		4				•	8				• (excluding battery holder)	•		
36		3B		Battery holder v2		W004ET022	•	•					•		•	•	2											•		
37		2B		Malleable Light v2-polyurethane single LEDs reverse		W004ET023	•	•								•		4						•	Double sided single LEDs with resistors	4	• (excluding battery holder)	•		
38		2B		Malleable furry - double reverse LEDs		W004ET024	•	•								•		4						•	Double sided, double LED with resistors	4	• (excluding battery holder)	•		
39		2A		Flashing LED connector base		W004ET025	•	•								•		8	•	Flashing module	1						• (excluding battery holder)	•		
40		3A		Flashing LEDs modules x 3		W004ET026	•	•								•	2							•	Single sided, double LED with resistors	1		•		
41		3B		Battery holder v3		W004ET027	•	•					•		•	•	2											•		
42		3A		Resistor module kit2		W005ET001	•	•	•	1						•		4										•		
43		1A		Switch module kit2		W005ET002	•	•			•	1				•		4										•		
44		3A		Cotton crimp module kit2 - single LED reverse		W005ET003	•	•								•		4						•	Double sided single LED with resistors	1		•		
45		3A		Velour module kit2 - double reverse LED		W005ET004	•	•								•		4						•	Double sided double LEDs with resistors	1		•		
46		3B		Battery holder module v4 (kit2)		W005ET005	•	•					•		•	•	4											•		
47		1A		RGB colour mixer v2		W005ET008																								
48			•	Heatable textile wool test patch1		W001ET001																							•	• (test layout)

Woven Construction

Row	Sample ID	Single Cloth	Double Cloth: Vertical	Double Cloth: Horizontal	Pockets/ housing: Yes	Pockets/ housing: What for	Conductive inlay weft	Broken tracks: Cut	Broken track: woven design	Woven pleat: Yes	Woven pleat: Qty.	Elasticised weft: Conductive	Elasticised weft: Non-conductive	Malleable	Heat set pleat	Floats: Warp floats	Floats: Weft floats	Finishing process
	F	AF	AG	AH	AI	AJ	AK	AL	AM	AN	AO	AP	AQ	AR	AS	AT	AU	AV
29	W004ET015	Selvedge only	•		•	LED, magnetic connectors	•											
30	W004ET016	Selvedge only	•		•	Magnetic connectors, velostat strip	•		•									
31	W004ET017	•	•	•	•	Magnetic connectors, magnetic clamp	•	•	•	•	4					•		Cut battery slot, cut warp floats,
32	W004ET018	Selvedge only	•	•	•	Buzzer module, magnetic connectors	•											Cut pocket
33	W004ET019	Selvedge only		•	•	LEDs, magnetic connectors	•								•	•		Cut warp floats
34	W004ET020	•	•	•	•	Buzzer module; vibe module, LEDs, magnetic connectors	•		•	•	3					•		Cut warp floats
35	W004ET021	•	•	•	•	LEDs, magnetic connectors	•							•		•		Cut warp floats
36	W004ET022	•	•		•	Battery, magnetic connectors, magnetic clamp	•											Cut battery slot, cut out excess fabric
37	W004ET023	•	•	•	•	Magnetic connectors, LEDs	•							•		•		Cut warp floats
38	W004ET024	•	•	•	•	LED. magnetic connectors	•							•		•		Cut warp floats
39	W004ET025	•	•		•	Flashing module, calico insulation, magnetic connectors	•		•							•		Cut warp floats
40	W004ET026	Selvedge only	•		•	LED, magnetic connectors	•											Cut into individual modules
41	W004ET027	•	•		•	Battery, magnetic connectors, magnetic clamp	•											Cut battery slot, cut out excess fabric
42	W005ET001	•	•		•	Magnetic connectors	•	•								•		Cut warp floats
43	W005ET002	•	•	•	•	Magnetic connectors	•	•	•	•	1					•		Cut warp floats
44	W005ET003	•	•		•	Magnetic connectors, LED	•							•				
45	W005ET004	•	•		•	Magnetic connectors, LED	•							•				
46	W005ET005	•	•		•	Battery, magnetic connectors, magnetic clamp	•											Cut battery slot, cut out excess fabric
47	W005ET008																	
48	W001ET001	•														•		

Appendix D WOVEN E-TEXTILES COMPONENTS LIST

Component Type — Electronic Integration

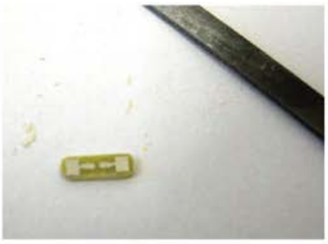
Row	Group ID: Pilot	Group ID: Sample	Group ID: Technical	Sample name	Image	Sample ID	Warp Tracks	Weft Tracks	Woven resistor: Yes	Woven resistor: Qty.	Woven switch/es: Yes	Woven switch/es: Qty.	Integrated battery holder: Yes	Integrated battery holder – Magnetic clamp: Single	Integrated battery holder – Magnetic clamp: Double	Woven conductive connectors: Yes	Woven conductive connectors – Single sided: Qty.	Woven conductive connectors – Double sided: Qty.	Integrated component – Non-LED: Yes	Integrated component – Non-LED: Type	Integrated component – Non-LED: Qty.	Integrated component – Lilypad: Yes	Integrated component – Lilypad: Qty.	Integrated component – Own made LED: Made LED	Integrated component – Own made LED: Type	Integrated component – Own made LED: Qty.	Complete circuit	Modular piece	Pilot test piece	Heated element
54			•	Heatable textile wool test patch2		W001ET002	•	•																					•	•
55			•	Heatable textile mark II (large sample)		W002ET001	•	•																						•
56			•	Test Strips v1		W003ET001		•																					•	
57			•	Test Strips v2 – elasticised conductive yarns		W003ET002		•	•	7																			•	
58			•	Pull cord variable resistor		W003ET005	•	•	•	8			•								8	•	1				•		•	
59			•	Elasticised conductive yarn double cloth test strips		W003ET011		•	•	4																			•	
60			•	Elasticised conductive yarn test strips – single cloth (satin/ sateen)		W004ET001		•	•	4																			•	
61			•	Modular kit1 – stretch variable resistors		W004ET002		•	•	3						•	6											•		
62			•	Connectors - base strips x 6		W005ET006	•	•								•	12 (2per piece)		•	2xconductive velcro, 2xsewn studs, 2xpress studs	12 (2per piece)							•	•	
63			•	Connectors – LED strip modules x 3		W005ET007	•	•								•	6 (2per piece)					•	3 (1per piece)					•	•	

Component Type — Woven Construction

Sample ID	Single Cloth	Double Cloth: Vertical	Double Cloth: Horizontal	Pockets/ housing: Yes	Pockets/ housing: What for	Conductive inlay weft	Broken tracks: Cut	Broken track: woven design	Woven pleat: Yes	Woven pleat: Qty.	Elasticised weft: Conductive	Elasticised weft: Non-conductive	Malleable	Heat set pleat	Floats: Warp floats	Floats: Weft floats	Finishing process
W001ET002	•					•									•		
W002ET001	•					•											Stitched to fleece backing
W003ET001	•																
W003ET002	•										•						
W003ET005	•	•	•	•	Battery holder, LED	•									•		Cut battery slot
W003ET011		•		•	Weft floats						•	•				•	
W004ET001	•										•	•					
W004ET002	Selvedge only	•		•	Magnetic connectors, weft float						•					•	
W005ET006	•																Cut into individual modules, sew in velcro x2, sew in poppers x2, attach press studs x2
W005ET007	Selvedge only	•		•	LED	•											Cut into individual modules

Appendix E i) – Own made components v1 process

1.

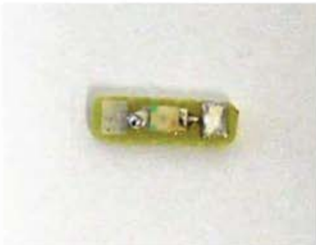


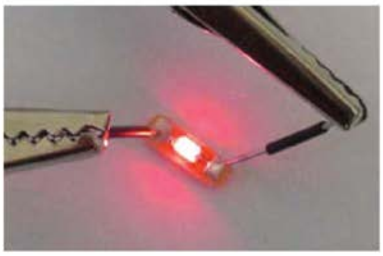
Printed PCB was filed to shape. Surface mount LED is positioned for orientation

2.

Component making set up. Third hand magnified PCB to assist with soldering

3.





Soldered component is tested using crocodile clips and wire tips attached to power source

4.

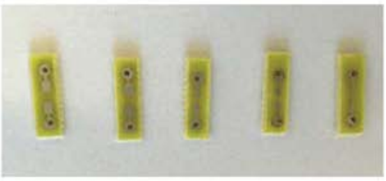
Conductive yarn was soldered directly onto the PCB component contact pads

5.

Crocodile clips attached to a power source were clipped to the conductive yarn to test the complete component

Appendix E ii) – Own made components v2 process

1.



PCBs for own made LEDS v2 cut to size and with holes drilled with micro drill

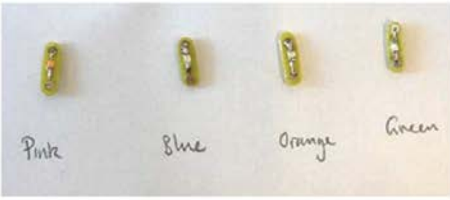
2.

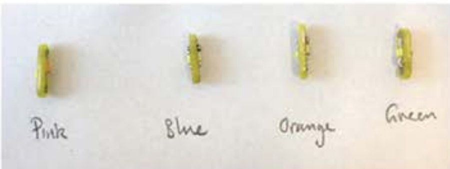
Components are filed to shape, reducing their size to minimum and smoothing corners down

3.

Surface mount LEDs are orientated and positioned onto the PCBs

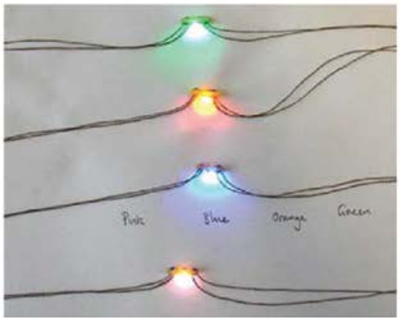
4.

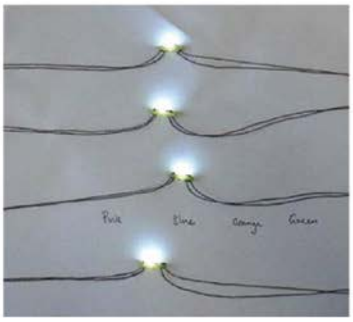




Completed components; face view and side perspective showing double sides

5.

