An exploration to integrate pliable textile and rigid metal properties within hybrid self-supporting woven forms using selective finishing

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This thesis represents partial submission for the degree of Doctor of Philosophy at the Royal College of Art. I confirm that the work presented here is my own. Where information has been derived from other sources, I confirm that this has been indicated in the thesis.

During the period of registered study in which this thesis was prepared the author has not been registered for any other academic award or qualification. The material included in this thesis has not been submitted wholly or in part for any academic award or qualification other than that for which it is now submitted.

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Abstract

This practice-based research aims to integrate and control pliable anisotropic textile properties with rigid isotropic metal properties in self-supporting three-dimensional woven forms. When constructing self-supporting form using textiles, the drape and pliability can become compromised, for example, when placed under high tensile force, or a rigid finishing process is applied. This inquiry aims to improve the integration and control of the pliability and rigidity within metallised woven hybrid self-supporting forms.

The methodology uses woven textile design methods and thinking, combined with industrial textile production and engineering techniques, to form integrated cognitive problem-solving spaces during practice-based experimentation and reflection. The design and making of the woven textiles are inextricably linked with the finishing process. This extends Seitamaa-Hakkarainen and Hakkarainen's (2001) dual-space parallel processing to incorporate a third specific thinking space: finishing. This is described as a Design-make Tri-space that is used as a research framework when problem-solving during this material investigation. My research question explores my hypothesis that using an experienced weaver's parallel processing method could offer an alternative finishing technique to previous metallisation of textiles. This approach simultaneously considers the composition and construction of a woven textile with the finishing process. In my collaboration with industry a second research framework was used: Tri-space Roles. The roles of academic researcher, designer collaborating with industry and apprentice were integrated to become one interconnected role.

Three case studies demonstrate how using different making and finishing sequences control and refine the properties of the hybrid forms. Qualitative haptic interaction was used to evaluate the relationship between the pliable fabric and the rigidity created by the finishing process. This research contributes new knowledge to the metallisation of textiles by establishing a new making process that enables the control of selective finishing on anisotropic woven textiles. It also proposes that the Design-make Tri-space and the Tri-space Roles problem-solving approaches are frameworks that facilitate parallel processing. These method frameworks have the potential to be modified and used by other design researchers using alternative textile processes, such as knit or embroidery, or other materials focused disciplines, such ceramics or glass.

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List of supporting material submitted with the thesis prior to Viva:

A memory stick containing digital files:

1. Two films of my haptic interaction with the samples produced within this research.

    a. **Film 1: Qualitative sample evaluation.** Examples of the haptic interaction by Hannah White with the thesis case study samples to evaluate their pliability and rigidity.

    b. **Film 2: Haptic interaction by Hannah White with samples 3.2A and 3.3 after finishing.** The film demonstrates the different levels of pliability and rigidity that can be achieved using the same bespoke jig with different making sequences.

2. A digital copy of the following for the examiners' reference:

R1	**Reference List**
R2	**Bibliography**
R3	**Conferences/ Lectures**
R4	**Exhibitions**

List of Figures

All figures, photographs and diagrams in this thesis were created by myself unless otherwise stated and are dated between 2015 - 2018.

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Acknowledgements

This thesis is dedicated to my parents Jan and Dennis White, my grandmother Joyce Comber and my electrodeposition master/ mentor [redacted]. I would like to express my gratitude to The Royal College of Art, The London Doctoral Research Centre and the AHRC for their generous scholarship. Without this support I would not have been able to undertake this doctoral research and I am very grateful for the opportunities that it has provided. I would like to thank the following people who have supported me throughout and provided valuable feedback, advice and guidance:

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Chapter 1: Introduction

1.1 Context of the research

Interdisciplinary research involving a craft-design approach is prevalent in the twenty-first century (Felcey et al, 2013). Researchers Kane (2007), Goldsworthy (2012), Philpott (2011) and Paine (2016) used an interdisciplinary design and making approach during their doctoral research, led by textile craft processes. The overarching factor in their analysis is the acknowledgement that textile craft-design thinking can contribute valuable insights to other disciplines. 'Craft-Technologist' (Shorter, 2007), 'Craft-Design' (Paine, 2016), 'CraftTech' (Toomey et al, 2018), and 'Parallel Practice' (Crafts Council, 2014b) are examples of research that incorporate craft-design practice with other disciplines. Figure 1.1 (Warburton/ From Now On, 2016) demonstrates the positive impact that craft approaches can have on a wider economy and other sectors.

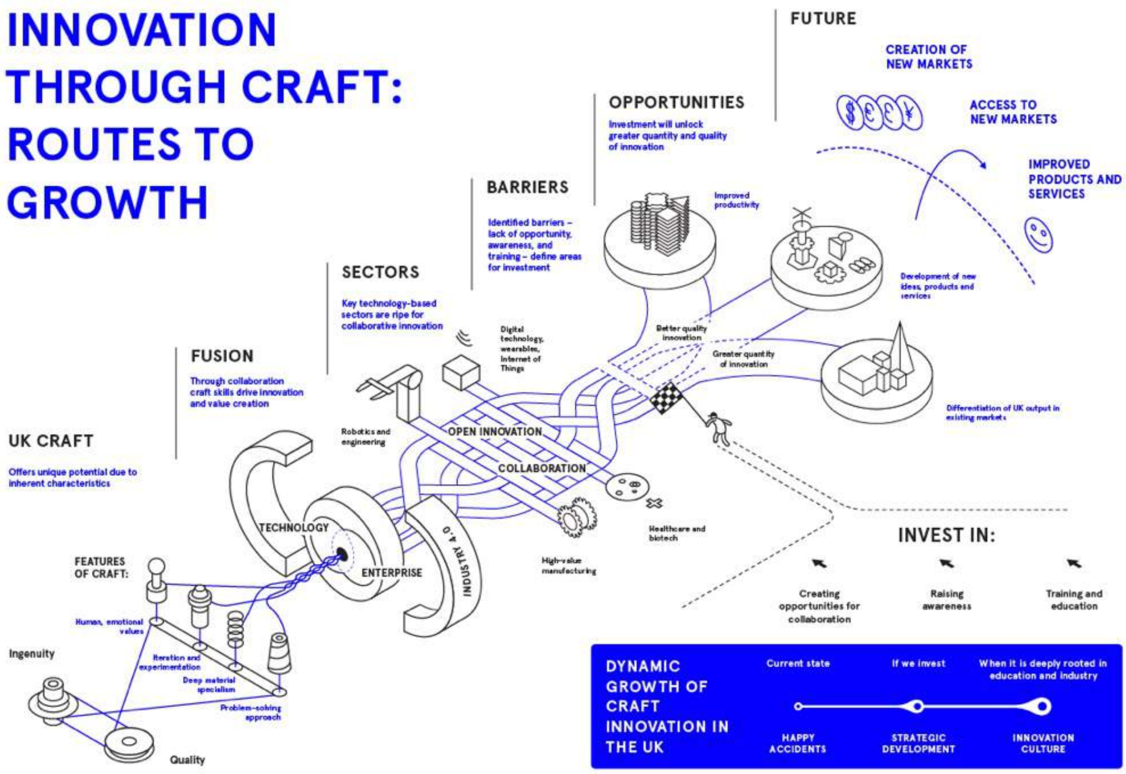


Figure 1.1: Annie Warburton, (infographic created by From Now On) illustrating how craft can facilitate innovation in UK industries, Available from: https://www.craftscouncil.org.uk/what-we-do/innovation-through-craft-opportunities-for-growth/

There are different nuances to design methodologies that relate to specific disciplines, such as architecture, graphic design, textiles and product design (Cross 2007; 2011; Philpott and Kane, 2017; Marchand, 2017). Interdisciplinary research is extensive in current fashion and textiles research (McQuaid, 2005; O' Mahony, 2011; Clarke and Harris, 2012; Warburton, 2016). Textile craft-design practitioners can contribute particular thinking approaches, methods and making skills to other disciplines such as science, engineering and medicine (Warburton, 2016; Morgan, 2017; Toomey et al., 2018). This research is textile design-led and relies upon practice-based research, using an understanding of craft skills and making approaches related to woven textiles. It has involved collaboration with a technical textile mill and an engineering electrodeposition metal manufacturer. This research combines making practices and explicit knowledge related to industry and my tacit craft-design-based woven textile knowledge (Schon,1991; Sennett, 2009, Collins, 2013; Ingold, 2013). This aimed to create a research process to enable the construction of innovative self-supporting textile forms drawing from both approaches.

1.2 The originality of the research

Designers have used a variety of engineering approaches, textile techniques and finishing processes to create self-supporting forms incorporating pliable textiles, as detailed in Chapter 2. There has been extensive contemporary research using textiles as component part of structures (Garcia, 2006; Ahlquist et al, 2013; Sabin, 2013; Lienhard et al, 2014; Ahlquist 2015; Menges and Knippers, 2015; Menges, 2015; 2016a; 2016b; Menges et al 2017). 'The Pliable Plane: Textiles in Architecture' written by Anni Albers' in 1957 (2001: 44-51) highlighted the advantages of the use of textiles when designing three-dimensional structures. Pliable textiles are easily formable, can create complex shapes and can adapt their form, when folded, draped or placed under tensile stress. Albers (2001) identifies that textiles have the ability to be lightweight, translucent, sound absorbing, insulating, transportable and adaptable. These aspects can be exploited to meet specific design requirements. However, soft pliable textiles, do not create stable self-supporting structural forms without introducing a rigid framework, tension, three-dimensional form or the application of a finishing process. When creating self-supporting forms using these methods, the textile characteristics of pliability, formability, adaptability and softness can become compromised. Textile designers such as Richards (2008; 2012) and Wood (2018) demonstrate that using weave structures combined with wet-finishing processes can produce three-dimensional form. However, their textile forms are predominantly pliable and do not offer the same three-dimensional structural stability as coated or tensile textile forms. This research demonstrates the concept of ‘designable materiality’ (Menges and Knippers, 2015:46). This means that the characteristics of the materials within my hybrid forms, combined with the means of production, directly affect the structure’s characteristics. In this research ‘hybrid forms’ are defined as:

- Comprising rigid and pliable areas within the same woven fabric.
- Composed of an integral crystalline copper framework and synthetic woven threads.

In the context of this thesis, finishing refers to a process that is applied to a material as means to alter its final characteristics. The aim is to weave a pliable metal framework within a textile that could be transformed into a self-supporting rigid skeleton, using electrodeposition as a finishing process. Three-dimensional metallised textile forms have been developed using sprayed, printed or dyed electrodeposited fabrics. However, it can be difficult to maintain precise control of the placement of the metal when using conductive solution as a surface application. Researchers to date have not exploited the potential of electrodeposition as part of a fabric’s integral woven structure. This inquiry adopts an alternative approach to those of the aforementioned researchers. It uses a novel application of electrodeposition on woven threads within textiles and it uses selective, rather than complete, finishing of my hybrid forms. The woven cloth is designed with the specific intention to selectively metallise conductive threads to influence the pliability or rigidity of hybrid metal and fabric forms. The design and making of the woven textiles are inextricably linked to the electrodeposition finishing process. The use of selective metallisation of conductive threads enables the structure of the woven cloth to influence the characteristics of the forms. A rigid framework is integrated into woven textiles. This enables the material properties of soft, pliable textiles and hard, rigid metal to be combined within the same integral form.

In this research the concept of ‘problem-solving’ relates to the cognitive processes used by a woven textile design researcher when exploring a design solution when integrating an electrodeposition finishing process during reflective practice. This research proposes the concept of a Design-make Tri-space framework, which combines three problem-solving spaces, the composition, construction and finishing of hybrid forms, into one unified thinking and making process. It uses a parallel processing approach which simultaneously considers problem-solving spaces when designing and making woven textiles (Seitamaa-Hakkarainen and Hakkarainen, 2001).

Research question: How can an experienced weaver's parallel processing be combined with selective electrodeposition finishing, to provide an alternative approach to the integration and control of pliable textile and rigid metal properties, in self-supporting hybrid forms?

1.3 Aims

1. To initiate and lead a cross-disciplinary textile design-led research project that uses integrated making knowledge from woven textile design, industrial textiles and electrodeposition engineering.
2. To position myself as the researcher, designer and apprentice within this research project, whilst engaging in first-hand experiential interaction of cross-disciplinary methods to gain new making knowledge.
3. To generate a new system of making to create an integral metal framework within woven textiles using electrodeposition, to combine and control pliable textile material properties and rigid metal material properties, in self-supporting forms.

1.4 Objectives

1. To describe how the parallel processing woven textile-design problem-solving is used within this research to generate transferable knowledge for other textile-design researchers.
2. To use personal engagement with an industrial weaving mill and a two-year apprenticeship with an electrodeposition specialist as a method to gain new technical making knowledge.
3. To produce practical samples as a means to document and reflect upon the iterative making processes developed in my case studies.

1.5 The scope of the research

The textile process used within this inquiry is limited to weave. Schön (1991) states that it is beneficial to use constants, which are routine problem-solving skills, when working in an unfamiliar discipline or situation. This enables the researcher to use their knowledge-in-practice, which includes routine problem-solving skills, as a basis on which to develop new knowledge (Schön,1991). In this research, using the constant of the knowledge gained from my twenty years' experience of woven techniques (see Appendix A1) enabled the focus of this research to be directed towards integrating the metallisation finishing with a textile approach to design. This included exploring how to alter the physical properties of the cloth when combining textile and metal processes.

To narrow the scope, the contextual review focuses on the use of finishing processes on woven textiles and how weave techniques can create form. This research does not concentrate on the functional use of the hybrid forms or issues such as sustainability. It is a material-led and method-led exploration to create a starting point for continued investigation. Due to practical constraints that I encountered when sampling (as detailed in Chapters 3 and 4), there are irregularities in both the textile outcomes and the making processes used. Therefore, the qualitative tests executed illustrate the indicative individual performance of particular prototypes created. Potential uses for the structures and their characteristics are discussed in Chapter 7: Future Research.

I have signed intellectual property non-disclosure agreements with the two manufacturers with whom I have been working on this research. Therefore, the specific details of the electrodeposition finishing that relate to my making processes are not provided in the thesis. Specific technical information relating to company names, collaborators full names, technical information such as the weave structures, threads used and the full process of the jig creation have been redacted to prevent disclosure of sensitive intellectual property information in the online version of this thesis.

1.6 Audience for the research

- Weave practitioners who wish to extend the parameters of their disciplinary boundaries through collaborative research.
- A wider range of craft-design practitioners. Adapted versions of the tri-space frameworks and decision flow-diagrams in this research have the potential to be applied to other textile specialisms and design disciplines. This could encourage practitioners to reflect upon their own methods and step out of their familiar 'knowing-in-practice' (Schön,1991:62) to facilitate innovation.

1.7 Overview of chapters

Chapter 2 provides a contextual background to the research. It focuses on relevant academic and practitioner research that use threads or woven textiles as a main component to create self-supporting forms using tension, frameworks of finishing processes. It provides examples of how the construction of woven fabric combined with finishing techniques can be used to create three-dimensional structures.

Chapter 3 details the conceptual framework and methods used. It defines my Design-make Tri-space and Tri-space Roles research frameworks and the methods used for evaluating the hybrid forms. The weave design, technical information and the electrodeposition process are explained in relation to the considerations that were required when adding a third problem-solving space to the weave dual-space.

Chapter 4 details the development and outcomes from three practical case studies. These provide insights into the stages of reflective practice, the iterative decision-making used and the paradigm shifts in this research to create my hybrid forms.

Chapter 5 discusses the outcomes of Chapter 4 and the effect experimental making and reflection has on integrating and controlling the samples' pliability and rigidity. The term 'Metal Integral Skeleton Textiles' is introduced to describe the practical outcomes. It explains how a researcher's relationship with the tri-spaces has the potential to evolve after multiple life-cycles of the tri-space frameworks. It proposes the tri-spaces have the potential to be used and adapted by other researchers to facilitate reflective practice during material-led problem-solving.

Chapter 6 concludes and summarises my research findings.

Chapter 7 considers future research and applications for the hybrid forms.

Chapter 2: Contextual Review

2.1 Establishing the gap in knowledge relating to woven self-supporting textiles and metal finishing on textiles

The research selected for this review is restricted to practitioners using threads or woven fabric to create three-dimensional self-supporting forms through the weave structure, tensile force or the application of a finishing process. These methods affect the pliability and rigidity of the textile or threads within the three-dimensional forms[1]. Due to the wide range of research in this area this review focuses on a selection of relevant examples that use woven textiles or threads as a main component within the self-supporting structure. These are divided into three main areas using:

- External structural frameworks to support pliable cloth.
- Finishing techniques such as resin, concrete, electrodeposition and physical vapour deposition to produce self-supporting textiles.
- Weave structure and finishing to create three-dimensional form.

2.2 Definition of structure in relation to the research question

Threads and textiles have been used to create self-supporting three-dimensional structures in a variety of ways:

- Pulled taut under tension.
- Supported by a framework.
- Applying a finishing process to change the surface quality or rigidity of the textiles. This includes pleating, folding, stitching, wet-finishing or applying a hard substance to the surface, such as resin or metal, to create form.

From a textile perspective, structure can be defined in terms of either interconnected threads (weave, knit, crochet, lace) or textiles that have been manipulated using finishing processes to create form (printing, folding, stitching). This research focuses on woven textiles. Weaving involves an understanding of structures, tension and the relationship between the properties of the materials to create a stable structure

[1] It is important to state that not all textile finishing processes alter the properties of textiles to create self-supporting form. Fire retardancy and waterproofing treatments or calendaring are examples of non-structural finishing techniques. Calendaring is a finishing process in which fabric is passed under high pressure between metal rollers to smooth the surface (Thompson, 2014).

(Albers,1965). Woven textiles are anisotropic, meaning they have different properties in different directions (Gordon, 2003). Metal is isotropic, meaning the properties of the material are the same in all directions (Gordon, 2003). Metal is used within engineering construction due to its structural stability, which enables the creation of self-supporting forms (Roland, 1972). Therefore textiles do not have the same structural stability due to their anisotropic properties. Woven fabric is stiff in tension when pulled on the square of the fabric, whereas it allows distortion in the bias axis because the Young's modulus[3] is low (Gordon 2003). The more open the sett of the weave (the more loosely it is woven), the larger the difference will be between the distortion when pulled on the bias and the square directions of the cloth (Albers, 1965; Hu, 2004; Gordon, 2003). When considering the use of woven textiles for three-dimensional forms, it is important to consider the distortion of the fabric when under tensile stress or attached to a framework.

There is a relationship between the orthogonal[4] grids in woven cloth and space frame structures used in architectural structures (Gordon, 2003). The linear threads that cross at right angles in weave structures such as plain weave and twill, as illustrated in Figure 2.1, resemble the linear elements of the cables or rigid struts that create space frame structures, as shown in Figure 2.2.

Images redacted.

Figure 2.1: (Left) Cambridge International Examination, diagram of weave structure notation (2015). [Online]. [Accessed 5th March 2016]. Available from: https://www.cambridgeinternational.org/

Figure 2.2: (Right) Frei Otto, *Pavilion for Federal Garden Exposition in Mannheim,* Germany, 1975. (Songel, 2010, p.44).

[3] Young's modulus describes the stiffness of a material and its ability to resist tension in a lengthwise direction (Gordon, 2003).

[4] Orthogonal: the structure of two-dimensional woven cloth can be described as the order and intersection of two groups of interlacing threads at right angles on a loom.

Threads within a woven structure are affected by force in a similar way to the cable networks used in tensile structures or rigid lattice frameworks. Gordon (2003) states that the forces are transferred through the lines in the structures. Woven fabrics that have longer floats, such as twills, drape more effectively than plain weave, as they have a lower Young's modulus. Weave structures are discussed further in Section 2.6.

2.3 Definitions of endoskeleton and exoskeleton

The term 'skeleton' has been adopted to describe a supporting framework or a basic structure for inanimate objects such as architectural buildings (Oxford Dictionaries, 2018c). Natural skeletons enable soft living forms to maintain form. An exoskeleton provides support and protection by means of a rigid shell on the outside of a living form. Endoskeletons are rigid internal bone structures that support animals or humans from within their bodies. The rigid bones are connected to the softer, flexible parts of the body by muscles that flex and stretch to allow for articulation and movement. In this research the supporting electrodeposited framework within the woven textiles is described as a 'metal skeleton' (see Chapter 5).

2.4 Textiles under tension to create form

Textiles are predominantly lightweight, flexible and formable, which are seen as advantageous characteristics when constructing lightweight structures (Roland, 1972). Gottfried Semper (2011) believed that woven textiles were the origin for all architectural enclosures or walls. From early civilisation, structures used for shelter were constructed from fabric or animal skins draped over rigid frameworks. These initial structures evolved and more complex tents were created by tensioning fabric over rigid poles and guy ropes to support the flexible fabric (Semper, 2011) (Figure 2.3).

Image redacted.

Figure 2.3: Traditional fabric tent using wooden poles and ropes to create a self-supporting structure. Photograph Seleznev Oleg, 2018. [Online]. [Accessed 7 June 2018], Available from: https://www.shutterstock.com/

Frei Otto's pioneering research, undertaken between 1954 and 2015 (Otto, 1967; 1969; Songel, 2010) created structures that used flexible cables and textiles under tension to generate structures rather than using a rigid framework. The shapes of these structures are not predetermined, but generated by the characteristics of the materials used to create it, combined with active forces. This is described as form-finding (Otto, 1969; Hassel, 2016). Otto explored form-finding using soap bubbles between 1960 and 1964 (Otto, 1967;1969) and wool threads in 1995 as a means to test architectural structural principles using small-scale prototype modelling (Spuybroek et al., 2004). Otto's influential research aimed to use 'completely flexible materials, possessing no stiffness of their own, to build undeformable structures which will retain their shape under a wide range of loading conditions' (Roland, 1972:V). Otto used the pliability of the materials to create and alter the shape of the structures, using tension to determine the form. This approach relates to the way weavers can create three-dimensional form using pliable threads under tension which is detailed further in section 2.6.

Image redacted.

Figure 2.4: Frei Otto, tensile roof over the dock at Bremen, Germany, 1960. (Roland, 1972, p.143).

The combination of pliable textiles and wire ropes cannot withstand loads without the application of tensile force when creating form (Roland, 1972). This can be achieved using suspended structures (hung under tension) (Otto, 1969), the use of pneumatic filled membranes (Otto, 1967; Fuller and Marks, 1973) or prestressed structures[5] (Roland, 1972) (Figure 2.4). The term 'prestressed' is also widely used to describe the use of cables or wires within a structure such as concrete to reinforce the structural integrity[6] of the rigid set form. Due to the stress forces applied to the

[5] Prestressed means the structure is made stronger by the use of tensile stress applied to structural supports such as cables or wires (Cambridge English Dictionary, 2018).
[6] 'Structural Integrity is the ability of the structure to retain its strength, function and shape within acceptable limits, without failure when subjected to the loads imposed throughout the structure's service life' (Al-Sherrawi, 2016).

textile in these structures it adopts a minimal surface (Roland, 1972). This means that the textile takes the shortest path between the cables, using the minimum amount of material to generate the form. It becomes smooth and rigid under tension, losing the characteristics of drape and pliability that textiles can offer (Roland, 1972).

It is an established fact that form follows force (Veenendaal and Block, 2012). This means that shape determines the mechanical behaviour of a form. Adding form to a flat material adds to its structural stability (Otto, 1969; Roland, 1972; Gordon, 2003). Using this principle, saddle shapes, arches and humped or pointed surfaces are used in tensile architecture to span large areas and create structures that have the ability to withstand large loads (Roland, 1972) (Figure 2.5).

Image redacted.

Figure 2.5: Frei Otto, drawings of tensile structures, 1966, (Otto, 1969, p 64).

Tent forms, tensile cable structures and textile-enclosed geodesic domes traditionally comprise two separate components, often metal and textiles. This construction method can create weak points at the joints within the structure, as the form is not made from one material (Roland, 1972).

Architect and engineer Robert Buckminster Fuller (1895-1983) used textiles as a means to enclose three-dimensional structures. His concept of Tensegrity (Fuller and Marks, 1973) combines the characteristics of tension and integrity. Tensegrity structures are composed of rigid rods under tension at the points where they meet, so that they push against each other when force is applied. This distribution of force through the structure creates rigid framework structures that are able to withstand significant load. The textiles used in Fuller's tensegrity geodesic structures did not contribute to the stability or formation of the framework structures (Figure 2.6).

Images redacted.

Figure 2.6 (Left): Robert Buckminster Fuller, an example of a geodesic dome with a textile enclosure used by the US military, c.1961. (Fuller and Marks, 1973, p.204).
Figure 2.7 (Right): Berger Brothers, pneumatic double-skin quilted geodesic dome inspired by Robert Buckminster Fuller's 1950s geodesic domes (Fuller and Marks, 1973, p.202).

Fuller's designs were developed further by Berger Brothers to create lightweight pneumatic double-skin quilted geodesic domes for the United States Air Force. The air pressure within the firm skin enabled the form to hold its shape under load (Figure 2.7). The textile therefore contributed to the form, unlike geodesic domes that did not use pressurised air, where the textile was non-structural.

Architect Chuck Hoberman (2018a) developed Fuller's ideas to create an Expanding Fabric Dome (1997) (Figure 2.8) that used a metal external framework to support a soft textile membrane. When the framework expanded the fabric was pulled taut and became rigid under tension. The structure utilises fabric's properties of pliability and softness that enable the dome to remain enclosed when it expands. Like Otto's and Fuller's forms, it is constructed of component parts and is not an integrated metal structure within the fabric itself. As identified by Roland (1972), the connections of the component parts are susceptible to weaknesses in the structures.

Image redacted.

Figure 2.8: Chuck Hoberman, *Expanding Fabric Dome*, Hoberman Associates, 2018. [Online]. [Accessed 17th March 2016]. Available from: htttp://www.hoberman.com/

2.5 Contemporary Research

2.5.1 A 'shift' in techniques

The first Crafts Council 'Make:Shift' conference in 2014 (Crafts Council, 2014a) discussed the use of new technologies in craft. Make:Shift refers to the *shift* from traditional craft processes to new ways of thinking in craft process, materials and design. Examples of this shift in the construction of structures can be seen in Figure 2.9 by Ammar Mirjan and Gramazio Kohler (Gramazio Kohler, 2018; Hobson, 2015) and Figure 2.10 by Maria Yablonia et al. (Menges et al., 2017).

Image redacted.

Figure 2.9: M. Ammar and G. Kohler, *Aerial Construction*, ETH Zurich Drones weaving large architectural structures with fibres. Film still by Gramazio Kohler Research, 2015, *Dezeen,* 4 March 2015. [Online]. [Accessed 26 March 2016]. Available from: https://www.dezeen.com/

Figure 2.10: Maria Yablonia et al., *Mobile Robotic Fabrication System for Filament Structures* created by a robot winding threads around metal supports on a wall, 2017, (Menges et al., 2017, p.203).

There are many contemporary examples in which textile construction techniques have influenced architectural form (Spuybroek, 2009; 2011; Brennan et al, 2013; Menges and Knippers, 2015; Menges, 2015; 2016a, 2016b;, Menges et al, 2017;). Lars Spuybroek (2009; 2011) has designed architectural structures inspired by macramé, crochet, weaving and knitting (Figure 2.11). He calls this approach

'Textile Computing' (Spuybroek, 2009:95). Spuybroek is inspired by Semper's (2011) concepts regarding the woven wall as the main element for architectural enclosures and Otto's (1967;1969; Spuybroek et al., 2004) use of architectural textiles within an engineering context.

Image redacted.

Figure 2.11: Lars Spuybroek and NOX Architects, *Seoul Opera House*, South Korea, 2005, (Ludovica Tramontin, 2006, p.58).

The fact that constructed textiles produce one continuous form, are flexible, can be transformed from soft to hard and can create irregular curvatures are key inspirations for his architectural designs. Spuybroek describes his concept relating to the use of soft and hard inspired by textiles as Soft Constructivism (Ludovica Tramontin, 2006). Spuybroek's architecture is rigid and self-supporting. He makes it clear that Soft Constructivism does not relate to hard materials imitating the fluidity and softness of textiles. He states that it is 'softness and flexibility building structure' (Ludovica Tramontin, 2006: 53). He refers to Otto's wool thread models, seen in Figure 2.12, as an example in which the flexibility of the threads is used to create the form (Ludovica Tramontin, 2006). The final outcome is a result of the combination of the making process and the material properties used while it is formed.

Image redacted.

Figure 2.12: Frei Otto and Bodo Rasch, *Finding Form* wool thread experiments, 1995, (Spuybroek et al., 2004, p.352).

2.5.2 Finishing processes applied to thread or woven textiles to create self-supporting form

Coating the entire flexible textile in a hardening substance is an alternative approach to enable soft textile structures to become self-supporting. In these circumstances, the entire textile becomes rigid, eliminating the opportunity for the soft textile characteristics to remain pliable within the structures once they have been finished. These rigid forms often have the visual appearance of a draped textile form, but have the tactile and structural properties of the finishing material applied. Coatings used in finishing processes to support textiles to produce rigid forms include:

- Printing with hard substances
- Concrete
- Resin
- Electrodeposition

Applying textile finishing processes to textiles such as print, stitching, pleating and weaving can create self-supporting structures. Rachel Philpott's (2011) doctoral research demonstrates opportunities that printed and folded techniques can create to generate self-supporting adaptable textile forms (Figure 2.13).

Figure 2.13: Rachel Philpott, folded and printed adaptable textile forms, 2011, (Philpott, 2011, p.54 & p.93).

2.5.3 Concrete: Fabric Formwork

Prestressed concrete uses a rigid framework to reinforce the brittle characteristics of pure concrete, which are referred to as Formworks (Veenendaal et al., 2011). Unset concrete has fluid properties that can be used to create a wide variety of shapes (Brennan et al., 2013). Contemporary researchers and engineers have adapted the process of reinforcing concrete to achieve more organic shapes using Fabric

Formwork (Veenendaal et al, 2011; Milne et al, 2015). This is a construction technique that uses flexible fabric moulds as an alternative to rigid formworks. Anne-Mette Manelius' doctoral research (2012) extensively explores the use of Fabric Formwork. Manelius' *Ambiguous S-shaped Chair* (2012) used fabric as the mould in which to pour the concrete, supported by a wooden and metal framework. The form expresses the fluidity and softness of the textile that is rendered solid and rigid in set concrete (Figure 2.14).

Figure 2.14: Anne-Mette Manelius, *Ambiguous S-shaped Chair*, 2012, (Manelius, 2012, p.182 & p.186).

Tailoring Fabric Formwork, research by Milne et al. (2015), used fashion and textile making techniques to construct the entire mould of the fabric formwork. Unlike Manelius' work (2012), their methodology does not use the rigid exoskeletons that are often used to support Fabric Formwork (Milne et al., 2015). Pliable woven fabric was used to create form rather than relying upon external materials. Tailoring darts were used to alter the shape of the Fabric Formworks. The aim was to adopt a new approach using a fashion-led method to control the creation of the form with no supporting framework. When the liquid concrete was poured within the mould, the fabric was able to move and change shape in response to the hydrostatic forces[7] of the concrete. The tension forces acting on the malleable formwork and the fluid concrete within the formwork create the form. 'The constraint is not applied subsequently to the formwork; it is inherent within the textile itself. It is completely integrated into the fabric' (Milne et al.,2015: 4). Figure 2.15 shows patterns used for their fabric columns and three final Fabric Formworks. This research relates to using a textile construction method which incorporates woven cloth and finishing to directly influence the form of the structures.

[7] Hydrostatic: relating to or denoting the equilibrium of liquids and the pressure exerted by liquid at rest (Oxford Dictionaries, 2018b).

Image redacted.

Figure 2.15: Milne et al, tailored Fabric Formworks, 2015, (Milne et al, 2015, p.7, p.8, p.10, & p. 9).

Research by Brennan et al. (2013) also focuses upon a constructed textile approach to Fabric Formwork which was part of a cross-disciplinary funded project between Bath, Belfast and Edinburgh universities. Brennan et al.'s (2013) research proposes that weaving specific textile Fabric Formwork can offer a more refined textile construction method. More complex woven structures offer the possibility for more complex Fabric Formworks. Designing the weave in relation to the final form and finishing process offers increased control over the appearance and properties of the final forms. Structural performance and surface finish can be improved by engineering woven fabrics specifically for Fabric Formwork, rather than using premade fabric (Brennan et al. 2013). Brennan et al. (2013) cite research by Soden and Stewart (2009), Stewart (2010), and Soden et al. (2012).

Soden et al.'s (2012) research explores the use of single-layer, double-cloth and multi-layer weaving to refine the properties and form of the woven textile composites. The sett of the cloth, the choice of fibre and weave structure affects the stiffness of the forms. The inherent structural strength of engineered woven composite forms, combined with their pliability, means the woven Formwork produces the mould as well as providing the reinforcement for the structures. The woven fabric creates and helps to stabilise the final forms (Figure 2.16).

Image redacted.

Figure 2.16: (Left, Middle) Soden et al., double-layered woven fabrics for Fabric Formwork, 2012, (Right) Soden and Stewart, three-dimensional woven X-profile preform, 2009, (Brennan, 2013, p. 232, p.233, 234).

2.5.4 Resin: Threads coated in resin to create self-supporting textile forms

Menges (2015; 2016a; 2016b) and the researchers at the Institute for Computational Design and Construction (ICD) and the Institute of Building Structures and Structural Design (ITKE) have pioneered the use of robotic fabrication combined with material properties to generate innovative structures. Menges cites Otto (1969) and Albers (1965) as inspiration for their research (Menges, 2015, 2016a; 2016b). Menges (ICD) and Knippers et al (ITKE) (2015) have carried out several research projects since 2012, focusing on the use of fibre systems and finishing processes to create self-supporting form.

Menges found that working with premade cloth when creating structures was frustrating, as it limited the potential to customise the form. He stated at the V&A 'Biomimicry and Design' symposium in 2016 that not having a textile background prevented him from engineering a woven base cloth to meet his structural requirements (Menges, 2016b). Creating single-filament textile structures does not require the same depth of textile knowledge that is required to design multi-filament textiles (Albers, 1965) therefore single filaments were a natural choice for Menges's construction method.

In 2012, Menges and Knippers (2015) used single-filament threads wound precisely in position by a robot around a structural framework (Figures 2.17 and 2.18). Resin is applied as the threads are wound around a former. The form becomes self-supporting when the resin cures. The framework is subsequently removed. Engineering fibre composites mainly rely on moulds to create form (Menges, 2015: 44). Menges's robotic construction process reduces the number of conventional moulds that are often used when engineering composite fibre structures, as the fibres can be placed precisely within the structure. The combination of this construction method using fibres and the application of cured resin as a finishing process creates self-supporting forms. The threads used are completely coated in resin, and therefore this is not an example of selective finishing.

Images redacted.

Figure 2.17: ICD/ITKE, Research Pavilion constructed by robots, 2012. Photograph by Roland Halbe, (Menges, 2015, p.45).

Figure 2.18: ICD/ITKE, Research Pavilion completed, 2012. Photograph by Roland Halbe. [Online]. [Accessed 26.7.16]. Available from: http://icd.uni-stuttgart.de/

The ICD/ITKE research team (Knippers et al., 2015a) were inspired by the composite material of a lobster's body which is reinforced in specific places depending on the structural need in relation to each part of the creature. This is achieved by different thicknesses of the composite material across the form. Specific areas of ICD/ITKE's 2012 structure are reinforced through a combination of the properties of the fibre and the finishing process used. The glass fibres create the formwork and stiffer carbon fibres provide load transfer once the resin is applied to set the form. Layers of the fibres are laminated together in selective areas during the construction. This approach enables the distinction between material and structure to be blurred, as it allows different material properties to be engineered at distinctive points within one structure (Menges, 2015). The material characteristics are the main influence upon the design of the form. By utilising their flexible and ‘morphic character’ (Menges 2016a:13), fibres become active participants (Menges 2016a:13-14) in the design process. The structure uses the anisotropic properties of different layers of fibres, combined with specific placement and finishing, to create an isotropic structure. ICD/ITKE have developed further filament-wound structures as shown in Figures 2.19, 2.20, and 2.21.

Image redacted.

Figure 2.19: ICD/ITKE, Research Pavilion 2013-14, (Menges, 2016a, p.14).

Image redacted.

Figure 2.20: ICD/ITKE’ Research Pavilion 2014-15. [Online]. [Accessed 26.7.16]. Available from: http://achimmenges.net/

Figure 2.21: ICD/ITKE *Elytra Filament Pavilion* at The V & A Museum. Photograph taken by myself, 2016.

In 2007 woven textile designer Samira Boon collaborated with the TU Delft Aerospace faculty, Droog Design and Next Architects to create the *Spacer Chair* (Boon, 2018a). The design uses elements from carpet weaving, in which two layers are woven with binding points. The pliable fabric is then folded over a mould and hardened using resin to provide compressive strength (Figures 2.22 and 2.23). The resin finish enables the weave to be self-supporting, without the need for an external frame. Boon's large-scale waffle-weave structure also uses resin finishing to create a rigid screen (Figure 2.24).

Figure 2.22: Samira Boon, *Spacer Chair* in production. The woven fabric is impregnated with resin over a mould, and when dry sets to form a self-supporting structure, 2007. [Online]. [Accessed 7.4.16]. Available from: http://samiraboon.com/

Figure 2.23: Samira Boon, *Spacer Chair*, 2007. [Online]. [Accessed 7.4.16]. Available from: http://samiraboon.com/

Figure 2.24: Samira Boon, woven *Waffle Screen*, 2007. [Online]. [Accessed 7.4.16]. Available from: http://samiraboon.com/

2.5.5 Metallisation finishing processes applied to textiles

This section details previous research using electrodeposition and metallisation of textiles. Doctoral research by Frances Geesin (1995), Tine De Ruysser (2009), Sara Keith (2010) and Joanne Horton (2017) has explored the use of textiles combined with the properties of electrodeposited metal. However, Geesin (1995) and Horton (2017) used metal as a surface embellishment rather than as an integral part of a woven fabric. Keith's doctoral research (2010) used conductive threads within woven fabric and conductive dye with electrodeposition finishing. De Ruysser (2009) used electrodeposition to create three-dimensional structures, but this was achieved by applying conductive mediums to the surface of the textile rather than by using integral conductive threads. Kinor Jiang (2009; 2018), Junichi Arai (Jiang et al., 2017) and Reiko Sudo (McCarty and McQuaid, 1998) have created new ways of using metal finishing processes usually used for industrial manufacturing and engineering. However there has not been specific research to explore how woven conductive threads within cloth can be selectively placed within the textile, with the intended purpose of creating a self-supporting structural integral framework.

2.5.5.1 Electrodeposition created by spray gun or paint

Spraying, printing or dyeing a conductive solution onto a surface on which the metal can be deposited is a method used in electrodeposition. Frances Geesin's doctoral research (1995) explored the use of electrodeposition upon different types of textiles to stiffen the entire fabric, to enable it to maintain its form when finished with metal. After her doctoral research Geesin collaborated with scientists and medical researchers, using the metallisation process to create narratives and artworks (Geesin, 2018). Geesin (1995) uses electrodeposition as an artistic medium (Figure 2.25).

Figure 2.25: Frances Geesin, *Fractured Rolls* (left) and *Silver Lattice Roll* (right), electrodeposition on textiles, 2008. [Online], http://www.francesgeesin.com/

Antony Gormley, in partnership with Aquascutum, created an electroformed suit for the *Singular Suit* exhibition in 2009 (Nikkhah, 2009) (Figure 2.26). To create a rigid form, the fabric was impregnated with molten wax, hung on an armature and blotted to remove the excess wax. The form was shaped around balloons to create the impression that a human body occupied the suit. When the wax cooled, the textile became hard; it was sprayed with conductive solution and placed in the electrodeposition tank.

Image redacted.

Figure 2.26: Antony Gormley, electroformed self-supporting suit manufactured by [redacted]. Photograph by Clara Molden, 2009. [Online]. [Accessed 11.5.18]. Available from: https://www.telegraph.co.uk/

Joanne Horton's research (2017) used electrodeposition inspired by embroidery. Horton has created a new process which she describes as digital drawing with conductive ink using electrodeposition as an embellishment rather than thread (Figure 2.27). The focus of the research was to use the lines produced by the process to create a conductive circuit and to explore and control the visual aspects of the application of the metal. The metallisation altered the rigidity of the textiles but Horton's (2017) use of electrodeposition was to embellish fashion garments, not to create structural self-supporting forms.

Figure 2.27: Joanne Horton, electroformed fashion detailing. Photograph taken by myself at The Fashion and Textile Museum, 2016.

2.3.5.2 Electrodeposition created by print

Tine de Ruysser's research (2009) used printed electrodeposition to create form and explores soft and hard characteristics using electroforming to harden printed areas of the fabric. The work does not explore the use of woven metal threads, and she did not engineer a structure in which the metal is integral to the base fabric or weave. De Ruysser's focus was to incorporate articulation within the forms for use on the body (Figure 2.28). De Ruysser did not specifically explore the refinement of the thickness of the metal deposit to control and vary the thickness in the same form (De Ruysser, 2009). Her 'Metallised Folding Textiles' (De Ruysser, 2009) rely upon the pliable anisotropic properties of fabric combined with the rigid properties of metal to create articulated forms that adopt a variety of different shapes. This relates to Boon's use of weave structures to create flexible points within a more rigid structure, which is detailed in Section 2.7.2. The softer areas in the structures allow the forms to move.

Figure 2.28: Tine De Ruysser, "*Wearable Metal Origami" Shoulder Cape*, 2009, (De Ruysser, 2009, p.154).

The metal in De Ruysser's textiles forms predominantly on the surface of the cloth where the conductive solution has been applied (Figure 2.29). Therefore, the metal deposits on the textiles from the 'outside in'. De Ruysser's research illustrates that the process of using conductive print, spray or paint to metallise specific areas can cause inconsistences in the application of the conductive solution. The small dots on the metal areas in Figure 2.30 demonstrates where De Ruysser has touched up the spray-painted pattern as required with the conductive solution (De Ruysser, 2009).

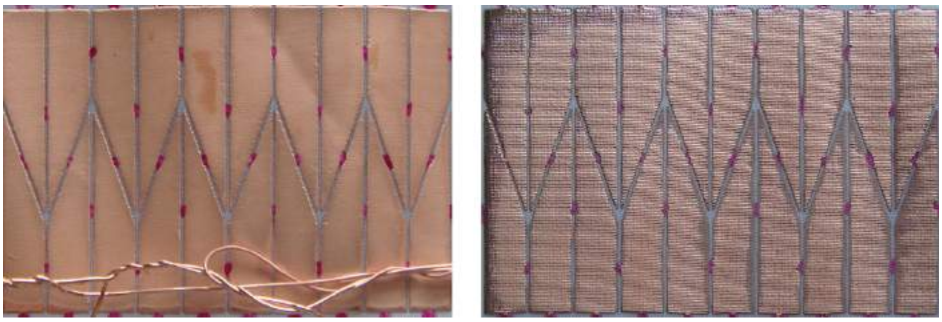


Figure 2.29: Tine De Ruysser, samples screen-printed with Electrodag, front (left) and back (right) 2009, (De Ruysser, 2009, p.117).

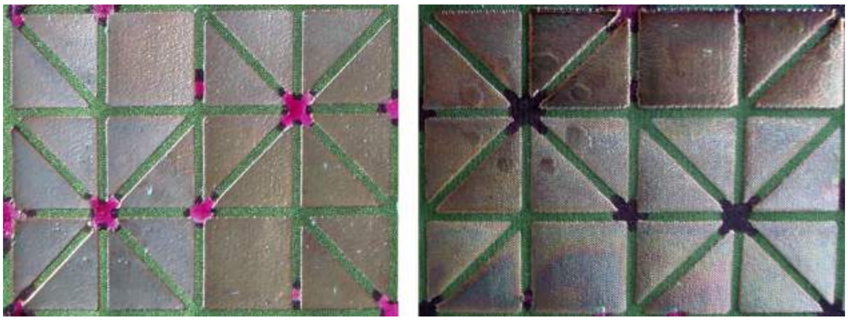


Figure 2.30: Tine De Ruysser, electroformed spray-painted Electrodag, front (left) and back (right), 2009 (De Ruysser, 2009, p.119). The right figure shows irregular dots in the top left of the image that have been touched out with conductive solution using a paint brush.

2.5.5.3 Electrodeposition created by dye

Sara Keith's research (2010) used Shibori[8] resist techniques to gather fabrics and mask areas prior to metallisation. Keith aimed to develop work that integrated the characteristics of metal and textiles, using metal as dye. The initial research used electroplating of semi-conductive woven fabric composed of a silk warp with alloy weft. The metal only deposited onto the conductive threads, and enabled the cloth to maintain a level of drape. Keith explains that the function and appearance of the fabric could potentially be adapted by altering the ratio of metal to natural or man-made fibres (Keith, 2008). The second part of the research explored electroforming the semi-conductive woven cloth to create heavier metal deposits. The conductive silver dye penetrated the fabric areas that were not compressed tightly by the bound threads. Keith explains that the thickness of metal deposit can be altered to affect the pliability of the cloth (Keith, 2008). The differences between the soft textile areas of the pieces create a variety of aesthetic and physical outcomes. (Figure 2.31).

Figure 2.31: Sara Keith, fully and partially electroformed silk organza bundles, 2008, (Keith, 2008, p.6).

[8] Shibori is a textile technique where the fabric is tightly bound, dyed and then unfolded to create patterns.

Keith (2008) refers to the peaks in the textiles growing more metal than the troughs in her work. This is due to the variation of high and low current density within the forms. This is explained in Section 3.9 of Chapter 3. The dye seeped through the cloth onto the other side of her samples, and this was valued as part of her making process. Therefore, this textile process was not concerned with the precise placement of the conductive dye on the fabric. The conductive dye penetrated the fabric and was applied in a more random way than the process using a woven conductive thread. Although Keith used conductive thread within her samples, the focus was not to create a precise integral framework to produce self-supporting forms.

2.5.5.4 E-textiles electroplating

KOBAKANT (2009) have used woven flexible conductive fibres to create pressure sensors and conductive textiles. They experimented with electroplating various textiles, which they documented in an online database, ‘How To Get what You Want’ (KOBAKANT, 2009). Figure 2.32 shows woven fabrics that have been plated onto areas of semi-conductive threads. The plating is thin and is not used as a structural element in the cloth. Figure 2.33 shows fabrics knitted in conductive thread where the entire textiles have become rigid. KOBAKANT’s experimental research was motivated by use in e-textile applications. It was not intended to be structural.

Figure 2.32: KOBAKANT, Soft & Safe conductive thread before and after plating, 2009. [Online]. [Accessed 15.12.17]. Available from: https://www.kobakant.at/

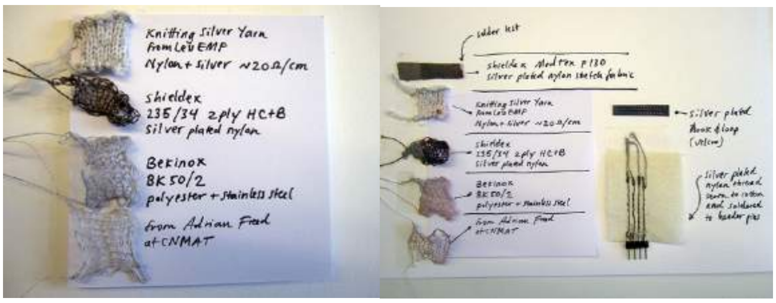


Figure 2.33: KOBAKANT, electrodeposition knitted conductive thread experiments, 2009. [Online]. [Accessed 15.12.17]. Available from: https://www.kobakant.at/

2.5.5.5 Physical Vapour Deposition

The application of metal to non-conductive surfaces can also be achieved by physical vapour deposition (PVD). Sputtering and electron beam evaporation are two types of PVD that deposit airborne atoms or molecules onto a surface within a vacuum chamber (Boone, 1986). This process is used extensively in the electronics industry to form thin conductive layers onto materials to create electronic circuits, including textiles (Pawlak et al., 2016; 2017). The process is used on textiles when conductivity and flexibility are required. Kinor Jiang's (Jiang, 2009) research uses chemical etching, chemical plating and sputtering techniques to apply metal to fabric. The thin metal deposit achieved by these processes makes the fabric pliable after finishing. Jiang's metal processes are used predominantly for decorative embellishment on fashion garments or for pliable textiles lengths of cloth (Figures 2.34 and 2.35). His research does not explore the use of a metal conductive integral framework within specifically engineered woven cloth to create self-supporting forms.

Image redacted.

Figure 2.34: Kinor Jiang, chemical etching metal finishing on fabric, 2009. [Online]. [Accessed 26.2.18]. Available from: http://kinorj.strikingly.com

Image redacted.

Figure 2.35: Kinor Jiang, chemical plating metal finishing on fabric for fashion, 2009. [Online]. [Accessed 26.2.18]. Available from: http://kinorj.strikingly.com

The late Junichi Arai and Reiko Sudo formed the Nuno Corporation in 1984 in Japan (McCarty and McQuaid, 1998). Their experimental approaches to weaving and dyeing combine traditional Japanese textile techniques with technological processes. Junichi Arai's woven fabrics use thread made from slit aluminium foil layered between clear films (Figure 2.36). His collaboration with Masami Kikuchi and Tatsu Hirayama, from the metal company Bridgestone Metalpha Corporation, resulted in the creation of Alphatex. This is a fibre that is composed of a 5.5mm diameter wire rod 'comprised of 1,700 iron-clad stainless steel filaments… gradually drawn or stretched over many stages' (McCarty and McQuaid, 1998). It was used by fashion designer Yokiski Hishinuma, who used spot-welding as a finishing process on the fabric instead of sewing it to form garments (McCarty and McQuaid, 1998). Reiko Sudo has explored the use of metal finishing processes within her fabrics. She uses calendar-pressed polyester with splatter plating to create fluid, pliable reflective metallic cloth that has drape (Figure 2.37).

Image redacted.

Figure 2.36: Junichi Arai, Melt-off fabric with warp nylon metallic slit yarn, 1990. Photograph by Masanao Arai, (Jiang, 2009, p.136).

Image redacted.

Figure 2.37: Reiko Sudo, Stainless steel gloss fabric, 1990. Photograph by Karin Willis, (McCarty and McQuaid, 1998, p.55).