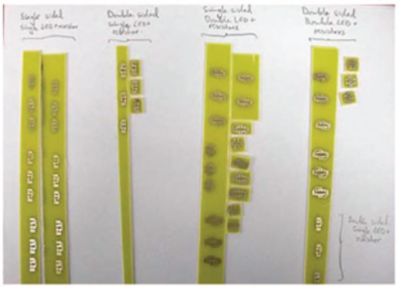




Components prepared with conductive yarn and tested on both sides with a power source

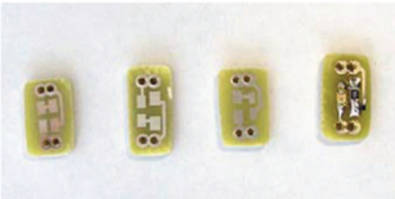
Appendix E iii) – Own made components v3 process

1.



PCBs organised in groups and beginning to be cut into individual pieces. Holes are drilled using the micro drill

2.

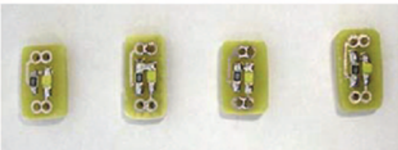


Components are filed into shape. Surface mount components (LEDs and resistors) are orientated and positioned into place for soldering

3.

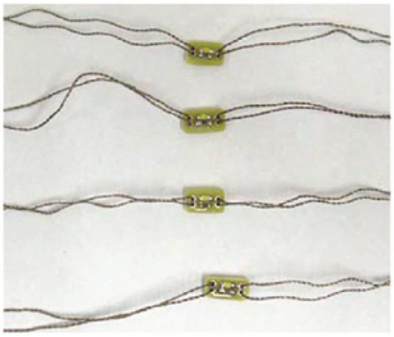
Side one components are soldered

4.



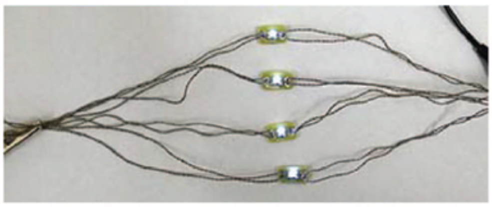
Side two components are orientated and positioned before soldering into place

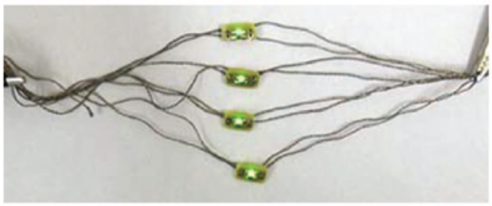
5.



Components are prepared with conductive yarn

6.

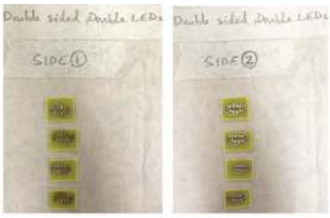




Components are tested on both sides with a power source; side one white LEDs and side two green LEDs

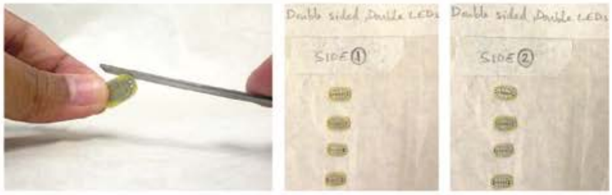
Appendix E iv) – Own made components v4 process

1.



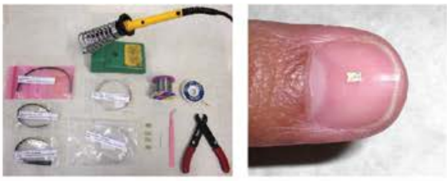
Double sided, double LED PCBs cut to size; holes are drilled using the micro drill

2.



Component PCBs filed to shape

3.

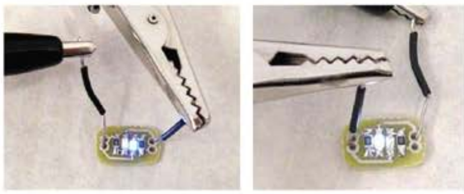


Soldering and component parts set up. Scale of surface mount LED shown on finger nail

4.

Surface mount components are soldered to the PCB on both sides; a total of 8 surface mount components (4 LEDs and 4 resistors)

5.



Component is tested with crocodiles clips and wire tips attached to power source.

6.

They are then prepared with conductive yarn weft

7.

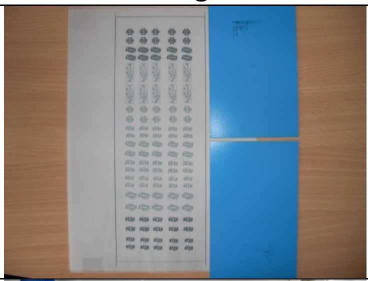
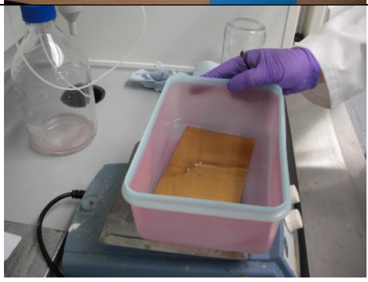
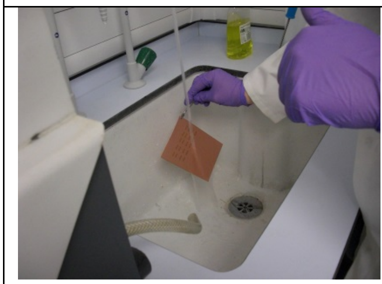
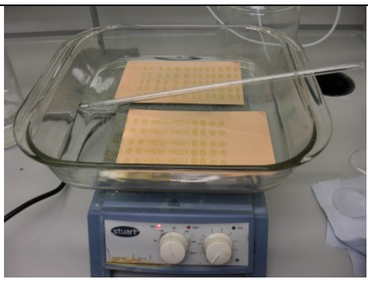
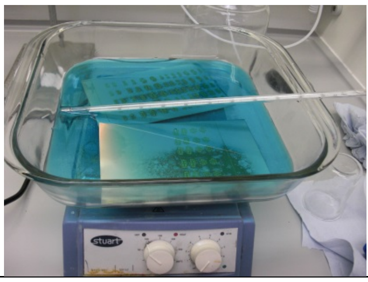
Component are tested individually once they are prepared with conductive yarn

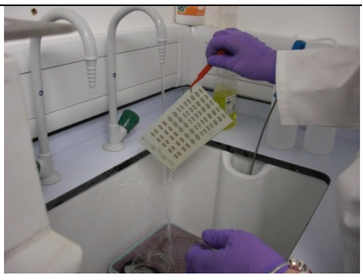
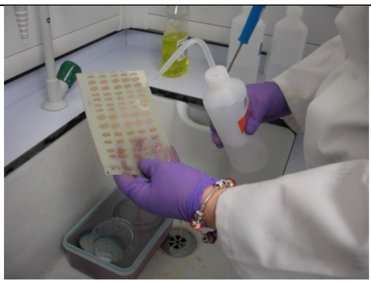
8.

Components are tested altogether as they would function once integrated into the woven e-textiles

Appendix E v) – own made components v5

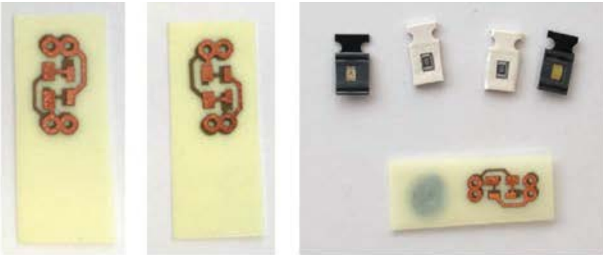
Flexible circuit boards etching process in the clean lab

Step	Image	Process description
1		Expose: Peel backing off, position circuit traces, expose boards (Bungard double sided copper FR4 0.125mm, 35µm copper) 100 seconds
2		Develop: submerge boards in 1.5g NaOH (sodium hydroxide) in 150ml DI H_2O (ionised water).
		Agitate movement to develop complete surface of boards. Rotate sides to repeat on reverse for 40 seconds
		Rinse boards with water and dry.
3	 	Etchant: 33% content ammonium persulfate $(NH_4)_2S_2O_8$ in 100ml water (i.e. 33g in 100ml), mixed and heated to 32-49°C. Board was placed into solution for 15-20mins and agitated to etch consistently over surface area of boards.

4		After this time, the boards were rinsed in water.
5		Acetone was used to clean off any debris left on the boards. Once dry they complete any ready to solder onto.

Appendix E vi) – Own made flexible components v5 assembly process

1\.

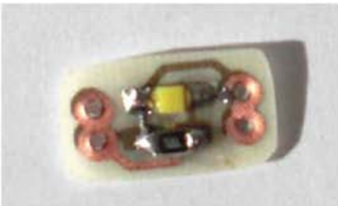


Double sided single LED flexible PCB is cut to approx size; surface mount components are prepared for soldering.

2\.

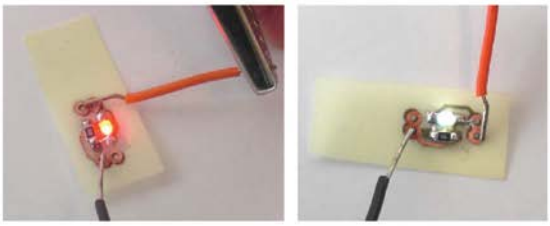
Side one is soldered followed by side two. Holes are pierced using a pin

3\.



Component is trimmed down to size

4\.

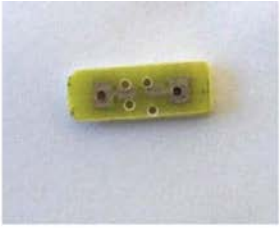


Component is tested on both sides with a power source

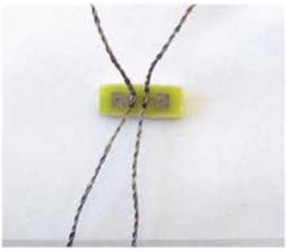
5\.

Component is prepared with conductive yarn weft and tested with a power source using crocodile clips. The component is ready for integration into a woven e-textile. Side perspective showing complete thickness dimension

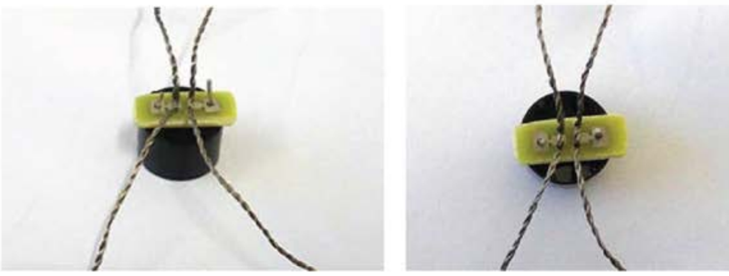
Appendix E vii) – Own made buzzer component

1. 

PCB is cut to size, filed to shape and drilled with holes using a micro drill for conductive yarn and buzzer module's legs; therefore, a total of 6 holes were required

2. 

For this component, the conductive yarn weft was prepared first, as once the buzzer module was positioned onto the PCB, it would restrict access to the PCB

3. 

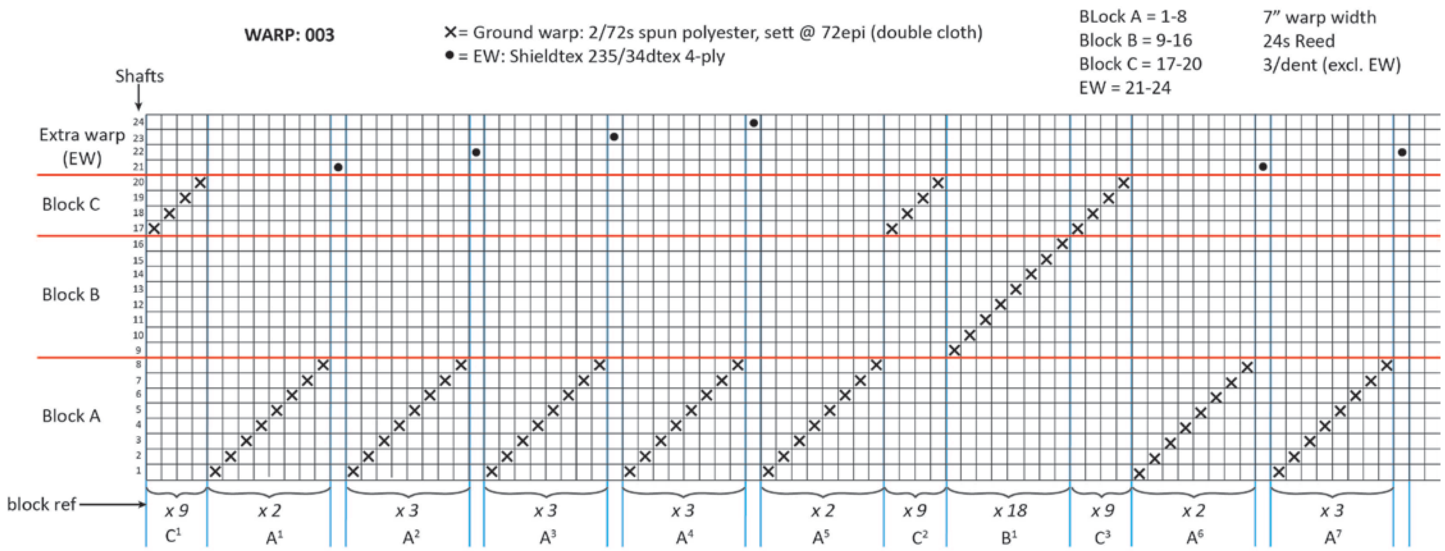
The buzzer module was positioned onto the PCB

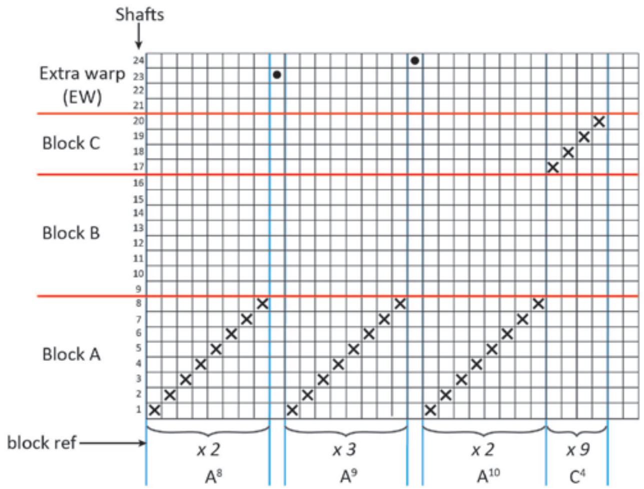
4. 

The conductive yarn wefts were taped back to clear space for soldering of buzzer legs and to refrain from damage from the soldering process

5. 

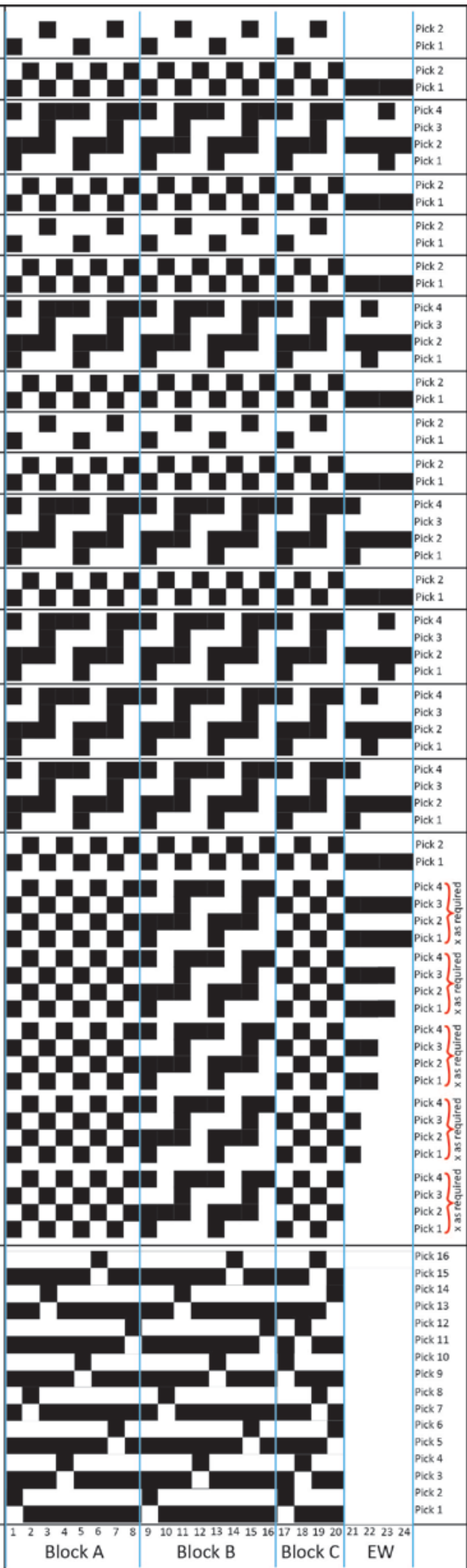
Buzzer module's legs were trimmed back to complete the component



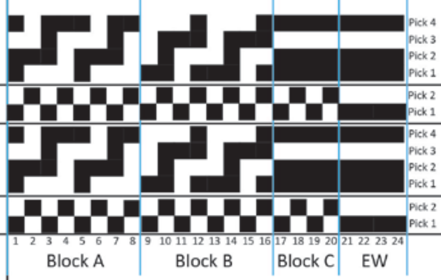


Appendix F
Warp 003 draft

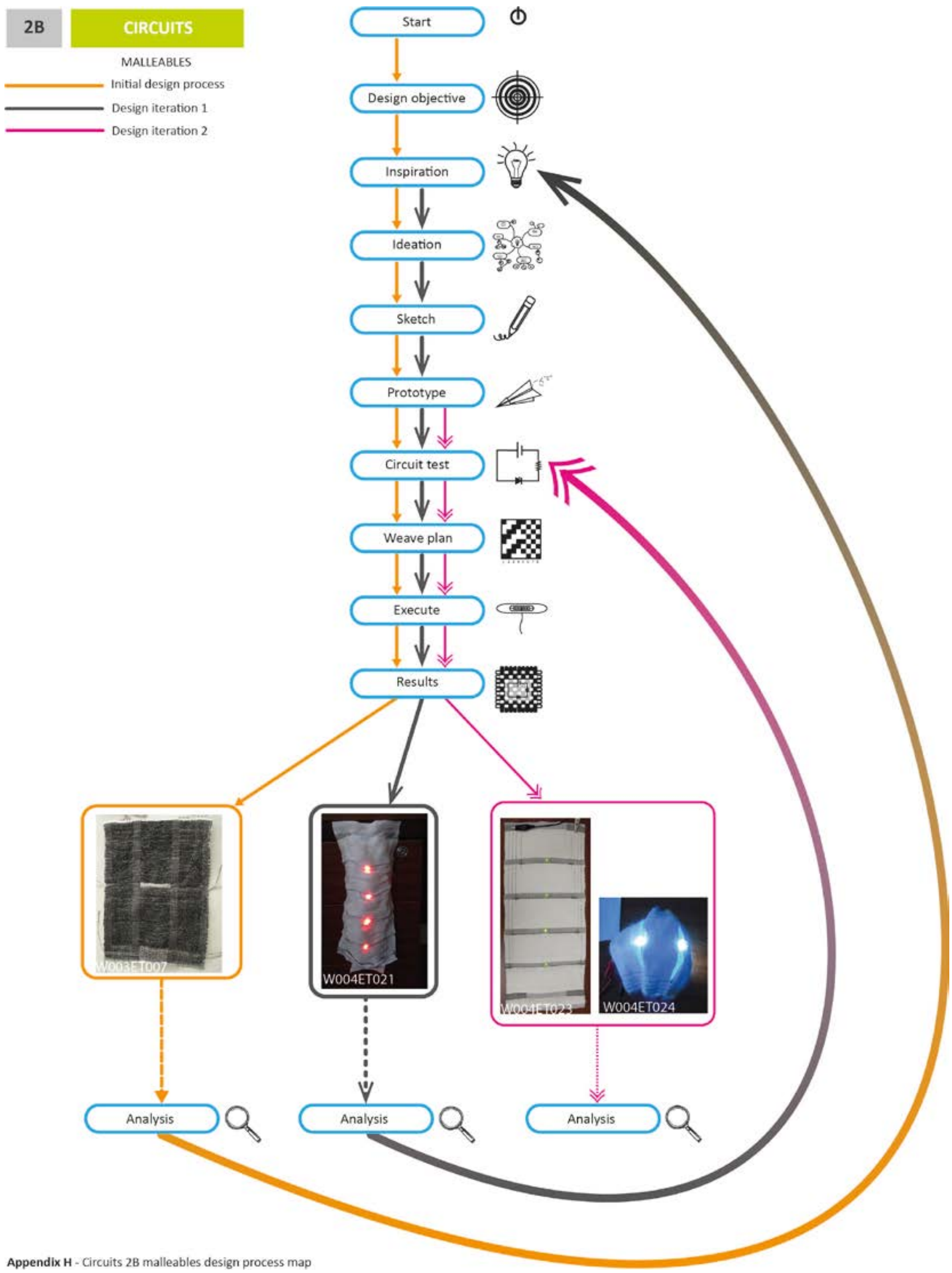
Appendix G – RGB Colour mixer woven structures