2.6 A weaver's approach to creating forms using weave structure and finishing processes

2.6.1 Engineering woven structure to create 3D form

Layered or stitching warps or wefts can be used to create three-dimensional forms integral to the structure of the woven fabric. Using different intersections between the layers can create interlinked pockets or more complicated forms. Integral structures within woven textiles offer the advantages of producing net-shaped structures.[9] This can reduce the need for machining or joining in the manufacturing process. This potentially reduces material waste and the possibility of weak structural points in stitched or layered components. These methods of construction can be enhanced when combined with different tensions or finishing techniques. For example, pockets can be created in weaving using double-cloths to create a circular woven fabric. Paul R. O'Connor's (2006) and Esther Van Scuylenbergh's (2018) work demonstrates that complex forms can be created by engineering the woven structure (Figures 2.38 and 2.39).

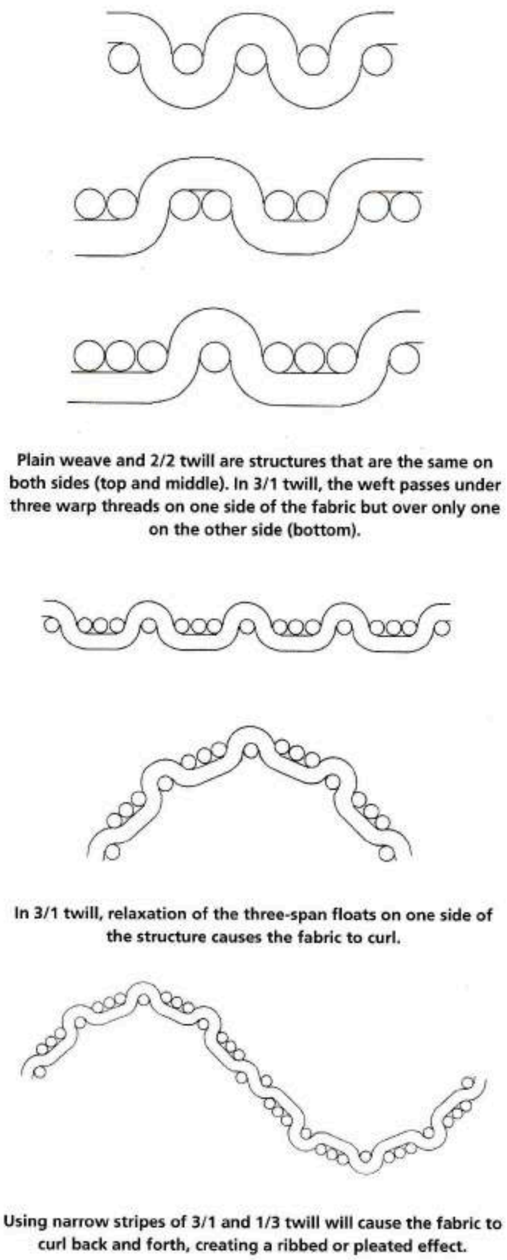
Image redacted. Image redacted.

Figure 2.38 (Left) Paul R. O'Connor, woven three-dimensional forms,1980, (O'Connor, 2006, p.31).
Figure 2.39: (Right) Esther Van Scuylenbergh, multiple layer woven cloth, 2014. [Online]. [Accessed 16.2.18]. Available from: https://www.esthervanschuylenbergh.be

9 A net-shaped form is a structure made from one single piece of material that is not cut or joined to create the form.

2.6.2 The influence different woven structures have upon material properties

Nasa's 1997 *Handbook of Analytical Methods for Textile Composites* (Cox and Flanagan, 1997) highlights the relevance of engineering the fabric as part of the overall form for lightweight aircraft wings. It explains that as the dimensions of engineering structures have become so small that there is no longer a distinct difference between engineering the structure and the fabrics used within the structure, stating: 'to fabricate the textile composite is to fabricate the structure' (Cox and Flanagan, 1997: 2-1).



Different weave structures have an impact upon the stability and drape of the fabric over complex shapes (Cox and Flanagan, 1997; Richards, 2012). These characteristics can be used to refine the properties of woven materials in relation to their intended use.

The threads in plain weave interlace every other thread, which creates frequent bends in the thread. Plain weave fabric has a more stable, stiffer construction than structures that have longer floats, when all other factors are the same (Albers, 1965; Richards, 2012).

Figure 2.40 demonstrates the path of the thread and the impact it has upon the drape of the cloth. The threads in twill structures intersect less frequently. The length of the float depends upon the type of twill.

Figure 2.40: Ann Richards, diagram of the path of a thread in plain, 2/2 twill and 3/1 twill structures, (Richards, 2012, p.74).

Despite plain weave's stability as a woven structure, it is seen as a disadvantage when used in laminated composites, as the frequent thread intersections reduce the strength and rigidity of the composite (Cox and Flanagan, 1997). In contrast, satin weave has fewer intersections, as the threads float over a minimum of five shafts and the stitching points do not line up in a diagonal pattern. The face and back of the fabric are asymmetric. Therefore, using weave structures that have reduced intersections produces longer floats and straighter sections of thread on the fabric surfaces. This increases the strength of the laminated composite: as the resin sets the longer thread floats with fewer breaks in the surface of the weave. The satin or twill structure fabric coated resin laminate composite is more rigid than the plain weave. Therefore the parameters that influence the structural stability of the resin-coated textiles are different from non-resin-coated fabric. The conventional characteristics of plain weave, that produces stiffer textiles than twill or satin, is reversed for laminated composites. Figure 2.41 shows the thread intersections and lifting plan for relevant weave structures.

Plain weave.

2/2 twill.

Image redacted.

Warp faced satin.

Weft faced sateen.

Figure 2.41: M.K. Bansal's weave notation of different thread lengths and thread intersections for plain weave, 2/2 twill and satin weave structures, 2015. [Online]. [Accessed 4.5.18]. Available from: https://www.slideshare.net/

2.7 Woven structures combined with finishing processes to create form

Thread tension within woven cloth also plays a role in the characteristics of the fabric. Figure 2.42 shows woven structures using a variety of tensions using different thickness threads.

A: Balanced tension with alternate thin and thick weft threads.

B: Tight tension on the thin thread and a slacker tension on the thick thread.

C: Two evenly tensioned thick threads.

Image redacted.

Figure 2.42: Z Grosicki, diagram of different warp and weft tensions through a cross section of a 1/3 twill fabric, 1912 (Grosicki, 1977. P37).

2.7.1 The effect that combining finishing techniques with weave structures has upon material properties

Warping or buckling of fabric is regarded in Nasa's report (Cox and Flanagan, 1997) as a negative characteristic when creating laminated composite structures for aircraft wings. However, it can be utilised as a positive characteristic within textured three-dimensional textiles. The relationship that physical forces and energy have in relation to finishing woven textiles is apparent when observing the movement of threads and fibres during textile finishing processes (Richards, 2008; 2012). The float lengths in weave structures, combined with irregular shrinking rates of active and passive threads (Richards, 2012), have the ability to create innovative surfaces.

- **Active threads:** Threads that alter when a finishing process is applied or when the fabric is released from the loom. Examples are natural active threads such as wool or silk that shrink and move position within the fabric when moisture or heat is applied.
- **Passive threads**: Threads that remain unchanged or stable when a finishing process is applied.

Active and passive threads are demonstrated by Richards' (2012), Brock's (2018) and Wood's (2018) three-dimensional woven textiles. Their work explores finishing techniques in relation to a combination of yarn choice, directional twist of the thread, sett, woven structures and floating threads. Richards' (2012) weaving explores woven structures, choice of thread and finishing techniques. She explains that there are different degrees of active and passive threads, and each yarn will have its own character. Richards' use of high-twist yarns that release energy through the textile finishing process are integral to the formation of her woven textiles' three-dimensional structure. Richards responds to the material properties of threads, allowing them to influence her textiles (Richards, 2012) (Figure 2.43 and 2.44).

Figure 2.43: Ann Richards, Tussah silk warp and mohair weft, hand-woven, unfinished sample (left). The same fabric creates pleats when the active threads shrink after finishing (right). Photograph taken by myself at the Crafts Study Centre, Surrey, 2018.

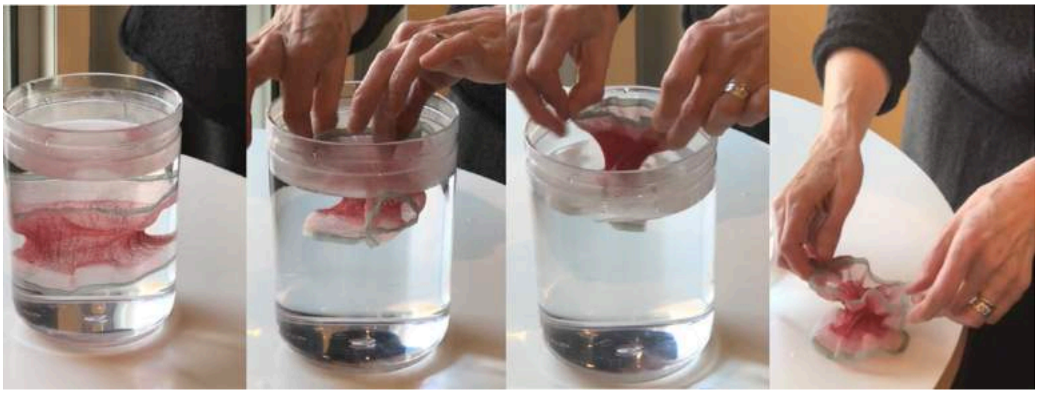


Figure 2.44: Ann Richards demonstrating haptic interaction during wet-finishing handwoven fabric. Photograph taken by myself at the 'Textiles Taking Shape' exhibition and talks, Winchester Discovery Centre, 2018.

Richards' Spiral fabric is a hybrid mix of textile and metal. Metal threads can be used as passive threads in weaving, as their comparable stiffness can prevent them from moving or altering within the cloth. This can be combined with active threads such as silk to create textured fabric when the silk shrinks after finishing (Figure

2.45). The metal thread can also provide a temporary memory for additional pleating and shaping (Richards, 2012).

Figure 2.45: Ann Richards, *Spiral* neckpiece, weaving using finishing processes that affect stainless steel and silk threads in different ways to create three-dimensional form, 2012, (Richards, 2012, p.134).

The weaver Deirdre Wood (Ellen et al, 2016) uses a wet-finishing technique to bend her strip weaves to generate curves. Wood uses linen-spun silk and linen warp threads on different edges of the woven cloth (Figure 2.46). As the silk shrinks when it reacts to hot water when finished, it pulls in one side of the strip to create a curve along one edge. The linen that does not shrink forms the outside of the curve. The curve is created through the wet-finishing of specifically placed threads with differing properties in the warp.

Figure 2.46: Deidre Wood, *Broken Disc*. Linen, spun silk and wool weaving, 2010. Photograph taken by myself at ‘Textiles Taking Shape’, Winchester, 2018.

Philippa Brock is a woven textile designer who describes herself as ‘a woven textile engineer’ (Hemmings, 2012: 65). Brock engineers weave structure using active threads to reduce the number of finishing processes needed to create a three-dimensional texture. Brock explains that this is both a more economical and a more sustainable approach to production. Her woven fabrics combine an understanding of woven structures, active and passive yarns and finishing techniques (Figure 2.47).

Image redacted.

Figure 2.47: Philippa Brock, woven fabrics exhibited at the 2D - 3D: Jacquard Woven Textiles Exhibition, Montréal, 2012, Online]. [Accessed 13.3.16]. Available from: http://www.theweaveshed.org/

Richards (2012) describes how metal threads can also act as active yarns within weaving, creating interesting textural effects when combined with active shrinking yarns. The metal in Junichi Arai’s weaving in Figure 2.48 acts as a high-twist active yarn to create random texture.


Figure 2.48: (Left) Junichi Arai, plain weave fabric with metal weft, (Richards, 2012, p.157).
Figure 2.49: (Right) Wendy Morris, spun silk and metal weave, 2012, (Richards, 2012, p.158).

Wendy Morris used different densities in the weave to create a texture, as this affects how the metal weft thread moves when the spun silk warp shrinks after finishing. Figure 2.49 shows the top of her unfinished fabric. The bottom half is the texture created after finishing. The metal thread becomes active in the structure, as it is able to move more freely in the looser areas of the weave and therefore creates an irregular texture (Richards, 2012).

2.7.2 Jacquard weaving to create large-scale 3D forms.

Samira Boon's research (2016a), commissioned by Amsterdam's TexileLab, explores jacquard woven self-supporting textiles. Boon's background as an architect informs her understanding of her textile structures. Her research aims explore self-supporting woven fabrics that use a combination of yarn choice and structures. These various material properties are combined with careful engineering of the binding or intersection points within the weave structures to create soft folds and planes of stiffness. The relationship between the pliable areas and more rigid planes in the structures produce the form. *Super Folds* in 2014 investigated the textural and sensual differences between hard paper and soft textiles. She explored flat rigid planes and soft folds within a folded woven structure to create self-folding textiles (Figure 2.50). This was developed to create *Archi Folds* in 2016. These larger structures are seen in Figure 2.51.

Figure 2.50: Samira Boon, *Super Folds* jacquard woven pleats, 2014. [Online]. [Accessed 8.2.16]. Available from: http://samiraboon.com/

Archi Folds (2016a) utilise the jacquard loom's ability to weave complicated folded structures that would be difficult to achieve on a large scale using paper. Boon's structures do not incorporate rigid metal, therefore they are pliable. She uses the fabric's anisotropic properties: *Archi Folds* and *Super Folds* can be folded in many different ways to create different shapes.

Figure 2.51: Samira Boon, *Archi Folds* structures at the 'Co-Creation' exhibition at the Dutch Textile Museum, Tilburg, 2016. [Online]. [Accessed 8.2.16]. Available from: http://samiraboon.com/

2.7.3 Weaving Metal

Incorporating metal into woven structures to create three-dimensional form has been explored by many weavers, including Richards (2012), Collingwood (Harrod, 2015), Mallebranche (2016) and Tandler (2016). Handweavers can interact with the metal during the weaving process to create sculptural forms, whereas industrial manufacturers use mechanised looms to create mesh fabrics that are often used for architectural or manufacturing purposes.

2.7.4 Handweaving metal to create structural form.

Handweaving with metal wire can pose technical challenges which require skill, patience and perseverance. If rigid wire is bent back and forth too many times it will break. Therefore, winding a wire warp around a warping mill and chaining it off to enable it to be tensioned on the loom can be difficult without causing kinks in the wire. When tensioned on the loom, any weaknesses in the wire can break.

From 1963 onwards, the influential weaver Peter Collingwood created Microgauze fabrics using stainless steel and natural fibres. Collingwood's diary (Harrod, 2015) documented the technical issues when working with rigid stainless steel fibres to create the Kiryu Microgauze large-scale interior sculpture in 1997. Collingwood also used stainless steel rods to form structural supports to hold open the warp threads to create the Microgauze three-dimensional wall pieces. Figure 2.52 shows linen warp threads tensioned using metal rigid rods in the weft to support the threads to create a three-dimensional form.

Figure 2.52: Peter Collingwood, Microgauze weave. Photograph taken by myself at the Crafts Study Centre, Surrey, 2018.

Lynn Tandler (2016) refers to the stiffness of different metal wires when handweaving her MA samples at the Royal College of Art (Figure 2.53). Tandler identifies that stainless steel wires are more rigid and brittle compared to copper or copper alloy wires of the same diameter (0.1mm and 0.2mm). She states that stainless steel and brass wires at these thicknesses were not suitable for industrial production weaving techniques (Tandler, 2016).

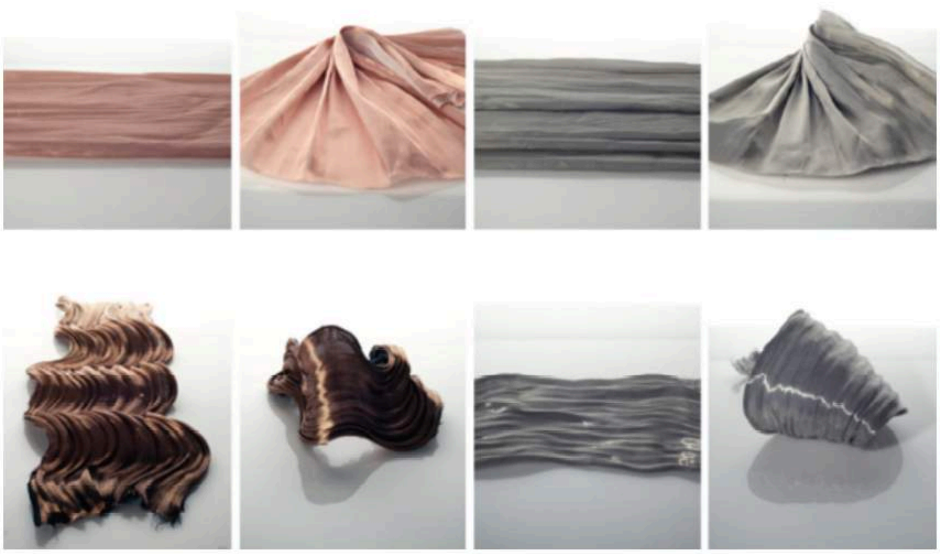


Figure 2.53: Lynn Tandler, copper and polyester handwoven MA fabrics, 2013, (Tandler, 2016, p.50).

Several textile practitioners, including Hiroko Takeda (Collectif Textile, 2013), Anastasia Azure (2018) and Donna Kaplan (Fisch, 2003) have handwoven metal wire structures (Figures 2.54-2.56). The forms appear to be self-supporting; however, they do not incorporate electroformed frameworks and do not explore the interplay between pliable and rigid material properties between textile and metal, using selectively metallised threads within the weave.

Image redacted.

Figure 2.54: Hiroko Takeda, Waffle weave, 2013, Takeda, [Online]. [Accessed 7.6.16]. Available from: http://collectiftextile.com/

Image redacted.

Figure 2.55: Anastasia Azure, *Accentuating Focus*, metal and plastic, 2018. [Online]. [Accessed 9.4.16]. Available from: https://www.anastasiaazure.com/

Image redacted.

Figure 2.56: Donna Kaplan, Copper wire form, 2003, (Fisch, 2003, p.135).

2.7.5 Industrially woven metal fabric and mesh

To weave with metal wires in the warp on a power loom requires particular industrial looms. Sophie Mallebranche (2016; Decanter, 2014) weaves metal textiles with a handcrafted aesthetic by using specialised industrial weaving looms capable of weaving with wire and thread. The warp yarns provide stability and rigidity. The weft yarns enable the fabrics to flex. The metals used include stainless steel, copper, enamelled copper, bronze, tin and gold. The fabrics are relatively fragile and are not able to withstand forceful manipulation (Figure 2.57).

Image redacted.

Figure 2.57: Sophie Mallebranche, industrial loom woven metal textiles, 2014. [Online]. [Accessed 17.3.16]. Available from: https://decanteddesign.com/

Companies such as Cambridge Architectural (USA), Twentinox (Netherlands), Rossi TTM (Italy) and Haver and Boecker (Germany) produce a wide range of industrially woven metal grids. Figures 2.58 and 2.59 show products that are created for architectural industrial use. Although some of the metals have the ability to articulate and form fluid shapes due to the weave structure, they do not combine soft textile fibres and rigid metal in the same integral structure.

Images redacted.

Figure 2.58 (Left): Cambridge Architectural meshes. Photograph by Jeremy Muckel, 2016. [Online]. [Accessed 1.9.18]. Available from: http://cambridge-intl.com/stacked-mesh/

Figure 2.59 (Right): Twentinox, Golf Romeo metal mesh room divider, 2018. [Online]. [Accessed 7.7.18]. Available from: http:www.twentinox.com/

2.8 Discussion

The research selected in this context review demonstrates that using threads and pliable woven textiles provides scope to create unusual forms that can be made fully or partially rigid using a finishing process. Soden and Stewart (2009); Soden et al. (2012), Stewart (2010), Milne et al (2015) and Menges et al (2015; 2016a; 2016b) have used thread or woven fabric to create self-supporting form without a reliance on using conventional engineering moulds. Menges' comments during panel questioning at the V&A's 'Biomimicry and Design' symposium (2016b) expressed his frustration with the constraints when using pre-made textile when creating three-dimensional forms. He stated that premade textiles did not offer the opportunity for the properties of the form to be adapted as they are not specifically engineered for the purpose of the research. Menges has not yet explored the design of loom woven textiles as a means to create self-supporting form due to the complexity of loom woven cloth and his lack of weaving knowledge. This highlights the specialist knowledge required to engineer a woven fabric for a specific purpose.

Designing the weave in relation to three-dimensional form is an established thinking approach demonstrated by Richards, (2012), Morris (Richards, 2012), Brock (2018) and Wood (2018). An experienced weaver can engineer the precise placement of specific threads within the weave structure in relation to the electrodeposition processes. This has the potential to generate new knowledge to control the rigidly and pliability of the forms. Research by Soden and Stewart (2009), Stewart (2010), Soden et al. (2012) and Brennen et al (2013) illustrates how the integration of two different disciplines' making approaches; woven textiles and engineering Fabric Formwork, can enhance the structural properties of the forms.

Electrodeposition on textiles has been explored using conductive solution (Geesin, 1995; De Russyer, 2009; Keith, 2010, Horton 2017). These researchers have not integrated the engineered woven integral framework with the specific purpose of using the structural properties of metal deposited through electrodeposition to support the form. As identified in this chapter on pages 46-48, the precise placement of fine lines or pattern can be difficult to control as the solution can bleed through the textile or the application process can cause areas to become uneven (De Russyer, 2009; Keith 2010). Placing conductive threads in strategic places in the woven cloth has the potential to give greater control over selective electrodeposition as it prevents this problem. The electrodeposition of pliable conductive threads also has the potential to alleviate the technical challenges associated with weaving brittle wire, as the rigidity is formed after the fabric is woven.

Therefore, this research focuses on the influence that designing a woven textile has in relation to the electrodeposition finishing process. The electrodeposition will become part of the construction of the woven cloth rather than a surface application. It explores if an experienced weave designer's knowledge of the construction of the woven textile has the potential to expand existing research by using finishing to metallise textiles, to refine the control of selective electrodeposition on self-supporting textiles. The review has highlighted the following considerations for this research:

- How can embedding conductive threads within the base cloth offer a means to control pliable and rigid properties within the self-supporting structures with precision?
- How does the way the metal deposits upon the conductive threads within the fabric provide alternative qualities to creating a conductive layer on the cloth, where the metal deposit forms on the surface of the fabric?
- How can exploring the use of three-dimensional form through the use of engineering moulds or woven structures affect the rigidity and pliability of the hybrid structures?

Chapter 3 Research Methods

3.1 Introduction

The previous chapter established the historical and contemporary background relating to the practical work in this research. It introduced researchers' use of thread and woven textiles to create structural forms using external frameworks, tension forces or finishing processes to alter the characteristics of cloth. My research seeks to address the gap in knowledge identified in this review and aims to contribute new knowledge to the field of metallised textiles. To the best of my knowledge, simultaneously considering the construction, composition and finishing of specifically designed woven textiles using selectively controlled electrodeposition to create self-supporting hybrid forms is new research.

This chapter describes my conceptual framework, the choice of methods, the tools used and how my practical exploration and reflective practice influenced my methodology. My methodology uses my weaver's parallel processing problem-solving (Seitamaa-Hakkarainen and Hakkarainen, 2001), which simultaneously considers the construction and the composition of the cloth, to create an integrated approach to material development using cross disciplinary knowledge acquisition. My conceptual framework is illustrated in Figure 3.1. Viewing this research through an experienced weave designer's lens (Crouch and Pearce, 2012:59; Gray and Malins, 2017:131) created a particular approach to how a woven textile making perspective can be integrated into the process of small-scale industrial electrodeposition. This aims to extend thinking approaches and making methods in both woven textiles and electrodeposition to facilitate original outcomes.

Established research methods of apprenticeship (Coy, 1989; Marchand, 2008), reflective practice (Schön, 1991) and experiential learning cycles (Kolb, 1984) are used as part of an 'art of inquiry' (Ingold, 2013:6). Thinking through making is common practice within textile design research, as demonstrated by Philpott (2007; 2011); Kane (2007), Philpott and Kane (2017), Glazzard (2014), and Toomey et al. (2018). In this approach, I use an iterative design process that relies upon reflective practice during sampling to modify the practical outcomes. The use of reflection combined with action enables a transformative change to occur: a practitioner's 'skills are reinterpreted and applied… as they are learned' (Crouch and Pearce, 2012:40). The integration of several making and thinking methods create frameworks of interdependent parts that form structures to aid problem-solving within a cyclical design-led approach to material exploration. My methodology was refined through practice-led research when using my method frameworks, which I describe as Tri-spaces (Section 3.7). Chapter 5 discusses the impact of the Tri-space frameworks on this research.

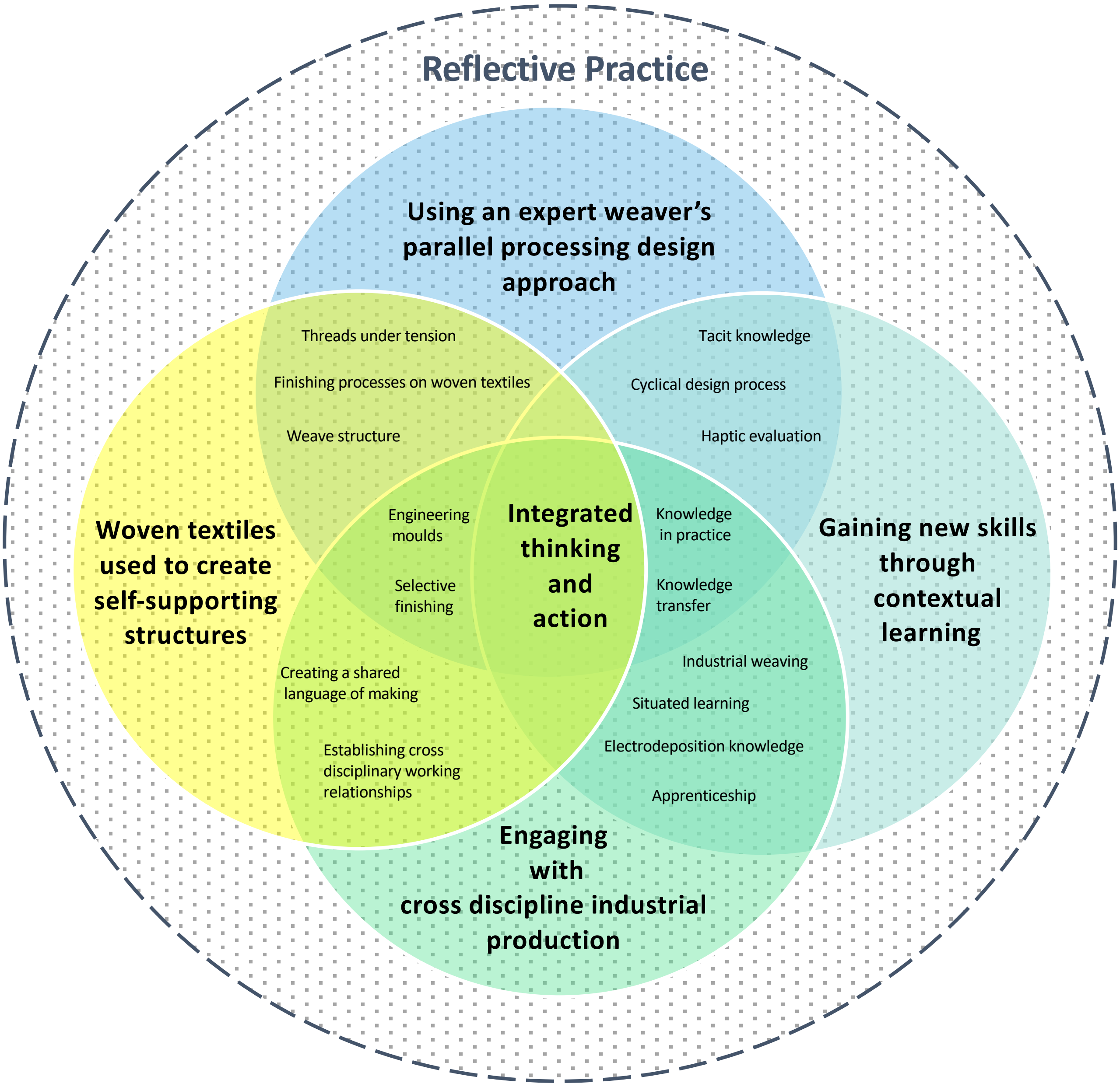


Figure 3.1: My conceptual framework used within the research process.

This research was conducted in phases of planning, action, reflection and analysis to enable dissemination of the key findings, as demonstrated in Figure 3.2.

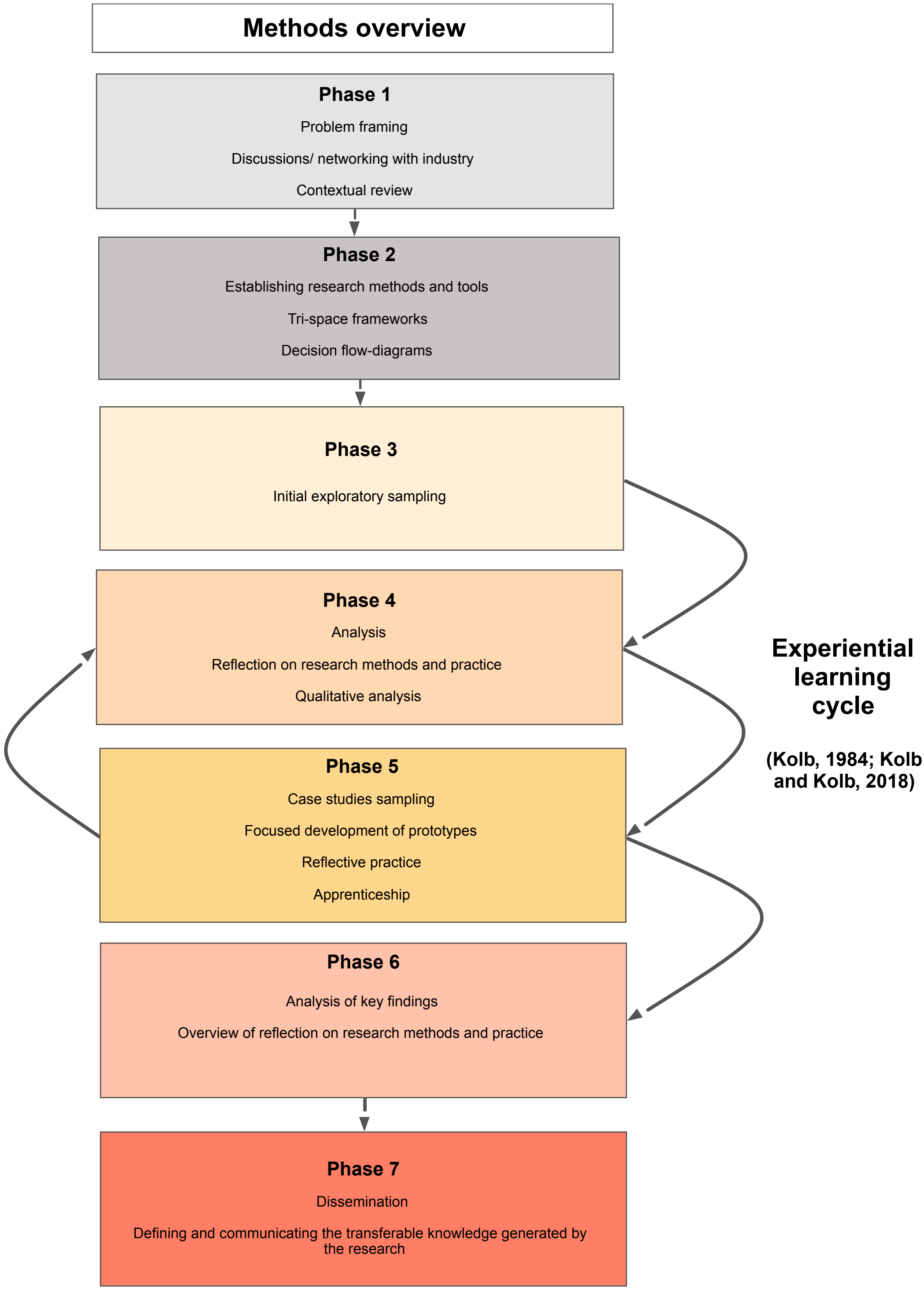


Figure 3.2: My method overview diagram.

3.2 Problem-framing using constants

Schön states that the process of problem-setting is an important part of problem-solving. This involves the active participation of the problem-solver to 'frame the context' (Schön, 1991:40) in which to work. When the problem has been framed it can fall outside the researcher's familiar approaches to problem-solving. Schön describes these instances as 'unique or unstable' (Schön,1991:41) problems. Mayer (1989) defines routine problem-solving as being able to solve a problem using a well-known procedure. A non-routine problem requires a new approach, as there is no well-known procedure to follow (Mayer,1989). Schön (1991) suggests that it is beneficial to use 'knowing-in-practice' (Schön,1991:62) that uses constants, which are routine problem-solving skills, when working in an unfamiliar discipline or situation. Grocott (2011:17) recommends that a practice based research question should be directly relevant to the researcher as it aids problem framing and investigation. This enables methods of exploration and solutions to develop concurrently which can offer new insights for the identification and investigation of research. As established in Chapter 1, the skills required to design woven textiles are constants within my practice, and are therefore routine. As an experienced weave designer I use parallel processing to consider the composition and construction of fabric as one process (Seitamaa-Hakkarainen and Hakkarainen, 2001). Introducing the unfamiliar finishing process of electrodeposition of the weave created a non-routine problem within this research. Therefore a new approach to problem-solving was required. This involved aspect relating to design, making and the physical material properties when incorporating the non-routine metallisation finishing process with my routine problem-solving relating to woven textile design. Schön (1991:40) suggests that frame experiments can be created as a way of approaching non-routine situations. I have established the scope and the context of my problem-solving in Chapter 1 and I have created a series of frame experiments to find solutions to my aims. These are detailed in the case studies in Chapter 4 that use practical sampling to incorporate electrodeposition within my textile practice.

3.3 Reflective practice and the relevance of context when problem-solving

Battistutti and Bork (2016) state that 'knowledge is … a fluid mix of framed experience, values, expertise, contextual information and insight that provides a structure for evaluating and incorporating new information and experiences' (Battistutti and Bork, 2016:461). My research supports this viewpoint as it mixes experiential and contextual knowledge relating to craft, woven textiles design, industrial textiles and electrodeposition.

Visser (2006, 2010a, 2010b), Schön (1991) and Cross (2007) explain that designers utilise their existing skills, knowledge and experiences when problem-solving. Simon (1977) states that when problem-solving a person ‘structures a problem and then solves it’ (Visser, 2006:109). Visser (2010b:32) challenges Simon’s (1977) view that problem-solving is not context-specific, citing studies that demonstrate that designers continue to structure their problems throughout the task, and that the context of the problem is relevant to the problem-solving approach. Cross (2007) concurs, describing the way designers problem-solve as using ‘designerly ways of knowing’ (Cross 2007:17). Cross (2007) states that this approach uses a cyclical method of problem-solving which uses a designer’s intuition to approach a task based upon past experience, rather than assessing all the facts before commencing.

In this research I have used my 20 years’ textile experiential knowledge to inform my problem-solving. Schön’s (1991) research discusses the way practitioners think through their actions when problem-solving, which relies upon reflective practice. Schön describes design as a ‘reflective conversation with the materials of the situation’ (Schön, 1991:79). After constructing the situation, the designer responds to the feedback created by the situation. A design approach allows methods and outcomes to be interpreted in a flexible adaptive way to respond to circumstances and viewpoints. It values the use and interrogation of tacit knowledge as a means to bring new perspectives or practical outcomes (Grocott, 2011).

Designers who align with Cross’ (2007) theory would have a specific target application when design problem-solving, such as a product or architectural building. Textile designers frequently explore material characteristics using a less application-specific approach. The focus of a textile practitioner’s initial design inquiry is often on the making process, the materials and what can be achieved through experimenting with these, (Kettley and Briggs-Goode, 2010:3; Philpott, 2011, Glazzard, 2014). The application of the ‘new’ material created by this type of inquiry is a secondary layer of problem-solving, explored after the new material has been created. This enables the material characteristics to inform the final application. My research aim was to explore the integration of the pliable and rigid properties of textiles and metal. Therefore my approach aligns with Schön’s (1991) perspective more closely than Cross’ (2007), as the application of my material will be a secondary problem-solving stage and the focus for my post-doctoral research.

Critics of Schön's Reflective Practitioner model (1991) have identified that he emphasises the importance of creative artistry over Technical Rationality, which is based upon scientific facts (Caceres, 2017:3). Schon suggests that reflective practice can free practitioners from the restrictions that Technical Rationality can produce (Schön, 1991:69). Engineers such as Caceres (2017) argue that this is not a logical approach when physical and practical factors have a significant impact upon the success of the final outcome. Caceres (2017) believes that technical knowledge is essential to problem-solving. My research is led by the subjective reflection of a single woven textile researcher, which values my experiential knowledge and reflective practice. It also engages with elements of Technical Rationality in relation to the electrodeposition process. Without a basic understanding of how the metal deposits on the conductive threads, the finishing process could not have been integrated into the making process effectively. Therefore, this research does not use reflective practice in isolation, it also uses technical knowledge from both woven textiles and electrodeposition.

Reflection-on-action involves evaluating past events and gaining new insights by interrogating past actions (Schön,1991). Reflection-in-action involves responding to circumstances, thinking and acting in the moment and reflecting on previous knowledge to inform the present situation (Schön, 1991). Reflection-for-action (Cowan,1998) uses previous experiences to inform future design iterations. These reflective processes work in conjunction with each other. Gray and Malins (2017) refer to a looping process of reflective practice (Figure 3.3). I have used this looping process of reflection on, in and for action during this research throughout my case studies. My use of reflective practice as part of my collaborative interaction with the industrial mill and as an electrodeposition apprentice are detailed in Section 3.10.

Image redacted.

Figure 3.3: Gray and Malins' Reflection-for-action looping process adapted from Cowan (1998), (Gray and Malins, 2017, p. 57).

Engaging with materials generates valuable insights into design practice, underpinning the opportunity for new discoveries (Schön, 1991; Dormer, 1997; Kane, 2007; Philpott 2007; Sennett, 2009; Ingold, 2013; Glazzard, 2014). Frayling (1993) proposes that this approach, which he describes as research *through* design, is a vital aspect of design. Through reflection-in-action I have analysed tacit knowing-in-action (Schön,1991) whilst the action is taking place. This 'reflective conversation with materials' (Schön,1991:79) guided the iterative development of samples in my case studies. Through reflecting on present action, past actions relating to my research were evaluated to consider what might be altered in the present task to enhance the outcome. These new insights informed subsequent samples when reflecting-for-action. This produced a range of samples with different characteristics.

3.4 Action research

Action research is prevalent in human centred research (Crouch and Pearce, 2012:157). As with design research, action research involves experiential learning cycles (Kolb, 1984) that use an iterative looping process that builds new knowledge to refine solutions to an identified problem (Figure 3.4). As each learning cycle progresses the researcher gains new insights to use during reflective practice. My research does not focus upon human centred participant action research. It uses aspects of an action research through the use of experiential learning cycles, using a material-led investigative approach. It focuses on the refinement of a single practitioner's design ideas through a non-linear research experimental approach to find design solutions.

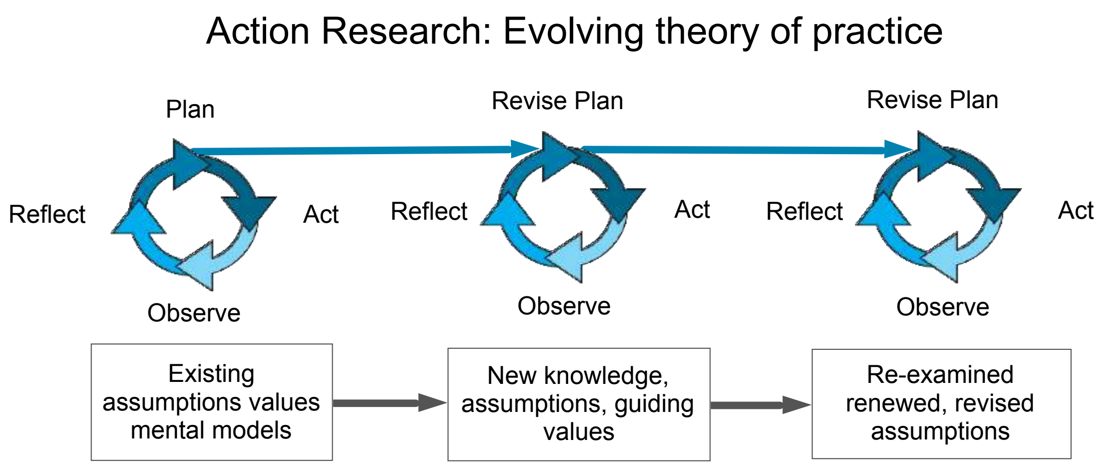


Figure 3.4: My diagram of the iterative nature of action research adapted from Damme (1998).

3.5 Summary of objective and subjective methods for testing the mechanical properties of the fabric handle of textiles

Established objective testing methods use machinery to assess the properties of fabric and include Kawabata 's KES[10] (Hu,2004:8), FAST[11] (Hu, 2004:27) and Peirce's Cantilever Test[12] (Hu, 2004:137). The quantitative data produced from these tests can be compared and analysed in a scientific and rational manner (Ghosh and Zhou, 2003) as demonstrated in research by Jedda et al (2006), Lammens et al (2014) and Sun et al (2018).

Qualitative analysis using subjective human interaction is a recognised textile designers' tool for fabric hand[13] evaluation, (AATCC, 2001). Research by Kane (2007), Philpott (2011) and Xue et al (2017) are examples of a subjective approach. When choosing evaluation methods for this research subjective tests were selected as opposed to objective tests due to the following:

1. The objective tests cited above specify the use of flat test fabric samples. My samples are three dimensional and these tests would not have been appropriate for my samples.

2. As an experienced woven textile designer, I have tacit experience of interacting and evaluating fabric handle using haptic subjective methods. I believe that the haptic interaction and somatic tacit knowledge gained from this approach was a more appropriate method in line with my research question, that focuses on a particular textile researcher's viewpoint when finding solutions to a design problem. Therefore this research uses a structured qualitative approach (Savin-Baden and Howell Major, 2012) led by tacit interaction, rather than a precise quantitative engineering approach, which would have changed the emphasis away from a textile design-led research perspective. This would have pushed my research outside of my known constants and experimental frames, as identified by Schön (1991).

Each sample was evaluated in terms of the characteristics of pliability and rigidity of the textile and metal within the same form and the level of controllability achieved

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[10] KES is the Kawabata Evaluation System created by Professor Kawabata, Kyoto University, Japan (Kawabata, 1975).
[11] FAST is the Fabric Assurance by Simple Testing created by CSIRO Division of Wool Technology (Hu,2004:27).
[12] The Peirce Cantilever test ASTM D13880 (Pierce, 1930; 1937).
[13] Fabric hand is a qualitative term to describe the tactile properties of the fabric in the hand.

through my making process. I created my own testing methods using a set of haptic interactions which were plotted against specific criteria using semantic descriptive scales[14] (detailed in Section 3.6.1 and Appendix A3). This approach is identified as a valid method in Section 8.1.2 of the AATCC Evaluation Procedure 5 (2001) for fabric hand. The type of qualitative analysis used in my research can be considered less robust than quantitative analysis (Savin-Baden and Howell Major, 2012:471). However, Atkinson et al.'s (2016:24) research concludes that human haptic interaction when evaluating the stiffness and pliability of textiles is a valid method for designers.

At the later stages of the research microscope images were used to validate my findings in relation to my analysis of how the metal deposits upon the conductive threads within the woven cloth, compared to printed and sprayed conductive lines. The microscope testing was carried out to prove my hypothesis that the metal deposited around the conductive threads by encapsulating the whole thread rather than the metal deposit being a surface application on the textiles. A FEI Quanta 3D FEG microscope was used at Queen Mary University London to obtain detailed imaging of the metal deposits on the woven cloth (Figure 3.5). The lead technician, Russel Bailey, set 1cm x 1cm sections of my samples in resin to view the cross-section clearly. The results were used to validate my conclusions relating to the rigidity of the samples and the way the metal deposits on the woven threads in the textiles. The results showed that the metal encapsulation of the woven conductive threads influences the rigidity of the overall form by making it more rigid than a surface application, as detailed in Section 4.7.

Figure 3.5: One of my samples being tested at Queen Mary University London, 2018. Photograph by Russell Bailey.

[14] A semantic descriptive scale rates the samples based upon descriptive extremes, such as pliable and rigid.

3.6 Analysis: The use of subjective haptic interaction during the research

The haptic nature of engaging with materials and my previous tacit experiences of weaving were important factors to this research. I share Albers' (1965) and Gordon's (Gordon et al., 2015a; 2015b) understanding that the combination of a weaver's structured thought processes and an experimental haptic interaction with threads is a valuable research method. This interaction with materials and the physical feedback received in this exchange was used to inform reflective practice (Schön, 1991; Dormer, 1997; Kane, 2007; Sennett, 2009; Philpott, 2011; Ingold, 2013; Scott and Gaston, 2017). I used my embodied tacit knowledge[15] of the physical properties of the textiles, combined with my embedded tacit knowledge[16] of the construction of the woven cloth within the research. During the electrodeposition process samples are placed into a tank of electrolyte solution[17] and an electrical current is passed through the solution which causes the metal ions to transfer to the conductive threads. The electrodeposition process is explained in more detail in Section 3.9. My experiential textile knowledge informed my haptic interaction when deciding when to remove the samples from the tank. I monitored the samples throughout the finishing process to assess the rigidity and thickness of the metal deposit. My analysis of my practical work relies upon my subjective observations during physical haptic interaction with the material forms. Dormer (1997) states that the characteristics and inconsistencies of the materials used in research 'can act as an agent for change, stimulating innovation and driving the evolution of process' (Dormer 1997:147). This is demonstrated within my case studies in Chapter 4.

3.6.1 Summary of tools and processes of evaluation

The sampling was developed in stages using different warps which were finished and evaluated before the next set within each case study, as part of an iterative experiential engagement with the properties of the forms. My reflective process was documented using text and images to record the different aspects of the samples in relation to the different interactive processes listed on page 76.

Tools used to evaluate and analyse the hybrid forms:

- Photography to record the stages of making process and outcomes.
- Audio recording discussions in the metal workshop between myself and

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[15] Embodied tacit knowledge relates to knowledge linked to the body or practical experience and actions (Collins, 2013).
[16] Embedded tacit knowledge is deep know-how and learning that is rooted in the mind through context-specific experiences and actions. (Collins, 2013).
[17] Electrolyte is a liquid that contains ions.

[redacted], my electrodeposition master.

- Documenting my correspondence with the technical staff at the weaving mill.
- Documenting technical records of my making process and design thinking in relation to weave design.
- Initial sampling tests of the electrodeposition process on the woven fabric.
- Focused case study exploratory sampling to compare practical outcomes.
- Haptic evaluation during and after finishing.
- Films of haptic interaction.
- Qualitative evaluation using semantic descriptive scales (See Appendix A3 for the description and the competed scales for the three case studies). Samples were evaluated and plotted against three scales answering the following questions:
  1. Question 1: Textile handle: What is the level of pliability and rigidity in the textiles within the form?
  2. Question 2: Metal handle: What is the level of pliability and rigidity in the electrodeposited metal within the form?
  3. Question 3: Control of fabric handle: What is the level of control of the pliability and rigidity of the characteristics of the form?
- Descriptive analysis: Analysis sheets for key samples to record haptic interaction, reflective practice and reflection for action were compiled to document and aid reflective practice (see technical notes with practical samples).

3.6.2 Defining the method for haptic evaluation of the samples

I used the following actions to evaluate the rigidity of the metal deposit:

Haptic tests during and after finishing (Figure 3.6 page 77):

- Applying pressure using my finger or hand to asses if this would compress the form.
- Flicking the metal deposit to assess how firmly it held the form.

Additional haptic tests after finishing (Figure 3.11 page 79):

- Holding the sample at the sides and gently flexing or expanding it back and forth to determine how rigid it had become.
- Placing my fingers/hands each side of the form and testing whether the form would crumple.

- Placing the sample on the widest and then the shortest edges to evaluate how rigid the forms were when flicked or pushed by hand.
- Case studies 3.2 and 3.3: Hanging and bouncing the samples from one edge to assess the spring properties.
- Holding the sample on the shortest edge, hanging and waving it up and down to assess rigidity.
- Applying pressure to the textile areas of the sample and flicking it using my fingers to assess it is taut or pliable.

Different levels of rigidity were explored depending on the aims for each of the case study experiments, as detailed in Chapter 4. When the metal deposit on the samples became sufficiently rigid in relation to the aims in the case studies, the samples were removed from the tank. Figure 3.6 shows my haptic interaction whilst the samples are on the frame-jig[22] to determine their rigidity.

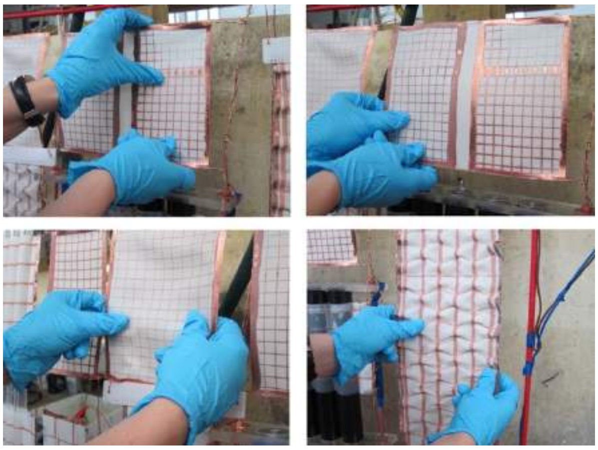

Figure 3.6: My interaction with samples on a frame-jig. Photograph by [redacted].

Image redacted.

Figure 3.7: Samples on a frame-jig being removed from the tank for me to assess the metal deposit on the conductive threads.

[22] A frame-jig is the supporting frame to which the samples are attached during electrodeposition.

A digital micrometer was used to provide an indication of the amount of metal deposited on copper guide wires that were placed on the frame-jig[1] (Figure 3.8). This is a conventional method used throughout the industry to assess the thickness of the metal. [redacted] process also uses material interaction and evaluation of the objects through haptic and visual observation.

Figure 3.8: The production manager at [redacted] using a digital micrometer to measure the metal deposit on the guide wires. [23]

[redacted] (Figure 3.10).

Image redacted.

Figure 3.9 [redacted]

Figure 3.10 [redacted]

[23] Guide wires are wires that are attached to the frame-jig to monitor the thickness of the metal deposit during electrodeposition.