SECTION	NOTES
Section 11 Switch3	2/74s spun polyester Shieldtex 235/34dtex 4-ply
Single cloth join	2/74s spun polyester
Section 10 Tracks3	2/74s spun polyester
Single cloth join	2/74s spun polyester
Section 9 Switch2	2/74s spun polyester Shieldtex 235/34dtex 4-ply
Single cloth join	2/74s spun polyester
Section 8 Tracks2	2/74s spun polyester
Single cloth join	2/74s spun polyester
Section 7 Switch1	2/74s spun polyester Shieldtex 235/34dtex 4-ply
Single cloth join	2/74s spun polyester
Section 6 Tracks1	2/74s spun polyester
Single cloth join	2/74s spun polyester
Section 5 Resistor3	2/74s spun polyester Shieldtex 235/34dtex 2-ply Calico insulation strip
Section 4 Resistor2	2/74s spun polyester Shieldtex 235/34dtex 2-ply Calico insulation strip
Section 3 Resistor1	2/74s spun polyester Shieldtex 235/34dtex 2-ply Calico insulation strip
Section 2 RGB LED	2/74s spun polyester Shieldtex 235/34dtex 4-ply
Section 1 Screen	2/74s spun polyester 0.2mm enamelled wire



SECTION	SHAFTS	NOTES
Section 14 Battery clamp	Pick 4, Pick 3, Pick 2, Pick 1	2/74s spun polyester 1 x 1cm neodymium
Single cloth join	Pick 2, Pick 1	2/74s spun polyester
Section 13 Battery holder	Pick 4, Pick 3, Pick 2, Pick 1	2/74s spun polyester Shieldtex 235/34dtex 4-ply
Section 12 Tracks4	Pick 2, Pick 1	2/74s spun polyester



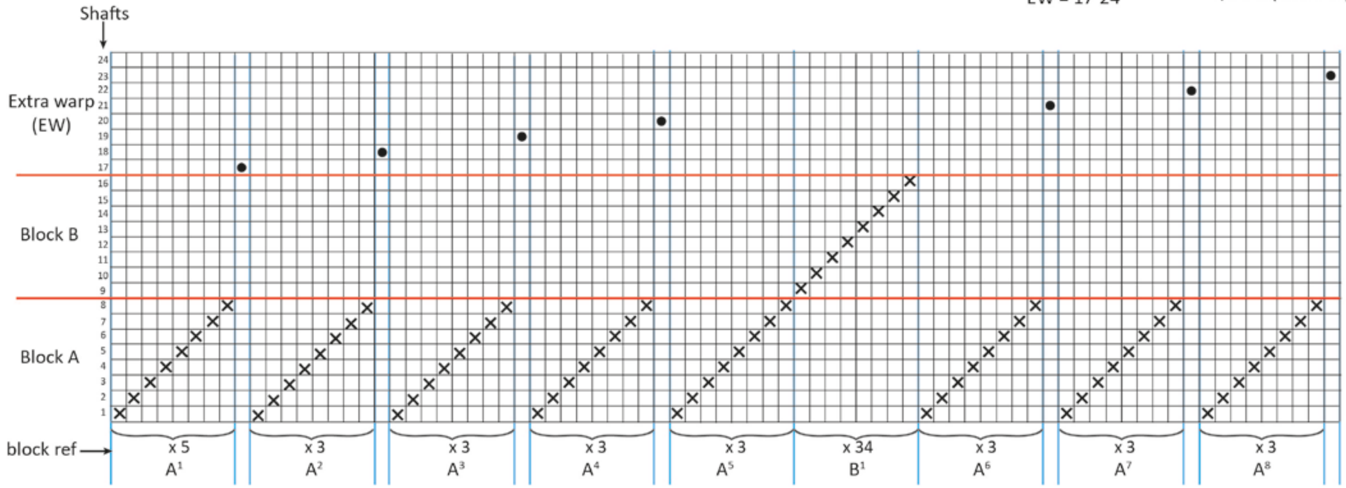
Appendix H - Circuits 2B malleables design process map

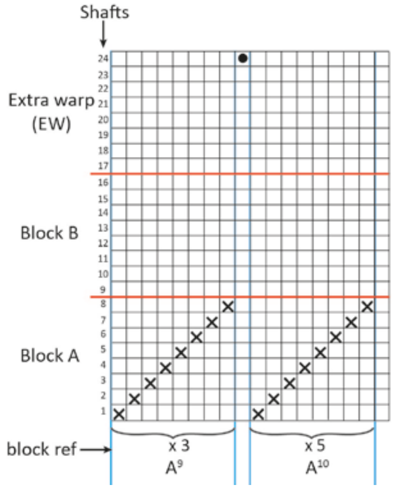
WARP: 004

× = Ground warp: 2/72s spun polyester, sett @ 84epi (double cloth)
● = EW: Shiledtex 235/34dtex 4-ply

Block A = 1-8
Block B = 9-16
EW = 17-24

5” warp width
22s reed
4/dent (excl. EW)

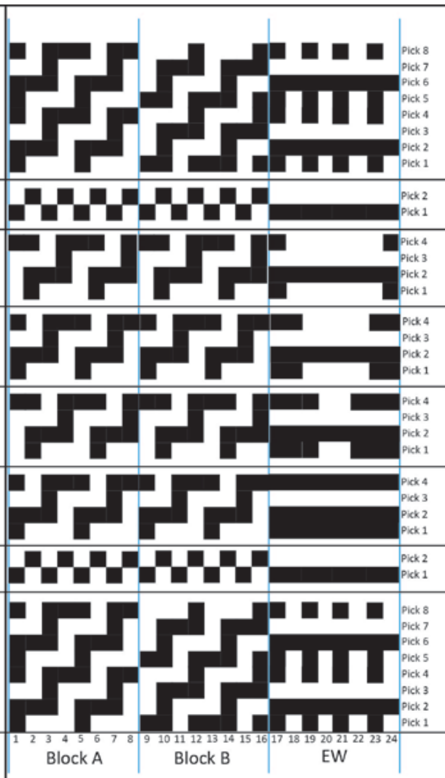




Appendix I

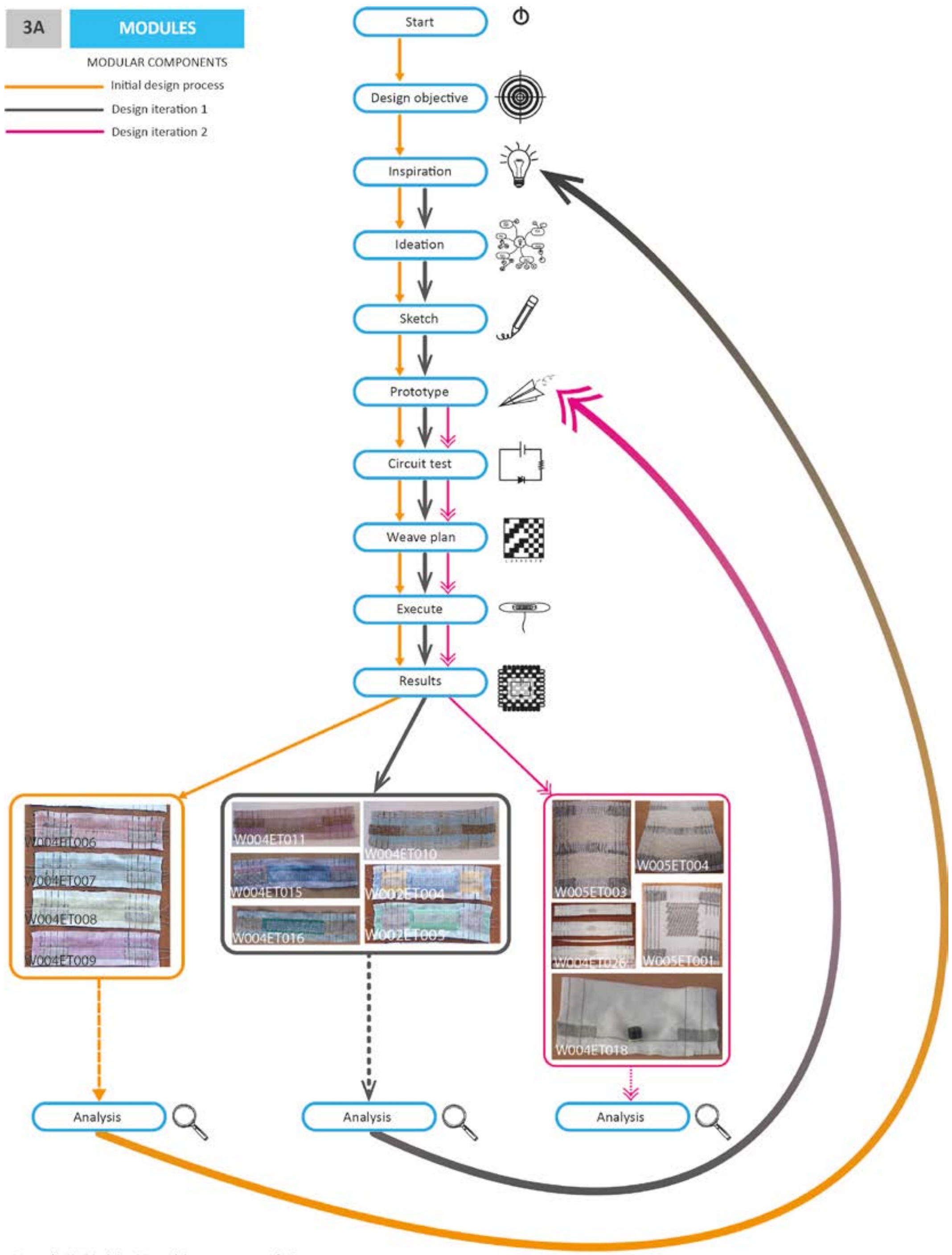
Warp 004 draft

Appendix J – CPLEDv2 woven structures



SECTION	NOTES
Section 6 Top magnetic connectors	2/74s spun polyester Shieldtex 235/34dtex 4-ply 2 x 2cm neodymium magnets
Single cloth join	2/74s spun polyester
Section 5 LED green/ white	80 denier monofilament Shieldtex 235/34dtex 2-ply Double sided own made v2 LED component
Section 4 LED orange/ white	80 denier monofilament Shieldtex 235/34dtex 2-ply Double sided own made v2 LED component
Section 3 LED blue/ white	80 denier monofilament Shieldtex 235/34dtex 2-ply Double sided own made v2 LED component
Section 2 LED pink/ white	80 denier monofilament Shieldtex 235/34dtex 2-ply Double sided own made v2 LED component
Single cloth join	2/74s spun polyester
Section 1 Bottom magnetic connectors	2/74s spun polyester Shieldtex 235/34dtex 4-ply 2 x 2cm neodymium magnets