My reflection-on-action informed my reflection-for-action for the next set of samples when evaluating the rigidity of subsequent forms as the case studies progressed. Films to document my haptic interaction after finishing are included with this submission, which should be viewed in conjunction with this section of the thesis (Figure 3.11). Film 1 is an amalgamation of the case studies and demonstrates my actions described in Section 3.6.2. Film 2 focuses on Case studies 3.2 and 3.3 to show the influence that different sequences and processes during finishing have upon the same-shaped hybrid form.

Figure 3.11: A series of clips from my haptic evaluation films included in the thesis submission. Photographs taken by myself using a timer.

3.7 Tri-spaces

We inhabit thinking search spaces in order to find a solutions to problems when achieving tasks (Simon, 1969;1996; Newell and Simon,1971; Klahr and Dunbar, 1988; Schunn and Klahr 1995). Within this research I have constructed specific thinking search spaces that consider the practical implications relating to design, collaboration and making. Each of my thinking-spaces involves three interrelated aspects, which I have considered simultaneously when problem-solving. I propose these as tri-space searches. These are titled Design-make Tri-space and Tri Space Roles.

3.8 Design-make Tri-space

Seitamaa-Hakkarainen and Hakkarainen (2001) adapted Klahr and Dunbar's (1988) Dual Search, interpreting it from a weave design perspective (Figure 3.12). Their study concludes that thinking approaches differ between novice and expert weavers. The novice weavers predominantly focused on one problem space at time, before moving to the other. Most time was spent within the composition space. The novice weavers' approach was described as 'serial processing' (Seitamaa-Hakkarainen and Hakkarainen, 2001:48). In contrast expert weavers in their study used an integrated approach where the construction and composition spaces were considered simultaneously. The relevance of the construction of the textile was recognised by the expert weavers as an important factor to the final outcome. This dual-space process used by expert weavers is described as parallel processing (Seitamaa-Hakkarainen and Hakkarainen, 2001:48).

Figure 3.12: My diagram interpreted from Seitamaa-Hakkarainen and Hakkarainen's (2001) weave design dual space.

My Design-make Tri-space extends Seitamaa-Hakkarainen and Hakkarainen's (2001) weave design dual space to include a third problem-solving space: finishing. Adding finishing as a separate problem-solving space acknowledges the diverse approaches that can be used to finish textiles, as identified in my Context Review. My Design-make Tri-space relates to the design and making decisions that were required to achieve the practical outcomes. This chapter highlights the differences between working in my routine weave design dual space and the non-routine

Design-Make Tri-space. The blurred edges of my Design-make Tri-space Venn diagram in Figure 3.13 illustrates that my three problem-solving spaces merge to become one unified problem-solving space in the centre, and that the boundaries between the spaces are indistinguishable. The blended colours within the text of the Design-make Tri-space represent the integration of the three spaces into one problem-solving space considered simultaneously.

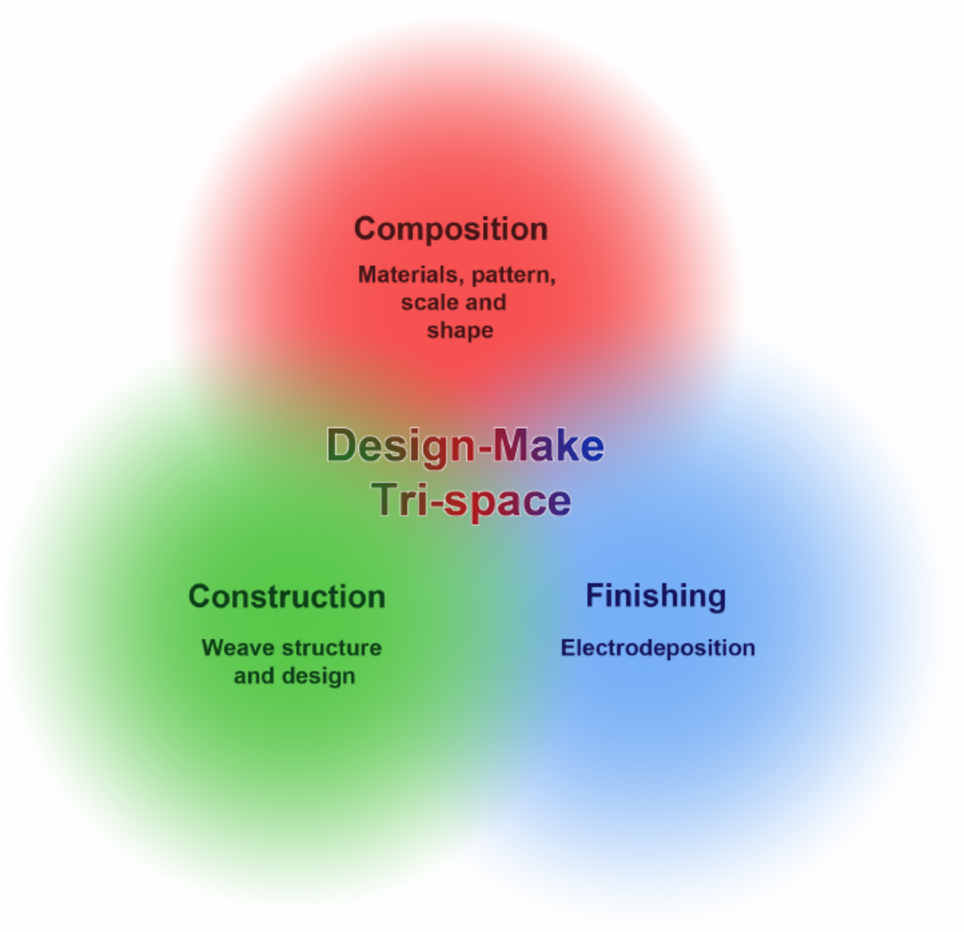

Figure 3.13: My Design-make Tri-space.

During this research the emphasis of my thought process moved within the blended space in relation to the different priorities at different stages of making. For example, at the end of the design-making process the emphasis was on the finishing process, and therefore I occupied a space closer to the blue finishing area in my blurred Venn diagram. However, at all stages the three aspects are considered as a unified process. The aspects of composition within the Design-make Tri-space are not domain-specific, as the principles of materials, pattern, shape and scale can be universally applied to a wider range of disciplines. However, the construction and finishing spaces are domain-specific as they relate to specific techniques and making processes. Therefore, specific knowledge relating to making processes was important when problem-solving in the domain-specific spaces of weave design and electrodeposition. My knowledge of metal finishing was gained from literature research and a two-year apprenticeship at [redacted], with electrodeposition expert [redacted]. Further details of my apprenticeship are given in Section 3.10.3.

3.8.1 Working within my Design-make Tri-space: Designing the weave in relation to the electrodeposition finishing process

Adding electrodeposition finishing to the dual space of composition and construction in my Design-make Tri-space affects the material and structural choices when designing the weave. Thinking within the Design-make Tri-space enables the electrodeposition process to be adapted to work in conjunction with my specifically designed woven fabric. The design considerations explained in this section demonstrate the relationship between the weave and the metal finishing process. The table in Figure 3.14 shows my categorisation of aspects of my Design-Make Tri-space thinking within this research. The different elements are colour-coded to differentiate them in the diagrams within this thesis.

Composition	**Construction**	**Finishing**
Shape	**Texture**	**Weaving**
Aspects of the form including scale, width and height of the woven textile.	Weave design, threading pattern, warp sett, number of available shafts for weave structure and lifting plan.	Suitability of thread, sett, position and number of conductive threads and weave structure in relation to the finishing process.
Pattern	**Procedure**	**Form**
Distance between conductive threads creating lines in the weaving. Visual repetition of lines and pattern.	Technical, practical considerations related to weaving such as thread float lengths, loom specifications and tension.	Form created by: 1. Weave structure. 2. Weave structure and plastic tubes. 3. Bespoke-jig.
Material		
Selection of the materials used, including warp, weft, active threads and conductive threads.		

Figure 3.14: My categorisation of different problem-solving decisions relating to the Design-make Tri-space.

The titles used in Figure 3.14 were used in a mapping diagram (Figure 3.15) which demonstrates that all three aspects within the Design-make Tri-space were considered simultaneously when designing the weave.

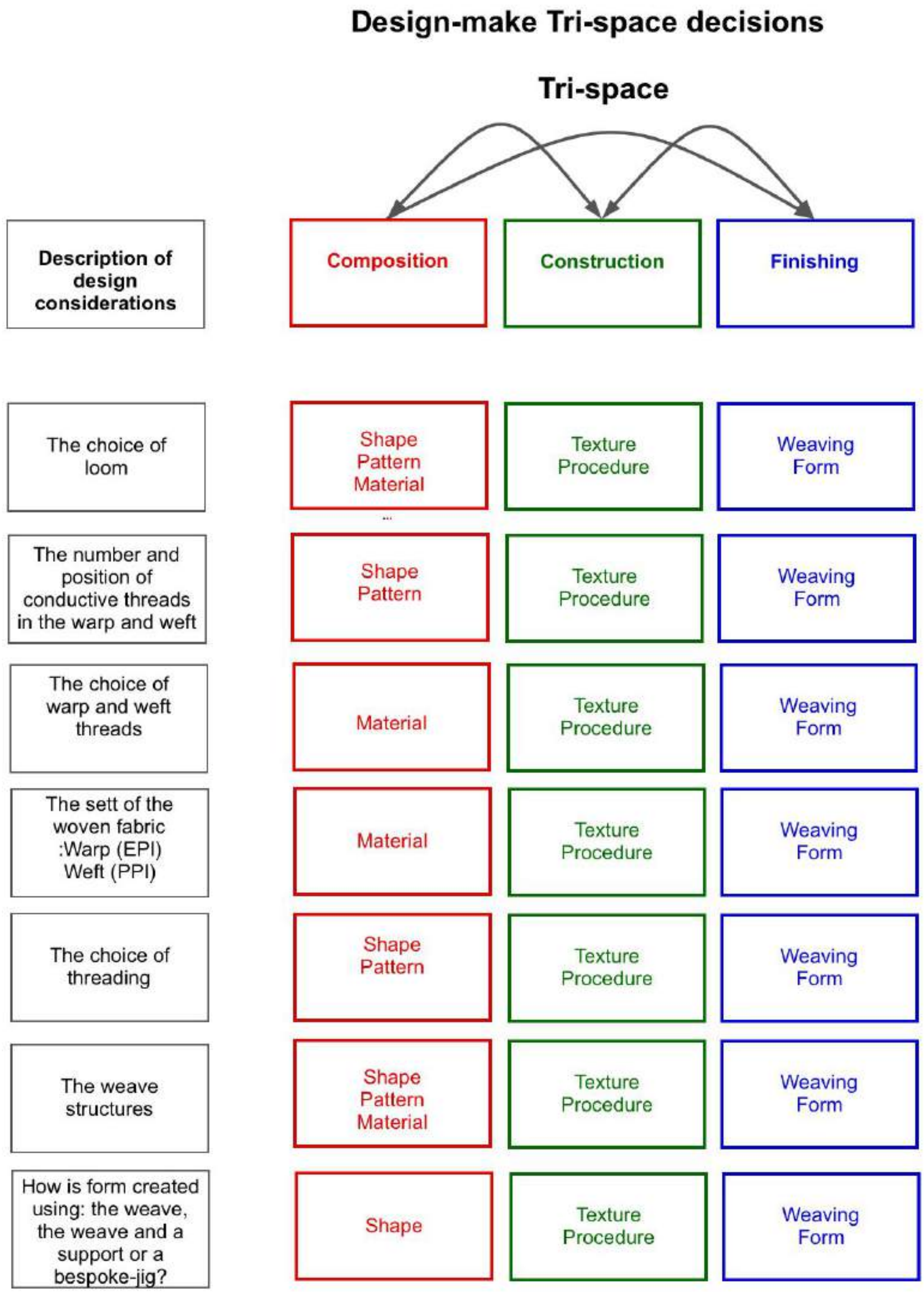

Figure 3.15: My diagram of the design decisions using parallel processing at each stage within the Design-make Tri-space.

When designing the weave it is essential to consider the relationship between the pliable textile and the rigid metal areas within the hybrid forms before and after finishing. Electrodeposition is a process that uses an electrical current to transfer metal onto conductive surfaces. Within this research context the electrodeposition process is used to set rigid the conductive threads and alter the properties of the weave. It is important to incorporate the finishing process within the planning of the weave structure, sett and material choices. Using the considerations in Figure 3.15, the fabric structure can be designed to influence the properties of the hybrid forms when finished. This is explored in the case studies in Chapter 4. When designing the samples, the following were considered**:**

3.8.2 Choice of Loom

To provide a wide scope for exploring pliability and rigidity within the case studies I intended to place conductive threads in the warp and the weft to create a rigid metal framework in both axes of the textile. Industrial Rapier dobby looms were chosen for their capability to incorporate conductive threads in the warp and weft alongside non-metallic threads with different physical characteristics. I researched suitable weaving mills and selected [redacted] were willing to thread warps to my specification, enabling control of the weave design process including the warp set-up. The technical specification of the looms at [redacted] had an impact on my design decisions, as they placed practical restrictions upon the sampling. This included the weave structures, thread choices and the number of conductive threads in the warp. Figures 3.16 and 3.17 show [redacted] looms weaving my samples.

Figure 3.16: A Rapier Dobby loom at [redacted], 2016.

Fig 3.17: [redacted] digital loom control screen, 2016

3.8.3 The number and position of conductive threads in the warp and the weft

The density, number and position of the metallised threads in relation to the polyester fabric areas in the weave are important when warp planning. These factors influence the pliability of the forms when metallised, as explored further in Chapter 4. The conductive threads are wound on separate spools and hung from the back of the loom (Figure 3.18). There was a limit of approximately 200 conductive threads across each warp, due to the maximum permitted number of spools across the width of the warp. This restricted my weave designs when planning warp set-ups, and I worked within these parameters.

During this research, different spacing, positioning and numbers of conductive threads were explored. I restricted the conductive threads to the central 15 centimetres of my first sample test warp to explore ideas without using large amounts of the expensive conductive thread. Once I understood how the conductive threads metallised within my woven fabric, these threads were extended across the full width of the warps in different proportions and spacings relating to my different designs. Chapter 4 and Section A2 in the Appendix detail the conductive thread spacings used in the case studies documented in this thesis. In Warp 2 (used in Case studies 1 and 2), the conductive threads were removed from the centre section of the warp across the width of the warp. This gave the option to have metal in one or both axes in comparable sample designs, giving a wider range of design options. Samples 2.1A, 2.1B and 2.1C, in Case study 2 have small gaps between the warp conductive thread blocks. Samples 2.2, 2.3 and 2.4, were redesigned to have no gaps in the warp conductive thread lines. The ratios of pliable textile to rigid metal areas within the forms were considered in relation to the thickness of the metal deposits applied.

Figure 3.18: Conductive threads spools hung from the back of the loom at [redacted], 2016.

3.8.4 The choice of warp and weft threads

The woven base cloth:

The choice of materials for the warp and weft threads was influenced by their ability to withstand the chemicals used in the metallisation process and their suitability for industrial weaving. Research included synthetic filaments such as polyester, nylon, glass fibre, Nomex, Kevlar and natural threads coated with synthetic coverings. Figure 3.19 shows samples of these threads and samples of woven textiles.

Figure 3.19: The range of threads and textiles that I researched to determine the choice of base threads for the weave, 2016.

Nomex and Kevlar are strong, and would have been resistant to the electrodeposition chemical. However, their high cost prohibited their use within this research. Polyester was chosen as it is a cheaper and durable alternative that worked effectively in the test samples. Polyester was also selected due to the following factors:

Discoloration: Nylon discolours in the electrodeposition sulphuric acid solution (as seen in the fabric trials (Figure 3.20). Polyester withstands the chemical process.

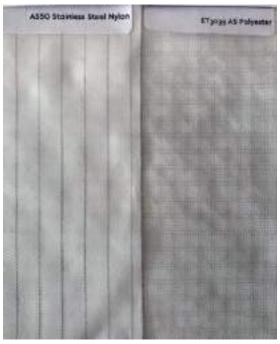

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Figure 3.20: Initial fabric tests that I carried out on nylon (left) and polyester (right) woven fabrics supplied from [redacted], 2016.

Stability: Natural fibres deteriorate in the acidic chemicals used in the electrodeposition process. Synthetic threads such as polyester are resilient to the chemicals and therefore were selected as the base thread of the woven fabric to maintain the integrity of the woven cloth after metallisation.

Roughness: Short staple fibres[24] such as wool or cotton create tiny metal splinters when metallised, due to their rough surfaces (Keith, 2008). Figures 3.21 and 3.22 show Issam Yousef's (2015) microscope images that illustrate the edge profile of woven non-metallised natural staple fibres and continuous synthetic filament threads to demonstrate the differences between their yarn architecture. I selected synthetic extruded filaments that form one continuous thread that do not produce rough edges when metallised.

Images redacted.

Figure 3.21: Microscope image of rough woven staple cotton fibres. Photograph by Issam Yousef, 2015. [Online]. [Accessed 7.4.16], Available from: http://www.uttu-textiles.com/

Figure 3.22: Microscope image of smooth woven synthetic filaments. Photograph by Issam Yousef, 2015. [Online]. [Accessed 7.4.16]. Available from: http://www.uttu-textiles.com/

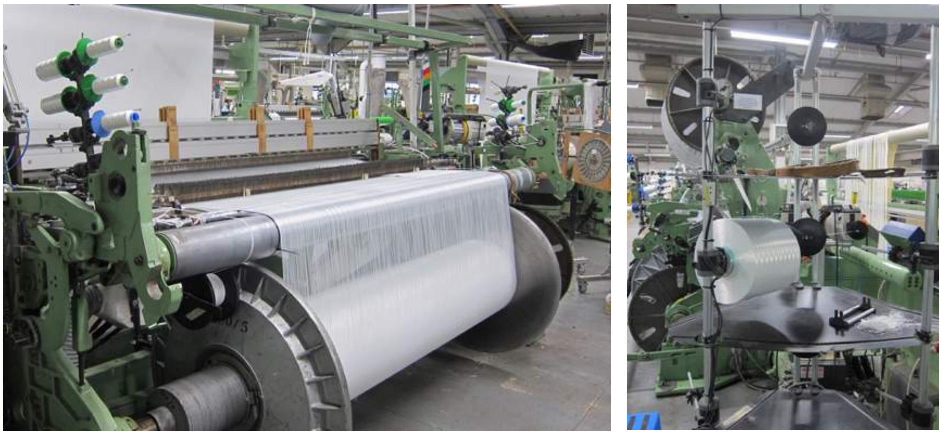


Figure 3.23: The warp and weft polyester threads on the loom at [redacted], 2016.

[24] Staple fibres are threads that are constructed by twisting short lengths of fibre together to form a continuous thread.

The same warp and weft polyester threads and the choice of filament thickness in dtex[25] were used within each case study to provide continuity between the sample warps[26].

Conductive threads:

Initial research was carried out to evaluate different conductive threads that could be used within the research in relation to the finishing process and the technical restrictions at [redacted]. Samples from [redacted] (2018) were obtained, which included different types and thickness of [redacted] threads (Figure 3.24). These were evaluated for their suitability for the weave set-up, finishing processes and cost. The [redacted] threads (see the right-hand cone in Figure 3.24) would not have withstood the finishing chemicals and would have become rough due to the short stable fibres, as demonstrated in Figure 3.21.

Images redacted.

Figure 3.24: (left) Conductive thread and weave samples: [redacted], 2016.
Figure 3.25: (right) [redacted] thread, 2016.

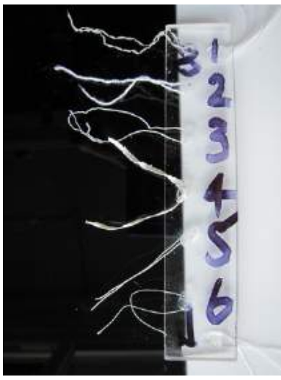
It was established from sample tests (Figure 3.20) that [redacted] 2-ply thread used by [redacted] metallised effectively (Figure 3.25). Consequently, more expensive, thicker [redacted] threads were not required in this research. The polyester is plied with [redacted] to provide support to the metal when it is placed under the high tension on the industrial looms. It is frequently used within industrial weaving by [redacted] for production of anti-static conveyor belt fabric. Therefore, it was also chosen because the equipment was in

[25] Decitex (dtex) is the unit of linear density of a continuous filament or yarn, equal to 1/10th of a tex or 9/10ths of a denier, (buinsessdirectory.com, 2018).
[26] [redacted] dtex high tenacity polyester was used in Case studies 1 and 2.[redacted] dtex polyester was used in Case study 3. The change in thread dtex in Case study 3 was due to restrictions of availability of the [redacted] dtex warp at the mill. All samples in Case study 3 used the [redacted] dtex warp for continuity with the sample set.

place to weave this conductive thread in a consistent and reliable way. The [redacted] thread will be referred to as conductive thread in this thesis.

Weft elasticated threads used in Case study 1:

Eight elastic weft threads were tested in the electrodeposition solution for twelve hours to evaluate whether they would disintegrate or weaken. Numbers 1 and 4 disintegrated (Figure 3.26). Of the six threads remaining that did not disintegrate, two were selected as being the most suitable due to their stretch and thickness. These were tested for a further twelve hours in the tank solution (Figure 3.28).



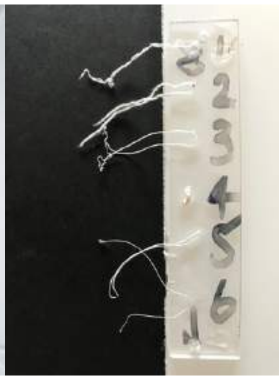


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Figure 3.26 (left): The eight elastic wefts tested, 2016. Figure 3.27 (right): Lycra thread selected for sampling, 2016.

Figure 3.28: Two types of elastic thread being tested in the tank solution, 2016.

The Lycra thread in Figure 3.37 had the most effective stretch capabilities and withstood the solution testing. I was unable to source polyester Lycra in small quantities despite researching thread suppliers, so Lycra nylon was used. Although it discoloured slightly during the tests, it maintained its stretch capabilities.

Colour of threads:

The weave structure and the properties of the cloth were the focus of this research. Therefore, white polyester was used to avoid any visual distractions that introducing colour might have generated.

3.8.5 The sett of the woven fabric: EPI and PPI

The sett of woven cloth describes the number of warp and weft threads per inch or centimetre. As [redacted] use inches to determine the sett, I have used inches in my notation to avoid confusion for their technical team. The warp is abbreviated as ends per inch (EPI) and the weft as picks per inch (PPI). As established in Chapter 2 (p.31), the sett of the weave influences the structural stability of the textile. Therefore, the sett of the textiles was designed to ensure that the textiles were robust. The fabric was required to withstand the 3D shaping by hand and being placed under high tension when incorporating particular jigs during making. [redacted] specified the EPI for each warp, based upon their experience of using the polyester filament threads used in this research. I refined the PPI through the different sample warps to create dense stable cloths that were able to support the conductive threads. This prevented fabric distortion when under tensile stress during finishing.

3.8.6 The choice of threading

The number of warps were restricted, due to the mill's production schedules and finances. For efficiency, blanket warps[27] and block threading were used to achieve multiple designs on each warp (Figures 3.29 and 3.30). Further details of warp threading relating to the case studies can be found in Appendix A2. This approach made full use of industrial warp set-ups and the constraints imposed due to production parameters and the research finances. The use of block threading as a design tool was important to enable a variety of different structures to be woven on the same warps, to allow for more design options. It also allowed integral structures such as the double-cloth pockets to be created in the weave (Figure 3.31).

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[27] Several warps were threaded using three or four different widths between the polyester sections and the conductive threads across the warp. Using different threading blocks across a warp for sampling is called a 'blanket warp'.

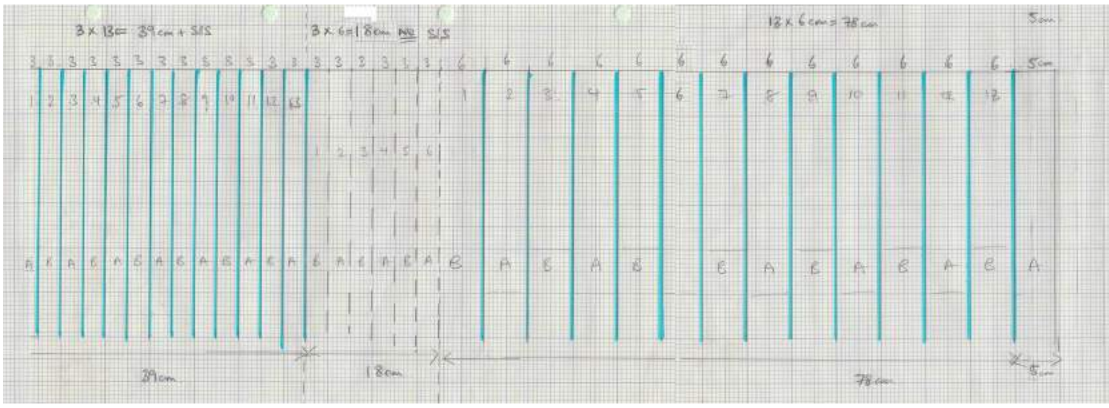

Figure 3.29: One of the my blanket warp plans showing two blocks with three different threading sections. This enabled three different samples to be woven across the warp in Case study 1.

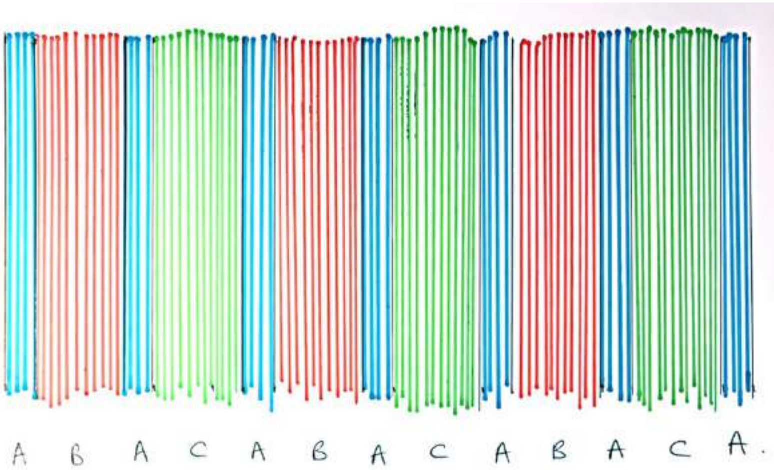

Figure 3.30: My drawing of three threading blocks, A, B and C, threaded separately to enable different weave structures in each section in Case study 2.

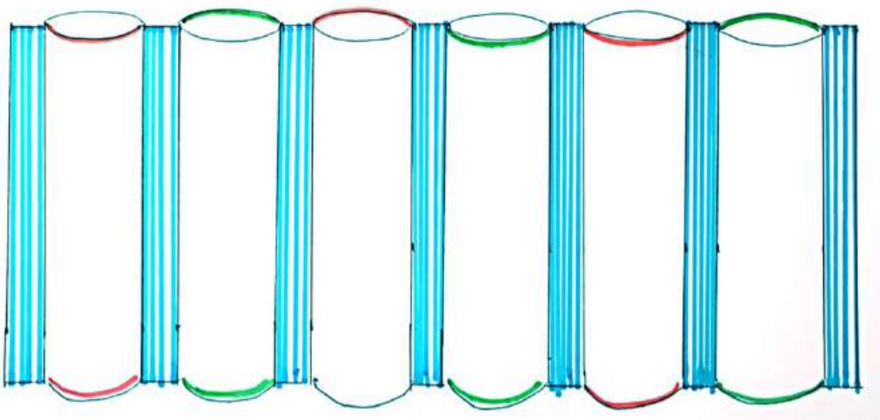

Figure 3.31: My drawing of the block threading sections that enable double-cloth pockets to be woven in Case study 2.

3.8.7 Weave structures

As identified in the context review in Section 2.6, the choice of weave structure affects the pliability of woven cloth. A variety of weave structures were sampled at the start of the research, including plain weave, twills and mock leno. After reflecting upon the results, the main weave structures within the case study samples were restricted to plain weave and 2/2 twill (Figures 3.32 and 3.33). This was to create constant factors within the sampling to be able to compare results more accurately. Plain weave creates a more rigid cloth than 2/2 twill when all other factors are equal. Using the two structures provided the opportunity to increase the drape (2/2 twill) or create a firm textile (plain weave) in the pliable areas. This was considered in relation to the conductive threads within the weave that would become rigid after finishing.

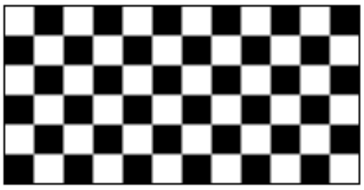

Figure 3.32: Plain weave.

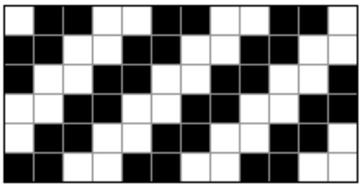

Figure 3.33 2/2 Twill.

Double-cloth and floating weft threads were also used in conjunction with plain weave and 2/2 twill to create form. The next section describes how the weave structure relates to the finishing process and the creation of the form.

3.8.8 Creating form

A jig in the context of electrodeposition is an external framework or bespoke mould to support the mandrel in the tank (Figure 3.34). The mandrel is the object onto which the metal is deposited during electrodeposition, in this research the conductive threads are the mandrel. The shape of the woven cloth in relation to the jig used is an important design consideration in relation to the finishing process. The significance that the shape of the jig has in relation to the woven fabric is discussed further in Chapter 4.

In each case study the form is created in a different way. Case study 1 uses the weave structure and Lycra threads in the weft to shape the textile. Case study 2 uses integral woven pockets supported by plastic tubes during finishing. Case study 3 uses bespoke jigs to create the form. The drape of the textile between the rigid metal frameworks is determined by the weave structure and the tensile force placed upon the fabric during finishing. Once the conductive threads are set rigid the metal framework holds the textile in place. If the textile is held under high tension by the use of jigs during metallisation, the pliable areas in the structures are stretched taut. If the pliable fabric is draped between the metal frameworks, a more organic and flexible form can be achieved.

Image redacted.

Figure 3.34: A frame-jig (left) and a bespoke jig (right).

The measurements of the woven double-cloth pockets in Case study 2 needed to correspond to the supporting tubes inserted. In Case study 3 bespoke jigs were required to create the shape of the hybrid forms. Therefore these were considerations when planning the design of the warp threading blocks and weave structures. The supporting tubes, the bespoke jigs and the weave structures need to be compatible with the weave if used in unison to create the form. Figure 3.35 shows the decision flow-diagram when designing the woven base cloth used in this research. Each set of decisions affects the characteristics of the woven textile and the final metallised hybrid forms. Coloured shading within this flow-diagram template will be used to illustrate the decisions made throughout each of the case studies in Chapter 4.

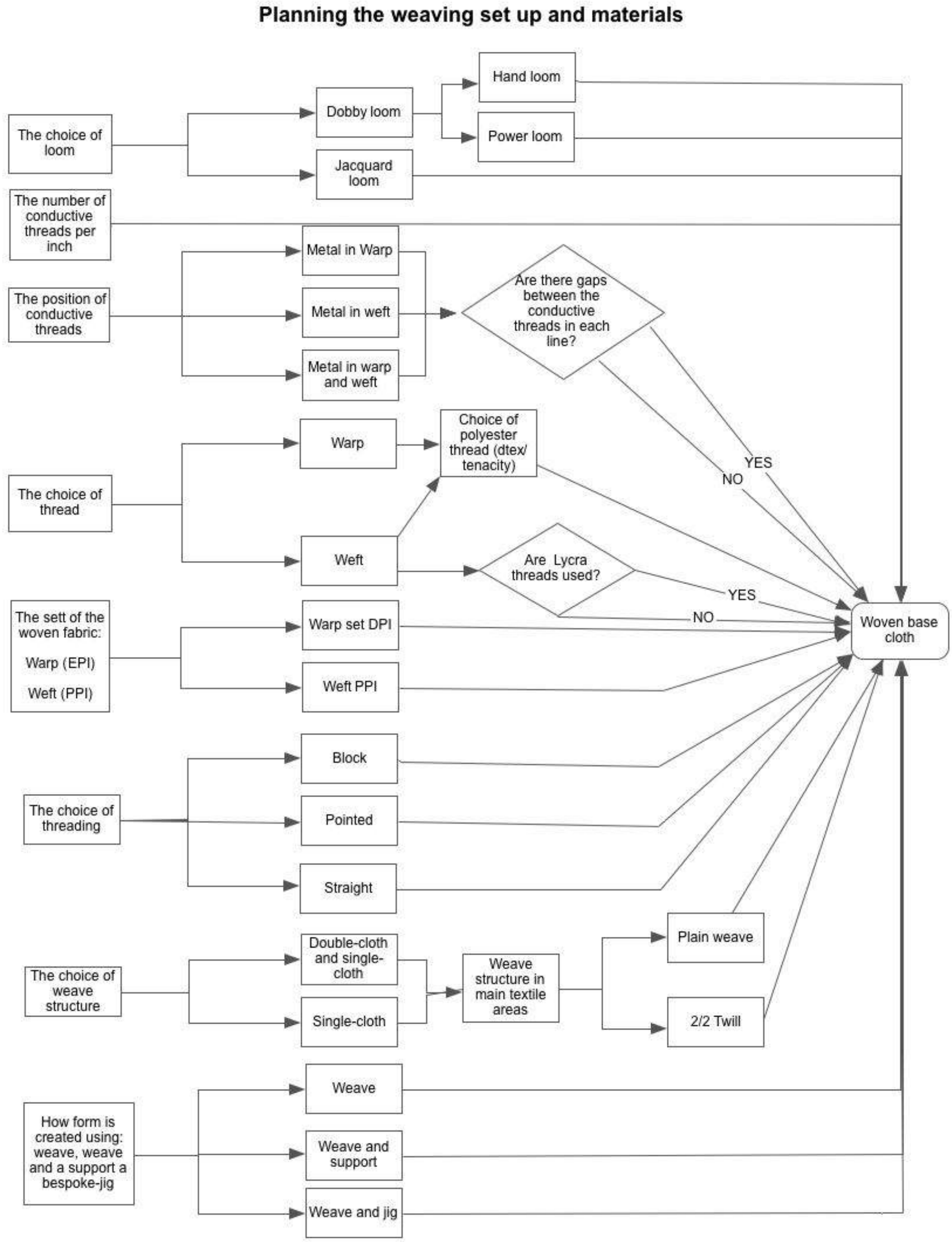

Figure 3.35: The decision-flow related to my design of the woven textile.

3.9 Finishing: Electrodeposition

Electrodeposition is a process that deposits metal onto another conductive surface using an electrical current passing through a tank of electrolyte[28]. Metal ions from the anode[29] are positively charged and move towards the negatively charged object within the tank. This builds up a continuous layer to create a metal form. The metal deposit develops over time, increasing in thickness (Bicelli et al., 2008). There are two forms of electrodeposition, electroplating and electroforming, as illustrated in Figures 3.36 and 3.37 (Thompson, 2007). Electroplating deposits a thin layer of metal onto the surface of a conductive material (Thompson, 2007). The base material remains within the final piece and the metal deposit is not self-supporting. Electroforming deposits a thicker layer of metal onto a conductive form called a mandrel,[30] and produces self-supporting forms.

The finishing I have used is an electroforming process[32]. In the initial stages, when the metal is very thin, the metal properties are similar to electroplating as they are pliable and have no structural integrity. When the metal deposits become thicker and rigid, the samples become self-supporting electroforms. For the purposes of this thesis I define that the samples become electroforms when the textile's structural integrity is increased due to the thickness of the crystalline metal deposit. However, the term electrodeposition will be used to describe the finishing process in this research as it is the overarching term for the metal deposition process.

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[28] Electrolyte is a liquid that contains ions.

[29] An anode is the metal that forms onto the object during electrodeposition (Curtis, 2013).

[30] The mandrel is the object onto which the metal is deposited during electroforming.

[32] The ASTM B832-93 (2013) standard guide definition of electroforming states that the mandrel is removed after metallisation and the deposited metal creates a self-supporting form (Parkinson, 1998). There are instances when the mandrel is deliberately left in place and it becomes encapsulated within electroforms, becoming integral. In these cases, the term 'electrofabrication' (Parkinson, 1998:2) is used. In the samples produced in this research the conductive threads (the mandrel) become encapsulated inside the copper deposit and remain inside the textile. My process could be described as electrofabrication. When the hybrid forms created in this research become rigid and self-supporting they are classed as electroforms rather than electroplating, as they are able to maintain their own form as a direct result of the metal deposit.

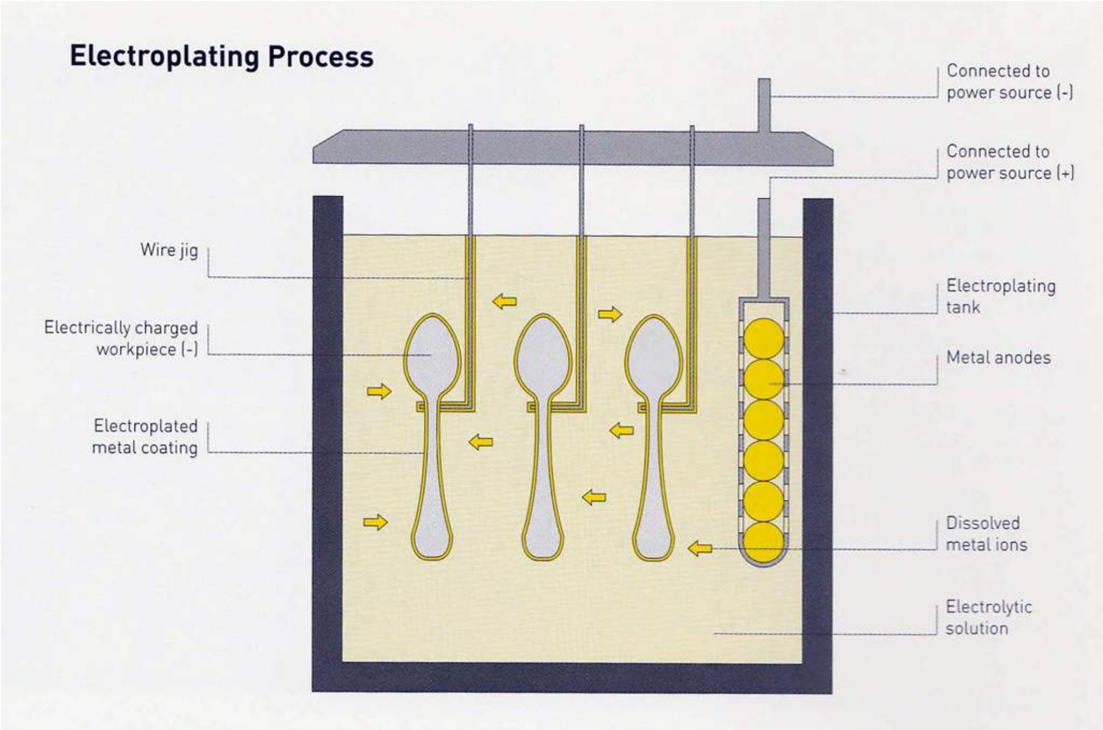

Figure 3.36: Rob Thompson, electroplating process diagram, (Thompson, 2007, p.365).

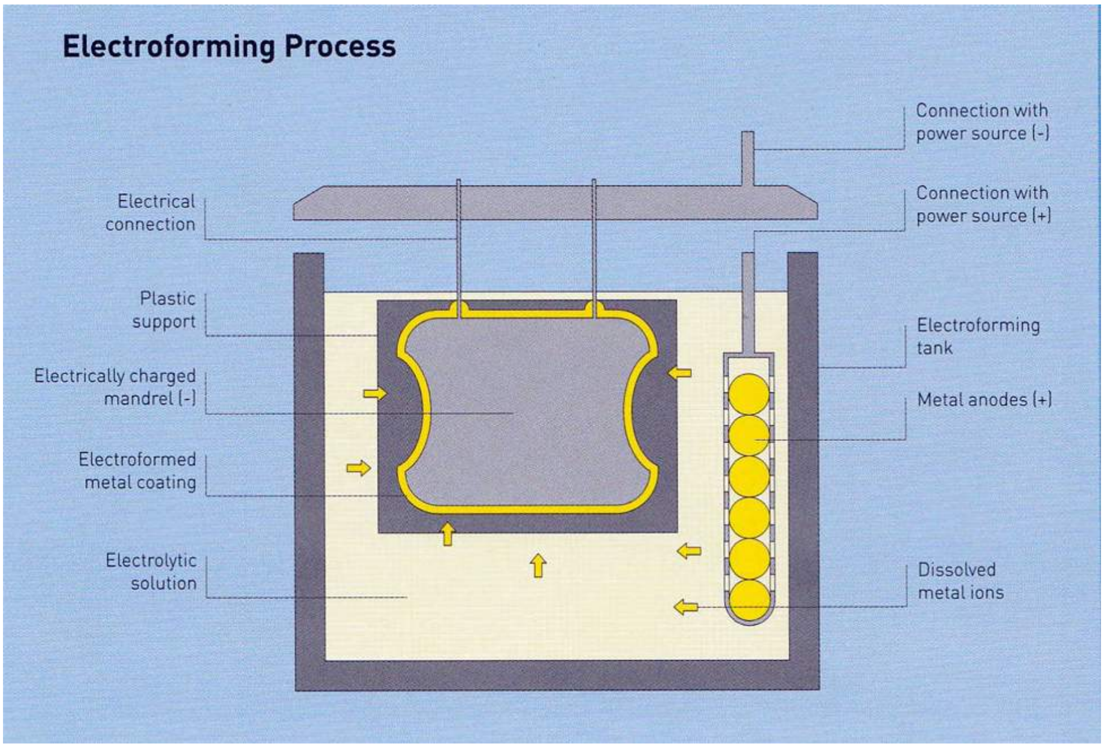

Figure 3.37: Rob Thompson, electroforming process diagram, (Thompson, 2007, p.141).

3.9.1 The importance of the shape of the mandrel in relation to electrodeposition.

The thickness of the metal deposit has an effect on the textile's character and form. The form of the mandrel affects the thickness and uniformity of the metal deposit (Kanani, 2006:76). As the current travels through the mandrel, the shape distorts the electrical field flowing through it. This alters the current density, affecting the size and thickness of the metal deposit. Current density is the measurement of electric current flowing across a material per cross-sectional area. Figure 3.38 (Kanani, 2006) demonstrates different current density in relation to the covering power [33] relating to mandrel shapes. In (a) and (b) there is a higher current density at the edges of the mandrels, as identified by the closer dashed lines representing the electrical current. This produces a thicker metal deposit. In image (c) there is a parallel field of resistance, which is impossible to achieve in practice due to the various factors that influence the metal growth during finishing (Kanani 2006:74).

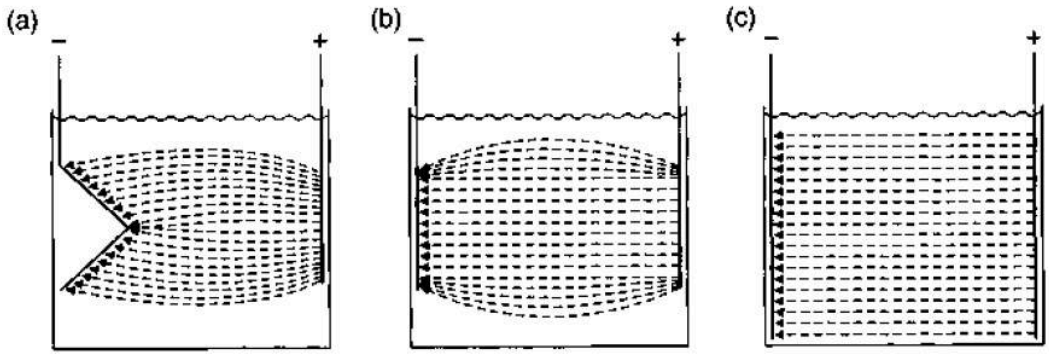

Figure 3.38: Kanani,'s diagram showing the different current density distributions in relation to the form of the mandrel, (2006, p.74).

The depth of recesses in the mandrel also influences the amount of metal deposited. High points within the shape of a mandrel, closer to the anode, create high current density areas. Recesses in the mandrel, further away from the anode, have a lower current density. The copper deposits more on the high current density areas than on the low current density areas (Kanani, 2006). In most engineering applications an even metal deposit is required to create consistency across the form created (Kanani, 2006). By controlling the uneven distribution of the metal deposition, it is possible to create both pliable and rigid properties within the same integral form. Different current densities can be artificially created by masking or

[33] The term 'covering power' is used to describe the 'extent to which an electrodeposition electrolyte can cover the entire surface of an object… with reasonably uniform thickness, including at least some deposition in the recesses and cavities' (Kanani 2006:73).

shielding areas of the form (for example, with plastic) to create different thicknesses of metal deposit in the same metal structure. Varying the current density during electrodeposition can enable the engineer/designer to design the material properties as required (Trzaska and Trzaska, 2008). Figure 3.39 shows my diagram of the high and low current density areas on a mandrel when using main tank anodes placed on the top of the mandrel. It also shows three ways to alter the current density and the thickness of the metal deposit, using either:

[redacted]

Image redacted.

Figure 3.39. My diagram of a mandrel indicating the high and low points of the form, illustrating different ways to affect the current density and subsequently the thickness of metal deposit upon the form during electrodeposition.

I have applied this characteristic of the uneven distribution of metal to my advantage. In this research it has been utilised to incorporate the textile characteristics of pliability. By controlling the current density in different areas of the form, the isotropic and anisotropic properties of textile and metal can be integrated in the same form by controlling the variation of the thickness of the metal deposit on the conductive threads. This is a novel way to use differences in current density relating to the form of the mandrel combined with textiles using electrodeposition. Case studies 3.2 and 3.3 in Chapter 4 demonstrate this process.

3.9.2 The process of electrodeposition used in this research

During this research the electrodeposition process was tailored to the specifications of my research aims. The following section details the finishing process from the perspective of my practical work. In the majority of the case studies the samples were attached to a frame-jig to hang in the tank. [redacted] (Figure 3.40).

Figure 3.40: [redacted] (the electrodeposition master) and I preparing samples on a frame-jig. Photograph by [redacted], 2018.

Bespoke jigs [34] that do not require a frame-jig [35] were used in Case study 3. If additional support was required:

- Tubes were inserted into the double-cloth fabric pockets.

[redacted]

The samples were tested for electrical conductivity before finishing to ensure consistency throughout the fabric, using a continuity tester, as seen in Figure 3.41.

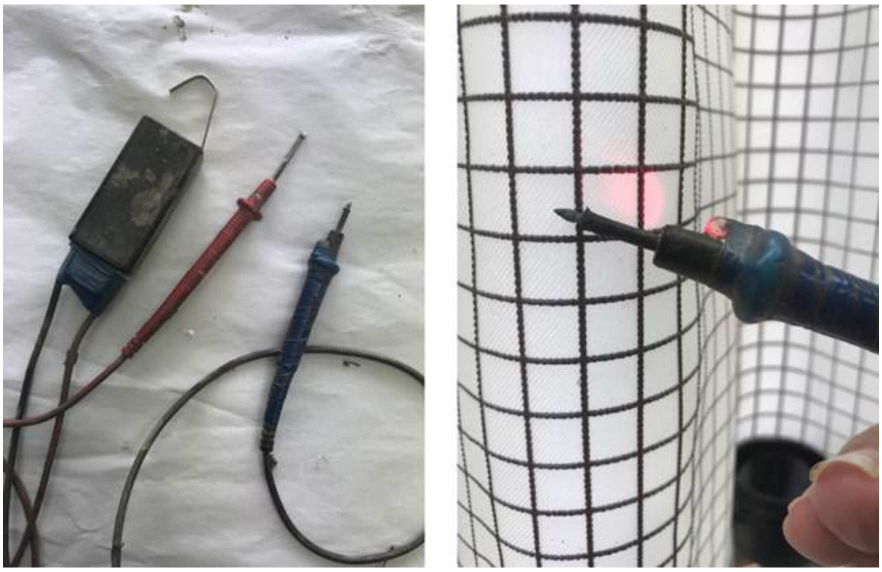

Figure 3.41: An electrical circuit continuity tester.

The conductive threads within the weave cross paths to form an integral conductive grid throughout the cloth. The electrical current travels across the entire structure of the fabric, which is evident as the metal is deposited across all of the conductive threads. The metal is deposited in a continuous form, as opposed to separate metal rods joined together, producing a net-shaped form.[36] Therefore, even if the metal deposit is not the same thickness across the form, it is part of the same continuous metal framework. The crystal structure grows precisely in the shape of the sample.

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[34] A bespoke jig is a support that is specifically designed to support the mandrel during electrodeposition.

[35] A frame-jig is a supporting frame that the mandrel is attached to during electrodeposition.

[36] A net-shaped form is a structure made from one single piece of material that is not cut or joined to create the form.

3.9.3 Controlling the metal deposition rate

Figure 3.42 shows an example of how the anodes were distributed in the tank in relation to the mandrel's form to concentrate the current in specific areas. The copper anode nuggets seen in Figure 3.43 transfer ions to the electrolyte.

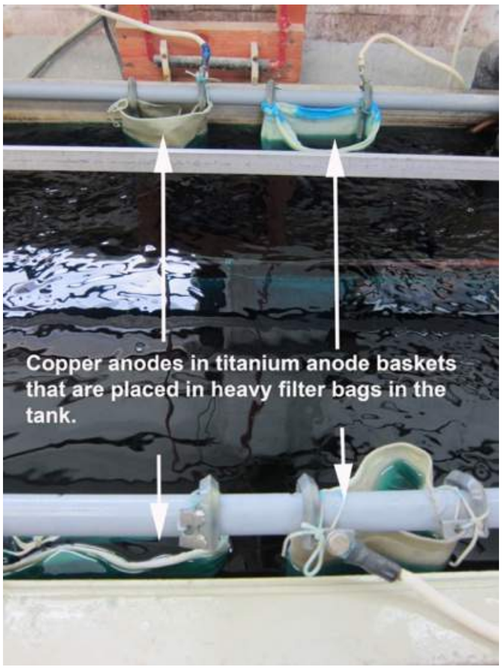

Figure 3.42: (Left) Four titanium anode baskets placed in heavy fabric filter bags.
Figure 3.43: (Right) Copper anode nuggets placed inside the titanium baskets.

Image redacted.

Figure 3.44: The mandrel on the jig is placed into the tank.

Figure 3.44 shows a separate bespoke jig rather than a frame-jig. The choice of jig relates to the shape and size of the mandrel.

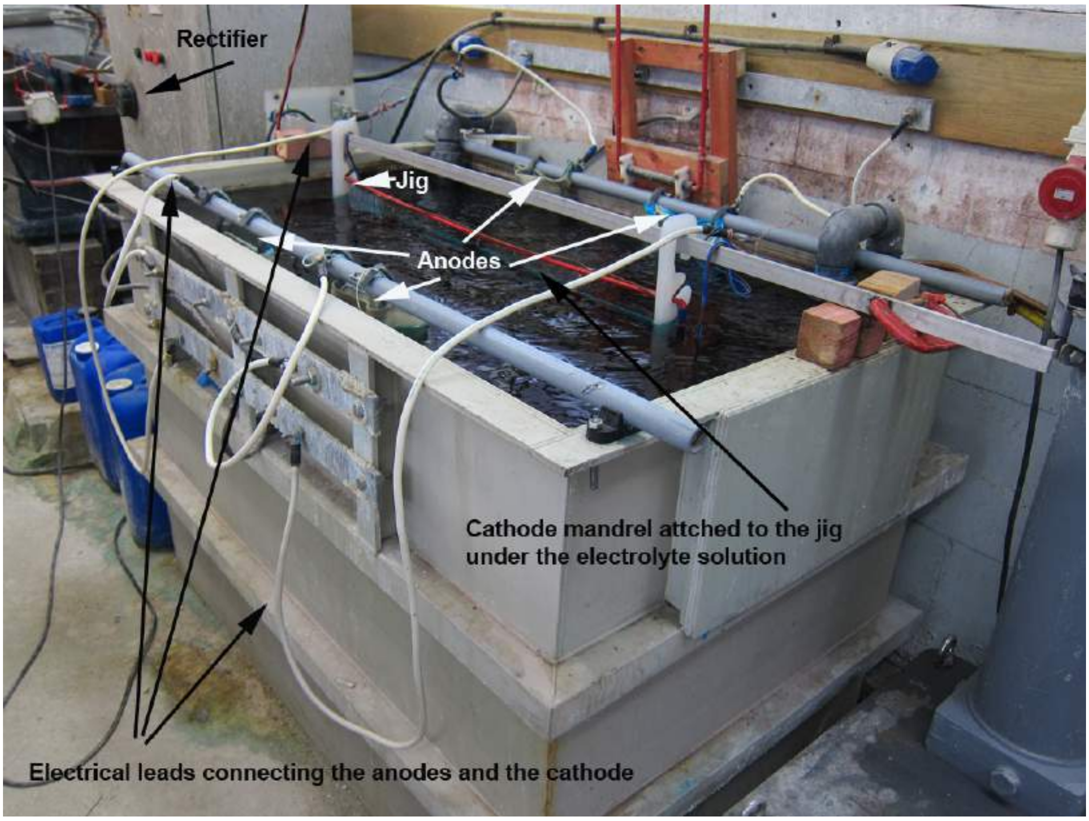

Figure 3.45: An electrodeposition tank with a frame-jig.

The rectifier converts the alternating current (AC) into direct current (DC). This connects the mandrel to the anodes via the electrolyte to complete the circuit (Figure 3.45 and 3.46).

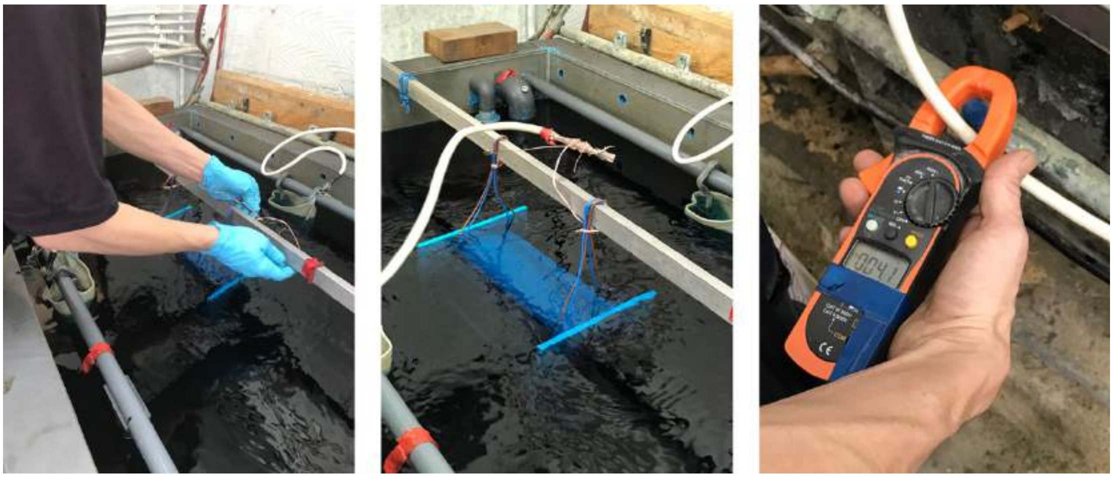

Figure 3.46: Technician attaching the electrical leads to the mandrel.

When the finishing process is complete the jig is removed, excess electrolyte is blown back into the tank with an air-compressor spray-gun to remove excess acid (Figure 3.47). It is placed in the wash-off tanks, then in a mildly alkaline neutralising tank and finally rinsed with water. No acid enters the waste water system.


Image redacted.

Image redacted.

Image redacted.

Figure 3.47: The washing off process.

Figure 3.48 over the page shows the full range of electrodeposition finishing methods that I have used to create the hybrid forms that are detailed in this section of the thesis. During my cycle of action research and reflective practice, additional choices where introduced to the flow-diagram as my electrodeposition knowledge increased. The colours in this diagram indicate that the number of options for finishing increased during the case studies. The yellow shows Case study 1 choices. Light blue shows the additional choices in Case study 2. Green shows the additional choices in Case study 3. The appropriate versions of this diagram will be used in Chapter 4 during the case studies. Areas shaded in the case study's colours will show the decisions made in relation to each sample.

The progression of the making choices during the electrodeposition finishing during the case studies due to action research and reflective practice

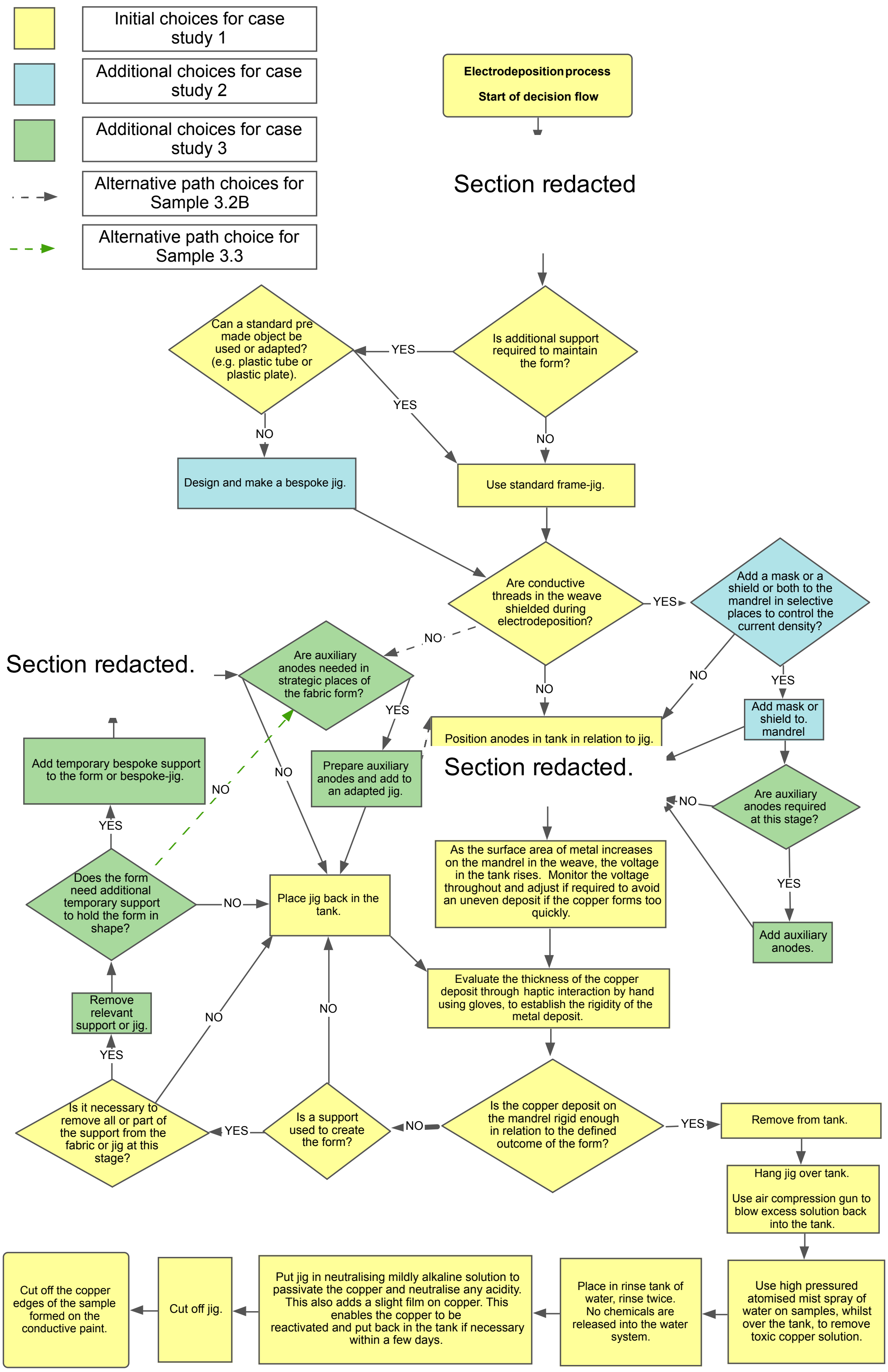

Figure 3.48: The electrodeposition decision flow-diagram used in my case studies.

3.10 Tri-space Roles

Although the main Design-make Tri-space led the making process I required another tri-space problem-solving approach which related to my roles within this research (Figure 3.49). I describe these as 'Tri-space Roles' which merge three established research roles into one:

- **Academic researcher:** developing the concept, problem-framing, finding solutions to the project's aims and evaluation.
- **Designer collaborating with Industry:** sourcing and building working relationships with a technical textile mill and a metal engineering company.
- **Apprentice:** as part of two-year apprenticeship with an electrodeposition specialist.

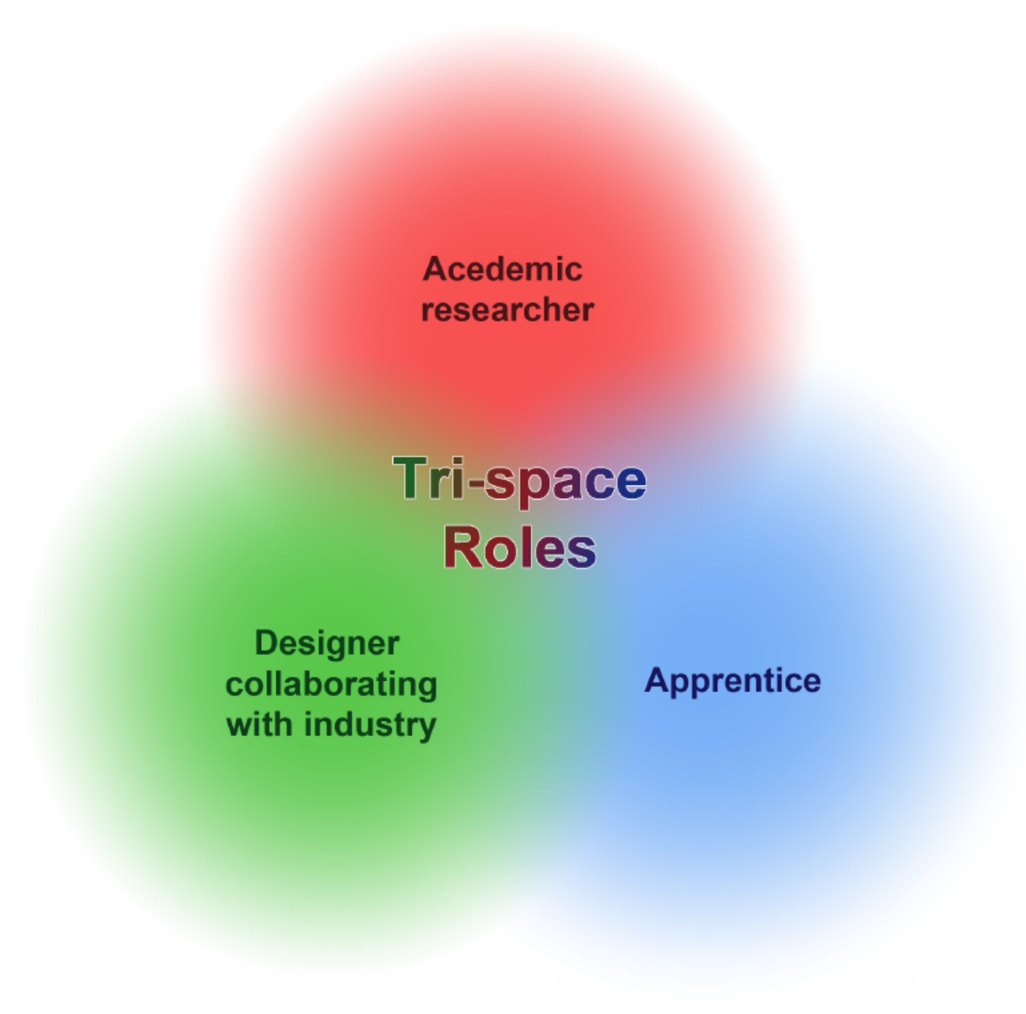

Figure 3.49: Diagram of my Tri-space Roles used during problem-solving.

The academic researcher role has been discussed in Sections 3.2-3.8 and the following sections describe the additional two roles within the Tri-space.

3.10.1 Designer collaborating with industry

At the start of this research I initiated collaborations with the mill and the metal manufacturers. This involved collaboration between me as a weave practitioner (design) with [redacted] Textiles weaving mill (industry) and [redacted] metal company (engineering). [redacted] Textiles Ltd. is a UK textile mill that specialises in high-performance technical textiles for applications in engineering, aerospace, protective clothing and filtration fabrics. Their technical expertise in weaving synthetic high-performance fabrics, combined with their experience of using conductive threads within warps, were important factors when choosing a mill for this collaboration.

Although I have used my experiences with the industrial collaborators to advance my research, I was the creative decision-maker throughout the process. I used this interaction to gain new knowledge of making that was necessary to achieve my aims. However, as stated in Sections 3.8.2 to 3.8.7, as a designer working with industry I had to adapt my designs to the parameters of the industrial weaving set up and the electrodeposition finishing process. These restrictions included the range of stock threads available for the warps, the number of shafts on [redacted]'s industrial looms, the warp EPI and the number of conductive threads across the warp. As discussed in section 3.8.6, when designing it was important that I considered how to thread each warp to enable several different weave structures to be woven on the same set-up. This was to effectively utilise each warp from a cost perspective and when working around [redacted]'s production schedules.

The emphasis of this research was on the design process and the physical outcomes of the experimentation. Therefore, it was not necessary to hand-weave the textiles to achieve the aims of this research. It was important to visit [redacted] to gain first-hand experience at the beginning of the practice in order to appreciate the technical restrictions of the industrial Rapier[37] dobby looms at the mill. During this research I undertook two three-day visits to [redacted]. In May 2016 I discussed my ideas with [redacted]'s Technical Director, [redacted], relating to the technical restrictions of their production set-up. In October 2016, I focused on sampling at the weaving mill. This was a key point within the research. It enabled me to plan a warp specifically for my designs, providing me with the opportunity to test ideas for the first time within the research and to weave a warp with a technician on the power

[37] A Rapier loom is a loom that uses mechanised finger-like grasping to transfer the weft across from one side of the loom to the other.

loom (Figures 3.50 and 3.51). Subsequently, weaving instructions were communicated remotely through further phone and email correspondence with [redacted] to discuss my new design ideas in relation to the parameters of [redacted]'s looms, as detailed in Section 3.10.3. Throughout the research significant time was spent in my studio researching, reflecting on the work and analysing the output. During the second and third year of this research I spent a considerable amount of time as an apprentice with [redacted] at [redacted]'s workshop. This is detailed in Section 3.10.4. Preparing and finishing the samples involved regular full-day sessions working on site.

[redacted] generously sponsored this research by offering me free access to facilities, the materials and technical advice, as the Technical Director saw promise in my initial samples and the potential for future collaborative projects. Due to their financial input, prior to commencing the research, IP agreements were signed to establish background intellectual property owned by both parties.

Figure 3.50: Photograph of me weaving at an industrial power loom. Photograph by [redacted], 2016.

Figure 3.51: [redacted] (Mill Technical Director) and I discussing weaving designs at the loom. Photograph by [redacted], 2016.

3.10.2: Communicating knowledge

My approach aligns with the knowledge-as-a-spectrum concept (Jasimuddin et al, 2005) that states that tacit[38] and explicit[39] knowledge are inseparable (Collins, 2013; Polanyi, 2009). Polanyi (2009) believes that all knowledge is generated from individuals' intuition. Tacit knowledge, which is located in the individual's mind, is hard to access. It can be described as fluid and unfixed. Explaining tacit knowledge and making it accessible to others is referred to as externalisation (Visser, 2006:117; Battistuttie and Bork, 2016:465). When tacit knowledge is made explicit, it is fixed and becomes 'crystallised' (Battistuttie and Bork, 2016:465). This is described as codified knowledge, which becomes accessible knowledge that can be shared easily (Lam, 2000).

Battistuttie and Bork's (2016) Life Cycle Model presents a methodology to convert tacit into explicit knowledge. They describe their model as a framework to manage knowledge acquisition that involves knowledge located in several individuals, such as within an organisation. It involves four stages: strategic planning of the project, initial modelling building, feedback model building and final model building. These stages form a spiral of tacit and explicit knowledge. When reflecting on my learning and problem-solving within this research I have made connections with Battistutti and Bork's (2016) Life Cycle Model: my adapted version of their Life Cycle Model is discussed further in Chapter 5 pages 214-215.

To enable mass-manufacturing, a designer's tacit knowledge needs to be made explicit and accessible. The communication of my somatic tacit[40] and collective tacit[41] textile knowledge to both collaborative manufacturers has been an important factor within the research. In Chapter 5 I discuss the impact of establishing a shared language of making (Collins, 2013:58-60) to facilitate the production of the practical samples. Collins (2013) has written extensively about how explicit and tacit knowledge are connected. To reduce the possibility of miscommunication Collins states that the recipient has to become fluent enough in the language to be able to

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[38] Tacit knowledge describes an individual's knowledge that is gained through physical interaction or experiences with materials or tasks. It cannot be communicated through written, drawn or spoken instructions, but has to be experienced.

[39] Explicit knowledge describes knowledge that can be shared and communicated through the written, drawn or spoken instructions, and does not have to be experienced by the recipient of the information.

[40] Somatic tacit knowledge is knowledge gained through the body and mind interacting with materials and processes.

[41] Collective tacit knowledge is domain-specific knowledge shared by a group of specialised people, (Lam, 2000).

adapt to social changes and circumstances. This relates to my interaction with the weaving mill's Technical Director [redacted] and my electrodeposition master [redacted] to establish shared languages. This was key to enable me to express my tacit information and to gain new information relating to their making processes that was necessary for my research.

3.10.3: The use of representations

Parallel processing was required when writing explicit production instructions to [redacted]. As established by Seitamaa-Hakkarainen and Hakkarainen (2001:63-64), an experienced weaver, unlike a novice, is able to progress design ideas to a more defined conclusion prior to weaving. The expert can imagine interacting with the textiles on the loom and the potential textile outcomes based upon experiential tacit somatic knowledge. This is an example of reflection-for-action, as it uses previous practitioner experience to inform the decision-making for new work.

When designing and communicating with [redacted] I have used my somatic tacit knowledge that relates to my previous experience of hand-weaving. These imprinted actions and the knowledge gained from handweaving enable me to anticipate the characteristics that changing technical weave set-ups can produce. Dormer describes this type of tacit interaction as a practitioner's 'three-way dialogue with the materials and the tools' (Dormer, 1997:147). This relates to Marchand's (2010a:109-111) description of motor-based, kinaesthetic actions[42] associated with interacting with a physical task involving materials. Once a handweaver has considerable experience, this knowledge can be used to design fabrics with proficiency prior to making. Dormer describes designers such as myself as having 'middle-aged wisdom' (Dormer, 1997:145). Utilising this experiential tacit knowledge, experienced weavers can generate and communicate explicit knowledge by recording elements of their design process. This type of knowledge is referred to as 'distributed knowledge' (Dormer, 1997:139). I was unable to be present at the mill for each warp, due to its geographical location and [redacted]'s production schedules. Therefore I used written instructions and CAD diagrams using Weavepoint software (Myhre, 2018) as forms of 'representations'[43] (Visser, 2006:115) to communicate design instructions, as seen in Figure 3.52.

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[42] Kinaesthetic actions describe hands-on interaction with materials and equipment.
[43] Representations are written or drawn instructions to communicate the making process to enable someone else to create a designer's ideas.

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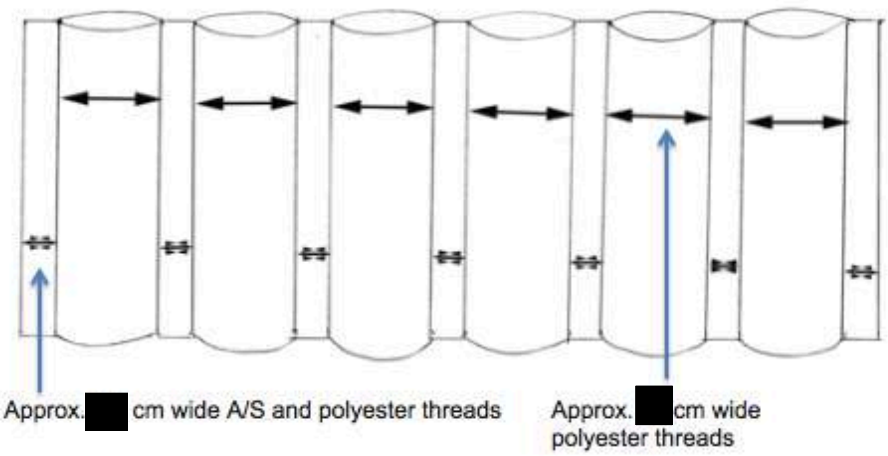

Figure 3.52: An example of a representation I provided to the mill (see Section A2 of the Appendix for full-scale images and further examples).

This use of representations enabled the transformation of my tacit knowledge into explicit knowledge. The disadvantage of using representations to communicate is that it omitted the possibility of interacting with the design process during the production of the cloth. This removed the spontaneity that is possible when handweaving or working directly with an industrial loom in real time.

3.10.4 Apprenticeship

Using cognitive and haptic interaction whilst learning in close proximity to a specialist is an effective way to gain new knowledge as a craft practitioner (Coy, 1989). In the context of this thesis the term 'apprenticeship' aligns to the craft guild model of an apprenticeship where a 'novice' spends a significant amount of time under the instruction of a ‘master’ in order to gain proficiency in a material process such as weaving, woodwork, ceramics or metalwork (Coy, 1989; Marchand, 2008; Sennett, 2009; Greene, 2012). In this type of apprenticeship, the transfer of new knowledge is a one-way exchange directed from the master to the novice.

Lave and Wenger’s (1991) concept associated with situated learning focuses on the impact that social and environmental contexts have upon learning. They present the term ‘legitimate peripheral participation’ (LPP) to describe engagement in social practice, in which learning is an integral part (Lave and Wenger, 1991). Like Schön’s, their theory centres around the idea that cognition and action are interconnected. Lave and Wenger’s theory maintains that the act of doing is essential to fully understanding a task. If all learning takes place solely in the mind, the participant only has a theoretical view of the situation, not a practitioner’s view. This may prevent full mastery of the task. Lave and Wenger’s (1991) case studies focus on the nature of learning within apprenticeships. Lave and Wenger’s (1991) research has been criticised for being ‘too culturally bounded and less relevant to the contemporary world’ (Patel, 2017:39). However, it is still cited by practitioners and academics (Patel, 2017). Greeno and Moore (1993) developed Lave and Wenger’s Situated Learning Theory (SLT), creating the term Situated Theory (SIT), which combines situated cognition (thinking) and situated action (doing). Visser (2006) explains that SIT allows for an analysis of design that is more specific than Simon’s (1969;1996) interpretation, that states that problem-solving is not context-specific. Visser (2006) cites Schön’s reflection-in action and knowing-in action as examples of SIT. These are types of contextual research that use concrete experiences and reflective practice to transform thinking (Kolb and Kolb, 2018:8-9). My tri-spaces demonstrate a SIT approach (Greeno and Moore,1993; Visser, 2006), as they utilise over twenty years’ experience of designing weave as a practitioner whilst working with industrial manufacturers. When framing and interacting in the tri-spaces I have used my experienced weaver’s knowledge to inform my industrial collaboration with the weaving mill and my use of the metal process during my electrodeposition apprenticeship with [redacted], which is discussed further in Chapter 5. This use of reflective practice within the tri-spaces combines my practical engagement with both materials and specialists with my own cognitive processing and problem-solving.

Explicit knowledge of electrodeposition was essential to this research. This was acquired through text-based research into conventional uses of electrodeposition and through my apprenticeship. Due to the innovative nature of this research it was not possible to find explicit guides relating to the specific use of the metal process using my woven textiles. The electrodeposition literature I encountered focused on engineering processes (Kanani, 2006; Bicelli et al, 2008), surface applications on textiles, as detailed in the context review on pages 44-49, and jewellery making (Peck, n.d.; Corti, 2002; Frenchette, 2004). Although this informed my general knowledge of electrodeposition, additional information about the metal process was required to provide a more specific application of the finishing process to my research context. Therefore, I used a personalisation strategy (Hansen et al., 1999; Connell et al., 2003) that refers to gaining knowledge that has been developed by an individual (Jasimuddin et al., 2005:105). This enables 'creative, analytically rigorous advice on strategic problems by challenging personal expertise' (Jasimuddin et al, 2005:105). As many of the processes used at [redacted] have been developed by [redacted] and not documented, the apprenticeship was the most effective way to gain from his extensive knowledge. Throughout the research I have used discussions with [redacted] and extensive photography to document the making process and to aid reflective evaluation.

In a traditional guild model of apprenticeship, the apprentice receives instructions and their task is to become proficient by replicating their master's actions and skill (Coy,1989; Marchand 2008; 2010a). There are three stages of knowledge acquisition during an apprenticeship. Stage one, the cognitive stage, relates to gaining initial understandings of the process. Stage two, the associative stage, is when the apprentice explores the process using experiential practice combined with their cognitive understanding. In this stage, mistakes are identified and corrected. Stage three is the autonomous stage, when the apprentice has developed their skills to an expert level (Greene, 2012). During my electrodeposition apprenticeship I moved through Stages one and two, and I have begun Stage three. Chapter 4 documents my progress as I become more autonomous throughout the case study explorations in relation to my electrodeposition skills. This conforms to a traditional apprenticeship learning model.

Discipline-specific language can create a barrier when working in cross-disciplinary research (Schön,1991). Therefore, my acquisition of new explicit and tacit knowledge was important to acquire sufficient fluency in the electrodeposition language to be able to apply the process effectively in the Design-make Tri-space.

Collins (2013:21), when describing communicating knowledge, uses the analogy of attempting to jump across a gap between two buildings. If the gap is small it can be jumped successfully. However, if the gap is too wide, communication will not be achieved unless ‘enabling conditions’ (Collins, 2013:21) are used to modify the situation. My discussions with [redacted], combined with my weave instructions (representations), and my apprenticeship were enabling conditions within this research to bridge this gap in knowledge.

3.11 Methods overview

My conceptual framework informed the construction of my methodology and tri-space frameworks used throughout this research. The tri-space frameworks and the decision-flow diagrams aim to provide useful tools when working within non-routine unstructured iterative experiential design cycles, using reflective practice during materials innovation. My hypothesis is that using an integrated approach using my tri-spaces would enable a holistic problem-solving space to emerge leading to innovation. A sequential research method (to design the weave and then consider the electrodeposition finishing process) was discounted, as it would not give the opportunity to consider the interplay between the design-make decisions in unison. My methodology was refined during the research as the impact that the tri-spaces have upon the research became more apparent, which is discussed in Chapter 5. This research draws upon Schön’s research which focused on product designers, architects, town planners and engineers. Although he considers how practitioners work when problem framing, solving and interacting with each other, he has been critiqued for not considering the context that created the environments for reflective practice (Usher et al 1997:147). My research remit does not attempt to explore an in-depth social context behind the material development. However, this research extends Schön’s ideas relating to reflective practice, as it introduces aspects of context through the interaction between a practitioner during collaborative research with an industrial mill and a master during an apprenticeship. This research uses a weave textile practitioner material focused inquiry which neither Cross (2007) or Schön (1991) include in their studies and considers how parallel thinking facilitates reflective practice during interdisciplinary weave and electrodeposition research.

Figure 3.53 identifies a more detailed overview of the iterative stages of problem-solving when using action research than the methods overview (Figure 3.2). It demonstrates how the Tri-space Roles were used as part of the research stages.

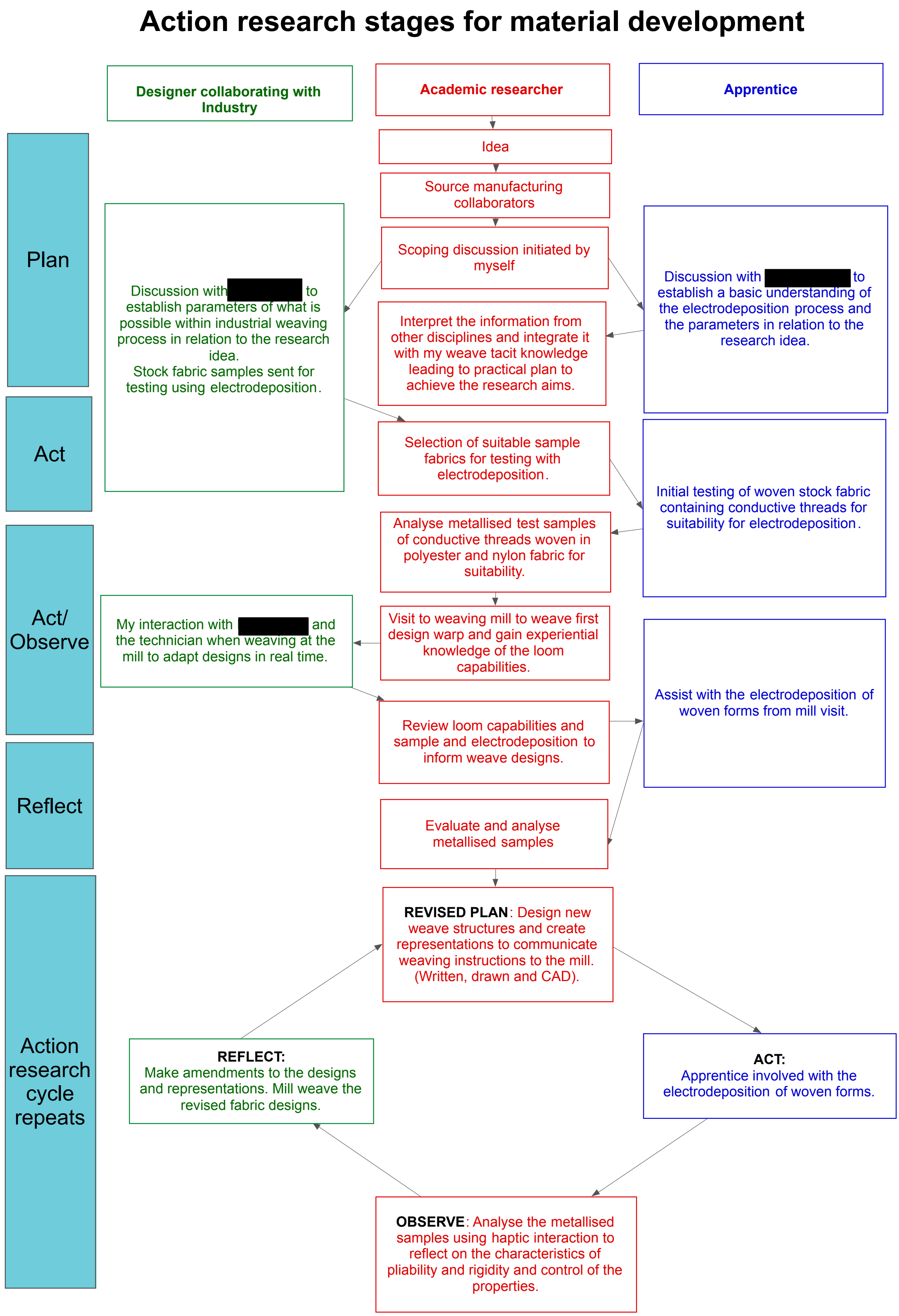

Figure 3.53: A diagram of my iterative reflection on, in and for action during action research.

Chapter 4 Practical Case Studies

4.1 Introduction

Chapter 4 documents the details of a series of design iterations that illustrate my problem-solving approach using the tri-spaces. Three practical case studies explore the relationship between the rigid integral metal frameworks within the woven fabric, the pliable base fabric and three-dimensional structural form. The following case studies document the making process used to construct my hybrid forms.

Making processes used:

- Design of the woven textile using my Design-make Tri-space.
- Industrial textile looms (power loom dobby weaving).
- Engineering processes (electrodeposition).

Initially a range of sampling was undertaken to explore how the electrodeposition process deposited upon the threads. This included varying the spacing and positioning of the conductive threads within the woven fabric in relation to the finishing. These are documented in technical notes that accompany the practical samples. Further sampling was developed and three case studies were selected for the thesis that focus on different making approaches. Decision flow-diagrams (detailed in Chapter 3) document the different paths chosen in the sequences of weave design and finishing for each sample detailed in each case study.

Case study 1: single-cloth was combined with Lycra weft threads to create the form. The weave structure and the choice of threads were the main influences on the creation of the form.

Case study 2: integral woven double-cloth pockets were combined with single-cloth. The weave structure created the form which was supported by the use of plastic tubes to hold open the woven pockets during finishing.

Case study 3 uses a single-cloth fabric. The focus was the importance of the use of bespoke jigs in relation to the textile to create form.

As described in Chapter 3, I designed the warps to create several samples across the width of the cloth using blanket warps and block threading for efficiency.

Throughout the practical research several warps were developed and metallised. Further details of the threading can be found in the section A2 of the Appendix. The weave structures and sections of the threading are provided for each sample within this chapter.

4.2 Key to abbreviations in the text and diagrams used in the case studies

Diagram Key:

Single cloth

Red	Polyester warp
Grey	Polyester warp in-between conductive threads
Green	Polyester weft
Dark blue-grey	A/S conductive threads
Light blue	Lycra

Double cloth:

Red	Polyester warp 1 threads
Dark green	Polyester warp 2 threads
Red	Polyester weft 1 threads
Light green	Polyester weft 2 threads
Dark blue-grey	A/S conductive threads
Light blue	Lycra

Figure 4.1: Key to my weaving notation diagrams.

In the representations sent to [redacted] (as detailed in each case study), the abbreviation 'A/S' was used to describe the conductive [redacted] threads as they are referred to as anti-static threads by [redacted]'s technicians. To assist communication, I coded the weave structure lifting plans on each warp. These codes are documented on the representations sent to [redacted] within the figures in this chapter. Weavepoint software was used, alongside written and drawn representations. The plain weave on shafts one and two in the representation diagrams has been used to weave the selvedge on the edge of the fabric. It does not contribute to the design of the samples, as it was cut off after weaving. When describing the design and making process, unless otherwise stated all creative decisions and processes were made by me during the case studies. My electrodeposition master [redacted] aided the making process by providing the technical input when making the bespoke jigs, but this was in relation to my design specifications.

4.3 Case Study 1: Using woven structure and Lycra threads to create form

Introduction

Block threading was used to enable Lycra weft threads to float over separate sections in the warp axis. When released from the loom the Lycra contracts, as it is no longer under tension in the weft axis. This creates integral pleats.

Aims:

- To create form using Lycra threads within the weave structure in relation to the metal finishing process.
- To create a rigid framework using the metal finishing process but maintain elements of the pliable fabric properties within the samples.
- To experiment with Lycra using the mill's production facilities. [redacted] had not used Lycra before, as their focus is to create flat 'non-crimped'[44] technical textiles[45].

Objectives:

- To use Lycra weft thread sections in combination with block threading to create three-dimensional form when the textile is removed from the loom.
- To use the electrodeposition process to set specific areas of the form into rigid shapes to create self-supporting three-dimensional form.
- To explore placing conductive threads in either both axes or one axis, to compare the pliable textile properties within the draped fabric between the rigid framework.

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[44] 'Crimp' in industrial weaving terminology refers to an uneven tension across the woven fabric.

[45] The mill's Technical Director [redacted] had concerns that [redacted]'s looms would have technical problems due to the higher tension created by the Lycra. I aimed to explore a new approach within the scope of [redacted]'s industrial manufacturing parameters to achieve my aims.

Summary of Design-make Tri-space decisions

Composition:

- Shape: The textile forms were designed to have an organic irregular appearance using the drape of the textile to influence the form.
- Materials: [redacted] dtex polyester and [redacted] 2-ply [redacted] threads.

Construction:

- Weave structures:
  - Single-cloth (Samples 1.1, 1.3, 1.4 and 1.5).
  - Double-cloth (Sample 1.2).
  - 2/2 twill.
- Procedure: Using Lycra weft threads in strategic places to enable the creation of three-dimensional metallised forms beyond the orthogonal woven grid of the fabric.

Finishing:

- Form creation: the form was created by the weave structure. Samples 1.3, 1.4 and 1.5 required a plastic plate support sewn to the edges of the samples to evenly tension the samples on the frame-jig.

The Design-make sequence for samples in Case Study 1

- Design the weave structure using block threading to place active Lycra threads in floats across the surface of the single-cloth or double-fabric structure. Warp 2 was used for Samples 1.1 and 1.2, Warp 3 was used for Samples 1.3, 1.4 and 1.5.
- Weave fabric at mill.
- Cut up samples and prepare for finishing.
- Place on a frame-jig at the metal workshop.
- Metallise samples without manipulation during electrodeposition.
- Evaluate the rigidity of the metal deposit by haptic interaction during finishing.
- Remove samples from the frame-jig when the required properties are achieved.

[redacted]

Sample 1.1: Weaving plan and design stage: single-cloth 2/2 twill 6cm sections with Lycra floating

Planning the weaving set up and materials

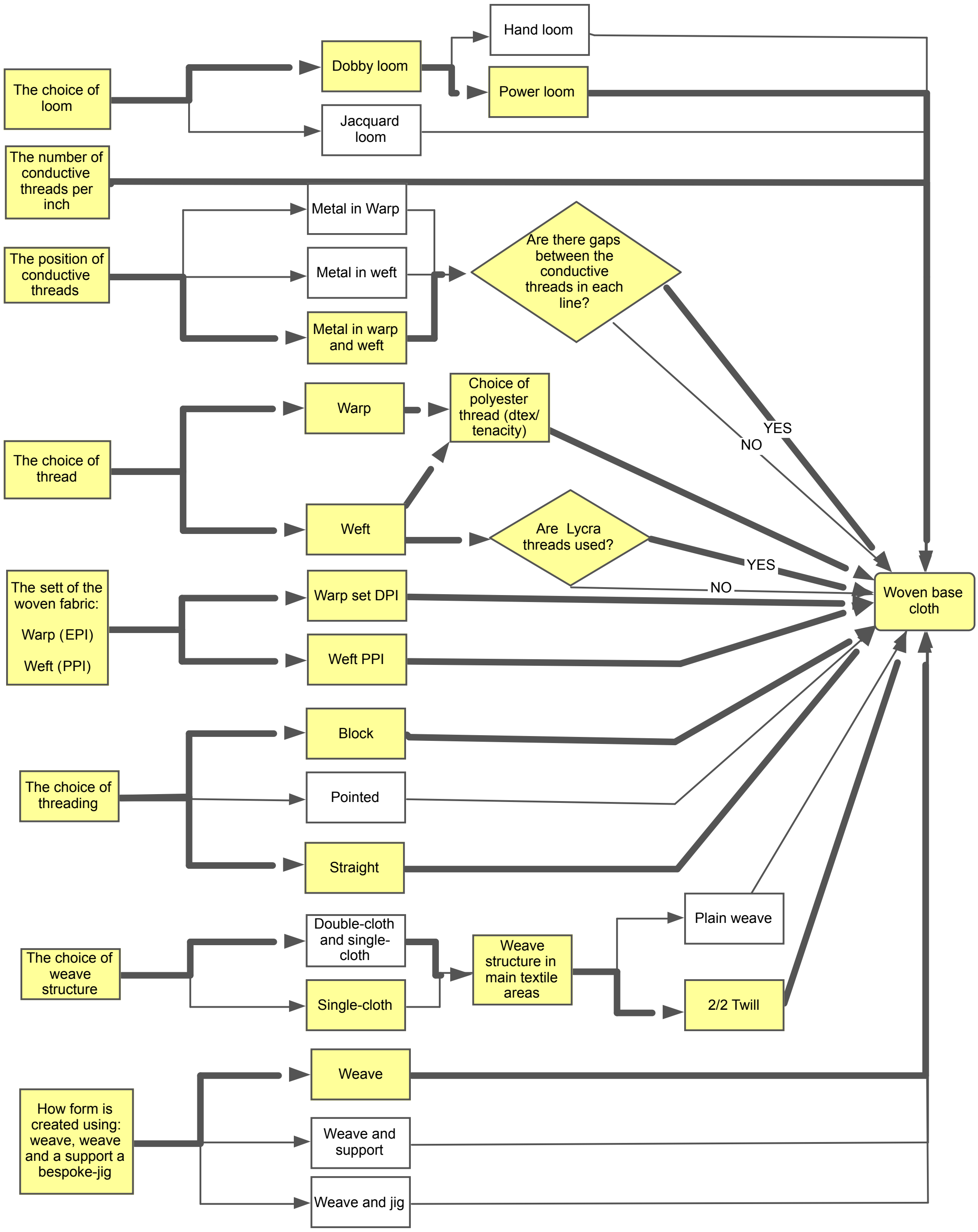


Figure 4.2: The sequence of my weave design choices relating to Sample 1.1.

Sample 1.1

Single-cloth 2/2 twill 6cm sections with weft Lycra floating on one surface of the cloth to create integral pleats.

Design process and communication

Figures 4.3A and 4.3B show the weft weave representations sent to [redacted].

Image redacted.

Figure 4.3A: A section of my instructions sent to [redacted] for Sample 1.1.

Image redacted.

Figure 4.3B: My weave notation for Sample 1.1. The light blue colour shows the Lycra floating across the metal lines in the warp section and weaving in the polyester section on the right.

Finishing Samples 1.1 and 1.2

Figure 4.4 shows in yellow the sequence taken in the decision flow-diagram relating the choices during the electrodeposition process for Samples 1.1 and 1.2. The Samples were placed on the same frame-jig for consistency of metal deposition.

Finishing Samples 1.1 and 1.2

Case study 1 making choices during the electrodeposition finishing process

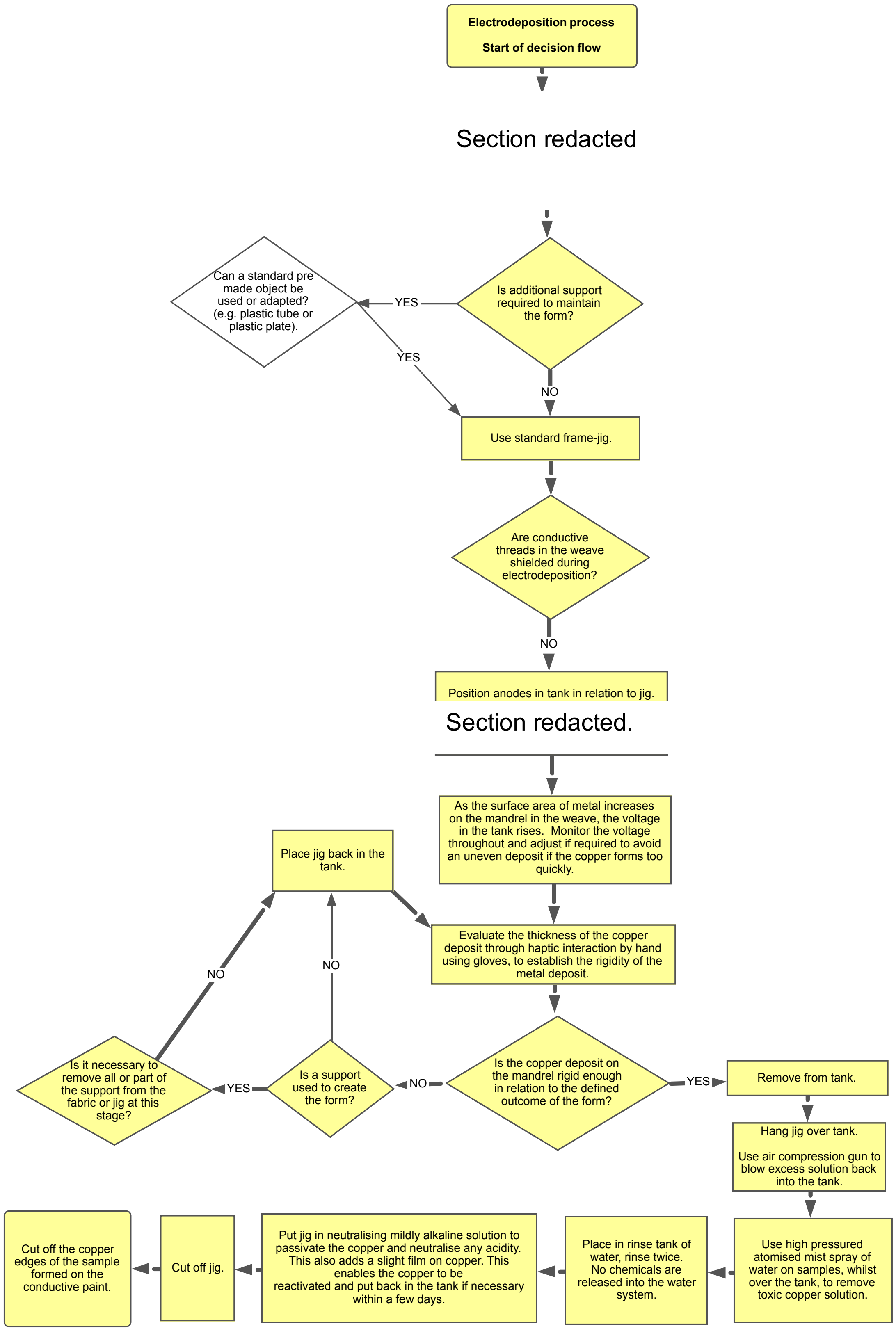


Figure 4.4: The finishing flow-diagram for Samples 1.1 and 1.2.

Finishing process for Sample 1.1

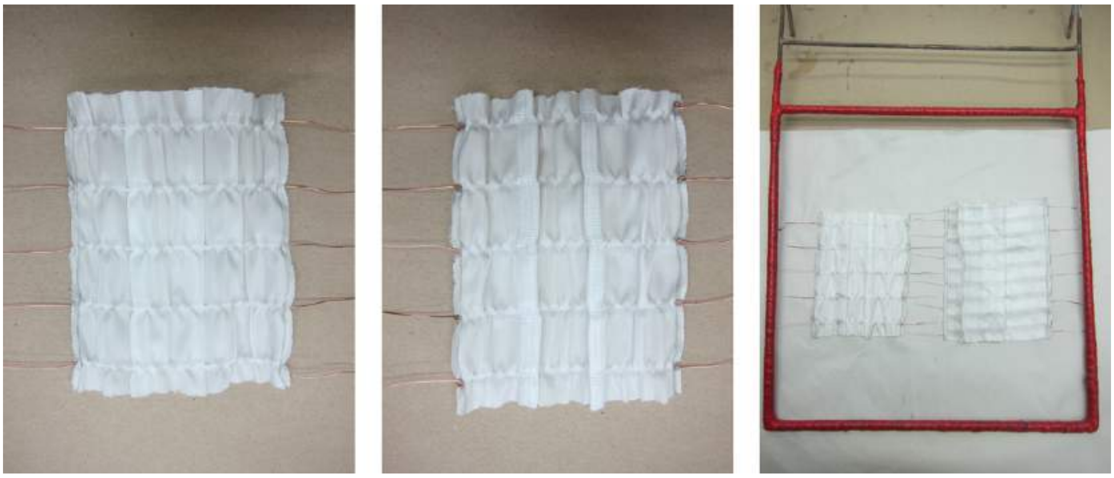


Figure 4.5: Preparing the sample and placing on the frame-jig.

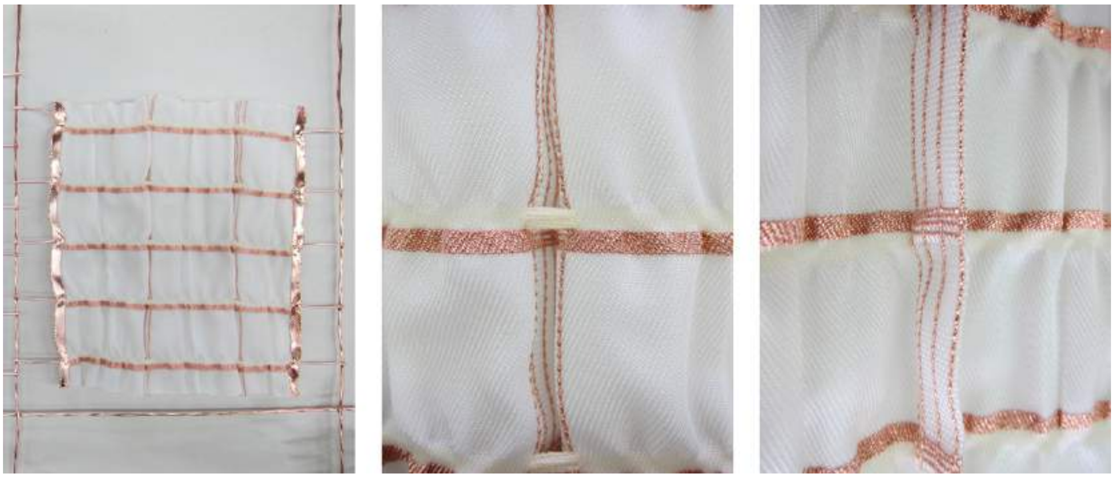


Figure 4.6: The sample once it had been removed from the tank for my inspection after initial metallisation to determine rigidity.