SHAFTS



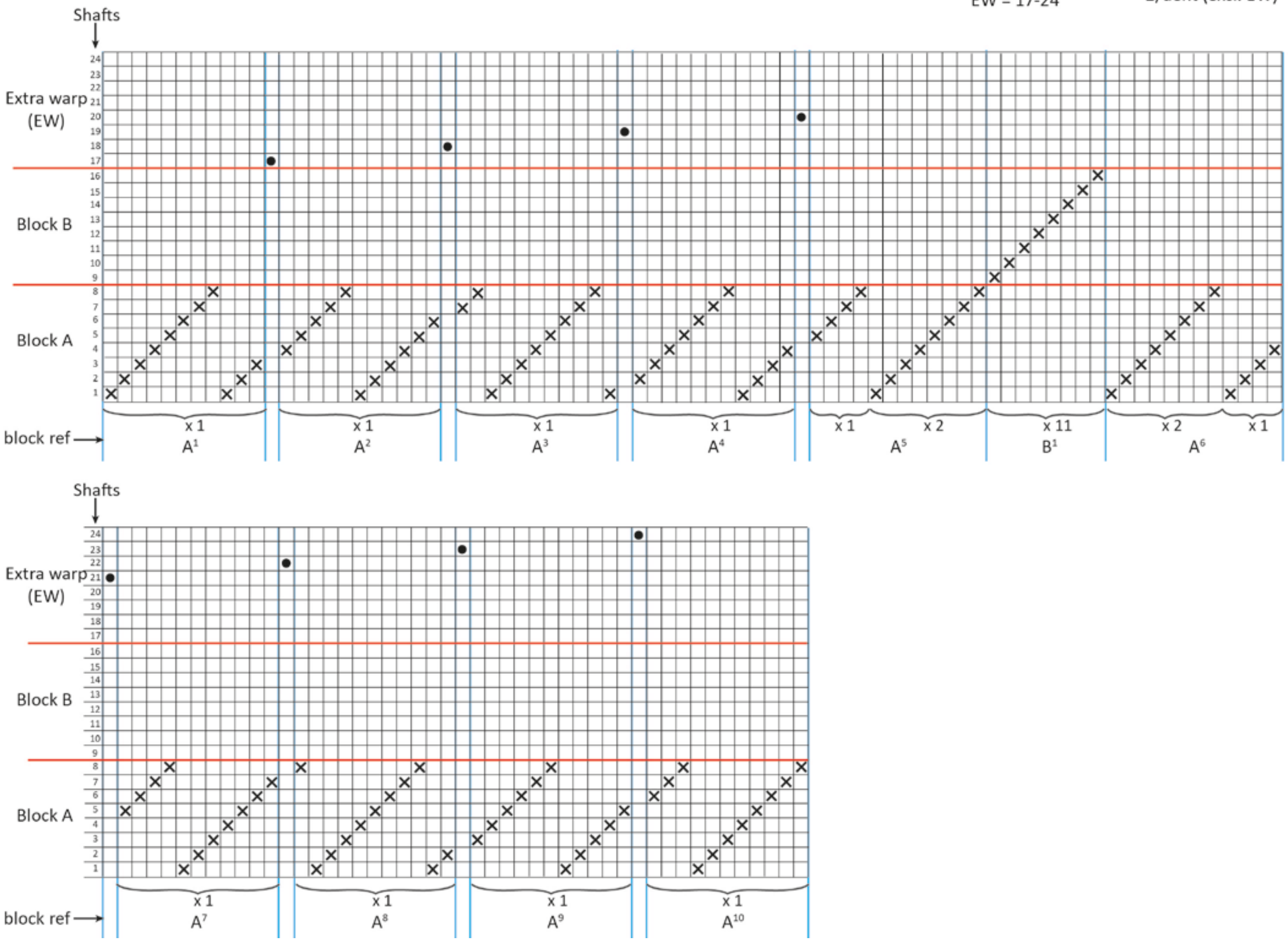
Appendix K - Modules 3A modular components design process map

WARP: 005

× = Ground warp: 2/20cc spun cotton, sett @ 60epi (30epi for double cloth)
● = EW: Shiledtex 235/34dtex 4-ply

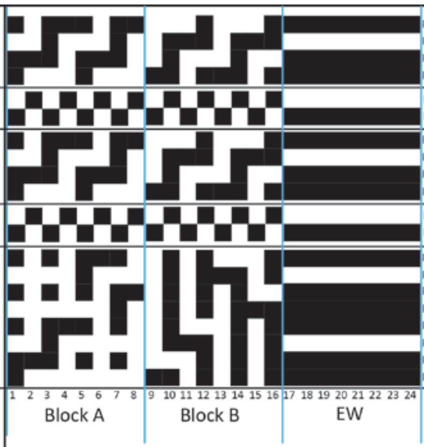
Block A = 1-8
Block B = 9-16
EW = 17-24

3½" warp width
30s reed
2/dent (excl. EW)



Appendix L
Warp 005 draft

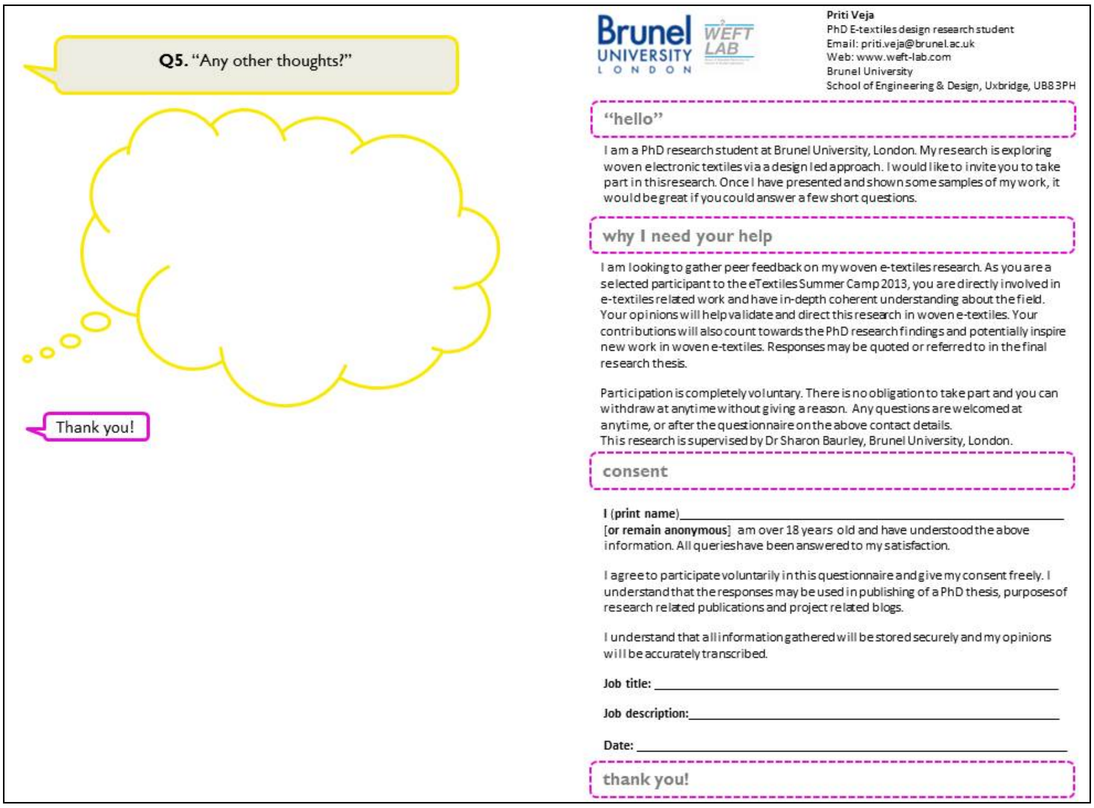
Appendix M – BHMv4 woven structures



SECTION	SHAFTS	NOTES
Section 5 Magnetic clamp2	Pick 4 Pick 3 Pick 2 Pick 1	2/20cc cotton 1 x 1cm neodymium magnet
Section 4 Plain weave spacing	Pick 2 Pick 1	2/20cc cotton
Section 3 Magnetic clamp1	Pick 4 Pick 3 Pick 2 Pick 1	2/20cc cotton 1 x 1cm neodymium magnet
Section 2 Plain weave spacing	Pick 2 Pick 1	2/20cc cotton
Section 1 Battery holder and connectors	Pick 8 Pick 7 Pick 6 Pick 5 Pick 4 Pick 3 Pick 2 Pick 1	Shieldtex 235/34dtex 4-ply 2/20cc cotton

Appendix N

eTextiles Summer Camp 2013 questionnaire based on woven e-textiles research



Q5. "Any other thoughts?"

Thank you!

Priti Veja
PhD E-textiles design research student
Email: priti.veja@brunel.ac.uk
Web: www.weft-lab.com
Brunel University
School of Engineering & Design, Uxbridge, UB8 3PH

"hello"

I am a PhD research student at Brunel University, London. My research is exploring woven electronic textiles via a design led approach. I would like to invite you to take part in this research. Once I have presented and shown some samples of my work, it would be great if you could answer a few short questions.

why I need your help

I am looking to gather peer feedback on my woven e-textiles research. As you are a selected participant to the eTextiles Summer Camp 2013, you are directly involved in e-textiles related work and have in-depth coherent understanding about the field. Your opinions will help validate and direct this research in woven e-textiles. Your contributions will also count towards the PhD research findings and potentially inspire new work in woven e-textiles. Responses may be quoted or referred to in the final research thesis.