Figure 4.7: Final 1.1 sample.

Analysis of outcome from Sample 1.1

- The Lycra created rigid pleats on one side of the fabric. The metal deposit has given structural stability and rigidity to the pleats, creating a self-supporting form. The pleats can be expanded when gently pulled apart by hand and contract once released.
- The metal lines within the weft are more rigid than the warp metal lines as they are wider and do not have gaps between the conductive threads.
- The Lycra discoloured slightly, due to the acid in the tank; however, it maintained its elastic properties.
- The fabric areas remain pliable and can be manipulated between the metal frameworks in the larger bands across the weft axis.
- The Lycra in the weft created a puckered effect in the textile areas in the cloth.

Sample 1.2: Weaving plan and design stage: double-cloth 2/2 twill 6cm sections with Lycra floating inside the double-cloth pockets to create form

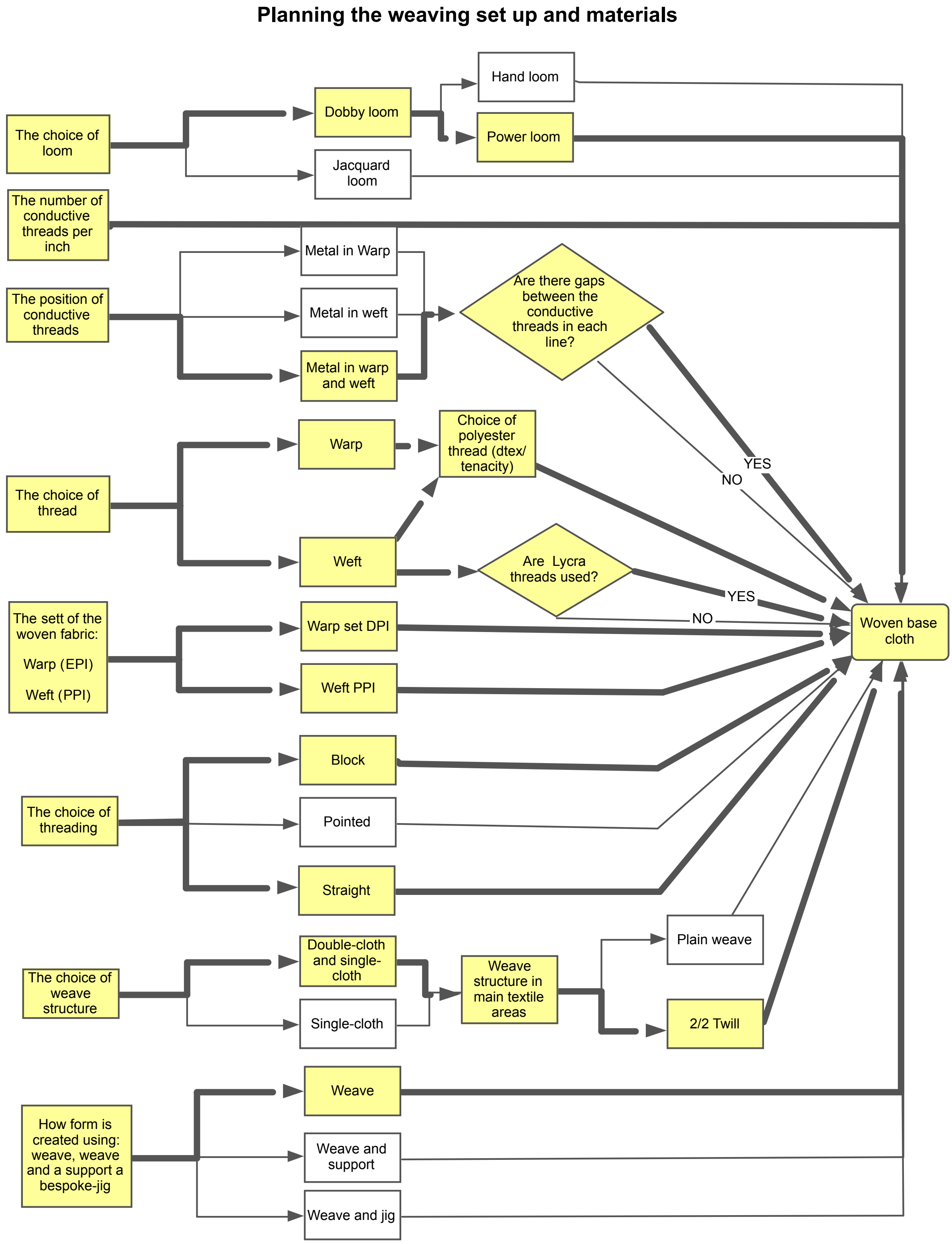


Figure 4.8: The weave flow-diagram for Sample 1.2.

Design process and communication

Weft weave structure representations sent to [redacted] are shown in Figures 4.9A and 4.9B.

Image redacted.

Figure 4.9A: My representations for Sample 1.2.

Image redacted.

Figure 4.9B: My representations for Sample 1.2.

As in Sample 1.1, the Lycra weft thread was woven at high tension across the warp. When removed from the loom the Lycra contracted in the areas where it floated in the weave structure. This pulled the polyester double-cloth sections together, creating vertical pleats on the front and back of the cloth. This is demonstrated by the mill's Technical Director [redacted] in Figure 4.10.

Image redacted.

Figure 4.10: [redacted] demonstrating the stretch of the Lycra in the double-cloth pockets in Sample 1.2. Photograph by [redacted], 2017.

Finishing process for Sample 1.2

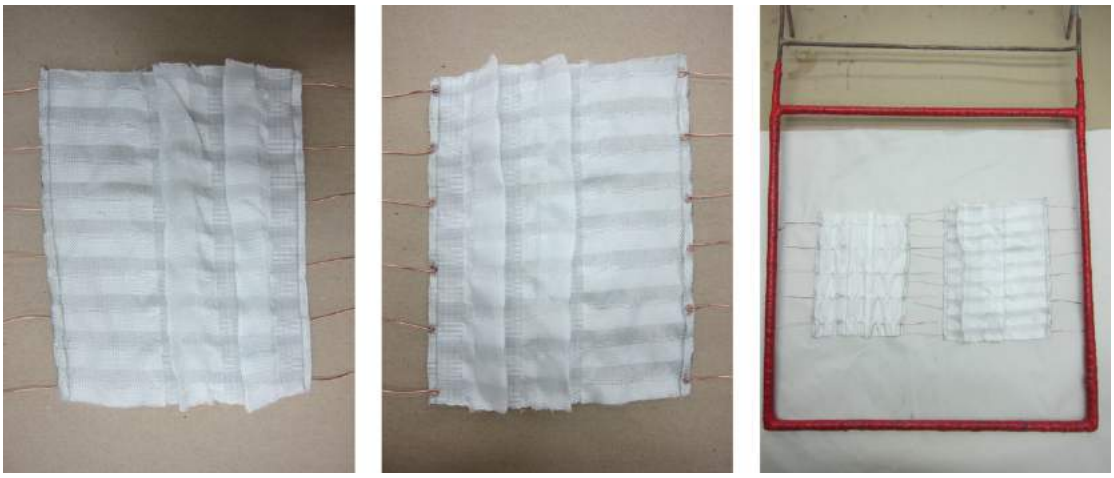


Figure 4.11: Preparing Sample 1.2 and placing on the frame-jig.

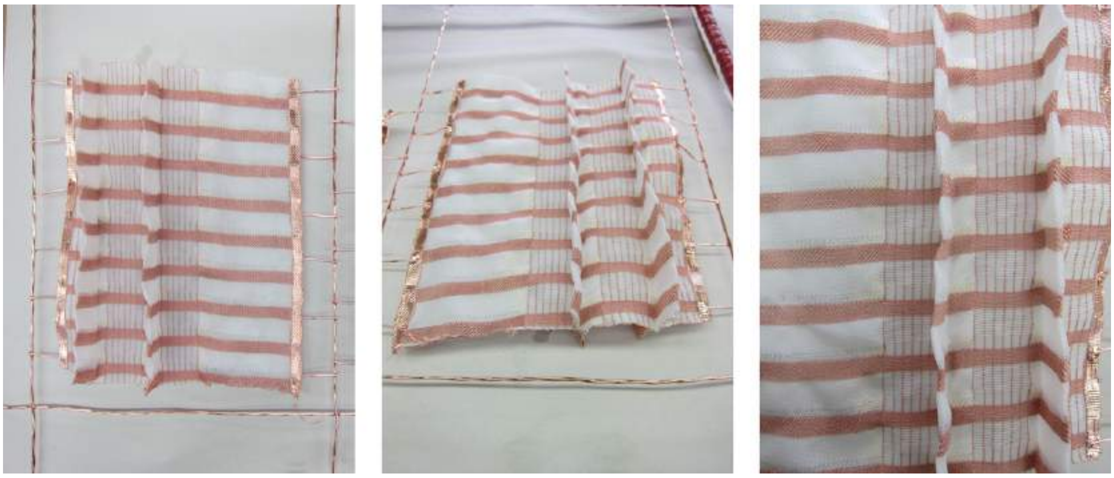


Figure 4.12: The sample removed for my inspection after initial metallisation to determine rigidity.

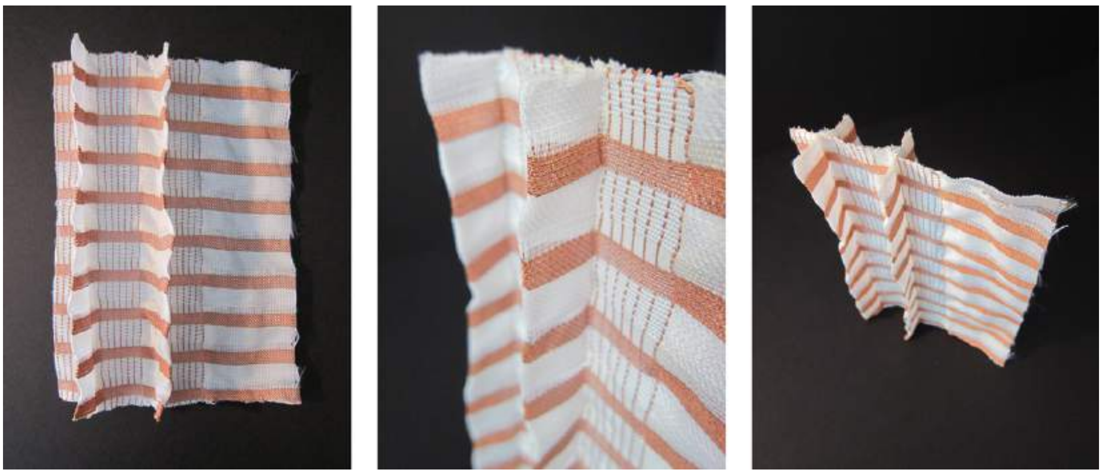


Figure 4.13: Final 1.2 sample.

Reflection-on-action: Analysis of outcomes from Sample 1.2

- The metal deposit has given structural stability and rigidity to the pleated form to enable it to become self-supporting.
- The Lycra floats across the middle of the inside of the double-cloth pockets, creating pleats.
- Where the conductive thread in the pleated sections touched, the metal joined to create a single-cloth. This increased the structural stability of the form.
- As the Lycra threads are woven within the weave structure between the two cloths, the discolouration is not visible on the exterior of the fabric.
- The fabric is more uniform in appearance than Sample 1.1 due to the conductive warp bands remaining flat.
- The metal deposit on either side of the double-cloth Sample 1.2 is not as rigid or thick as the single-cloth Sample 1.1. Therefore the conductive areas are more pliable, despite being placed on the same frame-jig as Sample 1.1 for the same amount of time.
- The gaps between the conductive threads in the warp allow for pliability when combined with the reduced metal deposit on the threads.

Amendments to Case studies 1.1 and 1.2 after reflection-for-action for Samples 1.3, 1.4 and 1.5

- In Samples 1.3, 1.4 and 1.5 the Lycra threads [redacted] The aim was to create a more pleasing visual aesthetic, as the Lycra slightly discolours during the process. It was hoped that the metal deposit would fully encapsulate the nylon Lycra. It also aimed to create a more integrated structure between the Lycra threads and the metal deposit.
- The conductive threads in the warp were placed in one line, with no gaps to create a more rigid structure, with fewer conductive threads than Samples 1.1 and 1.2. Warp 3 was used for Samples 1.3, 1.4 and 1.5.
- The samples were block threaded to create alternate Lycra floats to create an increase in the fluid drape to the pliable textile areas in the structure. Reverse straight block threading was used to create a diagonal drape either side of the conductive threads.

[redacted]

Weave design sequence for Samples 1.3 and 1.4

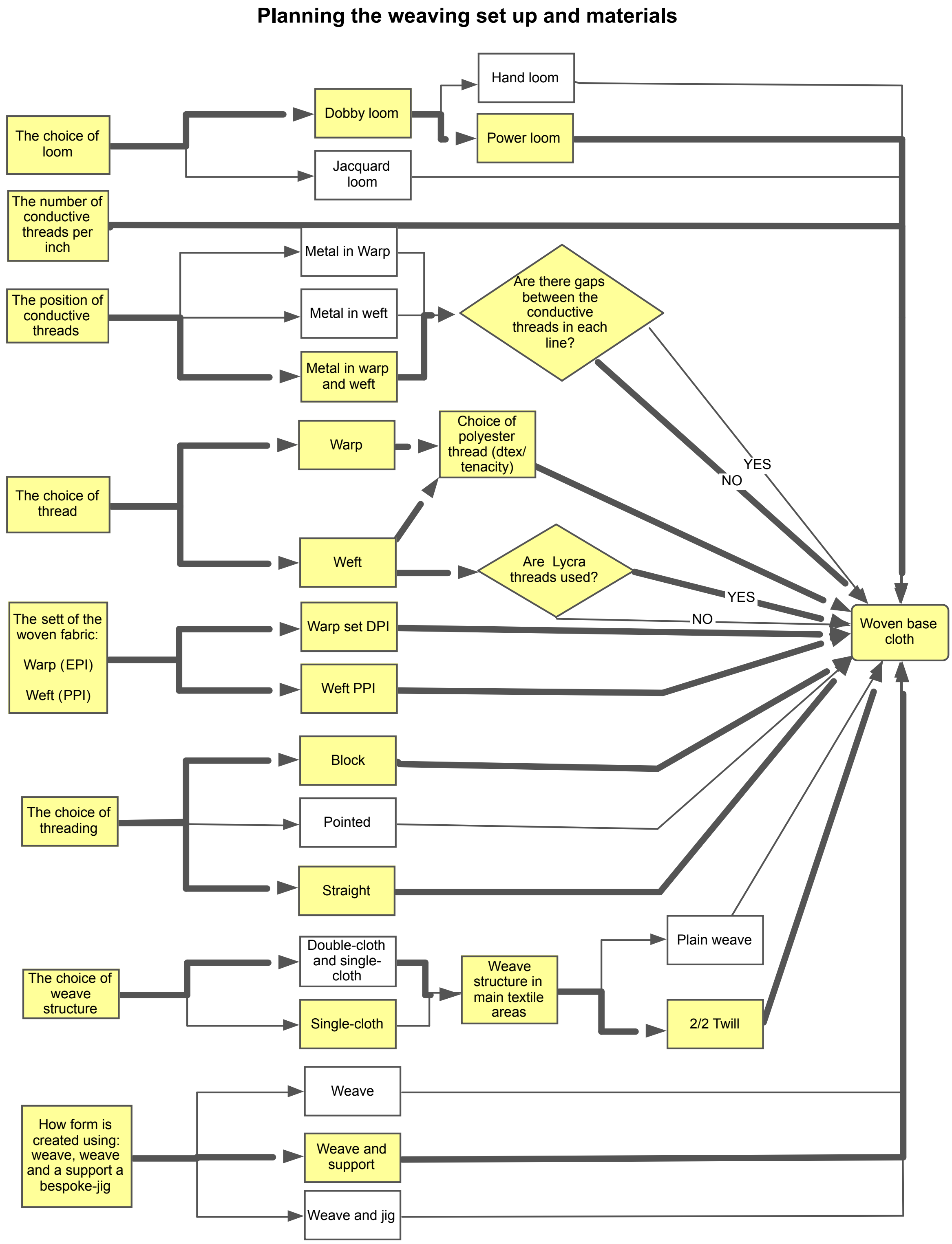


Figure 4.14: The weave flow-diagram for Samples 1.3 and 1.4.

Sample 1.3: Lycra floating on one side of the fabric with metal in both axes

Design process and communication

The weave structure representations sent to [redacted] are shown in Figures 4.14A and 4.14B.

Image redacted.

Figure 4.15A: My representations for Sample 1.3.

Image redacted.

Figure 4.15B: My representations for Sample 1.3.

Finishing Samples 1.3, 1.4 and 1.5.

Figure 4.16 shows the sequence taken in the decision flow-diagram relating to the choices during the electrodeposition process for Samples 1.3, 1.4 and 1.5.

Case study 1 making choices during the electrodeposition finishing process

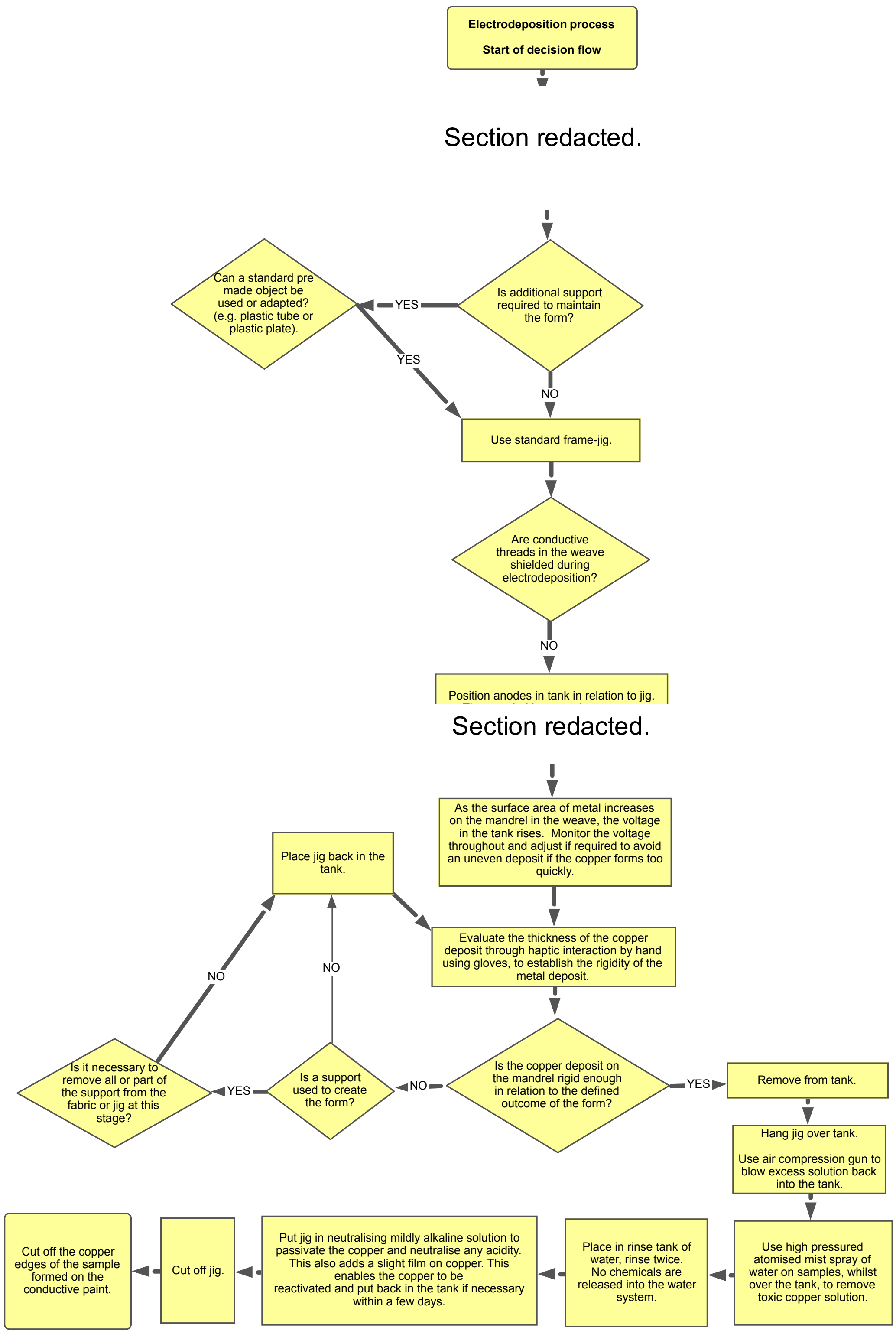


Figure 4.16: The finishing flow-diagram for Samples 1.3, 1.4 and 1.5.

Finishing: Sample 1.3

Image redacted.

Image redacted.

Figure 4.17: Sample 1.3 [redacted].

[redacted]. These were tensioned with wires on the frame-jig (Figures 4.18 and 4.19).

Image redacted.

Figure 4.18: Sample 1.3 before finishing [redacted] on the frame-jig (right).

Image redacted.

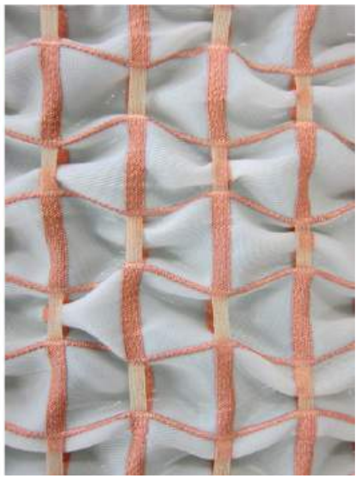


Figure 4.19: Sample 1.3 during finishing.

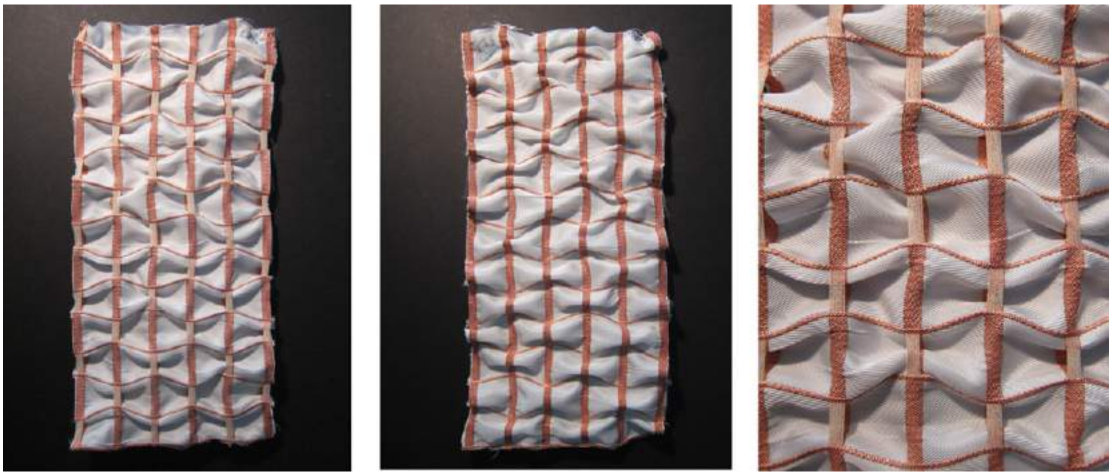


Figure 4.20: Final 1.3 sample. The front and back create different three-dimensional patterns.

Sample 1.4 Lycra floating alternate sides of the fabric. Metal in both axes.
The weave structure was altered to enable the Lycra to float on alternate sides of the fabric. This changed the structure of the cloth and created a different three-dimensional form to the one created in Sample 1.3.

Weft weave structure representation sent to [redacted]:

Image redacted.

Figure 4.21: My representation for Sample 1.4.

Finishing: Sample 1.4

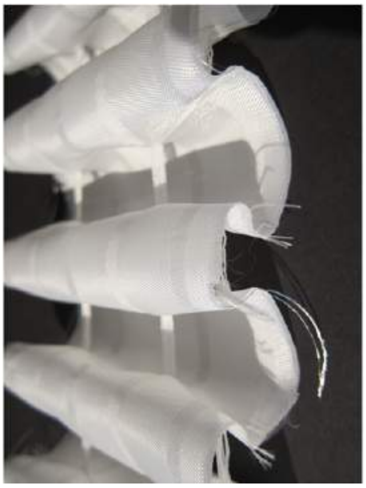



Image redacted.

Figure 4.22: Sample 1.4 prior to finishing.

Image redacted.

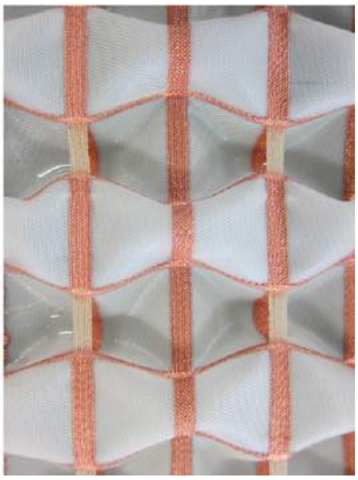


Figure 4.23: Sample 1.4 on the frame-jig removed from the tank for my evaluation to determine the metal rigidity during finishing.



Figure 4.24: Final 1.4 sample.

Reflection-on-action: Analysis of outcomes from Sample 1.3 & 1.4

- The woven Lycra weft floats distort the textile creating diamond shapes when released from the loom. When the conductive threads are metallised, the rigidity sets the shape and fixes it.
- The pliability of the base cloth allows the metal framework to follow the path of the drape of the cloth. This means that complex organic geometries can be created that incorporate the pliable textile characteristics. The electrodeposition process reinforces the textile and creates a more self-supporting rigid structure.
- Introducing the Lycra threads creates metallised forms beyond the orthogonal woven grid pattern of the woven fabric.

[redacted] As the metal deposit increased it fully encapsulated the Lycra threads within the metal. [redacted]

Sample 1.5: Lycra floating on one side of the fabric – metal in weft axis only

- When planning the warp for Samples 1.3 & 1.4 no conductive threads were threaded in the centre section. This enabled the same weave structure to be woven with metal in the weft direction only. Sample 1.5 is therefore the same in every other factor to Sample 1.3. This allows a direct comparison between a sample with metal in one axis and both axes.

The weave structure representation sent to [redacted]:

Image redacted.

Figure 4.25: My representation for Sample 1.5.

Sample 1.5: Weaving plan and design stage

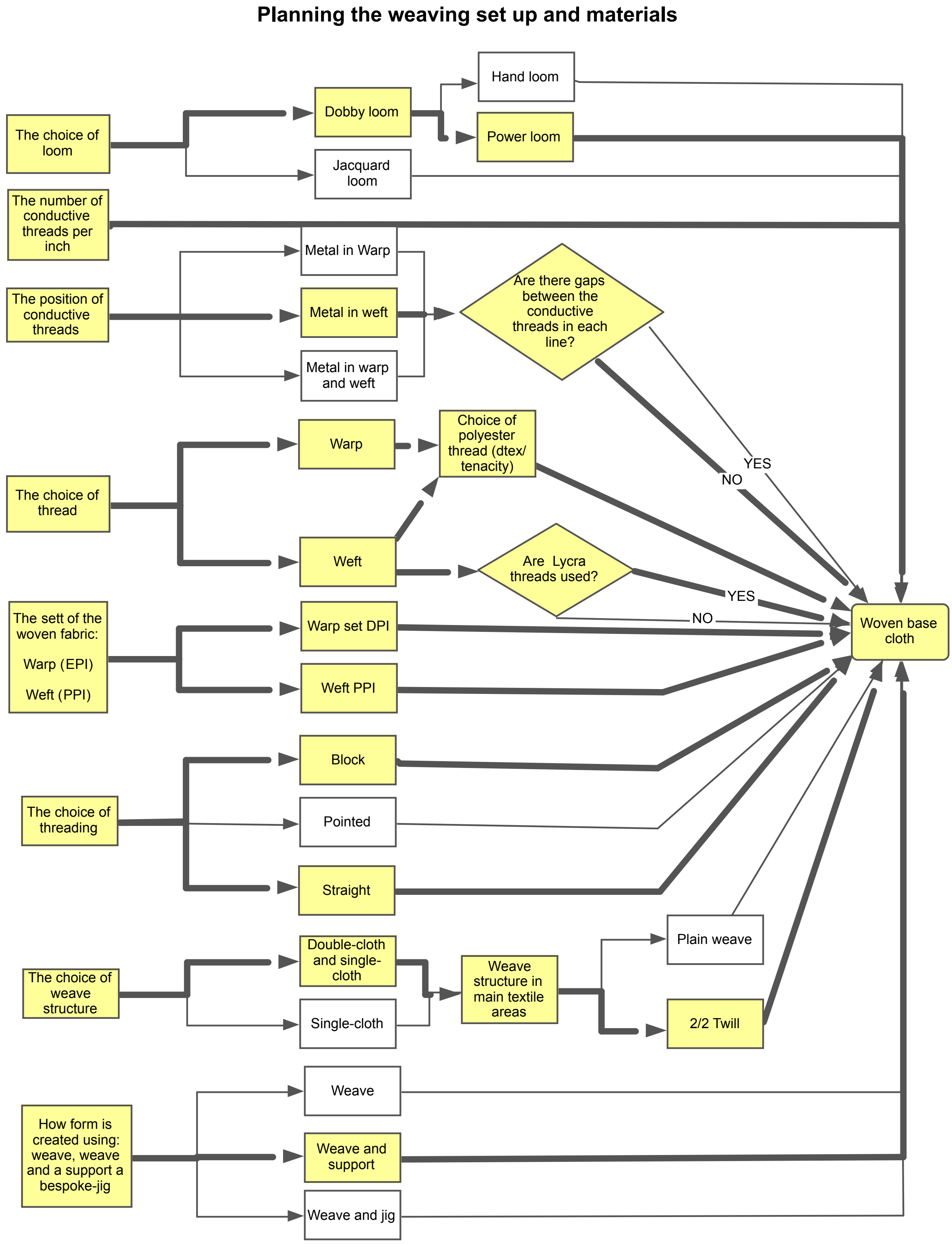


Figure 4.26: The weave-flow diagram for Sample 1.5.

Finishing process for Sample 1.5

Image redacted.

Image redacted.

Figure 4.27: Sample 1.5 [redacted] on the frame-jig before metallisation.

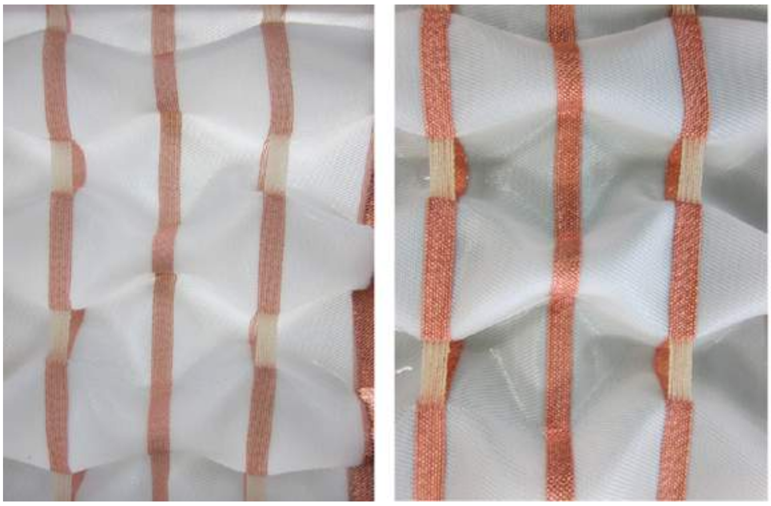


Image redacted.

Figure 4.28: Sample 1.5 during metallisation.

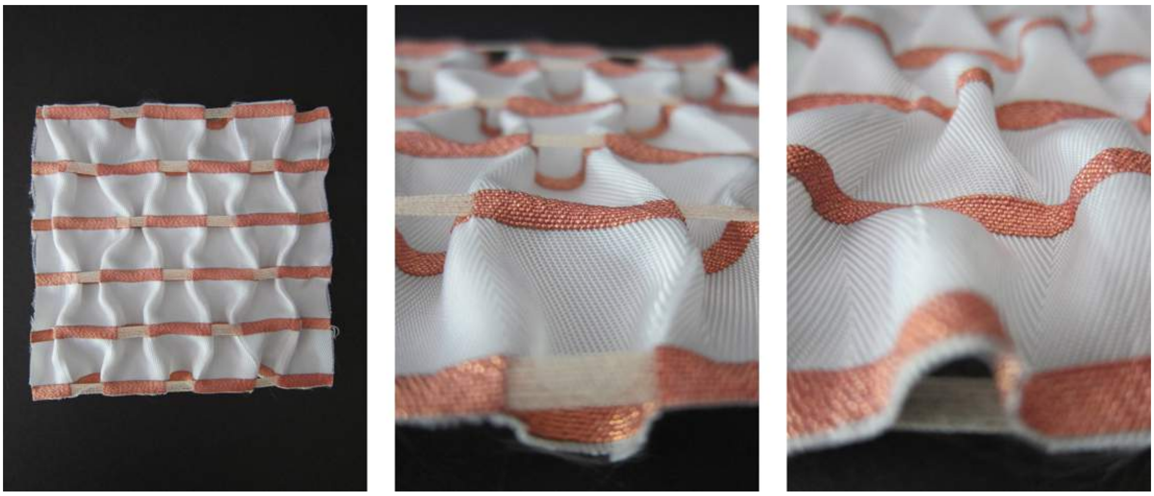


Figure 4.29: Final 1.5 sample.

Sample 1.5 analysis

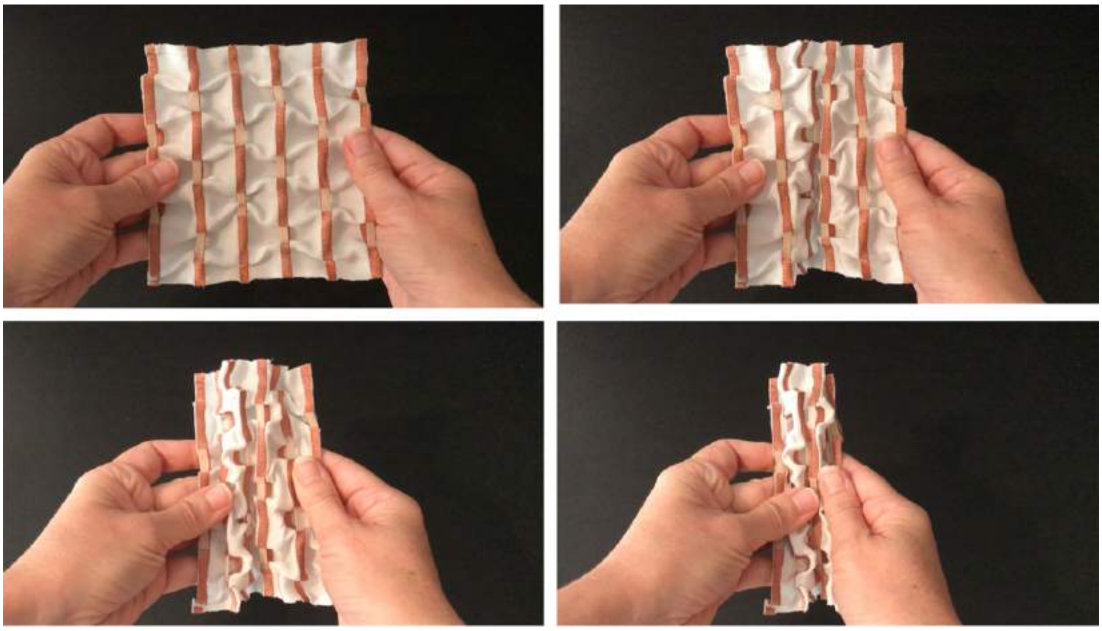


Figure 4.30: Sample 1.5 is pliable and collapses when manipulated by hand because the metallised threads were placed only in one axis. When released it will spring back to maintain its original form.

Analysis summary for Case study 1

- The polyester textile areas in Samples 1.1, 1.3, 1.4 and 1.5 are not under high tension and the fabric can be flexed and manipulated within the metal framework.
- [redacted]
- The Lycra enables fluid irregular textile forms to be created when the fabric is pliable prior to metallisation. The finishing process enables these forms to have greater self-supporting properties by providing a rigid integral framework within the textile.
- Weaving Samples 1.3 and 1.5 using the same lifting plan, but removing the metal in the warp in Sample 1.5, demonstrates how placing metal in one or both axes affects the form's structural properties. Sample 1.5 has the ability to compress in the warp axis, whereas Sample 1.3 does not. Sample 1.3 that has metal in both axes created a rigid conductive grid, as the conductive threads join up where they cross at right angles in the weave.

4.4 Case study 2: Using the weave structure to create integral form using double-cloth pockets and supporting plastic tubes

Introduction

Case study 2 used the weave construction to create the form combined with plastic tubes. Double-cloth was engineered into the woven fabric to generate integral pockets. Plastic tubes were inserted into the pliable double-cloth woven pockets to maintain their cylindrical form during metallisation. The woven threads in the pockets were tensioned tightly across the surface of the tubes, pulling them taut in a uniform curved form. Once the samples were metallised the tubes were removed. The aim was that the metallised conductive threads form an integral woven self-supporting cylindrical structure. When the tubes were removed, the metallised threads retained their curved form. After metallisation the rigid framework held the textile in a curved form and maintained a degree of tension across the polyester fabric areas in the structure.

Aim

- To explore how cylindrical forms can be created through engineering the weave structure.
- To explore how plain weave and 2/2 twill impact the forms in terms of the rigidity of the cloth after the electrodeposition process.
- To explore how creating a band of conductive threads with small gaps between the conductive lines can be used to reinforce wider areas.
- To explore the impact that increasing the scale of the pockets has upon the rigidity of the structures.

Objectives

- To engineer the weave to create integral pockets in the warp direction of the fabric using single-cloth and double-cloth weave structures.
- To use single-cloth warp direction sections in between the double-cloth pockets with conductive threads to stabilise the cloth in warp direction when metallised.

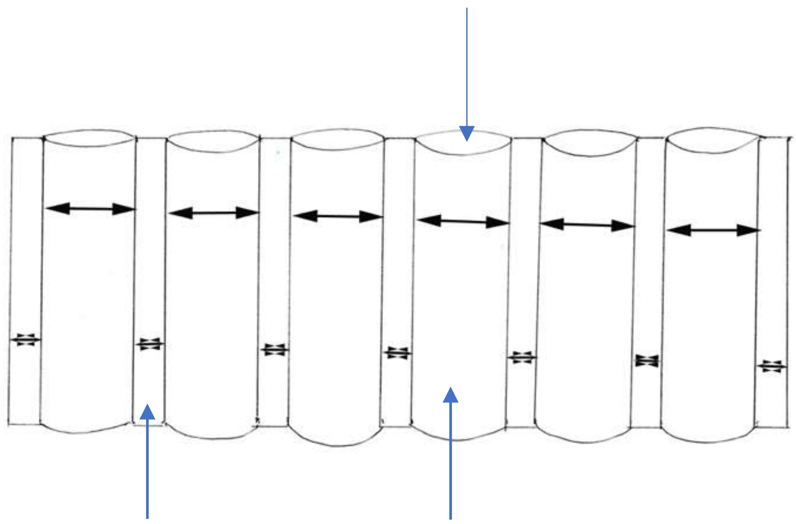


Figure 4.31: My diagram showing the single-cloth and double-cloth sections in the weave structures for Case study 2 samples.

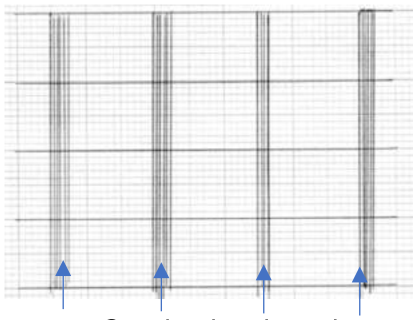


Figure 4.32: My drawing of the irregular warp grid with two conductive threads per warp line in the single-cloth areas of the samples.

- To weave samples in plain weave and 2/2 twill in the double-cloth areas to compare how the different weave structures affect the forms' characteristics.
- To use a blanket warp to enable different widths of double-cloth pockets to be woven in different samples on the same warp. This enables four different scales to be compared using two different proportions of conductive threads to compare the impact of increasing the scale has upon the rigidity of the forms. The larger 6cm and 12cm pockets were designed to have twice as many conductive threads as the smaller 3cm pocket samples. It was anticipated that the samples would need more structural support at a larger

scale. Further details of the different scale samples and the number of conductive threads can be found in the Appendix A2.1.

This case study focuses on the 3cm double-cloth pockets, as they illustrate the relevant findings of the study. Further technical details relating to the 6cm and 12cm samples and for Warp 1 set up can be found in the Appendix A2.1.

Summary of Design-make Tri-space decisions in Case study 2

Composition:

- Shape: The fabric areas are taut within the rigid metal framework. The textile form is regular because the plastic tubes hold the textile in a fixed position under tensile stress. The metal lines in the weft and warp are set at regular intervals.
- Materials: [redacted] dtex polyester and [redacted] 2-ply [redacted] threads.

Construction:

- Weave structures:
    - Plain weave and 2/2 twill weave.
    - The samples combine single-cloth and double-cloth.
- Procedure: The double-cloth enables integral pockets to be formed within the fabric, eliminating the need to stitch the fabric to create the form.

Finishing:

- Form creation: Plastic tubes were required to support the integral woven pocket structures, enabling them to remain open during finishing. The threads within the double-cloth weave were held under high tension around the tubes.

The Design-make sequence for Case Study 2 samples:

- Design the weave structure to create double-cloth pockets within a single-cloth fabric structure.
- Weave fabric at mill.
- Cut up samples and prepare for finishing.
- Cut up tubes to size.
- Place tubes inside the double-cloth pockets.
- Place on the frame-jig.
- Metallise without manipulation during electrodeposition.
- Evaluate the rigidity of the metal deposit using haptic interaction.
- Remove from frame-jig.
- Remove tubes.

[redacted]

Warp 1 was used for Samples 2.1A, 2.1B and 2.1C

Warp 3 was used for Samples 2.2 and 2.3.

Sample 2.1A Weaving plan and design stage

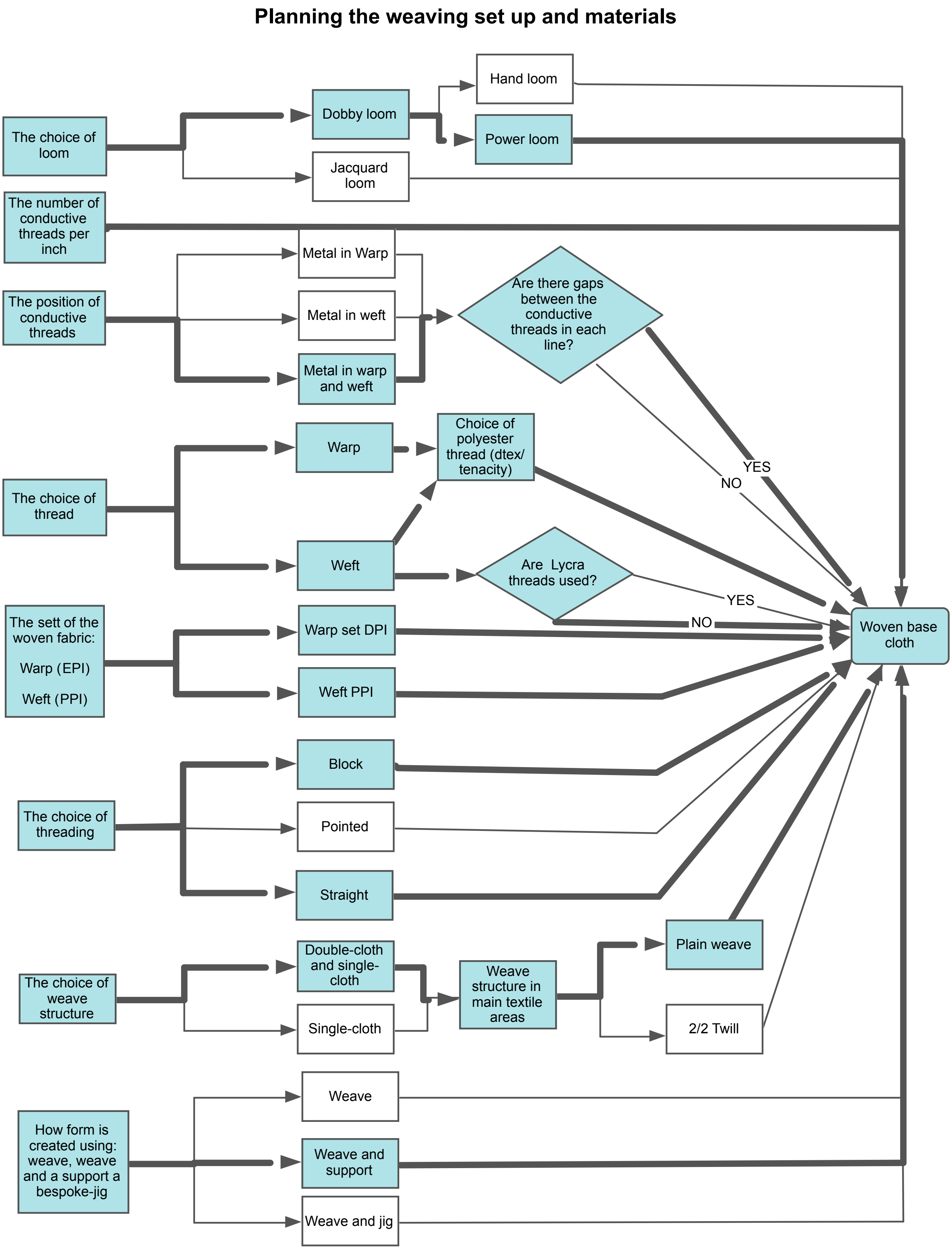


Figure 4.33: The weave-flow diagram for Sample 2.1A.

Sample 2.1A Design process and communication

The weft weave structure representation sent to [redacted] is shown in figure 4.34.

Image redacted.

Figure 4.34: My representations for Sample 2.1A.

Samples 2.1B & 2.1C Weaving plan and design stage

Figure 4.35 below shows the sequence of weave choices relating to Samples 2.1B & 2.1C

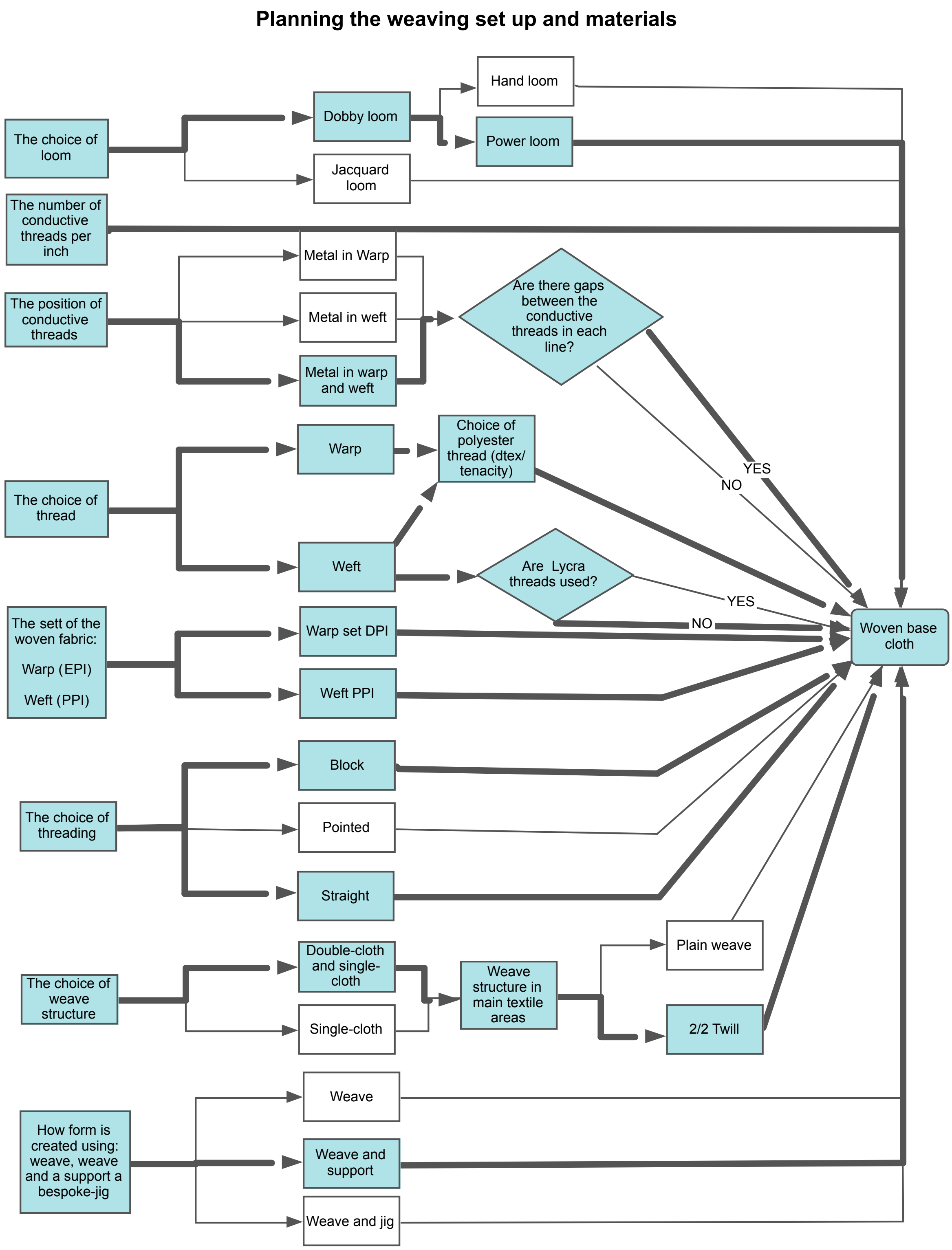


Figure 4.35: The weave-flow diagram for Samples 2.1B & 2.1C.

Sample: 2B & 2C Design process and communication

The weft weave structure representation sent to [redacted] is shown in figure 4.36.

Image redacted.

Figure 4.36: My representations for Sample 2.1B and 2.1C.