Participation is completely voluntary. There is no obligation to take part and you can withdraw at anytime without giving a reason. Any questions are welcomed at anytime, or after the questionnaire on the above contact details.
This research is supervised by Dr Sharon Baurley, Brunel University, London.

consent

I (print name)____________________
[**or remain anonymous**] am over 18 years old and have understood the above information. All queries have been answered to my satisfaction.

I agree to participate voluntarily in this questionnaire and give my consent freely. I understand that the responses may be used in publishing of a PhD thesis, purposes of research related publications and project related blogs.

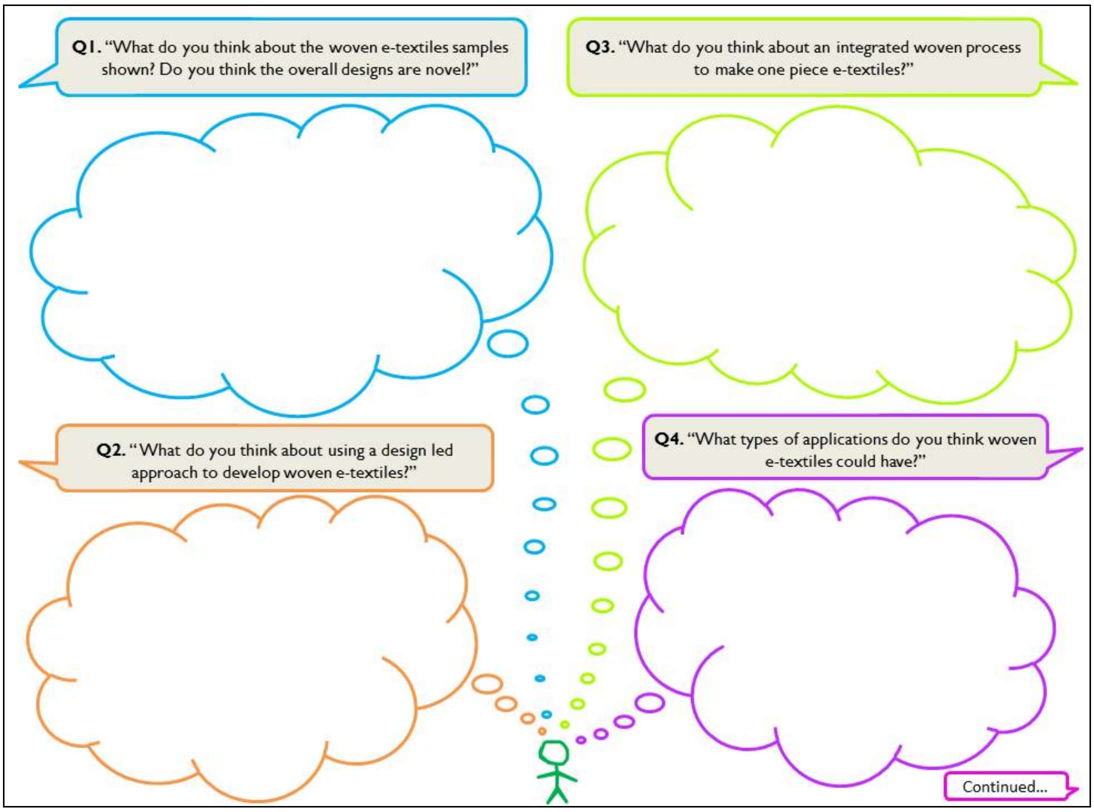
I understand that all information gathered will be stored securely and my opinions will be accurately transcribed.

Job title: ____________________

Job description:____________________

Date: ____________________

thank you!



Q1. "What do you think about the woven e-textiles samples shown? Do you think the overall designs are novel?"

Q3. "What do you think about an integrated woven process to make one piece e-textiles?"

Q2. "What do you think about using a design led approach to develop woven e-textiles?"

Q4. "What types of applications do you think woven e-textiles could have?"

Continued...

Appendix O – E-textile questionnaire transcripts and coding

Analysis criteria

Open ended questions were designed to address the following themes:

- Novelty of design
- Design and/ or aesthetics
- Making process
- Applications
- Industry manufacture

The following highlighted colours were used to categorise the answers:

- Novelty of design
- Design and/or aesthetics
- Making process
- Applications
- Industry manufacture

The following symbols marked beside each comment denote the positive, negative or neutral comments:

(+) Positive comment

(-) Negative comment

(=) Neutral comment

Participant number: 01.

Job Title: Creative Technologist

Job Description: N/A

Date questionnaire completed: 18/07/2013

Question 1: *What do you think about the woven e-textiles samples shown? Do you think the overall designs are novel?*

Answer 1: "Beautiful choice of materials (**+**) and craftsmanship (**+**). Yes (**+**)."

Question 2: *What do you think about using a design led approach to develop woven e-textiles?*

Answer 2: "I think it's extremely important as is allows a wide range of people to connect with the materials (**+**)"

Question 3: *What do you think about an integrated woven process to make one piece e-textiles?*

Answer 3: "Applications would have to be very specific (**=**). Probably more suited to interior and architectural uses than fashion because of scalability (**=**)."

Question 4: *What types of application do you think woven e-textiles could have?*

Answer 4: "Question is a bit broad… depends on the function and properties of the e-textile (**=**). Potentially could be used wherever 'dumb' textiles are used (**=**)."

Question 5: *Any other thoughts?*

Answer 5: "Really like the aesthetic quality of these woven e-textiles (**+**). Looks very simple but obviously a lot of thought has gone into it (**+**)."

Participant number: 02.

Job Title: Textile Designer (Masters Obtained)

Job Description: Searching for internship with European funding

Date questionnaire completed: 18/07/2013

Question 1: *What do you think about the woven e-textiles samples shown? Do you think the overall designs are novel?*

Answer 1: "I think it is an interesting work, research upon new or technical fibres also (=). And because of these the technique of weaving seems to involve some new results (=)."

Question 2: *What do you think about using a design led approach to develop woven e-textiles?*

Answer 2: "I think it is very interesting to work directly with LED on woven textiles (**+**), as we already know fabric made of optical fibres. It is new technical problems and I really interested in these research (**+**)."

Question 3: *What do you think about an integrated woven process to make one piece e-textiles?*

Answer 3: "This is also an interesting way to think about woven fabric (=). We already know such one piece in knitting but not so much for weaving (=). E-textile or not I think this is already something interesting (**+**)."

Question 4: *What types of application do you think woven e-textiles could have?*

Answer 4: "I guess it can be a garment or house application also (=). Like these curtains including optical fibres, LEDs and solar cells (Sweden, who I forgot?) Decorative, useful, poetic and conscious works! (**+**)"

Question 5: *Any other thoughts?*

Answer 5: "I wish you to complete your PhD successfully! Good luck and go on!"

Participant number: 03.

Job Title: General Manager

Job Description: N/A

Date questionnaire completed: 18/07/2013

Question 1: *What do you think about the woven e-textiles samples shown? Do you think the overall designs are novel?*

Answer 1: "I especially like the origami sample. It is light, airy and has a lovely fold structure (**+**). I haven't seen it before (**+**)."

Question 2: *What do you think about using a design led approach to develop woven e-textiles?*

Answer 2: N/A

Question 3: *What do you think about an integrated woven process to make one piece e-textiles?*

Answer 3: "It's an interesting approach that would allow designers in companies to easily create stable and reliable LED e-textiles (**+**). Industrialisation requires reliable and fast processes such as this (**+**)."

Question 4: *What types of application do you think woven e-textiles could have?*

Answer 4: "With the samples that were presented, various applications in interior design come to mind (**=**). Both Home and transportation interiors. Interior project market (hotels etc.) (**+**)"

Question 5: *Any other thoughts?*

Answer 5: N/A

Participant number: 04.

Job Title: Researcher

Job Description: Smart textiles research

Date questionnaire completed: 18/07/2013

Question 1: *What do you think about the woven e-textiles samples shown? Do you think the overall designs are novel?*

Answer 1: "The samples are fantastic (**+**)! The in-depth knowledge in weaving combined with the understanding of electronics (**+**) has resulted in beautiful e-textiles where both the electronics and textiles have been so perfectly integrated (**+**). The designs are novel and show a lot of (**+**) potential for future products/ developments (**+**). It's really exciting to see woven circuitry (**+**)!!"

Question 2: *What do you think about using a design led approach to develop woven e-textiles?*

Answer 2: "The samples are shown reflect a thorough process and can be seen as the result of multiple iterations (**+**). Design led research seems to be a successful methodology for developing these e-textiles samples (**+**)."

Question 3: *What do you think about an integrated woven process to make one piece e-textiles?*

Answer 3: "This is the way forward for e-textiles if it needs to come into the production stage of e-textiles (**+**). By creating these on the loom, one is able to scale it up to producing e-textiles fabric in the same way we get silk and cotton fabric in the market. This makes e-textiles more available and accessible (**+**). Integrated e-textiles pushes e-textiles from the home made embroidered small samples to a single fabric that contains all the electronics within itself. Here the textiles come back to being the focus (**+**)."

Question 4: *What types of application do you think woven e-textiles could have?*

Answer 4: "Because of how integrated the textiles and electronics are, it opens up more opportunities for how e-textiles can be used in our everyday environments such as interiors, garments, furnishing, etc., as well as in more specialised areas such as health care (**+**). E-textiles need to be more textile driven than electronics driven and textiles is around us in a myriad of ways (**+**). Therefore e-textiles have a myriad of roles to play."

Question 5: *Any other thoughts?*

Answer 5: "What happens at the time of discarding the e-textiles (-)? How do you separate the electronic components from the textile fibres (-)? How can e-textiles be like silk or cotton where someone can buy meters of a fabric that lights up and make whatever they want out of it? (=) How does one cut/ sew e-textiles? Or will they always be final 'products' off the loom? (=) Great work! It's really inspiring to see such a strong exploration of e-textiles where the textiles techniques and structures are the focus… its fantastic!! (+)"

Participant number: 05.

Job Title: PhD student

Job Description: Research student at digital interaction group

Date questionnaire completed: 18/07/2013

Question 1: *What do you think about the woven e-textiles samples shown? Do you think the overall designs are novel?*

Answer 1: "They look amazing (**+**) and push woven textiles/ woven electronics further (**+**)."

Question 2: *What do you think about using a design led approach to develop woven e-textiles?*

Answer 2: "Because e-textiles require so much testing, a design led approach is a very good way to think about it (**+**)."

Question 3: *What do you think about an integrated woven process to make one piece e-textiles?*

Answer 3: "It's a good way to do it, especially as materials are developing into new directions (**+**)."

Question 4: *What types of application do you think woven e-textiles could have?*

Answer 4: "All, from clothing to health, urban space (**+**). Different scales, from the personal to the public (**=**)."

Question 5: *Any other thoughts?*

Answer 5: "It would be good to see an application of the woven materials proposed that could offer a better insight into whether the novelty works in a real world scenario (**=**)."

Participant number: 06.

Job Title: Colour and trim designer

Job Description: designer of materials for cars

Date questionnaire completed: 18/07/2013

Question 1: *What do you think about the woven e-textiles samples shown? Do you think the overall designs are novel?*

Answer 1: "The functionality is completely new (**+**). These [*woven e-textiles*] technologies are completely shifting the way we perceive electronics. The 'design appearance' still needs to be improved [*in reference to other existing work in e-textiles, not samples shown*] I guess it is the next step!"

Question 2: *What do you think about using a design led approach to develop woven e-textiles?*

Answer 2: "This is a good approach because as a designer, you are probably more closer to the user (**+**). You tend to develop a user centered approach which makes your technologies immediately understandable and functional (**+**)."

Question 3: *What do you think about an integrated woven process to make one piece e-textiles?*

Answer 3: "I think that could be a good thing because you can have a completely integrated circuit (**+**). You can't feel it, you can't see it; it feels like fabric (**+**)! And completely change the way we can perceive textile and electronics (**+**)."

Question 4: *What types of application do you think woven e-textiles could have?*

Answer 4: "Medical, public shows (theatre, dance, sounds and light control), flexible ambient display for the home environment? (**+**)"

Question 5: *Any other thoughts?*

Answer 5: N/A

Participant number: 07.

Job Title: Textile artist and researcher

Job Description: Practical and theoretical research

Date questionnaire completed: 18/07/2013

Question 1: *What do you think about the woven e-textiles samples shown? Do you think the overall designs are novel?*

Answer 1: "Yes, I think that the approach related to the quality of woven e-textile it is novel (**+**). It is a next step research in e-textile (**+**)."

Question 2: *What do you think about using a design led approach to develop woven e-textiles?*

Answer 2: "Great idea, it worked [*for*] me in the last time, that LED and textiles can very well fit together (**+**)."

Question 3: *What do you think about an integrated woven process to make one piece e-textiles?*

Answer 3: "I'm [*it's*] balancing between an 'open box' perspective and a smart close to analogue approach (**=**)."

Question 4: *What types of application do you think woven e-textiles could have?*

Answer 4: "A very large use, from wearables to home applications (**+**)."

Question 5: *Any other thoughts?*

Answer 5: N/A

Participant number: 08.

Job Title: Textile designer and lecturer

Job Description: Designer at the automotive industry, lecturer at university

Date questionnaire completed: 19/07/2013

Question 1: *What do you think about the woven e-textiles samples shown? Do you think the overall designs are novel?*

Answer 1: "I haven't seen that kind of wovens before where the LEDs are inserted while weaving. This is novel for me (**+**). Also combining heat pleating and LED weaving is very interesting technique (**+**)."

Question 2: *What do you think about using a design led approach to develop woven e-textiles?*

Answer 2: "I think that those wovens could be developed for several products where light is needed (**+**)."

Question 3: *What do you think about an integrated woven process to make one piece e-textiles?*

Answer 3: "I think this method has a lot of potential to be developed for production (**+**)."

Question 4: *What types of application do you think woven e-textiles could have?*

Answer 4: "Light textiles could be widely used + ex [*for example*] in dark areas (Nordic countries) or areas with lack of power supplies (3rd world countries) – to use small batteries or solar energy (**+**)."

Question 5: *Any other thoughts?*

Answer 5: "Also other electronic components could be used. Good luck!"

Participant number: 09.

Job Title: BFA industry design, MFA textile design

Job Description: Freelance designer artist, e-textile maker

Date questionnaire completed: 19/07/2013

Question 1: *What do you think about the woven e-textiles samples shown? Do you think the overall designs are novel?*

Answer 1: "I think they are good. The one with more folds, I was interested in how the circuit connections could look like if there would be more folds (more lines?) (=) Could it look different? I like the aesthetics of the black shaping piece (**+**)."

Question 2: *What do you think about using a design led approach to develop woven e-textiles?*

Answer 2: "A good method to visualise the function (**+**)"

Question 3: *What do you think about an integrated woven process to make one piece e-textiles?*

Answer 3: "I think it is good to be able to do ready pleats it belongs to. If the woven piece is supposed to be a component or complete piece (**+**)"

Question 4: *What types of application do you think woven e-textiles could have?*

Answer 4: "Circuits, sensors, speakers (**+**). I like the LED because it looks like not 'applied' it is 'in' the material (**+**)."

Question 5: *Any other thoughts?*

Answer 5: "I like very much that you have nice aesthetics in the black piece (**+**). I think an advantage of the e-textile making is that we can influence the look, it doesn't have to look like electronic components (**+**)."

Participant number: 10.

Job Title: Lecturer in craft innovation/ smart materials

Job Description: [*as above*]

Date questionnaire completed: 20/07/2013

Question 1: *What do you think about the woven e-textiles samples shown? Do you think the overall designs are novel?*

Answer 1: "The samples are beautiful and extremely well designed (**+**). You can tell that a lot of experience, time and thought has gone into their development[1] (**+**). You can tell that a lot of experience, time and thought has gone into their development[2] (**+**). They have a beauty that means with or without the electronics, they speak for themselves (**+**). They are the most technically accomplished woven e-textiles samples I have seen (**+**)."

Question 2: *What do you think about using a design led approach to develop woven e-textiles?*

Answer 2: "I think a design led approach to combine the technical and go through that iterative design process is essential to bring together textiles and electronics in an intelligent, meaningful and aesthetic way (**+**). Also as a result of Priti's process they also function brilliantly (**+**)."

Question 3: *What do you think about an integrated woven process to make one piece e-textiles?*

Answer 3: "The [*integrated*] woven process is one way to bring textiles and electronics together and keep the fabric qualities that are so important to a breadth of people (**+**). It is a brilliant idea and one which gives real potential for commercial and/ or desirable e-textiles products[3] (**+**). It is a brilliant idea and one which gives real potential for commercial and/ or desirable e-textiles products[4] (**+**)"

Question 4: *What types of application do you think woven e-textiles could have?*

Answer 4: "That is a big question but I think their use is extremely broad due to the nature and flexibility of fabric (**=**). I think they have a larger part to play in craft and applied arts – there is huge potential and things are just beginning to get exciting (**+**)."

[1] Comment relates to two categories
[2] Comment relates to two categories
[3] Comment relates to two categories
[4] Comment relates to two categories

Question 5: *Any other thoughts?*

Answer 5: "Fantastically sophisticated work, really showing the potential of an experienced designer working in this field and advancing the knowledge in a clear and accessible way (**+**)."

Participant number: 11.

Job Title: PhD student

Job Description: Discovering sustainable textiles through craft inspired smart textile services.

Date questionnaire completed: 20/07/2013

Question 1: *What do you think about the woven e-textiles samples shown? Do you think the overall designs are novel?*

Answer 1: "The samples are of high quality and very neat integration (**+**). The use of double layer weaving to integrate electronics gives nice opportunities for smart textiles (**+**)."

Question 2: *What do you think about using a design led approach to develop woven e-textiles?*

Answer 2: "It allows the designer/ researcher to explore without expectations and this often results in unexpected interested results (**+**)."

Question 3: *What do you think about an integrated woven process to make one piece e-textiles?*

Answer 3: "It is a novel way to integrate electronics into textiles in a deep clean way[5] (**+**). It is a novel way to integrate electronics into textiles in a deep clean way[6] (**+**). There are some dangers to think about, for example disposable phase (-)."

Question 4: *What types of application do you think woven e-textiles could have?*

Answer 4: "Interactive interior textiles; automotive industry; furniture, healthcare area (**+**)."

Question 5: *Any other thoughts?*

Answer 5: It would be good to discuss about disposable phase. As a large amount of electronics mixed with textiles involves some difficult problems in terms of scarce metals and temporarily in use of textiles (fast fashion), the user behaviour (-). I'd like to talk to you about your textiles within smart textile services. Have you thought about how they could be used? I'd love to use the examples in developing services (**+**) [*participants email address noted*].

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[5] Comment relates to two categories
[6] Comment relates to two categories

Participant number: 12.

Job Title: PhD researcher/ smart textiles teacher

Job Description: E-textiles blogger/ e-textiles curator

Date questionnaire completed: 20/07/2013

Question 1: *What do you think about the woven e-textiles samples shown? Do you think the overall designs are novel?*

Answer 1: "Yes **(+)**, light designs struggle with the problem of ugly direct light **(+)**. It's clever that the diffusion is part of the weaving process **(+)**."

Question 2: *What do you think about using a design led approach to develop woven e-textiles?*

Answer 2: "That should be the default **(+)**. The technology is not new nor is it the weaving technique. The newness is in the integration, essentially suggesting a product **(+)**. There's no justification for ugly products or badly functioning ones."

Question 3: *What do you think about an integrated woven process to make one piece e-textiles?*

Answer 3: "Elegant **(+)**"

Question 4: *What types of application do you think woven e-textiles could have?*

Answer 4: "Interiors, especially curtains and room dividers. Light objects. Tapestries **(+)**"

Question 5: *Any other thoughts?*

Answer 5: "Lovely, looking forward to future designs."

Participant number: 13.

Job Title: Research associate

Job Description: Principle investigator on a smart consumes project

Date questionnaire completed: 20/07/2013

Question 1: *What do you think about the woven e-textiles samples shown? Do you think the overall designs are novel?*

Answer 1: "They are beautiful, creative (**+**) and innovative (**+**). Yes they are novel and appear to be new and explorative (**+**). I love the neatness and pleating combining the electronics without feeling/ looking 'e-textily' (**+**)."

Question 2: *What do you think about using a design led approach to develop woven e-textiles?*

Answer 2: "I think it's the best way for your project. I agree with designing through making approach (**+**)."

Question 3: *What do you think about an integrated woven process to make one piece e-textiles?*

Answer 3: "I didn't think about it. But I am beginning to now. I work with thermochromics and fluro [*fluorescent*] dyes so a cloth that can change for me to print on would be ideal. I can design a warp/ weft to then print on. Ideal!! (**+**)"

Question 4: *What types of application do you think woven e-textiles could have?*

Answer 4: "See above (for me) (**+**)."