Finishing: Samples 2.1A, 2.1B, and 2.1C

Case study 2 making choices during the electrodeposition finishing process

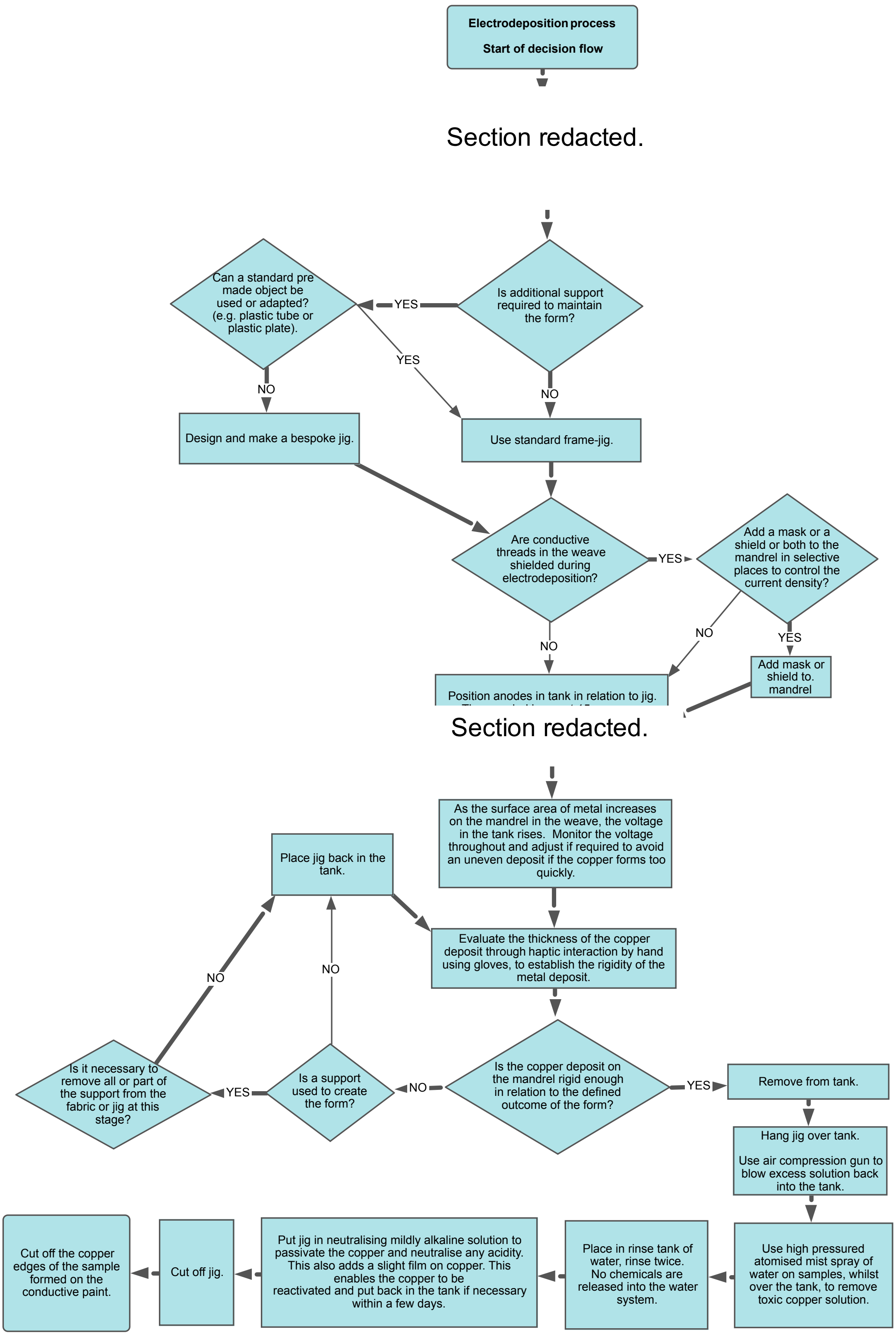


Figure 4.37: The finishing flow-diagram for Samples 2.1A, 2.1B and 2.1C.

Finishing process: Samples 2.1A & 2.1B Before finishing:

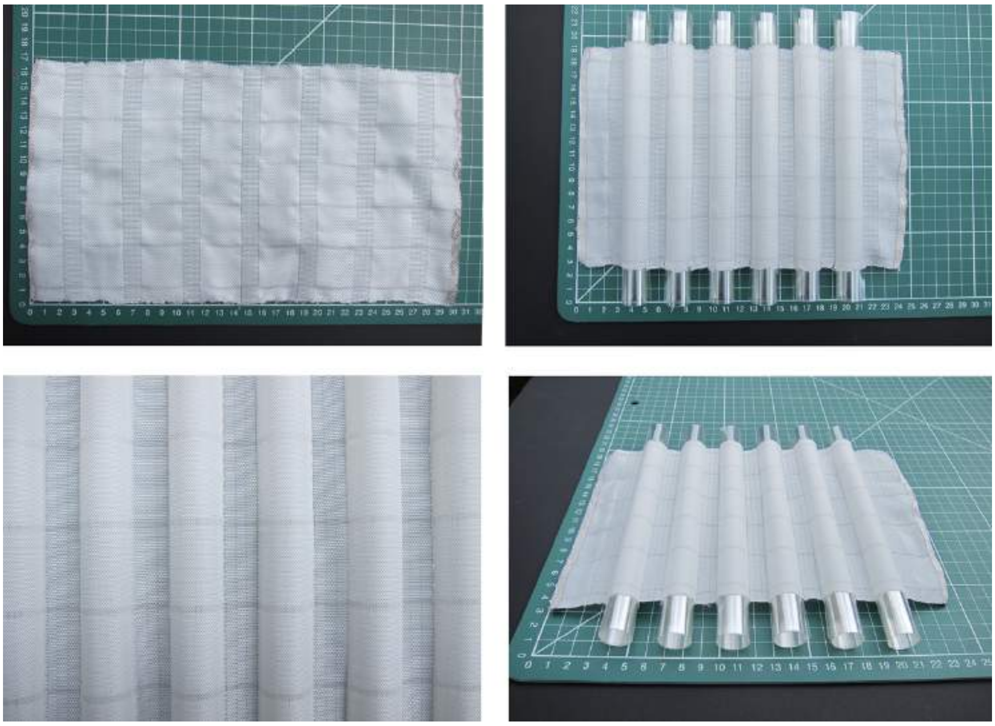


Figure 4.38: Sample 2.1A. (Top left) The flat 3cm plain weave sample. (Top right, bottom right, bottom left) the sample once tubes were inserted inside the double-cloth.

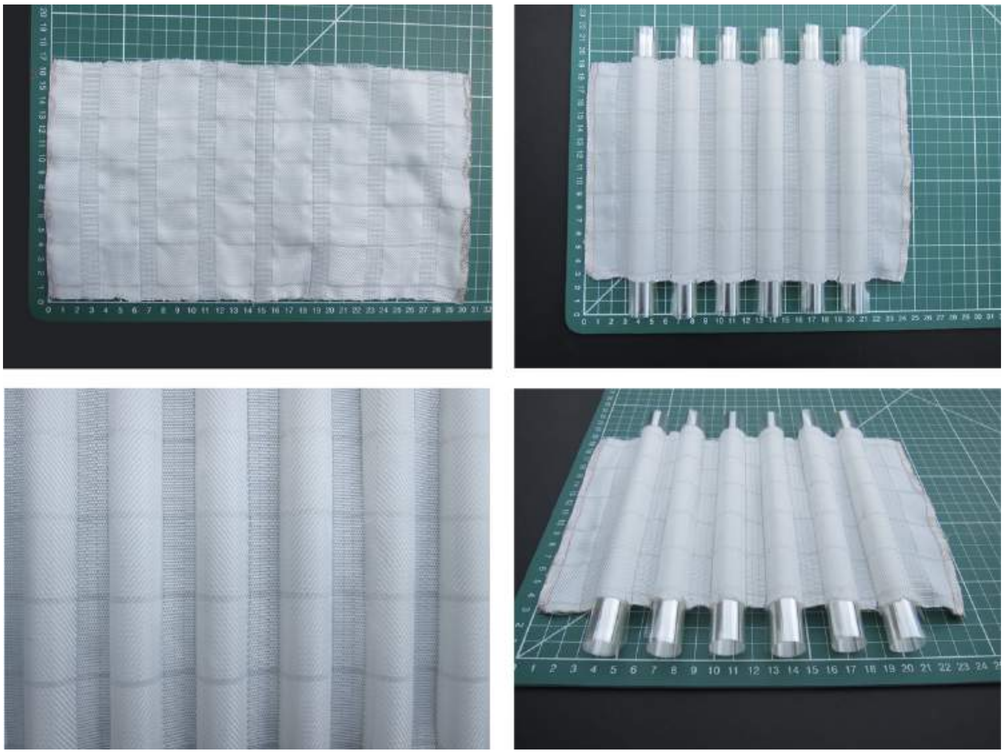


Figure 4.39: Sample 2.1B. (Top left) The flat 3cm 2/2 twill weave sample. (Top right, bottom right, bottom left) the sample once tubes were inserted inside the double-cloth.

Figure 4.40: A selection of samples from Case study 2, including the 1.5cm, 6cm and 12cm sized pockets.

The different sizes were placed together on the frame-jig to help create an even metal deposit in relation to the distance from the anodes in the tank.

Image redacted.

Figure 4.41: The 3cm plain weave and twill samples were placed on the same frame-jig to maintain continuity.

After finishing:

Figure 4.42: Plain weave, Sample 2.1A: 3cm wide pockets with 3 cm distance between the metal weft with four conductive threads in each weft line.

Figure 4.43: 2/2 twill, Sample 2.1B: 3cm wide pockets with 3cm distance between the metal weft with four conductive threads in each weft line.

Sample analysis

When observing the growth rates on Samples 2.1A (Figure 4.44) and 2.1B (Figure 4.45), the twill conductive threads built up metal at a faster rate than the plain weave despite the samples being placed on the same frame-jig, under the same conditions. The twill samples metallised more quickly, with a thicker metal deposit than plain weave.

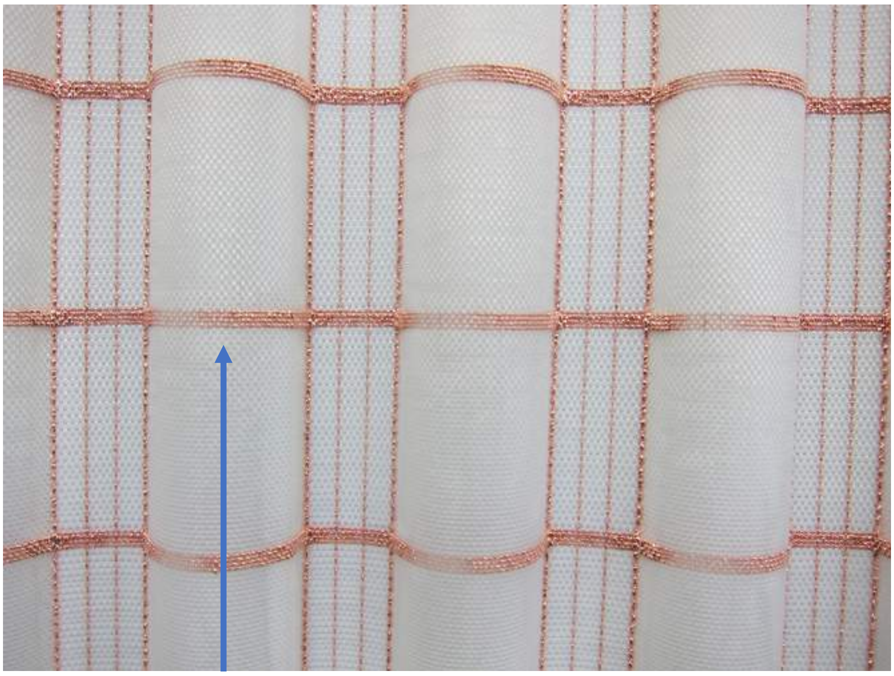


Figure 4.44: Sample 2.1A, plain weave 3cm double-cloth pockets at the early stages of finishing with less metal deposit than the 2/2 twill below in Figure 4.44.

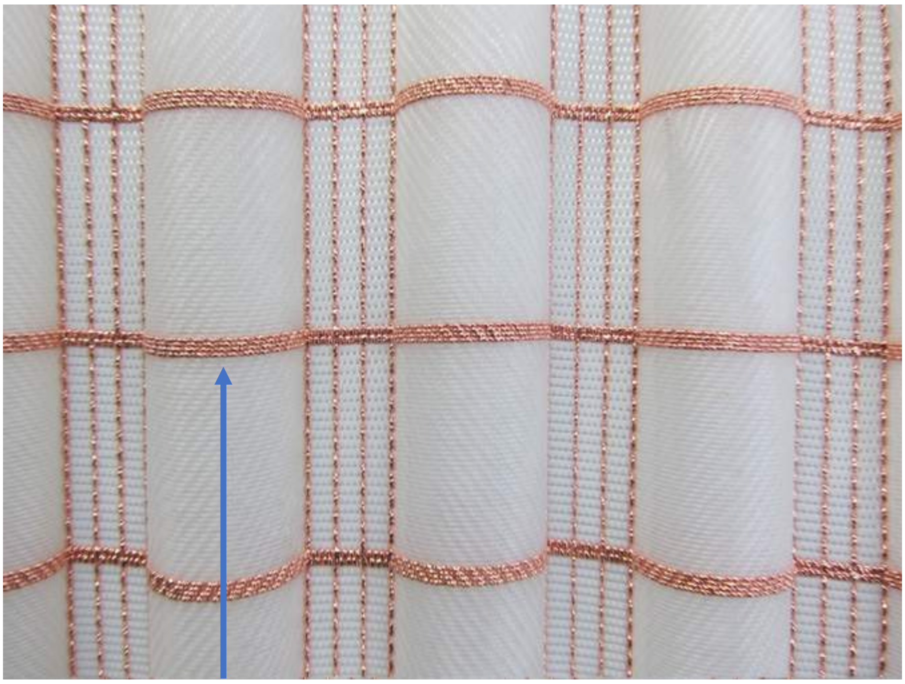


Figure 4.45: Sample 2.1B, 2/2 twill 3cm double-cloth pockets at the early stages of finishing. There is a thicker metal deposit than the plain weave, Sample 2.1A.

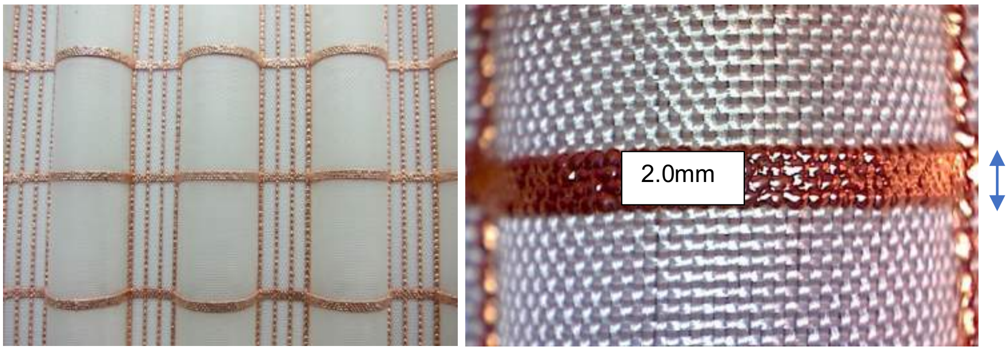


Figure 4.46: (Left): The plain weave 3cm double-cloth pockets after finishing have less metal deposit than the 2/2 twill seen in Sample 2.1B in Figure 4.47. (Right): A detailed image: the blue arrow indicates the measurement across the weft band, to show the density of metal deposit on the double-cloth pocket curved area.

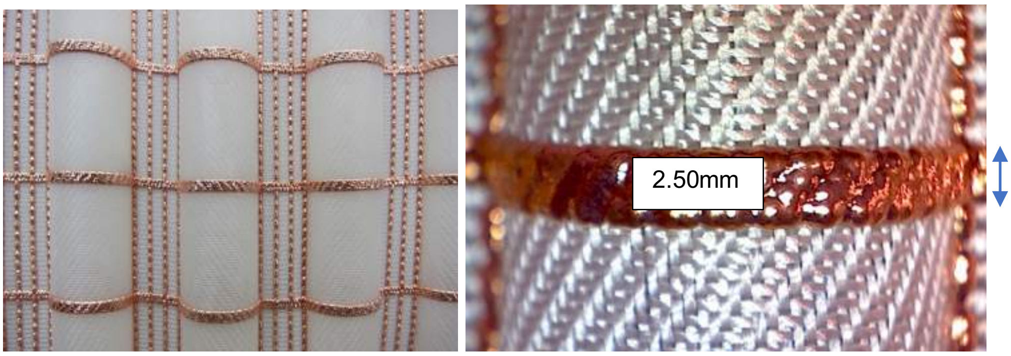


Figure 4.47: (Left) The 2/2 twill 3cm double-cloth pockets after finishing which have a slightly thicker metal deposit than Sample 2.1A. (Right): A detailed image: the blue arrow indicates the measurement across the height of the weft band, to show the density of metal deposit on the double-cloth pocket curved area.

I have concluded that the difference in deposition rate is because there are fewer intersections in the 2/2 twill weave. This creates longer weft floats of the conductive threads in a twill structure compared to plain weave. This creates a larger uninterrupted surface area of conductive grid on the surface of the fabric. The plain weave conductive threads interlace in and out of the fabric twice as much as the 2/2 twill. Therefore the 2/2 twill has longer continuous lines of conductive thread on the fabric surface. The current is able to deposit metal in longer lines at a quicker rate on the twill structure than the plain weave. This is because it has fewer physical interruptions in current during the initial stages of electrodeposition, as there are fewer non-conductive threads passing over the top of the conductive threads. This increases the current density and speeds up the deposition rate, because the 2/2 twill has longer uninterrupted conductive threads that are in direct line of sight to the tank anode, (refer to section 3.9.1 on page 98-99).

A comparison can be made with Cox and Flanagan's (1997) observation that weave structures with longer floats and less intersections create a more rigid cloth when resin is applied. This is due to the longer surface area of the thread being coated in continuous resin within the laminated layers of fabric. In the case of electrodeposition, the longer float in a weave structure affects the speed at which the metal deposits. Therefore twill structures form a more stable structure more quickly than plain weave, when placed under the same tank conditions.

Sample: 2.1C

In Sample 2.1C the gaps between the conductive weft lines in the 3cm samples were reduced from 3cm to 1.5cm to compare how increasing the metal weft lines can increase the rigidity of the form (Figure 4.48). Sample 2.1C is significantly more rigid than Sample 2.1B, which is a 3cm tube 2/2 twill with a 3cm gap between the conductive weft lines.

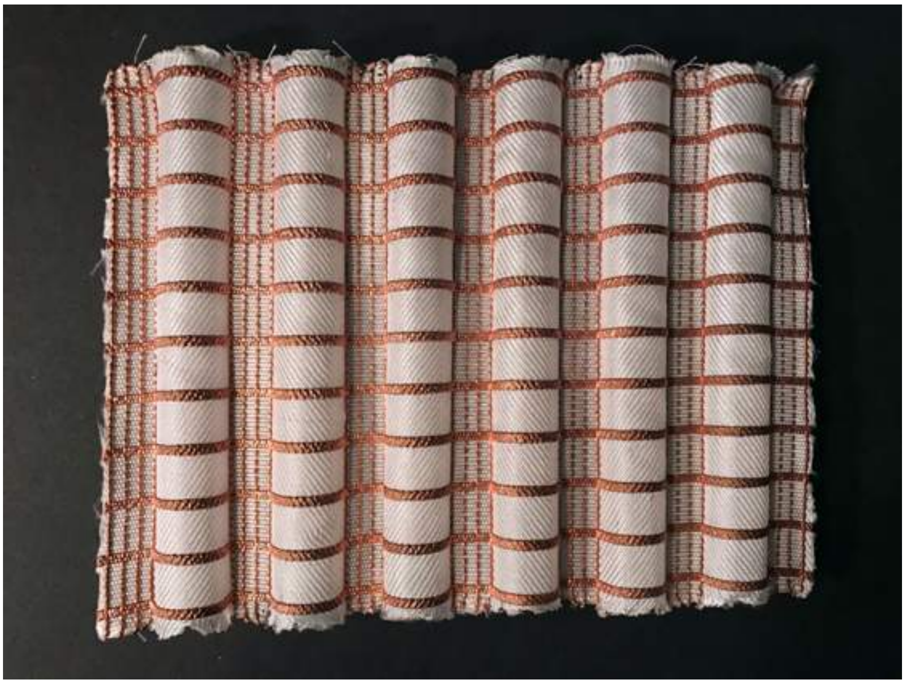


Figure 4.48: Sample 2.1C: 2/2 twill 3cm wide pockets with 1.5cm distance between the conductive weft, four conductive threads each side of the double-cloth.

Analysis of larger scale samples

The larger the scale of the double-cloth tube, the more metal is required to support the pliable form. The smaller scale 3cm samples are more rigid than the 6cm and 12cm double-cloth samples, due to the reduced proportions of metal to fabric as seen in Figures 4.49 and 4.50 below. Details of the technical information for these samples can be found in the Appendix Section A2.1.

Figure 4.49: (Left) Plain weave 6cm pockets, (right) 22 twill 6cm pockets.

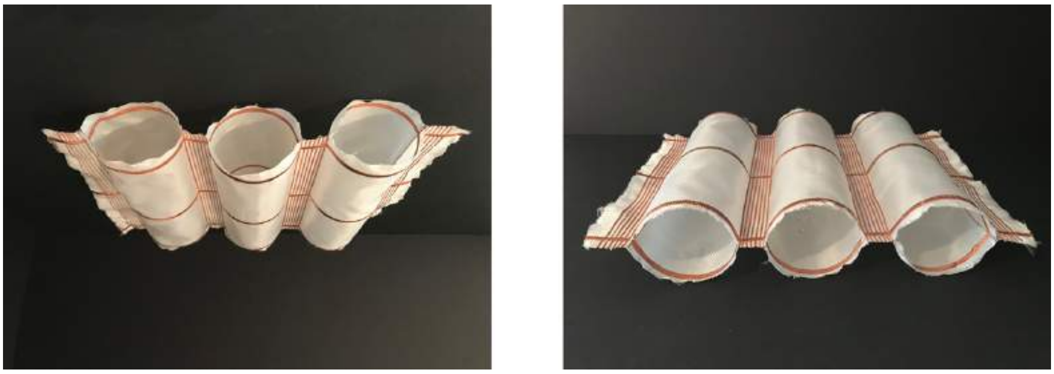


Figure 4.50: (Left) Plain weave 12cm pockets, (right) 22 twill 12cm pockets.

A higher proportion of metal is required to be deposited on the 6cm and 12cm double-cloth samples to make them as rigid as the 3cm double-cloth samples. This could be achieved either by increasing the number of conductive threads in the weave structure or by leaving the samples in the tank for longer. If the metal deposit was still not strong enough, the tubes could be removed and an auxiliary anode placed inside each fabric pocket. As the tubes would no longer mask the conductive threads, a thicker metal deposit would form on the inside of the fabric pockets. The hypothesis would be that this would increase the rigidity of the metal framework. The use of internal auxiliary anodes is explored in Case study 3.

If the textile [redacted], this creates fractures in the crystalline structure. If these metal fractures do not build up enough additional metal to repair the fracture, these become weak points in the metal framework. [redacted]

As in Case study 1, the pliable anisotropic textile and rigid isotropic metal properties are present in the final forms. In comparison with Case study 1 the textile areas in Case study 2.1 are under higher tension between the metal framework and therefore do not drape. When pressure is applied by hand to the fabric areas there is a slight degree of deflection, but it is more restricted than the drape in the fabric areas in the Lycra samples in Case study 1.

Amendments to Case study 2.2 after reflection-for-action on Samples 2.1A, 2.1B & 2.1C to resolve metal fractures and improve stability.

- Samples 2.2, 2.3, 2.4 and 2.5 all use the same finishing sequence as Sample 2.1 shown on page 151.

To provide greater rigidity in the form the following amendments were made:

- The gaps in the conductive lines in the warp were removed and the [redacted] conductive threads in the warp were threaded next to each other in the single-cloth areas. The pick rate in the weft was also increased from [redacted] threads to [redacted] threads to provide greater density in the plain weave pocket areas to help maintain the form. This was to increase the rigidity of the metal deposit on the conductive threads. The hypothesis was that the adjacent conductive threads should build up a thicker deposit of metal, as they are touching the conductive thread next to it. This should increase the current density and cause a thicker metal deposit to be applied more quickly and aid the stability of the form. This aimed to prevent the breaking of the metal deposit during finishing, due to the weight of the supporting tubes.
- Although the metal deposit formed at a slower rate on the plain weave than the 2/2 twill in Samples 2.1A and 2.1B, plain weave was chosen for the main textile areas. This was because the plain weave created a more stable cloth

in the pliable textile areas when compared to the 2/2 twill in the samples in created in 2.1A, which was an advantage when the textiles were placed under tensile stress over the tubes.

[redacted]

Image redacted.

Figure 4.51: The bespoke [redacted]-jig used for the 6cm sample in the second set of Case study 2 samples.

Sample 2.2

Aim:

- To explore the effect that placing the conductive threads next to each other in the warp has upon the rigidity of the form with the same number of conductive warp threads as Case study 2.1 A.

Objectives:

- Increase the pick rate from [redacted]PPI to [redacted]PPI on each side of the double-cloth pockets and remove the gaps in the warp between the conductive threads to increase the rigidity of the polyester areas.
- Use plain weave as opposed to 2/2 twill to create more rigid metal lines when finished.

Sample 2.2 Weaving plan and design stage

Figure 4.51 shows the sequence of weave choices relating to Sample 2.2.

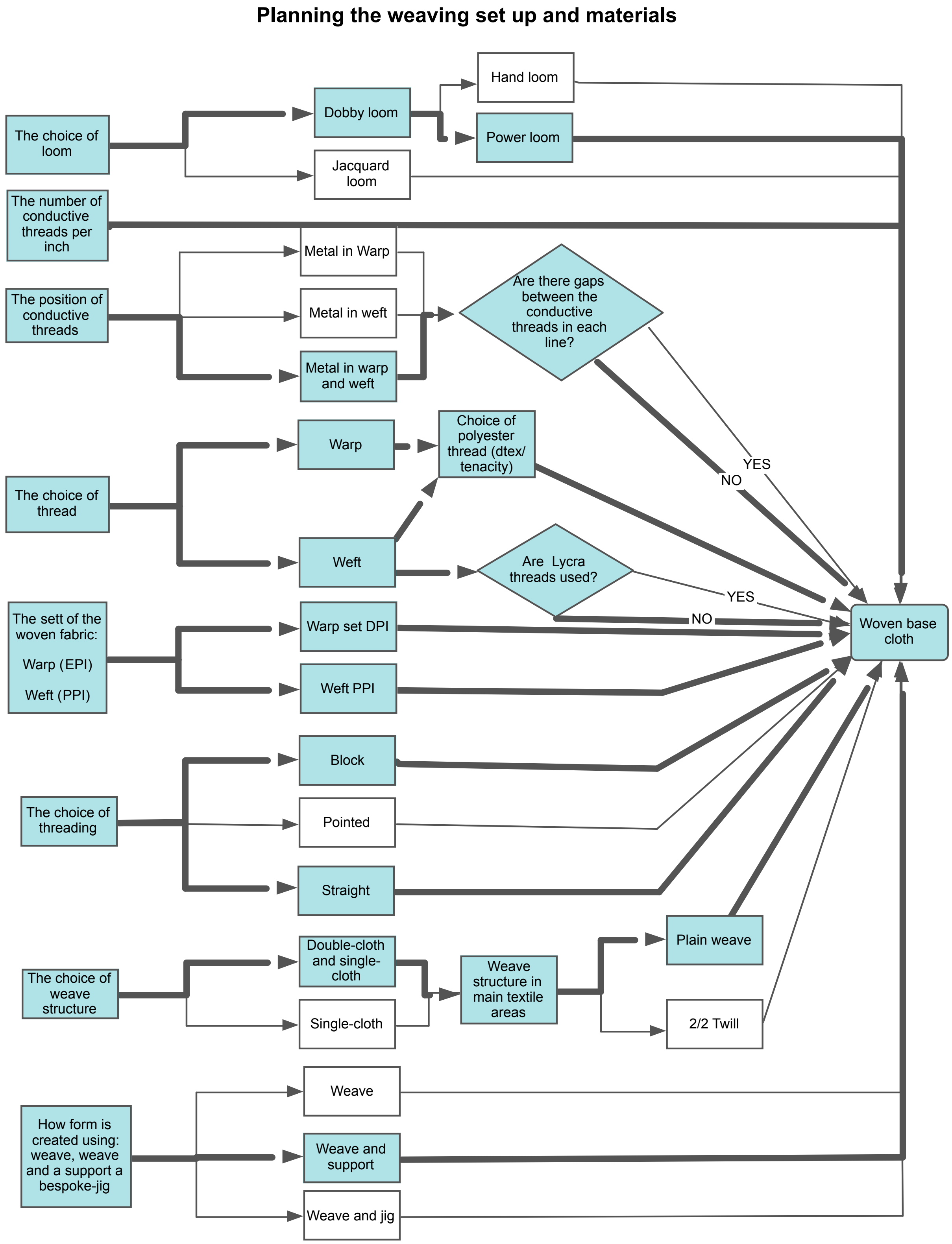


Figure 4.52: The weave flow-diagram for Sample 2.2.

Sample 2.2 Design process and communication

Weave structure representations sent to [redacted] are shown in figures 4.53A and 4.53B.

Image redacted.

Image redacted.

Figure 4.53B: My representations for Sample 2.2.

Finishing: Sample 2.2 and 2.3

Case study 2 making choices during the electrodeposition finishing process

Figure 4.54: The finishing flow-diagram for Samples 2.2 and 2.3.

Finishing: Sample 2.2

Image redacted.

Figure 4.55: Sample 2.2 before finishing.

Image redacted.

Image redacted.

Figure 4.56: Sample 2.2 during finishing.

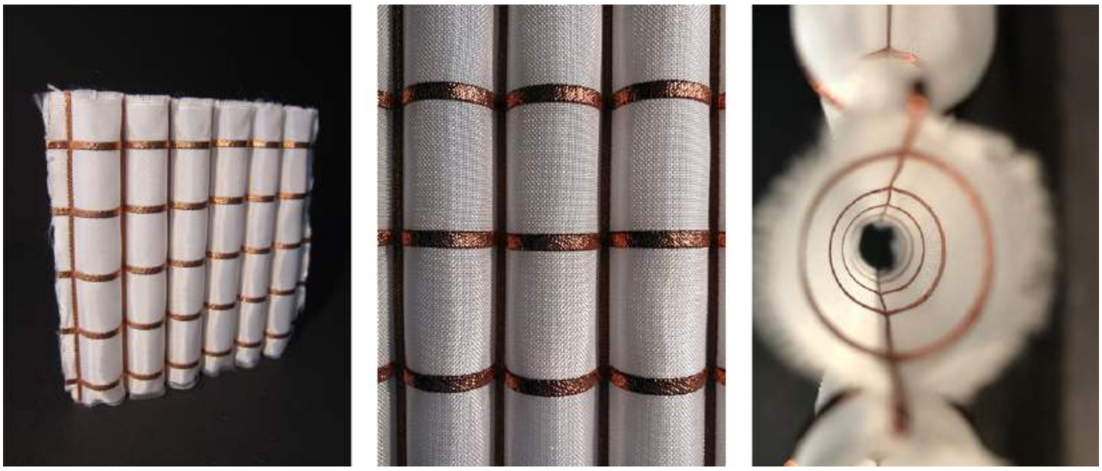


Figure 4.57: Final 2.2 sample.

Sample 2.3 conductive threads in the weft axis only

This sample used the same weave structure (plan H, page 163) as Sample 2.2, but there were no conductive threads in the centre section of the warp threading for Sample 2.3. This enabled different sample properties in the warp axis: see the Appendix, Section A2.3, Warp 3, for details of the warp threading. The weave structure and the weft instructions were the same as Sample 2.2, as the two samples were woven next to each other across the warp.

Aim:

- To create a collapsible form that has structural stability and rigidity in the weft axis.

Objective:

- Remove the conductive threads from the warp.
- Use the metallised conductive threads in the weft around the tubes to support the curved double-cloth pockets to maintain the self-supporting ability of the structure whilst having pliability in the weft axis.

Sample 2.3 Weaving plan and design stage

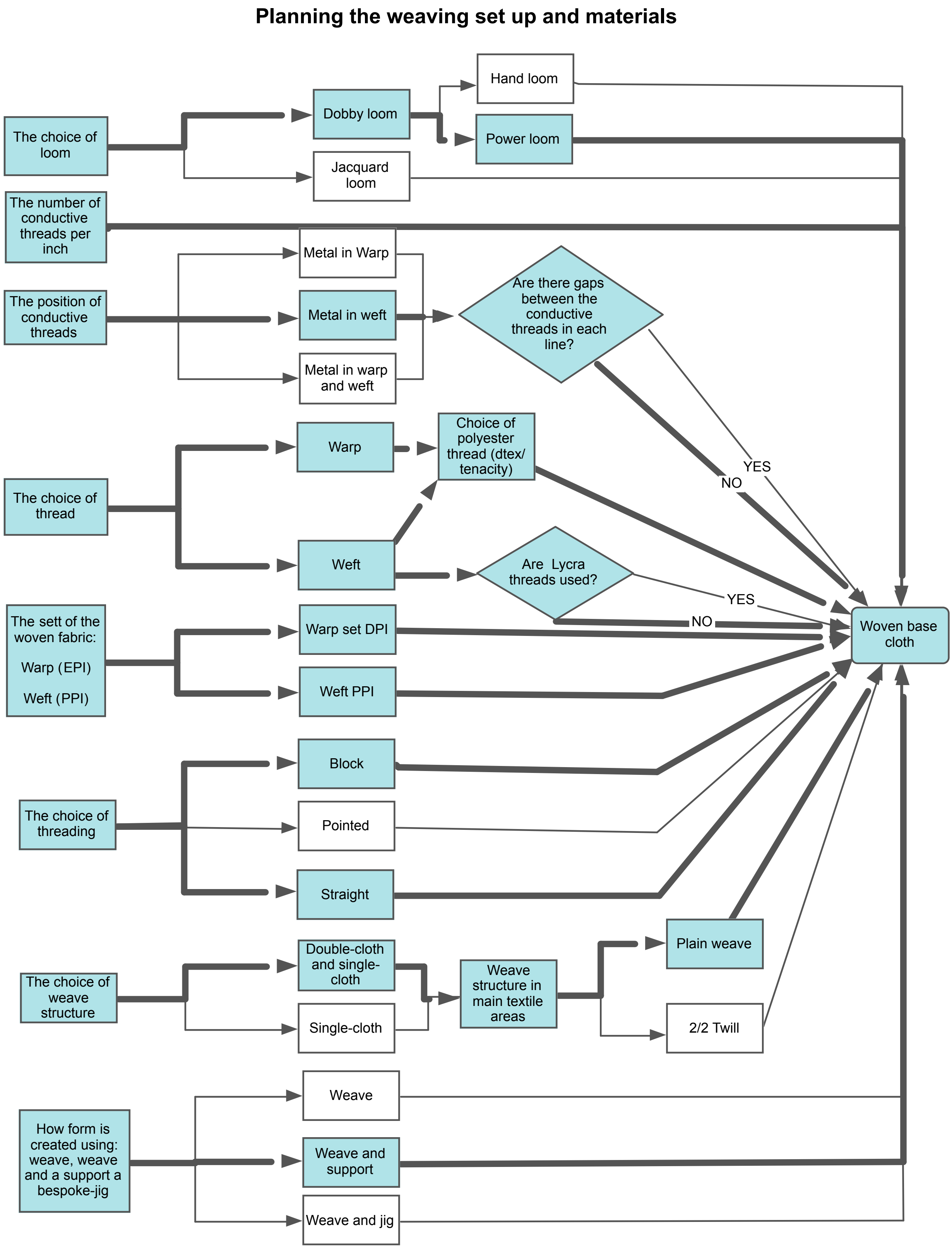


Figure 4.58: The weave flow-diagram for Sample 2.3.

Sample 2.3

Image redacted.

Figure 4.59: Sample 2.3 during finishing.

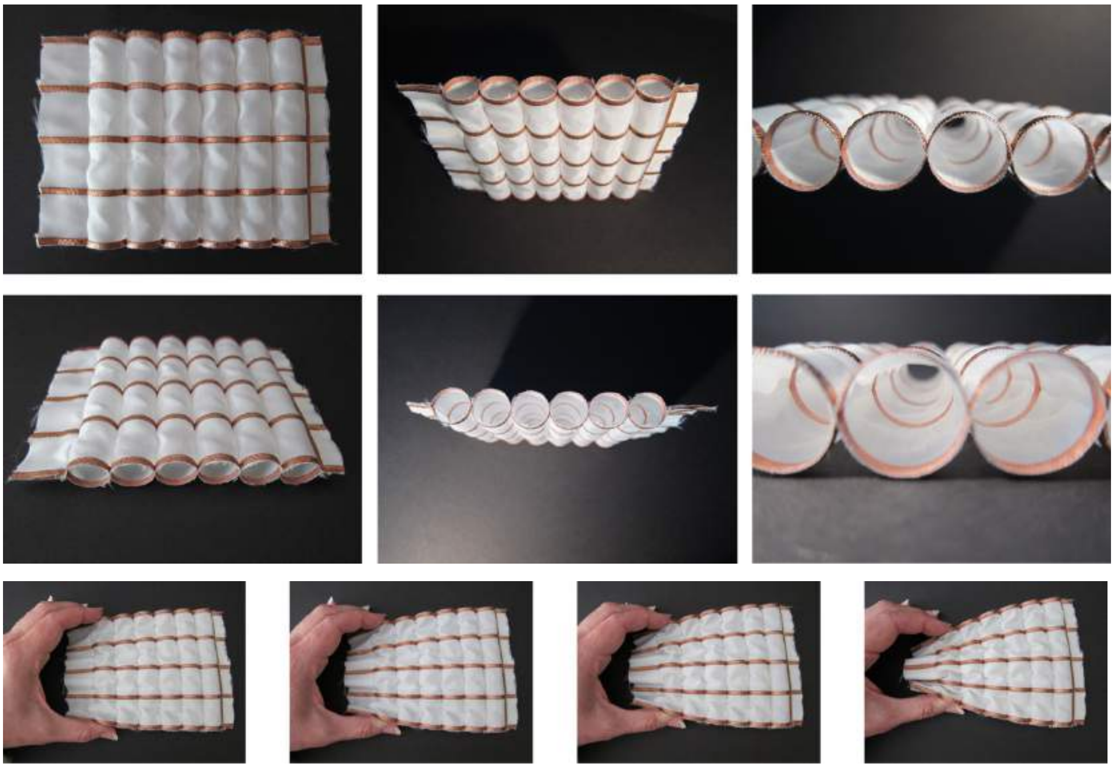


Figure 4.60: 2.3 final samples showing the compression of the form in the warp axis.

Reflection-on-action

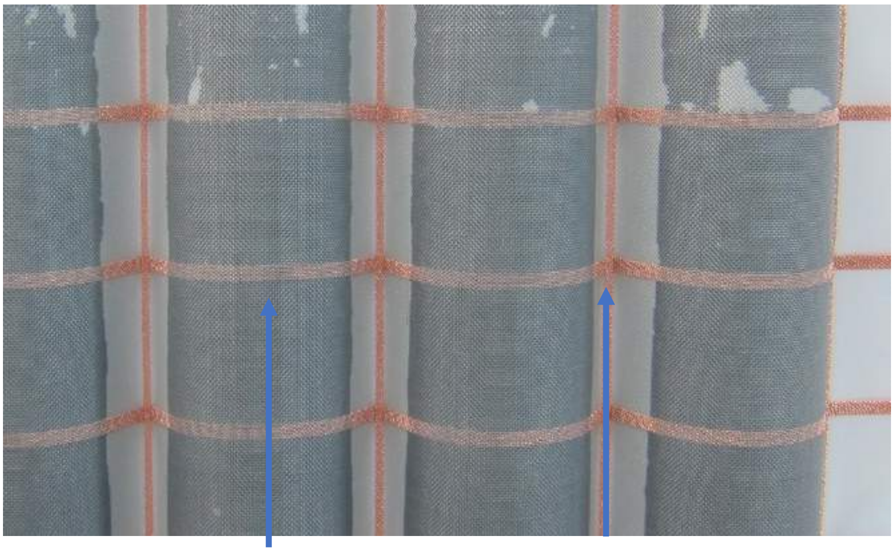
When Sample 2.3 was metallised, it became apparent that I had mistakenly included one conductive line at the edge of one pocket (as seen on the right-hand side in Figure 4.60). The aim was to have no metal in the warp axis. However, this mistake caused one end to remain rigid in the vertical direction and allowed for the opposite side which had no metal to be compressed. This produced asymmetrical properties in the sample and demonstrates that the rigidity and pliability can be adapted using the placement of the conductive threads to create a wide scope of properties. This is an example of how integrating the conductive threads within a woven textile can provide scope to precisely control the rigidity and pliability of the forms.

Sample analysis: Common factors between Case study 2 samples
The higher surface points on the mandrel (the conductive threads) that were closer to the anode deposited metal more quickly than the lower points, if all other factors were equal. This is an example of the effect of the shape of the mandrel in relation to the current density that affects electrodeposition, as described in Section 3.9.1. It was also observed that when the metal was depositing, the single-cloth areas built up metal at a slightly quicker rate than the double-cloth. There are two reasons for this:

1. The single-cloth sections have a greater density of conductive threads than the double-cloth sections, as they have twice as many conductive threads in the weave. This is because the number of warp threads used in the single-cloth areas are divided into two layers to form the double-cloth pockets.

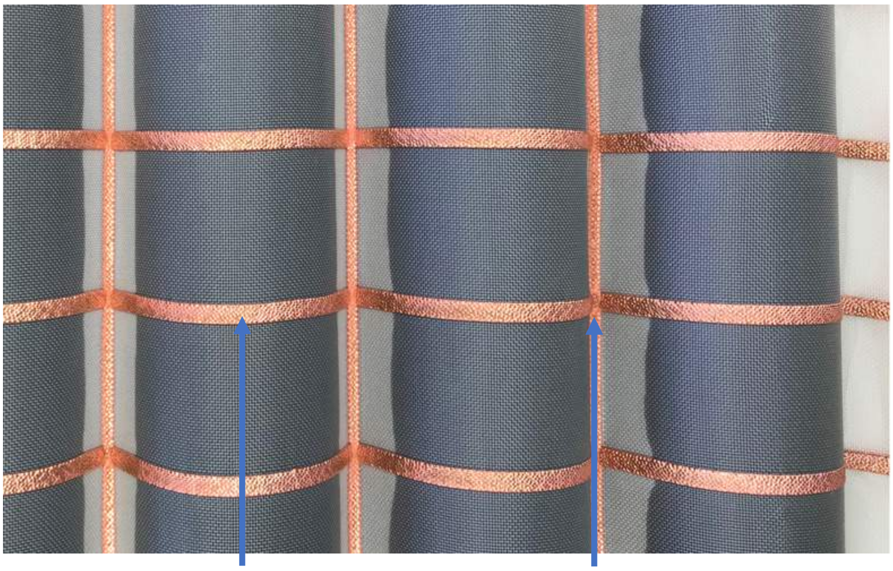
2. The tubes that were inserted to fit tightly into the double-cloth pockets masked the internal side of the conductive threads. Therefore, during the first stages of finishing less metal was deposited on the single-cloth when compared the double-cloth pockets on the same sample. The presence of the tubes as a mask, combined with half as many conductive threads in the double-cloth section of the weave compared to the single cloth, reduced the current density in the double-cloth areas. This reduced the metal deposit in the internal areas of the pockets during the initial stages of electrodeposition.

Figure 4.61 shows a discernible visual distinction between the different thicknesses of metal deposit on the single-cloth and double-cloth areas during electrodeposition. The metal deposits at a slower rate on the conductive threads in the double-cloth pockets masked by the tubes. This is due to the different thicknesses of crystalline deposit on the single-cloth and double-cloth areas within the same integral form. The fabric was left in the tank to build up a thicker, more uniform deposit across the form (Figure 4.62). This evened out the metal deposit on the surface of the sample. The metal deposit increases in size as the current density increases. This is due to the larger proportion of metal across the form, which in turn increases the current density. The metal deposits build up to the point where they rise above and incorporate the polyester threads surrounding it. The metal continues to grow in thickness as the current density increases, and eventually the metal creates an even distribution on the form. The polyester threads are integrated into the metal framework and the conductive threads are fully encapsulated. Figure 4.62. shows the even copper deposit on the conductive threads once the metal has grown and joined up to form one integrated framework with the threads woven within the cloth.



Double-cloth Single-cloth

Figure 4.61: The initial stages of metallisation on a 6cm double-cloth, Sample 2.2 from Case study 2, with a visually discernible difference between the metal deposit.



Double-cloth Single-cloth

Figure 4.62: The final stages of metallisation on a 6cm pocket double-cloth, 2.2 Sample from Case study 2, with a more even distribution of metal deposit than that in Figure 4.61.

Summary of Case study 2

- As described in section 3.9.1 there is potential to use this uneven metal distribution effect to vary the properties of the metal framework within the weave structure. By removing the tubes from the woven pockets at this stage in the metallisation process, the metal framework would have different levels of pliability and rigidity within the same structure. This was developed in Case study 3.

- Using double-cloth within the weave and masking half of the conductive threads alters the current densities on the form when combined with single-cloth. The tubes inserted into the double-cloth pockets offer the possibility of masking half the conductive threads from the anodes. The curved high points on the double-cloth pockets held open by the tubes would normally be high current density areas in conventional electrodeposition. However, by reducing the number of conductive threads in these raised areas the high points become low current density in comparison to the single-cloth recesses of the form. This alters the conventional way that the metal would deposit the mandrel, as the curved double-cloth high points deposit thinner metal than the single cloth recesses during the initial stages of finishing. This method could be adapted to help balance out the current density across a form using woven conductive threads within a fabric during electrodeposition.

- Altering the thickness of the metal deposit on the conductive threads in different areas of the structure changes the pliability of the form in the same structure.

- The double-cloth pockets within the weave structure replicate the curved form of the tubes due to the rigidity of the crystalline copper deposit that forms around the conductive threads.

- The non-conductive areas of the woven cloth are held in tension between the metal frameworks. The fabric areas are therefore not able to drape within the metal framework in the same manner as the Lycra samples in Case study 1.

- The double-cloth samples in Case study 2 have a more uniform appearance than the samples in Case study 1.

4.5 Case study 3: Using bespoke jigs and flat single-cloth to create form

Introduction

This case study uses single-cloth woven textile, bespoke jigs[47] and an engineering approach to create the form. The textile is tensioned tightly over the jigs which masks selective areas of the conductive threads within the fabric. In Case studies 3.2 and 3.3 the close proximity of the tubes within the jig also shield selective areas of the conductive threads in the fabric from the tank anode. Therefore Samples 3.2A, 3.2B and 3.3 use masking and shielding as methods to control the pliability and rigidity of the hybrid forms.

Sample 3.1 explored the single-cloth fabric over an arch-jig. Samples 3.2A and 3.2B developed the outcomes from 3.1 further by engineering a scroll-jig. The shape of the scroll-jig enabled the control of the current density in different areas of the same form. After reflection-on-action and reflection-for-action, Sample 3.2A was placed on a new frame-jig with additional auxiliary rod anodes to control the metal deposit. This sample became 3.2B. The positioning of the auxiliary anodes was refined in Case study 3.3. This prevented the need to remove the textile from the scroll-jig during finishing. This produced greater control over the metal properties, as detailed in the analysis section.

Case study 3: Using a 1cm x 1cm square conductive thread grid and bespoke jigs

Polyester fabric with a 1cm x 1cm conductive thread per line was used. A flat textile was tightly tensioned around an arch-shaped jig.

Aim

- To explore how masking and shielding areas of conductive thread within textiles, shaped around bespoke jigs, can affect the rigidity of the metallised forms.

Objective:

- To evaluate the flat fabric's ability to become self-supporting after metallisation when pulled taut around bespoke jigs.

---

[47] To enable the refined control of the electrodeposition finishing process, a bespoke arch-jig and a bespoke scroll-jig were used in Case study 3.

Summary of the Design-make Tri-space decisions in Case study 3.

Composition:

- Shape: The fabric areas are taut within the rigid metal framework. The textile form is regular because the bespoke jigs hold the textile in a fixed position under tensile stress.
- Materials: [redacted] dtex polyester and [redacted] 2-ply [redacted] threads.

Construction:

- Weave structure: 2/2 twill single-cloth.
- A textile with 1cm x 1cm 2/2 twill, [redacted] conductive thread per line was used.

Finishing:

- Form creation: Bespoke jigs were required to create three-dimensional forms as a mould to support and hold the fabric in place.
- The textile was wrapped under high tension around the bespoke jigs [redacted] to maintain the tension.
- The textile was metallised using electrodeposition.
- Different processes were used as identified in the finishing flow-diagrams relating to when the textile was removed from the jigs: see individual Case study 3 sample descriptions.

Weaving plan for case study 3

Warp 4 was used in all Case study 3 samples with the same 2/2 twill lifting sequence in the weft (Figure 4.63).

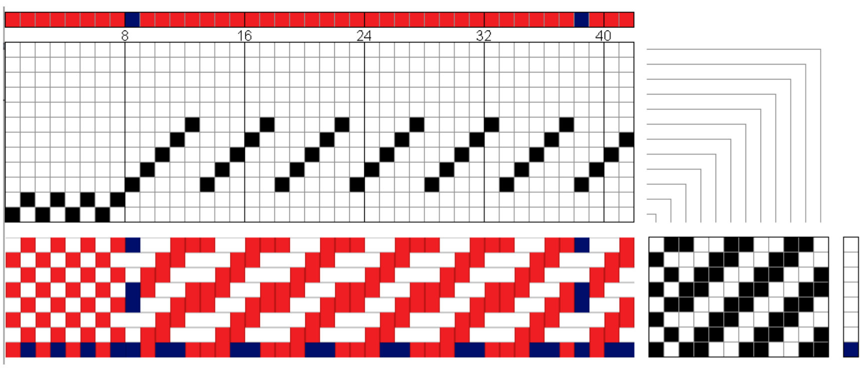


Figure 4.63: The weave notation for Case study 3 fabric.