Question 5: *Any other thoughts?*

Answer 5: "Can I email you!? You have provoked thoughts."

Participant number: 14.

Job Title: Social and experience designer

Job Description: Work 3 days/ week at TiO3 www.TiO3.be and am responsible for the smart textiles at TiO3

Date questionnaire completed: 20/07/2013

Question 1: *What do you think about the woven e-textiles samples shown? Do you think the overall designs are novel?*

Answer 1: "I think it is important to know the woven techniques behind it (**+**). The grey [*black and white*] example looks more 'normal' at the first sight (**=**). The white, fine example looks very new because all the components are included (**+**) and there are no stitches. I was very surprised about this (**+**)."

Question 2: *What do you think about using a design led approach to develop woven e-textiles?*

Answer 2: "These examples show how 'simple' a woven LED e-textile can be. I have also [*thought*] there must be an overall design – concept or meaning to make woven pieces with LEDs (**=**). LEDs integrated must have a reason to be woven in otherwise it's 'again' and 'another' example with light (**=**)."

Question 3: *What do you think about an integrated woven process to make one piece e-textiles?*

Answer 3: "For me, it's a huge field to explore and the interior architecture needs more examples like these (**+**). You quit [leave out] some parts in the production, which means the production becomes less expensive (**+**)."

Question 4: *What types of application do you think woven e-textiles could have?*

Answer 4: "More interior focus like museums, hospitals, etc. (**+**). More applications hidden light (**+**)."

Question 5: *Any other thoughts?*

Answer 5: "Is it possible to include other electronics or parts than LEDs? I think link wind so the textile inflates, hidden sound (**+**). You made two beautiful samples (**+**)! Go with it!"

Appendix P – E-textiles questionnaire results and analysis

Participant #	Answer #	Novelty of design			Design and/ or aesthetics			Making process			Application			Industry/ manufacture			Totals			
		+	-	=	+	-	=	+	-	=	+	-	=	+	-	=	+	-	=	Comments
01	1	1			1			1									3			3
	2				1												1			1
	3												2						2	2
	4												2						2	2
	5				1			1									2			2
	Pts. total	1			3			2					4				6	0	4	10
02	1			2															1	1
	2	1						1									2			2
	3	1		1						1							1		2	3
	4				1								1				1		2	3
	5																			0
	Pts. total	2		3	1			1		1			1				4	0	5	9
03	1	1			1												2			2
	2																			0
	3							1						1			2			2
	4										1		1				1		1	2
	5																			0
	Pts. total	1			1			1			1		1	1			5	0	1	6
04	1	2			2			1			1						6			6
	2							2									2			2
	3							1						2			3			3
	4							1			1						2			2
	5							1							2	1	1	2	1	4
	Pts. total	2			2			6			2			2	2	1	14	2	1	17
05	1	1			1												2			2
	2				1												1			1
	3	1															1			1
	4										1		1				1		1	2
	5												1						1	1
	Pts. total	2			2						1		2				5	0	2	7
06	1	1															1			1
	2				2												2			2
	3	1			1			1									3			3
	4										1						1			1
	5																			0
	Pts. total	2			3			1			1						7	0	0	7

Where **+** is positive comments; **-** is negative comments; **=** is neutral comments

Appendix P – E-textiles questionnaire results and analysis

Participant #	Answer #	Novelty of design			Design and/ or aesthetics			Making process			Application			Industry/ manufacture			**Totals**			
		+	-	=	+	-	=	+	-	=	+	-	=	+	-	=	+	-	=	Comments
07	1	2															2			2
	2				1												1			1
	3						1												1	1
	4										1						1			1
	5																			0
	Pts. total	2			1		1				1						4	0	1	5
08	1	1						1									2			2
	2										1						1			1
	3													1			1			1
	4										1						1			1
	5																			0
	Pts. total	1						1			2			1			5	0	0	5
09	1				1					1							1		1	2
	2				1												1			1
	3							1									1			1
	4				1						1						2			2
	5				2												2			2
	Pts. total				5			1		1	1						7	0	1	8
10	1	1			3			1									5			5
	2				2												2			2
	3							1			1			1			3			3
	4										1		1				1		1	2
	5				1												1			1
	Pts. total	1			6			2			2		1	1			12	0	1	13
11	1				1			1									2			2
	2				1												1			1
	3	1			1										1		2	1		3
	4										1						1			1
	5										1				1		1	1		2
	Pts. total	1			3			1			2				2		7	2	0	9
12	1	1			1			1									3			3
	2				1			1									2			2
	3				1												1			1
	4										1						1			1
	5																			0
	Pts. total	1			3			2			1						7	0	0	7

Where **+** is positive comments; **-** is negative comments; **=** is neutral comments

Appendix P – E-textiles questionnaire results and analysis

Participant #	Answer #	Novelty of design			Design and/ or aesthetics			Making process			Application			Industry/ manufacture			**Totals**			
		+	**-**	**=**	**+**	**-**	**=**	**+**	**-**	**=**	**+**	**-**	**=**	**+**	**-**	**=**	**+**	**-**	**=**	Comments
13	1	2			2												4			4
	2				1												1			1
	3													1			1			1
	4													1			1			1
	5																			0
	Pts. total	2			3									2			7	0	0	7
14	1	1					1	2									3		1	4
	2						2												2	2
	3										1			1			2			2
	4										2						2			2
	5				1						1						2			2
	Pts. total	1			1		3	2			4			1			9	0	3	12
TOTALS		19	0	3	34	0	4	20	0	2	18	0	9	8	4	1	99	4	19	122
Average																	**7.07**	**0.29**	**1.36**	122/14 = **8.71**

Where **+** is positive comments; **-** is negative comments; **=** is neutral comments

Appendix Q – E-textile questionnaire coding and results summary

The transcribed questionnaires were colour coded using five different colours, each representing the five subjects. Answers were scanned to see if any answers crossed over into more than one subject, where answers were applicable to more than one subject criterion these were repeated and re-highlighted to represent both points. Question 5 referred to general comments; significant comments were analysed to fit into any of the selected subjects. Comments not highlighted were not classified to fit any of the relevant subjects and were left redundant. All coded comments were broken up to represent one point at a time. The answers were then classified within the subject according to the type of constructive answer this was regarding – this included three codes; positive comments (+); negative comments (-) and neutral comments (=). These three classifications were significant to extract as they determined the type of opinion the participant provided, i.e. supportive or not supportive of the work.

In total, there were 122 selected coded comments made by the 14 participants whom answered 5 questions each; therefore, a total of 70 answers were analysed. Table Apx-Q.1 shows a summary of results.

		Classified codes		
		Positive comments (+)	Negative comments (-)	Neutral comments (=)
Classified subjects	Novelty of design	19	0	3
	Design led and/ or aesthetic	34	0	4
	Making process	20	0	2
	Application	18	0	9
	Industry manufacture	8	4	1

Table Apx-Q.1 Summary of e-textiles questionnaire results

Although the questions were designed to provoke answers in relation to the subjects highlighted, the responses covered multiple subjects; therefore, were coded to reflect the five specific classified subjects. Each participant made an average of 8.71 comments. From the 122 coded comments, 99 were classed as positive, 4 were classed as negative and 19 were classed as neutral. Notably, all the negative comments were coded in the industry manufacture subject, where 4 comments were based around recyclability and sustainability. The neutral comments remained general passing observations and were not classed as positive or negative views, but were impartial remarks.

The results from the questionnaire were considerably insightful, and classifications of answers were distilled systematically with an unbiased view to structure a breakdown and establish core insights of the answers. The coding of the questionnaires was overviewed by a qualitative trained researcher in design research to validate the subject classification codes.

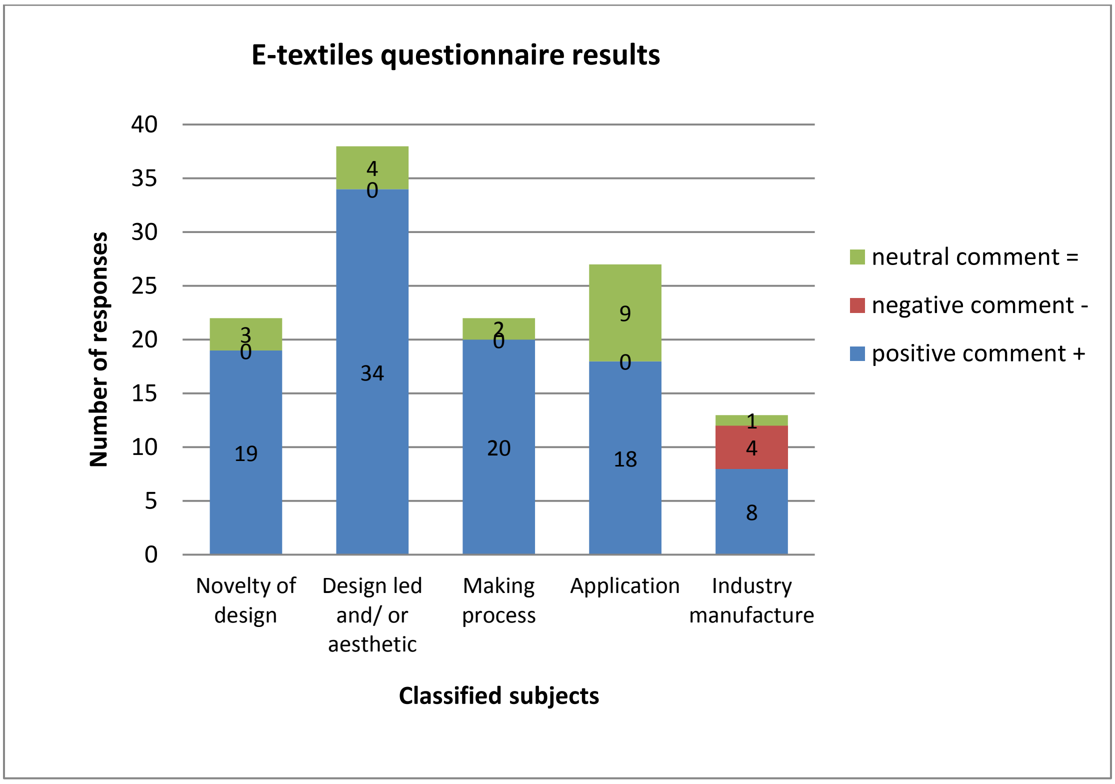

Figure Apx-Q.1 E-textile questionnaire results visualised in a bar-stack graph