Samples 3.1, 3.2 and 3.3: Weaving plan and design stage

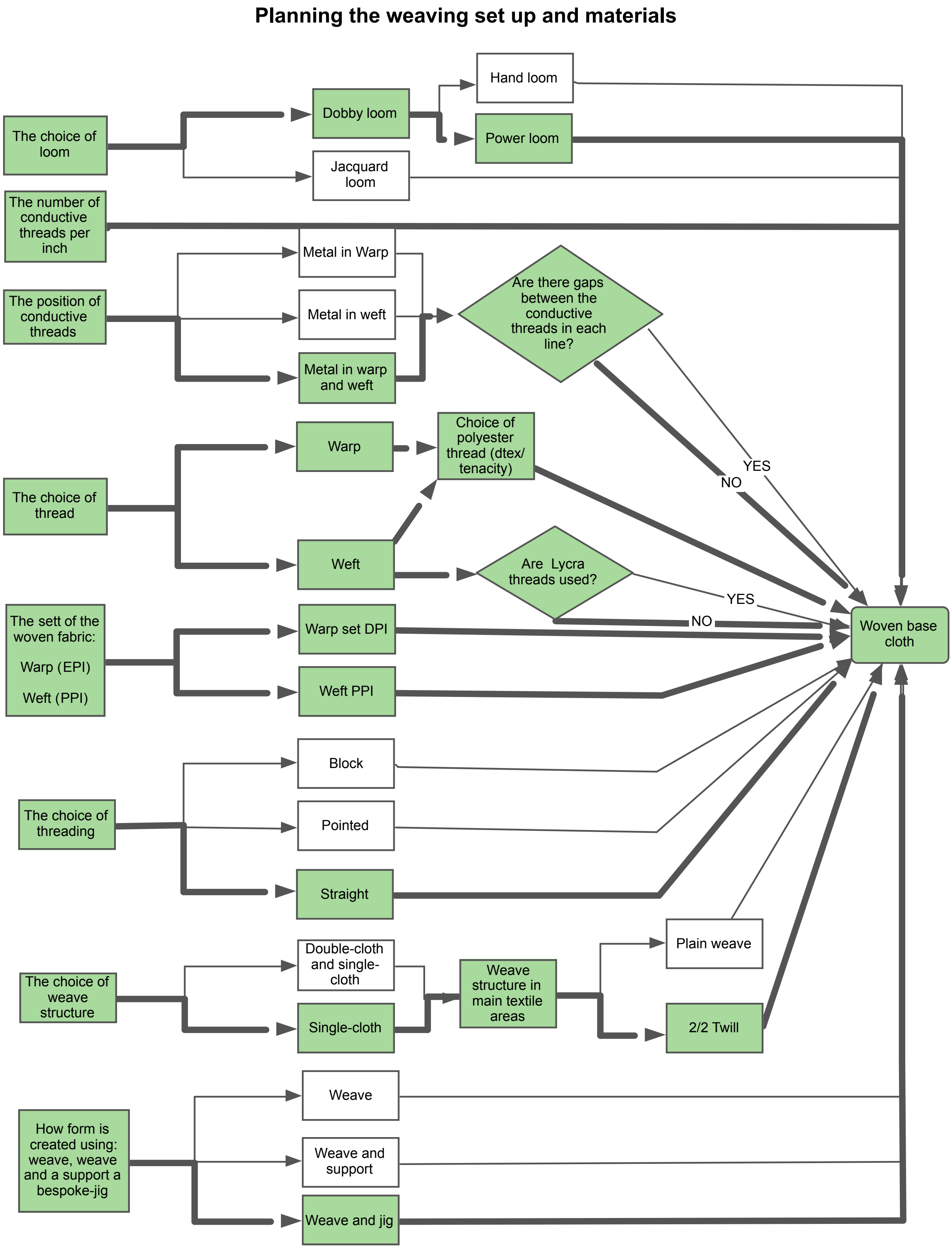


Figure 4.64: The weave flow-diagram for Samples 3.1, 3.2 and 3.3.

Case study 3.1

The making process sequence:

- Create a bespoke arch-jig.
- Pull the fabric around the arch-jig [redacted].
- Place on a frame-jig.
- Place in electrodeposition tank.
- Remove from tank.
- Remove arch-jig.

[redacted]

- Place back in the electrodeposition tank.
- Remove from tank when rigid.
- [redacted].

Finishing: Sample 3.1

Case study 3 making choices during the electrodeposition finishing process

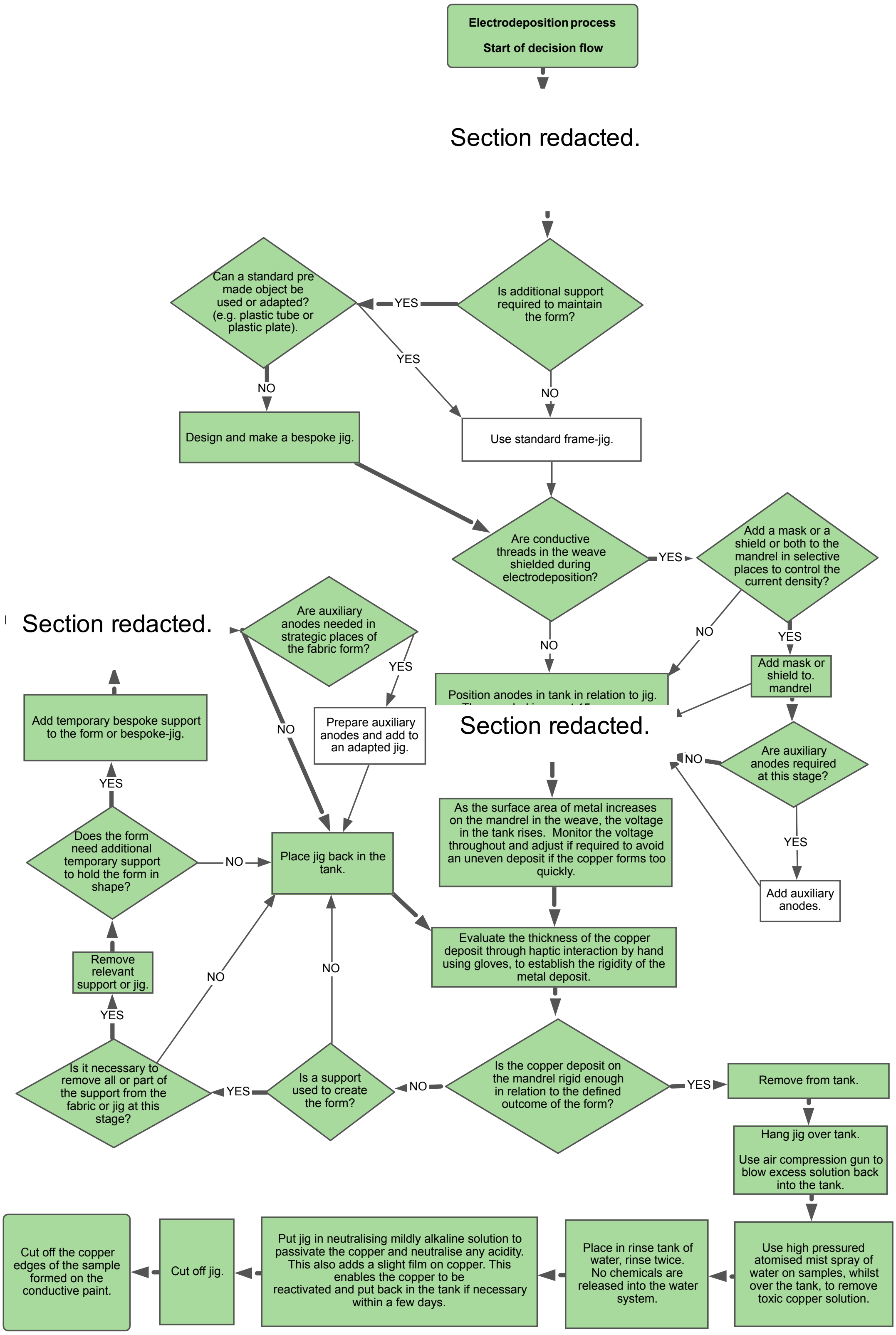


Figure 4.65: The finishing flow-diagram for Sample 3.1.

Images redacted.

Figure 4.66: The fabric was pulled taut [redacted] around an arch-jig that [redacted] (my electrodeposition master) and I created.

[redacted] arch-jig generates the form before the fabric is metallised. The non-metallised fabric is unable to support itself to create the arch form prior to the metallisation.

Images redacted.

Figure 4.67: The arch-jig was placed on a frame-jig and placed in the tank.

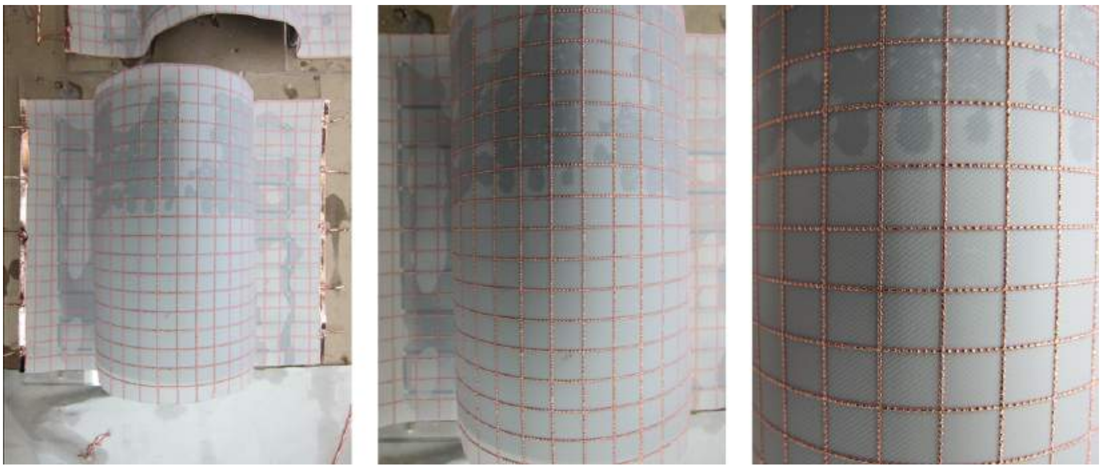


Figure 4.68: The arch-jig was removed when the conductive threads started to metallise.

The arch-jig masked the underside of the form, which created a lower current density. The aim was for the form to have built up enough metal to be self-supporting and be placed back on a frame-jig without the arch-jig. This would allow the metal to deposit on the underside of the shape. At this stage the form was not fully self-supporting as the metal deposit was not thick enough to support the form when the arch-jig was removed. [redacted] (Figure 4.69). This allowed metal to be deposited on the underside of the sample, which was previously masked from the anode by the arch-jig.

Images redacted.

Figure 4.69: (Left) Sample 3.1 with the arch-jig removed; [redacted]

The sample was placed back into the tank and more metal deposited until it became fully self-supporting. [redacted] (Figure 4.70).

Image redacted.

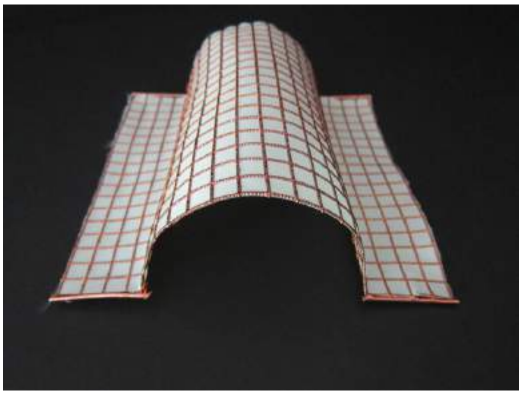


Figure 4.70: (Left) 3.1 after finishing; (right) 3.1 [redacted]

Outcomes

- The metal deposit did not form thickly on the inside of the arch, as the fabric that was pulled tightly around the former was masked from the anode. This meant that it needed more time in the tank to achieve the same thickness of metal. The metal deposit inside the form, closest to the arch-jig, was thinner and flatter than that on the external side. The form was not able to become fully self-supporting until the arch-jig was removed and placed back in the tank to enable the internal arch to be in direct line of sight of the tank anode.
- The fabric was fixed taut within the metal framework.

Reflection-on-action

Reflection-on-action was used to evaluate the way that the metal deposited in different thicknesses when masked by the jigs in Case studies 2 and 3.1. This was used deliberately to affect the characteristics of the final form in Case study 3.2 and 3.3. The aim was to achieve different pliable and rigid properties in the same form by strategically masking and shielding areas of the metal conductive threads in the weave wrapped around the jig in Case studies 3.2 and 3.3.

Reflection-for-action: Sample 3.2

I created a scroll-jig, see page 181. I anticipated that the areas of the conductive threads that are masked or shielded by the scroll-jig during electrodeposition should deposit less metal than the outside faces of the fabric. This is due to the fact that the inside of the fabric scrolls wrapped around the tubes in the scroll-jig would be masked from the line of sight to the tank anodes. The recesses created by the close proximity of the tubes in the scroll-jig should shield areas of conductive threads in the fabric. The hypothesis was that the scroll-jig's shape, combined with shielding and masking, should create variations in the pliability of Sample 3.2.

Case study 3.2

Aim

- To explore how masking and shielding areas of conductive threads within the textile shaped around a bespoke scroll-jig can affect the pliability and rigidity of the metallised form.

Objectives

- To create a bespoke scroll-jig that tightly pulls the textile around closely positioned tubes to create a scroll form.
- To wrap the fabric around the bespoke scroll-jig whist holding the textile under tension to ensure it sits tightly around the tubes.
- To place it in the electrodeposition tank and observe the thickness of the metal deposit.
- When sufficient metal has been deposited to form a rigid shape, remove it from the tank.

The making process sequence:

First finishing of Sample 3.2 (3.2A)

- Create a bespoke scroll-jig.
- Pull the fabric tightly around the jig [redacted].
- Place in electrodeposition tank.
- Remove from tank.
- Evaluate metal deposit.
- Remove scroll-jig.

[redacted]

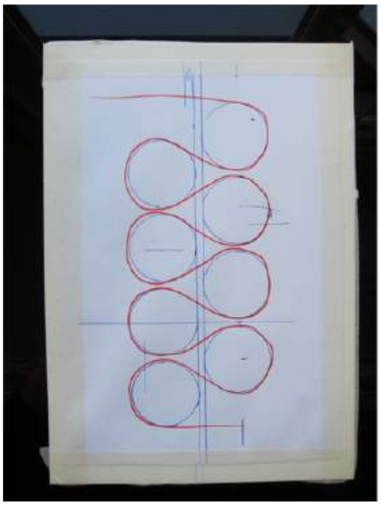
- Evaluate the pliability and rigidity.

Second finishing of Sample 3.2 (3.2B)

- Place the sample back on a frame-jig, opened out.
- Insert auxiliary rod anodes in the scroll fabric recesses to create higher current density in these areas.
- Place in the tank to deposit more metal.
- Remove from tank. Evaluate metal deposit.
- Remove from frame-jig when the required rigidity of the form is achieved.

The bespoke scroll-jig used in Samples 3.2A, 3.2B and 3.3.

[redacted] and I developed a bespoke scroll-jig to explore different metal densities across the metal grid in the same form. I helped create the jigs and become more involved with their manufacture as the apprenticeship progressed. [redacted] used his technical know-how to translate my intended design outcomes and how I wanted the cloth to be held on the jig.



Images redacted.

Figure 4.71: The fabric is wrapped around the tubes on the scroll-jig to form a snake-like pattern. The fabric is under high tension around the tubes and follows the precise form of the scroll-jig.

Image redacted.

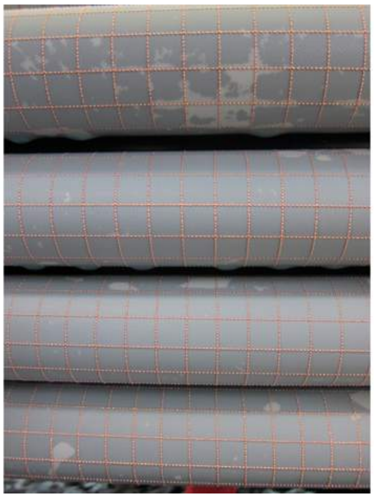


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Figure 4.72: Sample 3.2A during finishing.

Finishing: Sample 3.2A

Case study 3 making choices during the electrodeposition finishing process

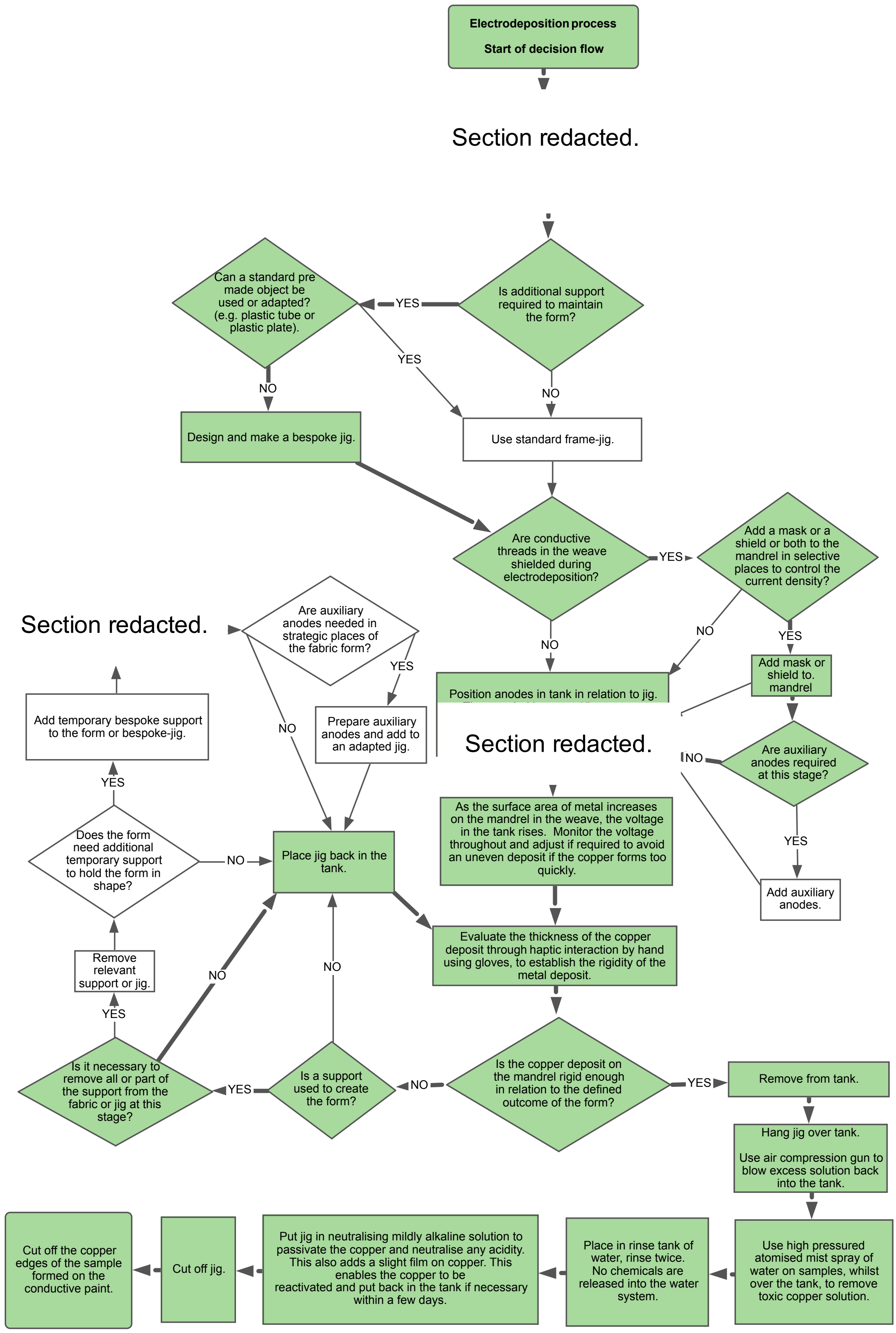

Figure 4.73: The finishing flow-diagram for Sample 3.2A.

Sample analysis 3.2A

Interlacing the fabric tightly around the tubes in the scroll jig created the form in Case study 3.2. The use of the scroll-jig enabled my intentional uneven distribution of the metal deposit to directly align to the form, (the uneven distribution of metal is explained in Section 3.9.1). Where there are very small gaps between the tubes on the scroll-jig, the fabric was shielded from the line of sight of the anode. The tubes also masked one side of the fabric. Therefore, the metal deposit formed more thickly on the outside of the fabric wrapped around the tube. The conductive threads create an interconnected grid within the fabric. Therefore, metal was also deposited on the inside of the fabric face wrapped around the tubes, despite being masked on one side from the anode. However, it was a thinner metal deposit than that on the outside of the fabric.

Masking and shielding areas of conductive threads within the fabric shaped around the scroll-jig affects the rigidity of the metallised form, as the metal is deposited unevenly. The areas masked or shielded from line of sight to the anode build up a thinner metal deposit than that on the areas on the outside of the scroll (Figure 4.74 and 4.75).

Figure 4.74: The inside areas shielded and masked by the tubes within the scroll form.

Figure 4.75: The outside curves of the scroll form that have built up a thicker metal deposit.

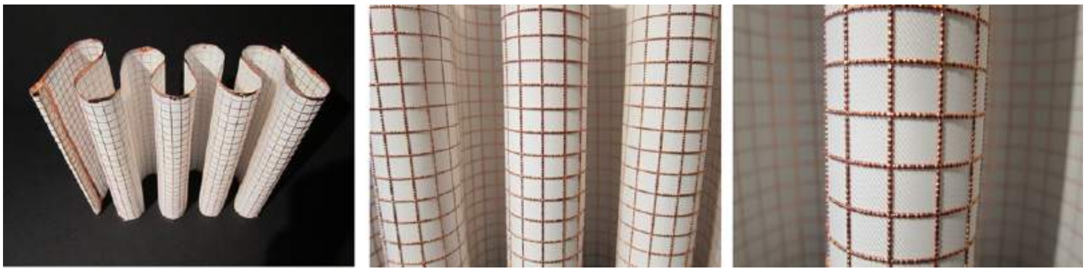

Image redacted.

Figure 4.76: The finished Sample 3.2A scroll form [redacted].

The metal and textile are interdependent on each other throughout the process. The woven textile supports the conductive threads prior to electrodeposition. The stability of the textile weave structure enables the conductive threads in the fabric to be tensioned evenly and follow the form of the scroll-jig. The metal deposit supports the textile after electrodeposition and enables the form to be self-supporting once removed from the scroll-jig (Figure 4.76 and 4.77). The fact that the areas that are masked and shielded still metallise demonstrates the importance of the integration of the conductive threads within the textile, as they form an interconnected electrically active grid throughout the textile. Where the thinner metal deposit appears on the inner curves of the structure, it has less rigidity than the outside face of the cloth. The electrodeposition process in this case study is therefore tailored to the requirements of the structure.

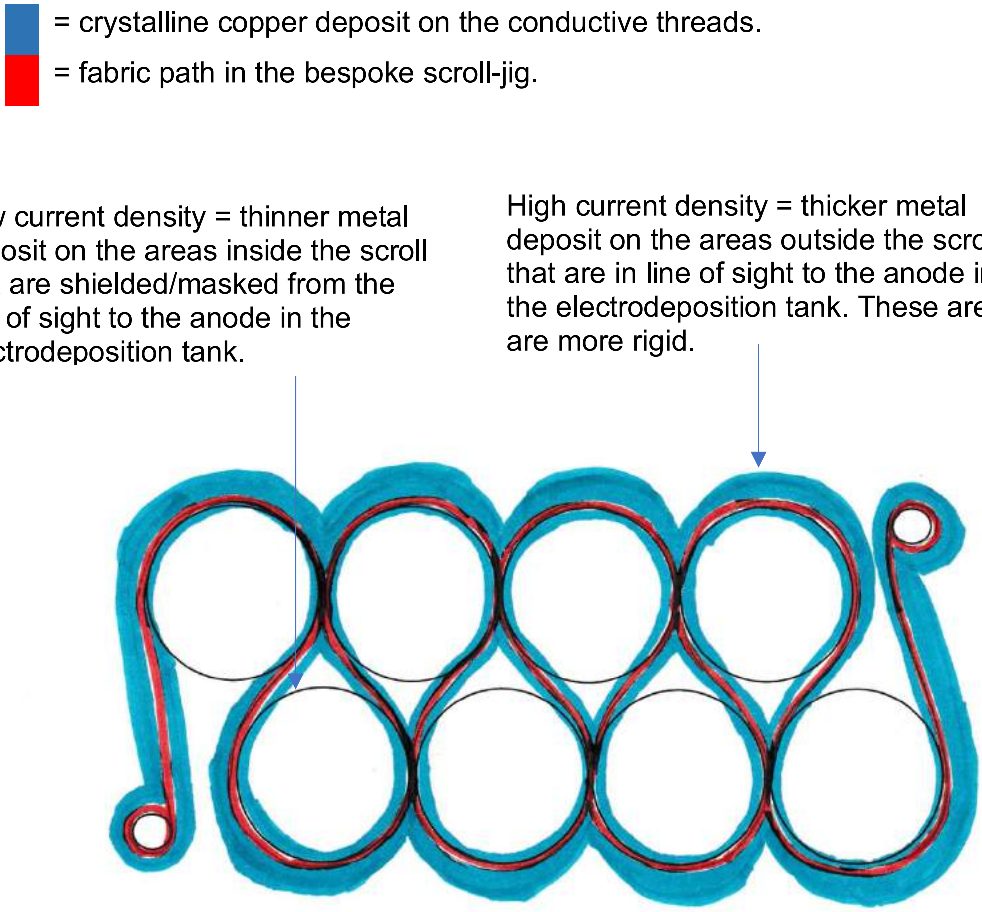

Figure 4.77: My diagram of Sample 3.2A illustrating the path of the textile on the scroll-jig and the thickness of metal deposit on different areas of the form in relation to different current densities.

The effect that the uneven distribution of metal has upon the structure is evident when the two edges of the form are expanded. The thinner deposits do not hold the hybrid form in a fixed shape, and they remain pliable. The areas where the deposit has built up thicker deposits on the outside of the scroll-jig are rigid in comparison. This rigidity holds the scroll shape but the thinner areas allow the recesses to flex. This creates a spring action. The rigidity of the outer areas pulls the form to recover its shape. These spring properties within the metallised form are due to the different thicknesses of metal deposit combined with the form created by using the scroll-jig. The form synthesises rigid metal and pliable textile properties. This is due to the combination of the integral woven conductive framework within the weave, the curved form of the scroll-jig and the masking and shielding of the conductive threads at strategic points within the form. The metal has a degree of pliability in the thinner metal deposit areas. The textile has a degree of rigidity, as it is under high tension between the metal framework.

Reflection-for-action

[redacted] (Sample 3.2B).

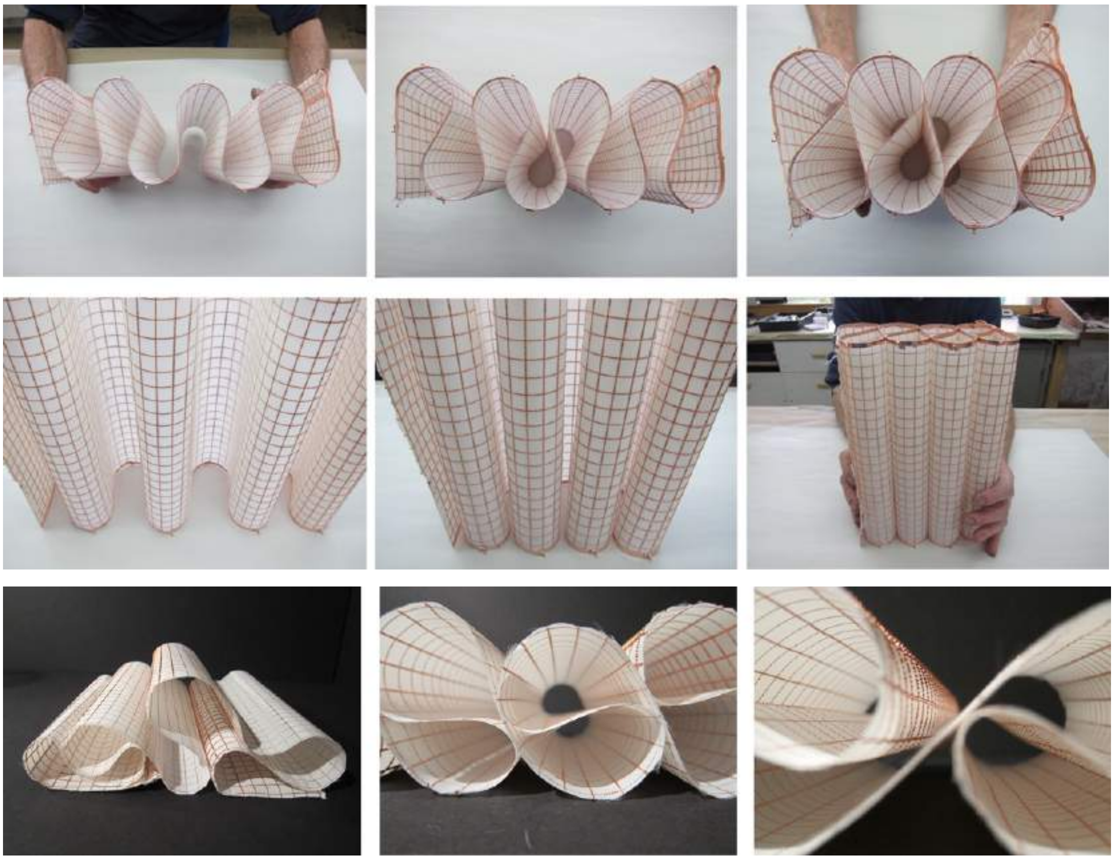

Figure 4.78: Sample 3.2A: (Top and middle) sample [redacted]; (bottom) [redacted]

Second stage of finishing for Sample 3.2B

Case study 3 making choices during the electrodeposition finishing process

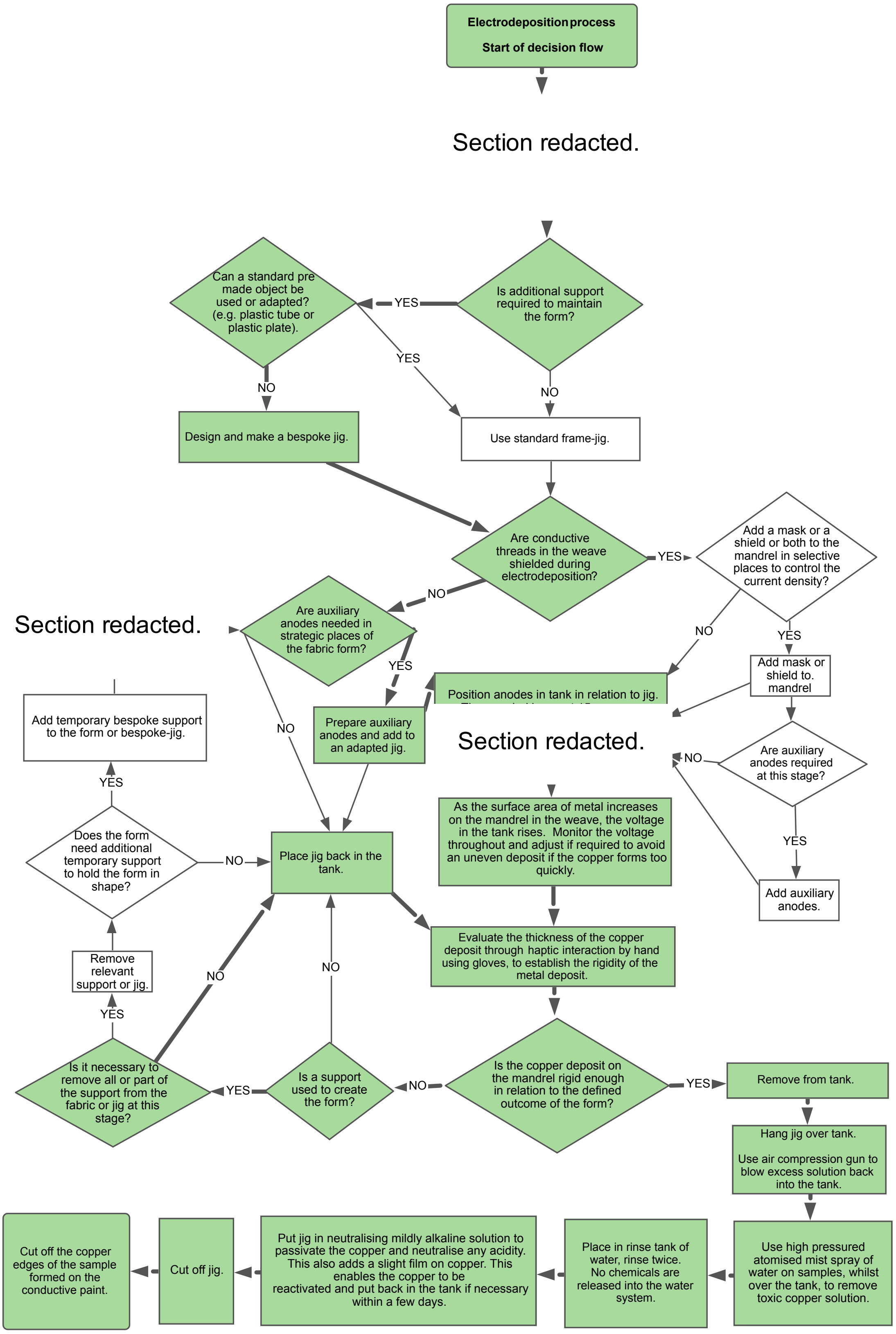

Figure 4.79: The flow-diagram for the second finishing stage to Sample 3.2B.

Finishing: Second stage of finishing for Sample 3.2B

Images redacted.

Figure 4.80: Placing Sample 3.2B on a frame-jig for the second finishing stage.

[redacted] The sample was attached to a frame-jig.

Images redacted.

Figure 4.81: Sample 3.2B during second finishing and the final sample (left).

Auxiliary anodes were placed each side in the recesses of the scroll, where the current density was reduced to build up greater metal deposits on the thinner areas of the form. After the frame-jig had been in the tank for two days, I assessed how rigid the pliable areas had become. When it maintained the form more rigidly it was removed.

Second analysis of Sample 3.2B after second finishing

Sample 3.2B metallised well after the second finishing. However, due to movement on the frame-jig, fractures were created in the metal deposit during the initial stages of metallisation. This created inconsistencies in the rigidity of the metal deposit across the form that were not related to the current density. The metal did not form in a continuous piece during this finishing stage: this caused different spring properties from those it had before the edge was removed. Sample 3.3 was created to resolve this issue.

Reflection-for-action:

Sample 3.3: The second scroll-jig

After reflecting on the results from Sample 3.2B I decided to not remove the sample from the scroll-jig until it was fully metallised to prevent the metal fractures. A new sample was attached to the same scroll-jig used for Sample 3.2A, then placed in the tank. Once enough metal had built up to support the form, the tubes within the scroll-jig were removed to prevent them from masking conductive threads inside the fabric's curves. Auxiliary anodes were placed inside the scroll form to build up metal from the inside of the fabric's curves to reinforce these areas.

Finishing Sample 3.3

Case study 3 making choices during the electrodeposition finishing process

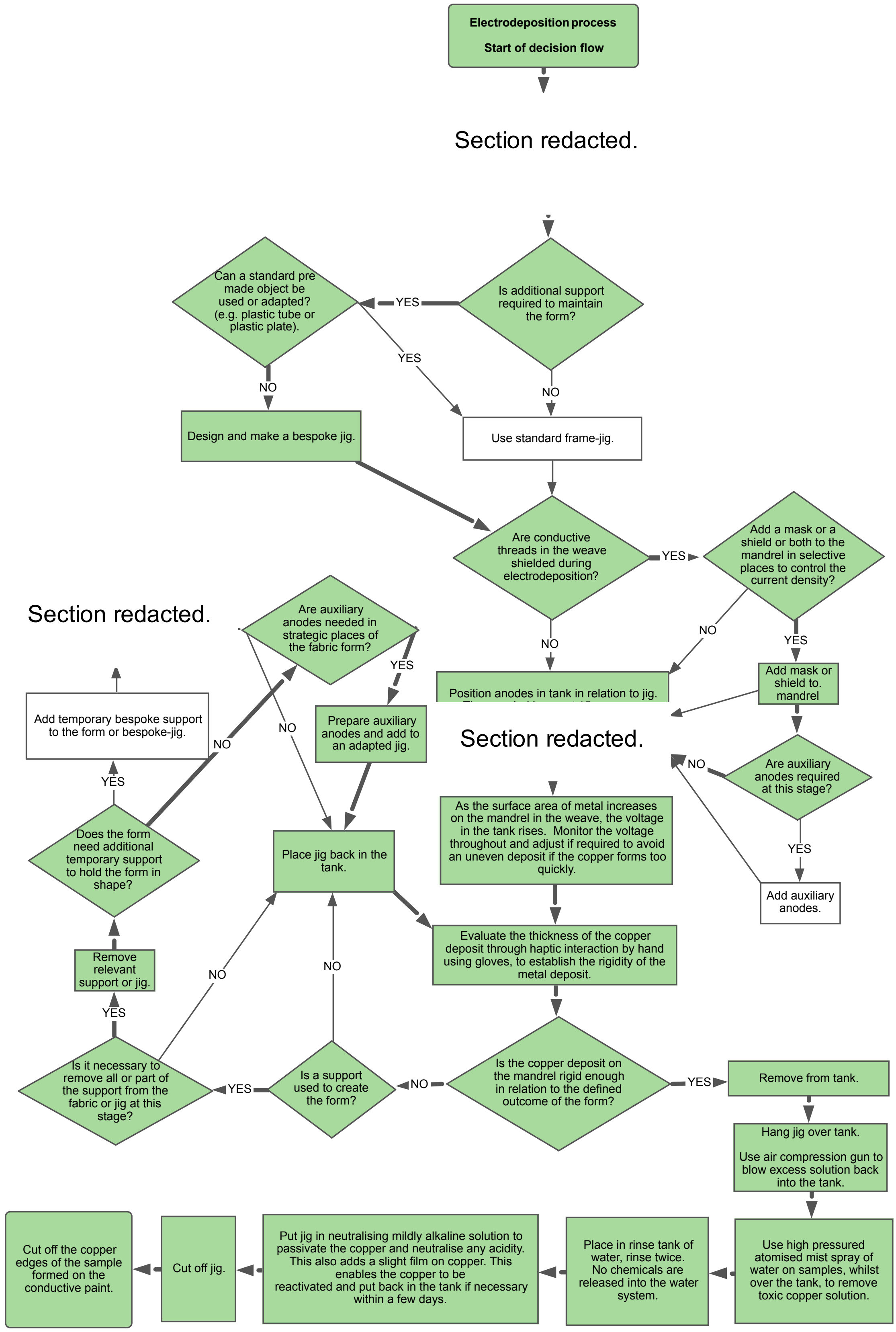

Figure 4.82: The finishing flow-diagram for Sample 3.3.

Sample 3.3

The fabric was wrapped around the scroll-jig, metallised, the tubes removed and auxiliary anodes added.

Images redacted.

Figure 4.83: The tubes are removed from the scroll-jig after initial metallisation.

Images redacted.

Figure 4.84: Auxiliary anodes are inserted inside each of the fabric's curves.

The scroll-jig was re-placed in the tank. I checked the rigidity in each section of the scroll. I chose to remove two auxiliary anodes on the outside fabric because the outside of the fabric's curves built up more metal than the inside. Then I placed the scroll-jig back in the tank. The fabric was not removed from the scroll-jig until the end. This prevented the metal fracturing during the metallisation process.

Images redacted.

Figure 4.85: Sample 3.3 on the jig; me assessing the rigidity of the metal; the final sample.

Analysis of outcomes from Samples 3.2A, 3.2B and 3.3

The metal framework in Samples 3.2A, 3.2B and 3.3 all exhibit different levels of pliability and rigidity within the same structure. The high current density areas on the outside of the scroll-jig provide a stable rigid framework to support the more pliable areas within the structure. The low current density areas, where the metal was unable to deposit sufficient crystalline copper to create a fixed form, maintain a degree of pliability. This relates to the method described in Section 3.9.1 which focuses on the impact of the shape of the jig in relation to the mandrel. The textile is supported by the metal framework within the weave once metallised. The rigid areas maintain the form created by the scroll-jig. The pliable areas where the metal is thinner allow the form to extend in the horizontal axis. The whole form demonstrates a synthesis of the pliable and rigid properties of the textile and the metal. The metal and textile properties are no longer separate and distinct within the same structure. This is in contrast to the Lycra samples in Case study 1 and double-cloth samples in Case study 2, where the metal and textile characteristics are not integrated to the same extent. In the previous case studies the properties of the textile or metal areas maintain more consistent characteristics across the whole form.

Unlike annealed[48] metal, the crystalline structure created on my samples has not had a previous form (Pickup, 1998). The electrodeposited metal inherently adopts the form on which it was deposited. The crystalline structure was deposited in the shape of the scroll-jig, causing the form to adopt this curved shape when the tensile force is removed. When tensile force is applied to pull the vertical edges of the structure apart, the pliable areas allow the form to expand. When the tensile force is removed the rigid areas within the form pull it back towards its original shape. The metal will spring up to an approximately 15 per cent variation from the original form without breaking. The characteristics of Sample 3.3 are the result of the combination of the properties of the electrodeposition process, the pliability of the textile and the shape of the structure. This synthesis of pliable and metal properties in the overall structure in Sample 3.3 was only achieved after reflecting on Case study 1 and 2 and Samples 3.2A and 3.2B. To be able to engineer the spring form with its integrated characteristics, a deeper understanding of the electrodeposition process was required in relation to the scroll-jig form.

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[48] Annealed metal is heated and cooled to increase its ductility and reduce its harness. This allows it to be formed into shapes and cut more easily. The crystalline structure of the metal recrystallises during the process, and this can reduce the metal's original compressive and tensile strength.

4.6: Summary of case studies

Case study 1 used active Lycra within the weave structure, and did not require an external framework to create the form within the textile. However, it did require the use of plastic plates during finishing to tension the textile to create stability in Samples 1.3, 1.4 and 1.5 when placed on the frame-jig. My method of construction in Case study 1 allows the threads to develop their own route and assert their position within the woven structure. The polyester filament and conductive threads drape and move in relation to tension when released from the loom. The textiles also move within the fluid in the electrodeposition tank, due to the pump that circulates the liquid. This also adds to the organic appearance, as the textile interacts with the ebb and flow in the tank.

Case study 2 relied upon the weave structure to generate the form within the textile, supported by plastic tubes. The textile was placed under high tension across the tubes, creating taut fabric areas in between the metal framework that produced a more uniform appearance.

Case study 3 focused on the use of the bespoke arch-jig and the bespoke scroll-jig and the use of different current densities to affect the forms' characteristics. As the depth of my understanding of the electrodeposition process increased, my control of the pliability and rigidity of the samples in Case study 3 became more refined (see Appendix A3.3 pages 252-254). My deeper understanding of the electrodeposition process through haptic making and gaining explicit knowledge of the metallisation process provided the opportunity for further scope for innovation when developing the hybrid forms.

I started this research with a binary approach to pliable and rigid characteristics within the forms. Through the experimental sampling it became clear that these properties could be developed beyond a binary classification. I have created a nuanced ability to control both the soft fabric and hard metal characteristics, as demonstrated in Sample 3.3. Designing the weave in conjunction with electrodeposition has provided me the opportunity to fine tune these qualities. This has created a new technique using electrodeposition on fabric.

Case study 3.3 was informed by the accumulation of new knowledge through my apprenticeship and my reflective practice when evaluating previous case study samples. Knowledge of how the electrodeposition process can be used to create different thicknesses of metal on the metal framework was vital to create the spring characteristics. This is an example of my experiential cyclical reflective practice during action research. This process has enabled my methods to develop towards achieving my research aims. The success of the practical sampling was determined by the controllability of the pliability and rigidity that was achieved through my making process. Figure 4.86 plots the samples in the case studies against the control of the pliability and rigidity within the hybrid forms against a time line. This indicates the paradigm shifts in my design-make thinking and shows a clear progression towards achieving greater integration and control over time, as demonstrated by Sample 3.3. Samples 3.2A, 3.2B and 3.3 utilise different current densities across the woven fabric through masking or shielding selective conductive threads. Figure 4.86 demonstrates that Sample 3.3 (top right) has achieved a level of refined control of the fabric hand properties within the form (see Appendix A3 pages 243-254 for a more detailed analysis).

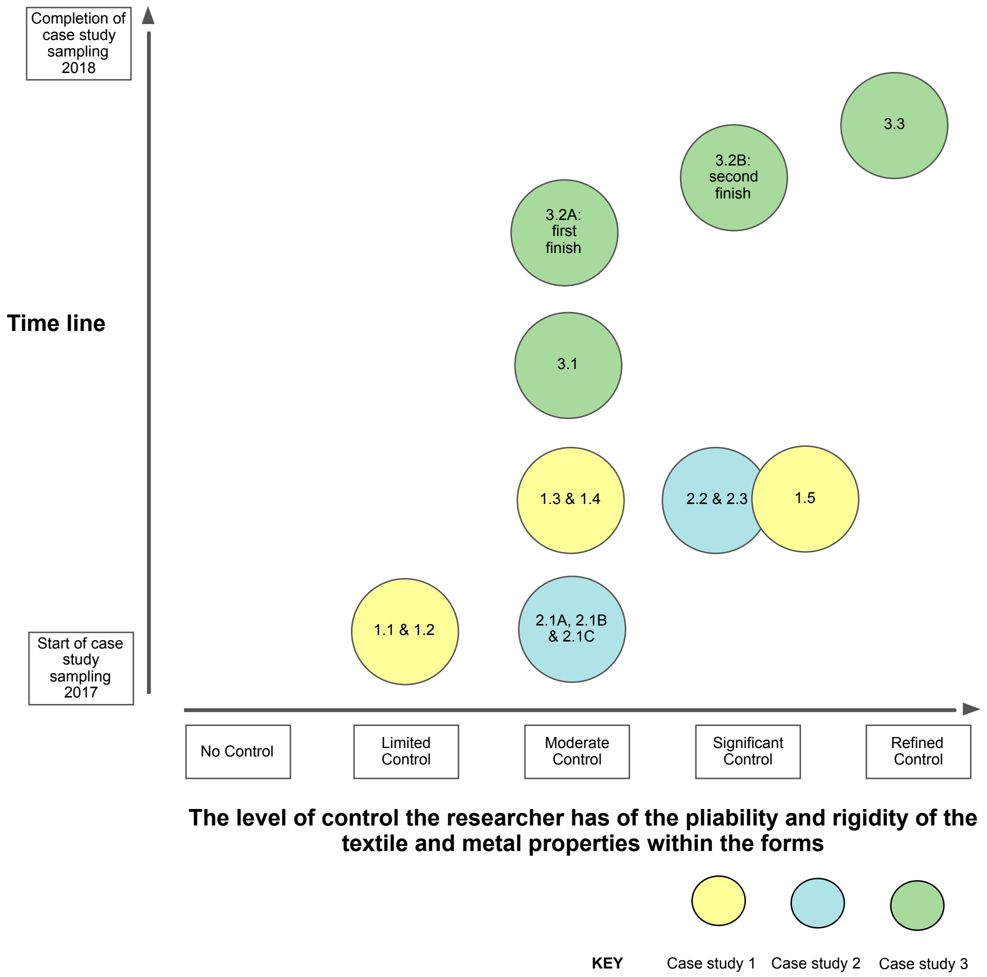


Figure 4.86: My diagram of the refinement of the integration and control of pliable and rigid fabric hand properties in the samples over time in relation to the research aim as a result of reflective practice and action research.

4.7: Comparing the rigidity of woven, printed and sprayed electrodeposition grids to demonstrate the innovative properties of the hybrid forms

I carried out tests to compare the characteristics of different methods of applying a conductive grid to the woven cloth[49]. I discovered that woven fabric, when printed or sprayed with conductive paint, does not produce the same level of rigidity that is created by an integral woven framework when metallised.

Due to technical difficulties in producing a fine conductive grid, the printed and sprayed samples have thicker conductive lines than the woven thread, that is 0.6 microns thick. As a result, my tests are an illustration of each method, rather than a direct scientific comparison. This experiment focuses on the way the metal is deposited, not on its thickness. The samples were evaluated using haptic interaction by flexing, holding the shortest edge. The printed and sprayed grids flex more than the woven grid when shaking the sample from side to side holding the shortest edge, and when compressing the opposite edges. Despite being finer in dimension, the metallised woven grid holds its form more rigidly. This indicates that the woven conductive grid has greater rigidity.

Microscope images in Figures 4.87, 4.88 and 4.89 over the page identify that the metal deposit does not grow as evenly across both sides of the printed or sprayed fabric as the woven conductive thread.

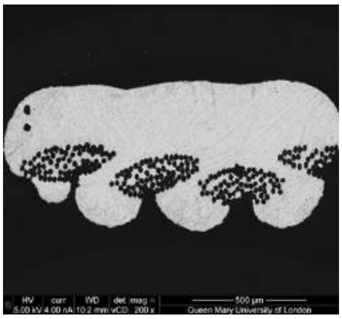
[49] The woven sample in my tests used a 1cm x1cm conductive thread grid fabric. The sprayed and printed samples used the same polyester base cloth without the 1cm grid conductive thread woven within the fabric. The sprayed sample used a laser-cut plastic film to mask the fabric. The print was hand screen-printed. The grid samples were placed on the same frame-jig to attempt to achieve similar thicknesses of metal deposit.

The top nine images are at 50 times magnification (images taken by myself). The bottom three images are electron microscope images, at 200 times magnification, of cross-sections of the metal deposit on each sample (images by Russel Bailey). The light areas are the copper deposits and the black dots are the polyester threads.

Sprayed grid front.

Sprayed grid back.

Side: the metal deposit is not even on both sides.



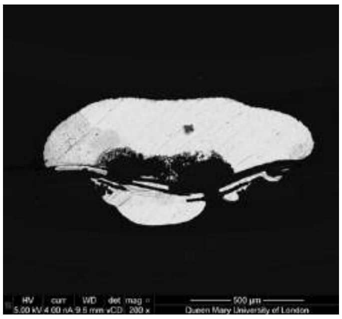
The metal has not formed evenly on both sides of the fabric. The sprayed paint has penetrated either side of the threads. The gaps at the bottom centre of the sample shows that the metal deposit has not joined up on the back.

Figure 4.87: Sprayed sample.

Printed grid front.

Printed grid front.

Side: the metal deposit is not even on both sides.



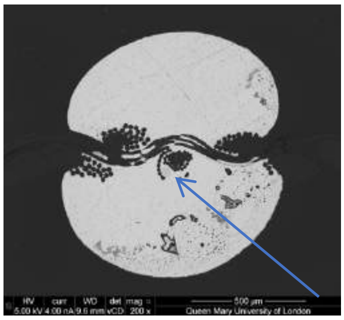
The metal has not formed evenly on both sides of the fabric. Some of the paint has bled through the fabric which has created a metal deposit on the back. But it is not evenly distributed and is not formed of one piece of metal.

Figure 4.88: Printed sample.

Woven grid front.

Woven grid back.

Side: the metal deposit is even on both sides.



The grey dot highlighted by the blue arrow shows one of the conductive threads. The metal deposit has fully encapsulated the conductive threads. The metal has formed evenly on both sides of the fabric.

Figure 4.89: Woven sample.

4.8: The impact of using multiple conductive threads in the weave

When analysing the samples woven with conductive threads, it is apparent that a greater number of conductive threads next to each other in the weave creates a larger area of solid metal in each line. This is because the metal grows on each conductive thread and joins up with the adjacent threads as the metal deposit thickens, (as seen in the electron microscope images in Figure 4.90 and the diagrams in Figure 4.91). The thicker the metal deposit becomes, the higher the current density becomes, which in turn increases the metal deposition rate. Figure 4.90 shows two conductive threads in the weave compared to four conductive threads. The top images show that the copper deposit forms a larger encapsulated area in the textile when more conductive threads are adjacent to each other. The two bottom images show enlarged sections from the images above. The grey conductive threads have been fully encapsulated in the metal deposit, which is the light-coloured area.

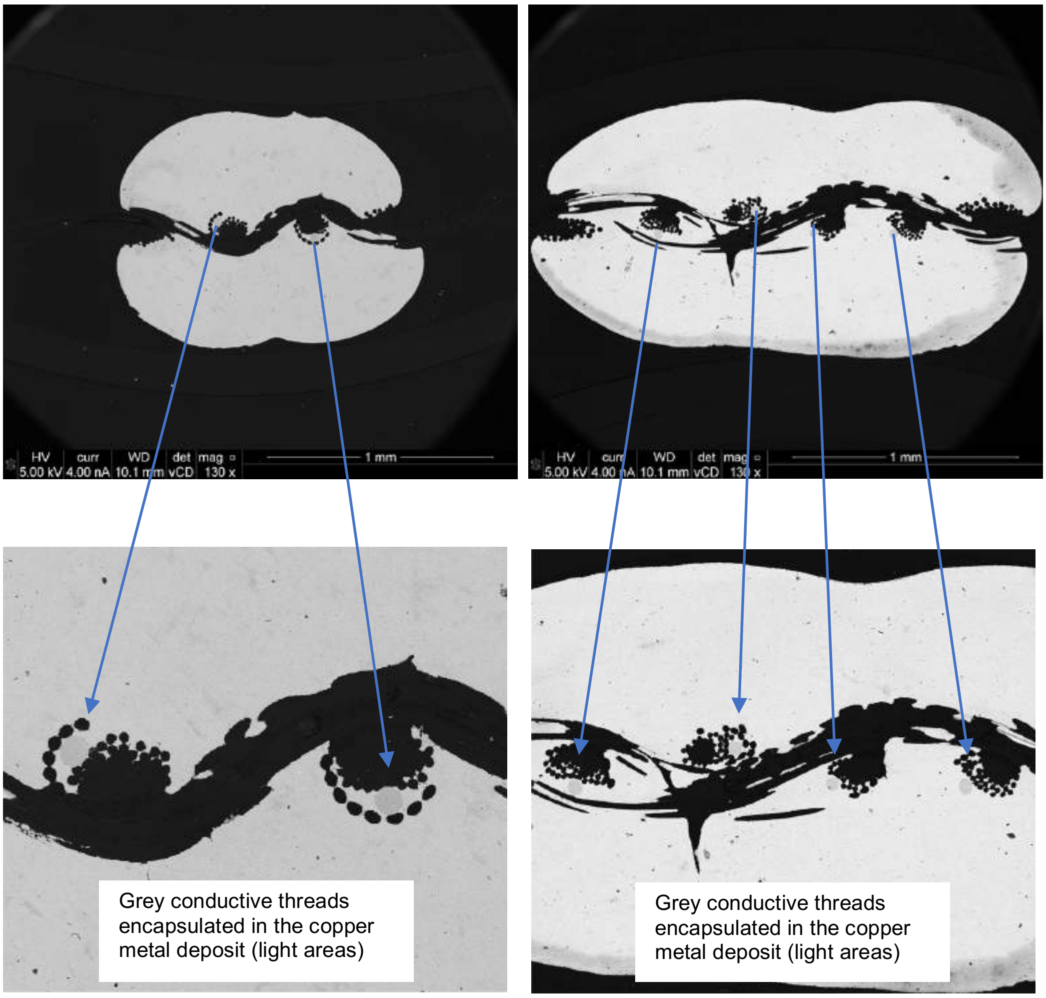
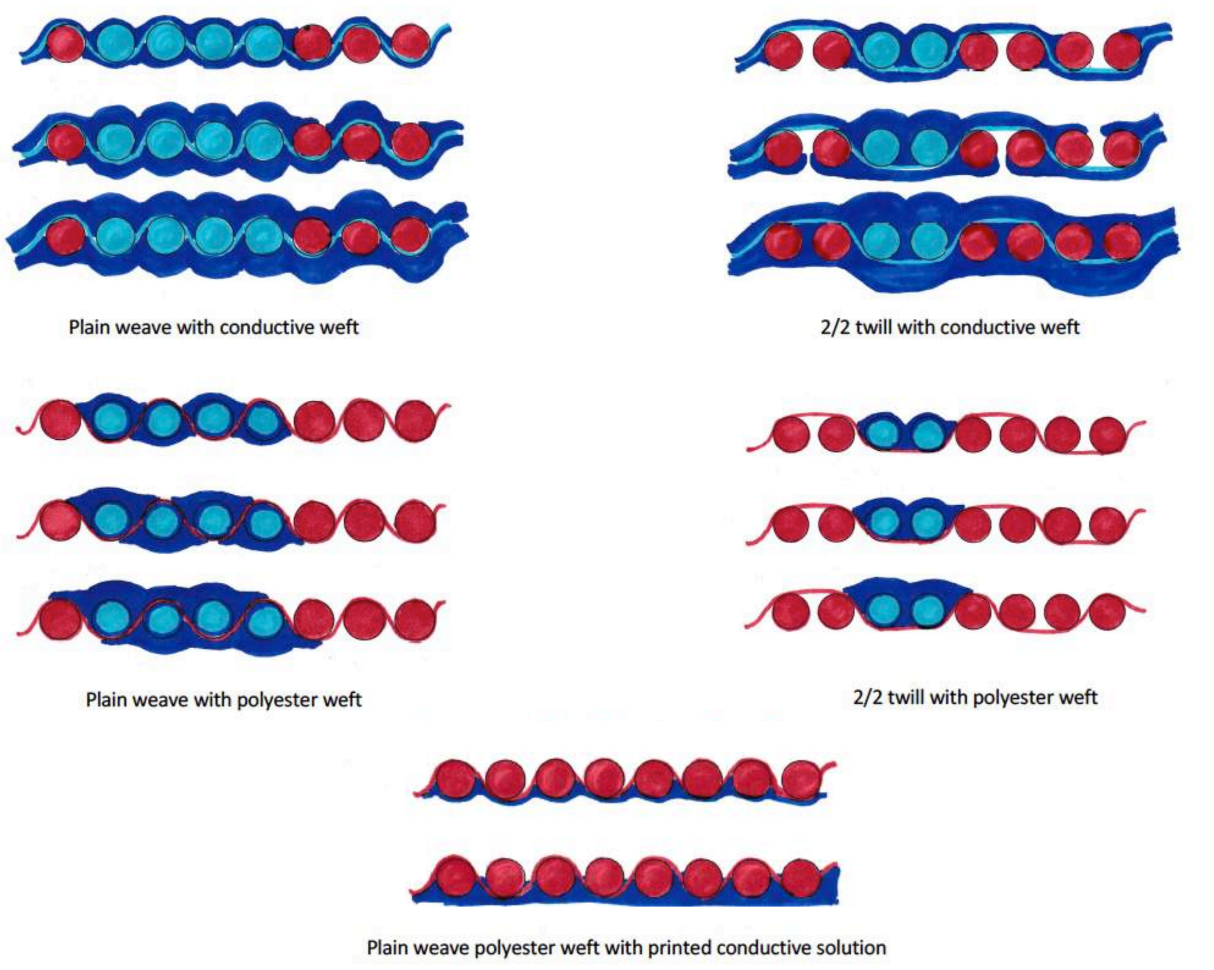


Figure 4.90: (Left) Two conductive threads compared to (right) four conductive threads in the weave when metallised. Microscope images by Russel Bailey, 2018.

If there are conductive threads in the warp <u>and</u> the weft: the two conductive threads join up to form a more rigid integral metal structure within the cloth. As the metal grows on the conductive threads it incorporates the adjacent polyester threads. The metal and the polyester become integrated which increases the rigidity of the forms. Figure 4.91 illustrates plain weave and 2/2 twill with a conductive weft at the top compared to a polyester weft in the middle. The metal weft samples will build up a metal deposit more quickly, as there are fewer interruptions in the electrical current. The bottom image shows a printed conductive line creating a grid. The metal deposit does not form to encapsulate the polyester threads.



Key:

- Metal deposit increasing over time.
- Conductive threads.
- Polyester thread.

Figure 4.91: My illustration of the metal deposit on plain weave, 2/2 woven twill fabrics and conductive printed fabrics.

4.9: Refining the control of the electrodeposition process

Using conductive threads allows for fine conductive lines to be integrated within the textiles. The multi-element construction of weave allows for these threads to be situated precisely in a wide variety of positions depending upon the warp set-up and the weave structures used. The thickness of the metal deposit in relation to the form and ratio of textile to metal influences how hard or soft the hybrid forms become. Whether the metal or non-conductive threads are dominant within the textile relates to the choices made during the making process, the amount of metal deposited and the three-dimensional forms created. This allows flexibility to tailor bespoke characteristics of rigidity and pliability. The transition from pliability to rigidity is influenced by the weave and the finishing.

The hybrid forms are affected by the weave process in the following ways:

- Tension
- Weave structure
- Sett
- Choice of thread, thickness (dtex[50]) and material composition
- Position and number of conductive threads
- Ratio of fabric to metal

Weaving the conductive element within the cloth means that the drape of the fabric surrounding the metal integral framework does not distort as a result of a mismatch between the metal framework and the grain of the cloth. This distortion can occur when printing or spraying a conductive painted grid onto cloth, as the lines may not match precisely to the threads in the base cloth. The conductive threads within the hybrid forms align to the construction and drape of the cloth, as they are part of the fabric's structure (Figures 4.92 and 4.93).

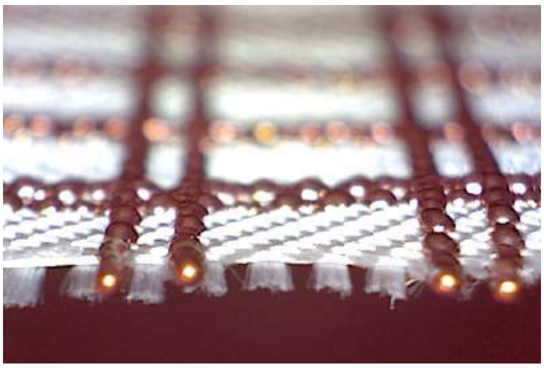
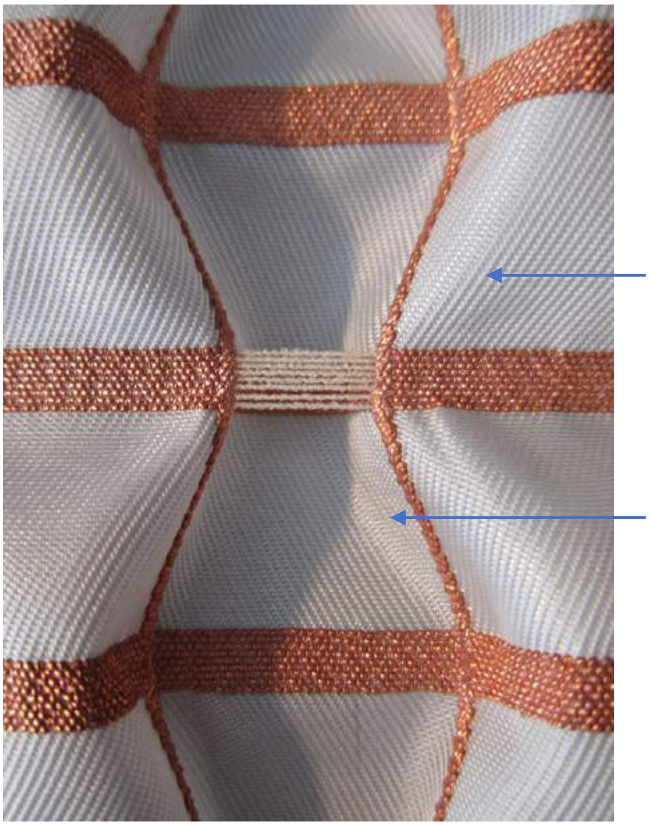


Figure 4.92: A 2/2 twill in precise line with the conductive threads.

[50] Decitex (dtex) is the unit of linear density of a continuous filament or yarn, equal to 1/10th of a tex or 9/10th of a denier, (buinsessdirectory.com, 2018).

Designing the weave in relation to the conductive threads enables the soft woven areas in the hybrid forms to be designed in relation to the metal framework. For example, a 2/2 twill can be used in a reverse block-threaded warp, either side of the conductive threads. The 2/2 twill drape of the cloth will fall in opposite directions away from the conductive threads. This is shown by the blue arrows on Figure 4.93: the weave fits exactly around the metal framework.



Right drape direction of the 2/2 twill due to the weave structure.

Left drape direction of the 2/2 twill due to the weave structure.

Figure 4.93: Close up of Sample 1.4.

The double-cloth samples produced in Case study 2 enable the conductive threads to align precisely to the three-dimensional form. The woven conductive threads within the weave structure create rigid connections to reinforce the pocket structure at the point where the double-cloth joins the single-cloth. Figure 4.94 shows a detail of the double-cloth pocket joining the single-cloth. The woven form of the conductive integral threads eliminates the need to use an additional finishing process such as stitching two pieces of fabric together to create the pockets. The metal framework is one single component form. It is not a series of separately assembled component parts, as those used to create a tensile spaces frame or geodesic domes.

Figure 4.94: Close up of Sample 2.1B.

Figure 4.94 shows where the double-cloth pocket meets the single-cloth in the 3cm samples in Case study 2.1B. This shows that the integral woven metal framework follows the path of the weave and creates a single component three-dimensional form.

Figure 4.95: The inside of Sample 2.1C.

Figure 4.95 demonstrates that the metal framework is formed as part of the double-cloth weave structure that joins at the edges of the pockets, with metal lines of single-cloth in the warp axis.

The hybrid forms are affected by the finishing process in the following ways:

- How the form is created, either using the weave structure on its own or the weave structure supported by plastic tubes or with bespoke jigs.
- The time in the electrodeposition tank.
- Manipulating samples during electrodeposition.
- The sequence of making techniques.
- Masking or shielding conductive threads to reduce the current density in specific areas.
- The shape of the jigs to mask and shield areas of the conductive threads.
- The position of the anodes in relation to the mandrel.

The case studies demonstrate the variety of characteristics that can be created using my Design-make Tri-space. Using conductive threads within a woven cloth allows the pliability of the form to be refined in different areas or be consistent across the form depending on the designer's requirements. The Lycra thread in Case study 1 is an active thread. The conductive threads in all the case studies can also be described as active threads within the weave, as they enable a change in the structure and properties of the textiles after the finishing process of electrodeposition is applied. The polyester can be described as passive, as its characteristics do not change during the finishing process. The integral metal framework can be formed into fluid shapes that combine organically formed metal frameworks with soft pliable areas of fabric, as used in Case study 1. The textiles in Case studies 2 and 3 are under higher tension between the rigid metal integral framework and maintain a more consistent form.

Chapter 5: Discussion

5.1: Metal Integral Skeleton Textiles (MIST)

Using the Design-make Tri-space method creates an integral rigid metal framework to support a pliable textile within woven hybrid three-dimensional structures. I define the rigid metal deposit that forms after finishing as a skeleton, as it provides structural support to the flexible textile. I propose the term Metal Integral Skeleton Textiles (MIST) to describe the hybrid forms created by the integration of the electrodeposition within the woven fabric structure.

Although the word ‘skeleton’ is used, the properties and physical construction of MIST differ from conventional endoskeletons or exoskeletons. Flexibility is a key characteristic of an endoskeleton due to jointed rigid supports that enable articulation. MIST forms have flexibility if the conductive threads are woven only in one axis (warp or weft), or if there are varied thicknesses of the metal deposit across the form. However the term endoskeleton is not an adequate description for the hybrid forms, as the rigid metal framework within MIST is not encased inside the structures. The metal deposit does not fit into the category of an exoskeleton, as although the hard metal deposit that forms on the conductive threads is similar to an external rigid exoskeleton, the forms also have soft textile external areas. The metal does not form a complete protective shell over the entire textile and the rigidity is therefore selective within the structures. The metal deposit forms on the outside of the conductive threads and is integrated within the fabric structure. In addition, weave structures can be used to create integral form within the cloth itself, as demonstrated in Case studies 1 and 2. The metal skeleton and the textile are integrated into the same structure. Therefore I have created the term ‘integral skeleton’, which is a more accurate description of the metal skeleton within the hybrid forms. The woven fabric and the metal skeleton are interdependent. The weave structure and density of the textile supports the conductive threads before electrodeposition. The metal skeleton supports the fabric after electrodeposition: the two are engineered together.

5.2 Designable materiality: Creating a new approach to construct self-supporting electrodeposited hybrid forms

The various iterations within the MIST making flow-diagrams used in Chapter 4 allow variations in the forms’ physical properties. These making methods have generated a non-typological approach to construction. This enables the creation of three-dimensional shapes that do not conform to ubiquitous form typologies. The use of a Design-make Tri-space framework within such an adaptable making system can offer researchers a structure within which to work. I propose that the researchers in the context review identified in Figure 5.1 are also working in types of Design-make Tri-space spaces. Each researcher considers the composition of the materials, form and scale using a non-domain-specific design approach, whereas the construction of the form for the textile aspects and the finishing processes used require domain-specific problem-solving.

Researcher	**Composition**	**Construction**	**Finishing**
Boon (2016a)	Natural threads, resin and weave patterns.	Weave structure and mould.	Resin.
De Ruysser (2009)	Various pre-woven fabrics, conductive solution and paste/foils.	Surface application on woven cloth using print, paint and adhesive foil.	Electrodeposition.
Manelius (2012)	Pre-woven fabric, metal, wood and concrete.	Fabric formwork using woven fabric and metal supporting framework.	Concrete.
Menges (2015)	Carbon and glass-fibre filament threads and resin.	Robotic fabrication using filament fibres and moulds.	Resin.
Milne et al (2015)	Pre-woven fabric, thread and concrete.	Fabric Formwork using woven fabric tailoring/ stitch.	Concrete.
Richards (2012)	Natural and synthetic threads and weave patterns.	Weave structure and thread choice.	Textile wet-finishing.
Soden and Stewart (2009); Stewart (2010); Soden et al (2012); Brennan et al (2013).	Synthetic threads and concrete.	Fabric formwork: the shape is created by the weave structure and thread choice.	Concrete.
Wood (2018)	Silk and Linen threads and weave patterns.	Weave structure and thread choice.	Textile wet-finishing.

Figure 5.1: My description of researchers' methods selected from the context review in relation to the Design-make Tri-space.

Although the researchers in Figure 5.1 have used finishing techniques on textiles in relation to composition and construction, no studies were found in published research that articulated my concept of a Design-make Tri-space in relation to electrodeposition finishing selective threads in woven textiles to create self-supporting forms.

There are similarities between my approach and Menges' method for building the Elytra-Filament Pavilion (Menges, 2016b). Menges's use of single-filament glass fibre and carbon fibre relate to my use of single-filament polyester. During both construction processes pliable elements are transformed to create rigid self-supporting structures. My research uses a combination of weave structure and the use of jigs to generate the form. The interplay between the weave structure and the jig is an important factor in the MIST making process as described in more detail in Sections 3.8.1 and 3.8.8. Menges' (2015) and Boons' (2016a) research also used temporary structural jigs to support the pliable filaments until the resin cured.

The MIST system of making offers a different construction method and result from structures using textiles and tensile cables or tensegrity rods, as it explores the relationship between the rigid metal and pliable textiles. The pliable woven textile is an integral component of the engineering of my MIST forms. Although jigs can be used to tension the textile and the conductive threads to support the form during finishing, strong tension forces are not required to maintain the form after finishing, as required in cable net tensile structures. Otto's and Fuller's constructions used separate frameworks to support the textiles within their structures. Although MIST self-supporting metal and textile structures are composite materials, due to the use of integrated construction methods, the metal skeleton within MIST is created in one continuous form, rather than from several material components. Therefore, textiles within MIST are affected by tensile stress in a different way from traditional space frames. When the tensile stress created by the jigs is removed, the textile is supported by the metal skeleton and maintains the shape, but the textile areas are not required to be under high tensile force. The metal skeleton is self-supporting and the integrated soft textiles are able to have their own characteristics within the forms. This offers different material properties to structures that rely on the application of tensile force that generate taut and rigid textiles. This means the conductive threads in MIST can take a path more closely related to the natural drape of the textile if the designer chooses. Spuybroek's concept of Soft Constructivism (Ludovica Tramontin, 2006) within architectural design that involves using ‘softness and flexibility’ (Ludovica Tramontin, 2006:53) to build structure relates to the methods used to create MIST.

Menges et al. (2015; 2016a, 2016b) and Boon (2016a) used resin finishing to coat the entire filaments or textile. The engineered Fabric Formwork by Soden and Stewart (2009), Stewart (2010), Manelius (2012), Soden et al. (2012), Brennan et al. (2013) and Milne et al (2015) used concrete finishing to set rigid the entire pliable textile forms. In contrast, MIST uses selective finishing to maintain areas of pliable textile within the final forms by using the woven textile design as a means to maintain pliable aspects of the textiles within the forms.

MIST relates to the three-dimensional structures created by weavers Richards (2012) and Wood (2018), where the finishing process applied only affects specific active threads within the weave. Their approach relies upon a parallel processing of the finishing process in relation to the construction of the woven cloth. Their research demonstrates that designing the weave in relation to wet finishing processes is essential to the physical properties of their woven structures. My research uses my Design-make Tri-space, which identifies electrodeposition as a finishing process, to alter the characteristics of specific threads to create selectively rigid woven self-supporting forms.

Keith’s (2010) use of electrodeposition on weave differs from this research, as it relies upon the serendipity of conductive dye to influence her forms. My precise placement of the conductive threads enables a detailed level of control over the rigidity of the forms. This allows for highly selective positioning of where and how the threads cross within the weave structure. This does not apply to the electrodeposition used for De Ruysser’s (2009) or Keith’s (2010) use of conductive solution combined with electrodeposition, as they do not have the same precision when applying the metal deposit. Horton (2017) has explored a more controlled application using the electrodeposition of digitally drawn conductive lines on textiles, but these lines do not interlace throughout the fabric to create a two-sided integral conductive grid exhibited by MIST. These practitioners’ outcomes differ from my research, as they have used electrodeposition as a surface treatment. These surface application electrodeposition methods do not offer the same structural rigidity as MIST, as demonstrated in Section 4.7. My research outcomes exemplify a weaver’s parallel processing when integrating electrodeposition. The electrodeposition techniques become part of my experiential knowledge of how the textile will alter after finishing. This is an innovative use of electrodeposition on textiles. My intention was that the framework is designed within the fabric, rather than it being applied afterwards using conductive solution.

5.3 Reflection on research methods using tri-space frameworks to refine my methodology

My methodology was refined through an engagement with the materials, processes, tri-spaces and collaborators within this research project. This section considers how the methods used in the case studies in Chapter 4 influenced the research outcomes and highlights the transferable knowledge generated. As detailed in Chapter 3 the initial Design-Make Tri-space methods and tools were identified prior to the sampling. This provided the tri-space frameworks and technical parameters to work within. However, how these frameworks meshed together was a journey of discovery. As the research progressed tools such as the decision flow diagram for electrodeposition were extended to include new decision pathways, as I gained new insights to the finishing process. The use of reflective practice before, during and after making within the tri-spaces using parallel processing reinforced my hypothesis that integrated thinking and making were essential to achieve my research aims. I propose that combining the construction and the composition processes of weave with electrodeposition as a finishing process has established a new approach to making rigid and pliable self-supporting hybrid structures. The key to my methodology is the *integration* of established design research methods of reflective practice, making processes and the roles used within my tri-spaces.

This research has been significantly influenced by the context of the collaboration and my skills base. It required particular skills that combined my tri-space thought processes with an experimental approach of material interaction. I suggest that my previous experience as a craft-design weaver using parallel processing when collaborating with industry has been a useful foundation for this research. My skill-set has been extended through the use of my routine weave textile problem-solving, alongside non-routine industrial specific problem-solving. Through my apprenticeship, the non-routine electrodeposition finishing process has become part of a new routine problem-solving space.

5.3.1 Adapting the Design-make Tri-space

When a design researcher's tacit knowledge is translated into a language that can be shared by others, it can become the basis for new knowledge creation by other researchers. As identified in Chapter 3, this research relies on the context in which the learning occurs. Situated Theory[54] methods are reliant on the researcher's active participation in the context of the inquiry, rather than a purely abstract cognitive approach. However, despite the contextual emphasis within my own research, I propose that my Design-make Tri-space can be generalised to provide flexibility for other design practitioners to insert their own specific contexts within my framework. Figure 5.2 illustrates my revised discipline-general Design-make Tri-space. It enables my experience of situated learning[55] (which is context-specific), to be translated and applied in a context that is wider than this research inquiry.

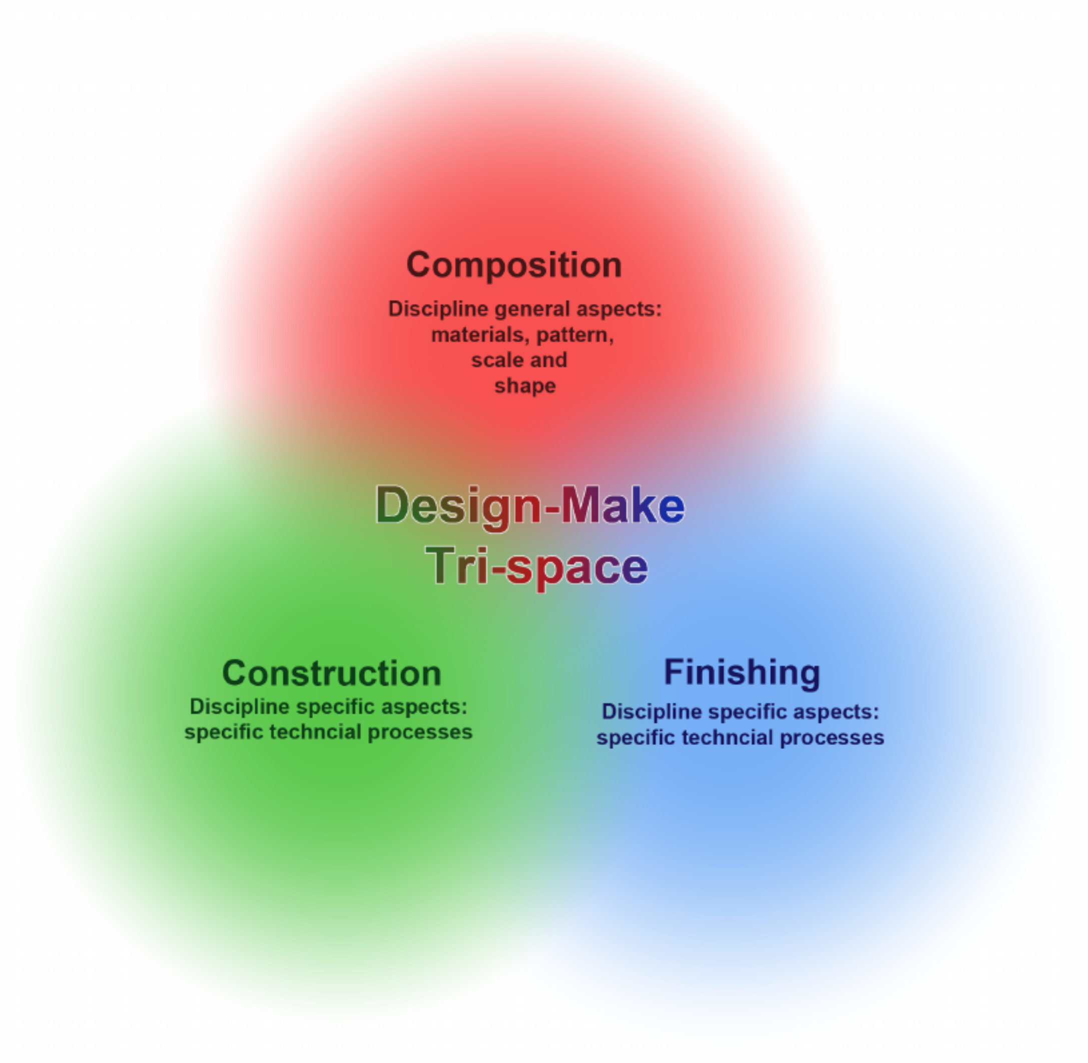


Figure 5.2: My revised discipline-general Design-make Tri-space.

[54] Situated Theory, see Chapter 3, p.112 of this thesis.
[55] Situated learning relies upon the context of the situation in which the learning takes place. see Chapter 3, p.111.

The composition space, which relates to the visual aspects of the form, is domain-general, as the principles can be applied across many disciplines. However, the construction and finishing spaces rely upon technical aspects, which are domain-specific. Therefore, the specific technical skills of the researcher are relevant to these problem-solving spaces. Acquiring new knowledge through collaboration or apprenticeship can facilitate the use of non-routine domain-specific processes within this type of research.

5.3.2 The importance of the integration of the Tri-space Roles to facilitate innovation

5.3.2.1: The role of academic researcher

This research demonstrates that designing, planning and making from an integrated perspective encourages a cohesive research methodology. Using a parallel process approach when problem-solving enables several aspects of making to be considered simultaneously. This encourages the designer to integrate separate aspects of making, such as construction and composition, with finishing processes. Within my research, the main design decisions were guided by my experiential woven textile design knowledge that combines aspects related to the visual balance of the fabric with the structural balance of the construction of the form. This knowledge was integrated with the new knowledge gained from my electrodeposition apprenticeship. This included where to place the lines of the conductive threads to form visual design details and structural supporting rigid metal lines within the woven fabric.

I propose that when parallel processing within tri-space problem-solving is used as a distinct research method it can aid reflective practice and facilitate innovative outcomes. This type of integrated thinking can be used as a tool to discover new design solutions, which may only be possible when adopting this synthesised method.

5.3.2.2: The role of designer collaborating with Industry: Using a textile craft-design method during industrial manufacturing

I have built up strong working relationships with the technical industrial weaver as part of industrial collaboration and the electrodeposition specialist as part of my apprenticeship. This has enhanced my understanding of interdisciplinary knowledge and skills which are valuable in relation to this research and my future practice. A significant change has taken place in my ability to adapt and respond to new cross-disciplinary experience and knowledge as a result of this research.

The collaborative aspects within this research relate to:

- The practical aspects relating to the parameters of the manufacturing to make the physical outcomes.
- The transfer of design intentions to the weaving mill and the metal finishers. This includes the interaction and knowledge exchange that occurred during the making processes.
- The transfer of information relating to the electrodeposition finishing process from the specialist as part of my apprenticeship.

These considerations were integrated with routine (Mayer,1989) woven textile problem-solving approaches to facilitate new ways of design problem-solving.

5.3.2.3: The benefits of an apprenticeship method for non-routine knowledge acquisition

As established in Chapter 3, a lack of discipline-specific knowledge relating to non-routine processes can create a barrier for a researcher engaging in cross-disciplinary research**.** An apprenticeship can offer researchers a learning environment to test ideas and build on reflective practice. Using a personalisation strategy (Hansen et al., 1999) enables a researcher to discuss and adapt problem-solving solutions on site, with their apprenticeship master, relating to specific aspects of their research. During my apprenticeship I frequently asked my electrodeposition apprenticeship master [redacted] to explain discipline-specific information in relation to my own research inquiry. Through observing, questioning and copying [redacted]'s actions I gained explicit knowledge. During these discussions with [redacted] I was the creative researcher in the process. [redacted]'s technical knowledge was the means to facilitate the use of electrodeposition as a finishing process on my woven textiles. I created the designs for the bespoke jigs used in the sampling. I explained the shapes of the forms to be produced and [redacted] helped me create bespoke jigs using his technical expertise. As my experience and knowledge grew, I was able to refine my specification for the jig design. The use of the new knowledge gained from the apprenticeship method was applied in relation to my textile design making knowledge to discover how to apply metal deposits to the conductive threads in the weave. I was able to use reflection-in-action and reflection-for-action during discussions with [redacted].

At the start of this research I could be classified as an expert in terms of weave and as a novice in terms of the electrodeposition process. The aim of an apprenticeship is for the apprentice to become a master in the related field. As illustrated through the case studies in Chapter 4, my skills have progressed from those of an electrodeposition novice towards stage two of an apprenticeship, which enables problems to be identified and corrected. My apprenticeship with [redacted] enabled me to participate in practical engineering elements when producing the samples. This provided insight to enable me to adapt and use the metallisation process in ways that I would not have considered without a hands-on approach. Through experiential interaction with the metallisation process I gained new embodied somatic tacit knowledge of electrodeposition in relation to my samples. I used my weave design thinking during the electrodeposition finishing to bring new perspectives for its application in my tri-spaces. Therefore, I propose that an apprenticeship is a useful method for researchers wishing to engage in non-routine practice-based research. The experience provided an opportunity to appreciate how to apply the electrodeposition specifically in relation to my research. This inquiry demonstrates my experimental exploration with the metallisation finishing process and the knowledge gained from this interaction.

This research demonstrates that apprenticeship can be used as a component part of a wider research methodology as part of a Tri-space Roles framework, to gain new knowledge from a master whilst also becoming a platform to explore specific research agendas. Traditional models of apprenticeship in historical craft guilds refer to single craft disciplines (Sennett, 2009). Therefore, they do not always suit the extensive possibilities for the type of knowledge acquisition that cross-disciplinary research can produce in an apprenticeship. My use of a traditional guild apprenticeship method evolved during the research. The traditional apprentice role as a recipient of new knowledge is combined with the role of the academic researcher and designer collaborating with industry. This means that different types of cognitive processing occur during experiential interaction with the materials and the master. When integrated within the Tri-space Roles framework the traditional hierarchical nature of the relationship between novice and master alters as the researcher integrates their knowledge-in-practice related to their own making process, with the new knowledge from the master. This approach aligns to Kolb and

Kolb's (2018: 9) view that in experiential learning cycles the researcher is both the receiver and creator of information. This parallel processing changes the traditional role of an apprentice, who is solely a recipient of knowledge, to include the researcher's own expertise in relation to the new knowledge gained. As an apprentice, he or she is the recipient of specialist information from the master whilst learning new skills. As an academic researcher, he or she simultaneously evaluates how these new skills can be utilised in relation to practice-based research aims as part of reflection-in-action, for action. As a designer collaborating with industry, practical considerations relating to manufacturing need to be considered. This demonstrates the importance of my Tri-space Roles method in relation to the creation of my hybrid forms. I propose that through applying my Tri-space Roles and Design-make Tri-space I have generated a new making approach and I am becoming a master in the creation of MIST.

Using apprenticeship as a component part of my tri-space methods has also influenced and expanded [redacted]'s knowledge of his own specialism. Although [redacted] adopted the role of the master during my apprenticeship, when the guild apprenticeship model is placed within the context of my tri-spaces, [redacted] gained new knowledge of his own process. At the end of my research the hierarchy of the 'unskilled' novice and 'skilled' master, as seen in a craft guild apprenticeship, moved towards a collaborative interaction. This is demonstrated by the sharing of our knowledge to achieve the aims of a project. In my discussions with [redacted] there was an exchange of specialist knowledge which was key to the transfer of knowledge, and also to the generation of new knowledge between both parties. It was the transfer of information in a verbal and practice-based way that enabled this dynamic to occur. An open-ended, design-led approach which combined engineering methods and a design experimental approach led to more refined outcomes in Case study 3. My aim to incorporate the pliable characteristics of fabric with an electrodeposited integral skeleton within custom-designed woven cloth was an atypical application for the metallisation process in which [redacted] is a specialist. This research challenged [redacted] to develop new technical solutions and insights for a finishing process which he would consider as a routine problem-solving space. My tri-space problem-solving, which integrates an apprenticeship method, created an environment to enable inventive research outcomes. I propose that this type of exchange can provoke each party to look outside their discipline's toolbox and extend their knowledge base.

The apprenticeship provided the opportunity for me to develop my own specialist knowledge through embodied making in relation to my hybrid forms. This research demonstrates that discussions whilst working can facilitate the integration of the researcher's discipline-specific knowledge with new knowledge of the unfamiliar making process. When specific questions arise, they can be discussed with the master with the aid of their experience and the materials in the workshop, creating a different dynamic from the detached individual problem-solving situation in a researcher's studio. This demonstrates that using a personalisation strategy during an apprenticeship is an effective approach to problem-solving when thinking through making.

5.3.2.4 Adapting to technical constraints and the use of failure as part of action research and iterative sample progression in the tri-spaces

During collaborative projects a researcher needs to be able to modify their practice to adapt to changing circumstances whilst ensuring that their aims are not compromised. I suggest that adopting a design approach that uses reflective practice and iterative design development is an effective method when working collaboratively. The flexibility of a design-thinking approach enables the researcher to adapt when faced with technical and practical challenges. As this is a single-practitioner-focused research, the key factor when adapting any design or making decisions was to keep control over the process by maintaining my research aims at the centre of the collaboration.

I suggest that an important factor in successful collaborations is the recognition of the contribution of shared cross-disciplinary knowledge. This type of approach to problem-solving relates to the work of Schön (1991) and situated learning (Lave and Wenger, 1991), as my knowledge was enhanced by exploring materials and processes. Although I acknowledge the influence of the mill's Technical Director [redacted] and my electrodeposition apprenticeship master [redacted], I led the research. I was the creative practitioner, and it was my application of the new technical knowledge gained from the collaborations that informed the decision-making. Through interaction with the material processes I acquired first-hand knowledge of the industrial weaving and metal electrodeposition processes. This enabled me to remain in control of the research focus. I propose that when a researcher has gained significant new knowledge to apply independent thinking within the new research field, to enable them to develop design solutions, they are able to adapt where necessary without compromising their ownership of the research direction. Examples of technical challenges and failures which had the potential to hinder my practical outcomes were:

- The technical parameters of the industrial looms and the electrodeposition process. My first-hand experiential research was valuable when adapting designs, as demonstrated throughout the case studies.
- Inserting and removing the plastic tubes from the double-cloth in Case study 2 required a series of iterations to produce a successful outcome. I made a tool to hold open the fabric when inserting the plastic tubes and I ensured that the plastic tubes were removed before too much metal deposited.
- [redacted].

5.4 New insights relating to routine practice

I suggest that discussions with non-discipline-specific practitioners is a useful method to highlight the areas of information that are routine within a researcher's practice. My interaction with [redacted] during the apprenticeship has made me more aware of the specific textiles methods and approaches that I have used instinctively in my previous practice, and how the metal process affects these. Examples of new insights are my use of single and double cloth, plain and 2/2 twill weave structures in relation to the metal finishing process, to achieve different characteristics in the forms. The use of double cloth masks the internal pockets within the weave structure, as it blocks the line of site to the electrodeposition anodes. This reduces current density in these areas and reduces the metal deposit (p169-170). Another discovery was that the structural properties of the metal deposit on twill weave creates a stiffer fabric than plain weave, when all other factors are equal (p155-156). The opposite is true of non-metallised fabric. This is an example of collaboration shedding new light on a researcher's well-known subject. It can also highlight to the researcher their specific unconscious actions and thoughts that are so instinctual that they can become lost in communication. This occurred regularly when I discussed my textile process with [redacted] during the apprenticeship. It was also apparent when writing the representations to provide the mill with weaving instructions. This hidden tacit knowledge is often clearly visible to an individual from the viewpoint of another discipline. Collins (2013) refers to this type of tacit knowledge as unrecognised tacit knowledge, which can be one of the barriers to successful communication.

5.5 Summary of the stages of knowledge exchange within the research

My routine knowledge base and my problem-solving approaches have been transformed by using my tri-spaces during this research. The knowledge acquisition within this research relies upon the communication of tacit knowledge. I have adapted Battistutti and Bork's (2016) Life Cycle Model relating to tacit and explicit knowledge to describe different stages of knowledge exchange within this research. These are:

Strategic planning of the project: Establishing collaborative relationships with industrial partners. This relied upon the use of my textile tacit knowledge as a base on which to build the research aims and objectives.

Initial model building: Making elements of my tacit knowledge explicit through the use of representations, text and dialogue with the weaving mill. This enabled the externalisation of my tacit knowledge.

Feedback model building: Interaction with the materials, people and making processes during the apprenticeship and discussions with [redacted] and [redacted]. From this feedback I was able to combine my tacit and explicit craft/design textiles knowledge with their external explicit industry-specific knowledge.

Final model building: The explicit knowledge gained through the apprenticeship, and the collaborative making with [redacted], were internalised as part of my own routine problem-solving. 'When knowledge is internalised to become part of an individual's tacit knowledge base in the form of shared mental models or technical know-how, it becomes a valuable asset' (Battistutti and Bork, 2016:467). This internalised knowledge can be used to inform future research and knowledge acquisition.

I propose that my tri-spaces are flexible evolving research frameworks that have cyclical life cycles related to the progression of a researcher's practical and cognitive processes. I have gained new internalised tacit knowledge from using the tri-space frameworks. I propose that a researcher's problem-solving ability is likely to evolve each time they approach a new design problem-solving task when using the tri-spaces, as non-routine knowledge is internalised and becomes routine. This is evidenced through my progression in the case studies in Chapter 4 towards more effective solutions to accomplish my research aim. Therefore, the tri-spaces have the potential to become dynamic tools that can be modified to incorporate the researcher's continuing accumulation of knowledge-in-practice. I suggest my tri-spaces offer an adaptable but structured approach to reflective practice in design-led making, whilst allowing flexibility for the researcher to build upon their reflective experiences. It would require further research to establish validity to this claim but the tri-spaces could become a useful framework as part of reflective practice in relation to design-led action research cycle of problem-solving. This approach has the potential to produce innovation as demonstrated through my research.

Chapter 6: Conclusion

6.1 Summary of research

This research sought to develop a method to integrate and control the pliable properties of woven textiles and rigid metal within self-supporting forms. It explores my hypothesis that using an expert weaver's parallel processing approach combined with electrodeposition can provide new insights to the metallisation of woven textiles. The process I have created incorporates the design of the weave structure with an understanding of an engineering approach to metal finishing. Therefore this research extends previous electrodeposition of textiles, as it integrates the properties of the crystalline copper deposits that form on the threads to influence the forms' physical characteristics. This approach offers the opportunity to maintain the pliable textile properties within the self-supporting forms, which are often lost when using tensile force or finishing techniques. The term Metal Integral Skeleton Textiles (MIST) is used to describe the hybrid forms created by this process.

6.2: Methodological overview

The methods used in this research synthesise theory and practice. Whilst engaging with industry I have initiated the collaborations, framed the research aims, objectives and methods and led the research. A Situated Theory (SIT) problem-solving approach was used, which acknowledges the context of the situation in relation to the outcomes. This research demonstrates that the design researcher's skills and their interaction with specialists in cross-disciplinary research are key contributory factors within this type of research. When the design researcher combines their routine problem-solving with non-routine problem-solving within cross-disciplinary collaboration, it can provide scope for novel making perspectives and methods.

The concept of tri-space problem-solving is introduced as a method to frame and generate new models of making practice. My tri-space methods acknowledge the importance of integrating the different cognitive problem-spaces used within this collaborative research. My Design-make Tri-space framework encourages the knowledge generated by a single researcher to be merged during the making process, whilst adopting my Tri-space Roles; academic researcher, designer collaborating with industry and apprentice. It is this integration that generated the opportunity for innovative research outcomes. Through experiencing the tri-spaces, the researcher can gain a degree of mastery of using the parallel processing integrated methods frameworks. The knowledge acquired can be incorporated within subsequent research projects. As a result of my accumulation of new knowledge that was gained through experiencing the tri-spaces, whilst engaging with practitioners, I have moved beyond my routine problem-solving approach to generate a new model of practice. I have identified researchers who use similar Design Make Tri-space methods in Chapter 5. However, to date this tri-space has not been articulated as a distinct and valuable research method.

The method and case study chapters document the relationship between the Design-make Tri-space problem-solving approach in relation to the practical outcomes. Chapter 4 explores the considerations raised in Section 2.8 relating to:

- embedding the conductive metallised threads within the weave to control the material properties.
- how the metal deposits upon the conductive threads.
- the use of engineering moulds to enhance and control the properties of the hybrid forms.

Chapter 4 demonstrates that by using the Design-make Tri-space the rigidity and pliability of MIST can be controlled in relation to the designer's requirements. Figure 4.86 (page 194) shows the refinement of this control over time as evidence of my cyclical reflective practice during this action research. I propose that the tri-space frameworks are dynamic models to aid reflective practice. The new experiential knowledge gained during each research cycle informs and influences the decisions made within the Design-Make Tri-space and the Tri-space Roles during collaborative research. This is discussed in Section 5.5.

6.3: Practical outcomes overview

The benefits of integrating the mandrel within the woven textile are summarised below:

1. Using selective electrodeposition of conductive woven threads creates an integral metal skeleton that supports the pliable textile base. The pliability and rigidity of the metal skeleton can be used to create complex forms prior to metallisation. These structures can be selectively made rigid through metallisation to become self-supporting. The combination of the weave design and the electrodeposition can be used to refine and control different characteristics in a MIST form (as evidenced in Appendix A3 and Chapter 4).

The variety of making processes used within the research offers different ways to create the form:

i. The weave structure can be adapted to alter the drape and form of specific areas of the textile (as evidenced in Chapter 4).

ii. Creating the metal skeleton in the weave allows for different densities of metal to be formed within different parts of the same textile form. The positioning and number of the metal threads within the woven fabric has a significant influence on the characteristics of the metallised skeleton (as evidenced in Chapter 4).

iii. The thickness of the metal deposit can be adapted by masking or shielding areas of conductive threads and adding auxiliary anodes. This creates different current densities during the electrodeposition processes to influence the textile's pliability and drape, which impacts on the form (as evidenced in Chapter 4).

iv. The weave structure used for the metal threads affects the appearance of the threads when metallised. Twill structures metallise more quickly than plain weave, as there are fewer intersections in the weave. Double-cloth combined with single-cloth fabrics can create different thicknesses of metal skeleton within the same three-dimensional structure (as evidenced in Case study 2).

2. The integral skeleton within MIST has greater structural rigidity than conductive print or sprayed electrodeposited metal on cloth. The crystalline structure of the copper deposit integrated into the woven cloth provides structural stability, creating a net-shaped form which produces a continuous piece of metal throughout the cloth. This is evidenced in the microscope images of the metal deposit on the conductive threads in Figures 4.87-4.90 on pages 196-197.

3. Integrating conductive threads within a woven textile reduces the number of production processes needed when creating a metal support for the fabric.

This inquiry focuses on a limited number of examples demonstrating what can be achieved using this approach. The research was intended as a starting point for future exploration. Potential postdoctoral research is identified in Chapter 7.

6.4: Final conclusions

Themes that have emerged throughout this research are:

- Knowledge in practice and constants (Schön, 1991) (a practitioner's routine knowledge base) are beneficial to create a stable base on which to build when using non-routine problem solving, (as discussed in Sections 3.2 and 5.2 and 5.3). My skills and experiential knowledge as a weaver are a constant within my practice, which provided a strong foundation on which to build new knowledge.
- The importance of using an integrated parallel processing approach created by my Tri-space Roles and Design-make Tri-space frameworks. This approach influenced the methodology used during this research and the physical material properties of the MIST samples produced, (as discussed in Sections 5.3 and 5.3.2).
- Using my tri-space methods has facilitated the creation of innovative practical MIST outcomes (as demonstrated in Chapter 4 and discussed in Chapter 5).

6.5: Contributions to knowledge:

- **A Design-make Tri-space** that considers the construction, composition and finishing of woven textiles simultaneously when textile-design problem-solving and making. This combines weave-led parallel processing (Seitamaa-Hakkarainen and Hakkarainen, 2001), cross-disciplinary collaboration and apprenticeship as a research framework. This can be used to extend the scope of an expert weavers' approach to problem-solving when designing woven textiles.
- **Tri-space Roles** as a framework to facilitate parallel processing. This integrates three research roles into one interdependent role, when collaborating during textile materials research.
- **A new production method to create MIST**. Using selective electrodeposition onto woven threads within textiles enables the integration and control of hybrid metal and textile characteristics within self-supporting forms.

I propose that the creation of the MIST making process and my tri-spaces have provided a practical and theoretical framework that design researchers can adapt in relation to their aims when designing, making and collaborating to generate innovative research outcomes. The creation of MIST would not have been possible without the combination of my tri-spaces and my weave-based craft-design skills.

In answer to my research question, I have established ways in which using an expert weaver's parallel processing approach to the electrodeposition of textiles has developed a new method to integrate and control pliable textile and rigid metal properties within self-supporting forms. MIST can be controlled and customised as required to meet individual design specifications. Examples of such customised specifications in this research include, collapsible hybrid self-supporting formable structures, cylindrical structures that are re-enforced at strategic points for stability or structures that have spring properties through incorporating the material properties of the net shape metal and the pliability of the textiles. MIST incorporates the structural stability provided by the use of rigid isotropic metal to support the anisotropic textiles. The placement of thread in conjunction with the weave structure and electrodeposition processes creates a variety of characteristics. These nuances provide an opportunity to incorporate pliable textiles properties, whilst maintaining a degree of structural rigidity.

Chapter 7 Future research

This research has extended my practical skills base and established a methodological framework on which to build the foundation for future research. The research has focused on the control and interplay between anisotropic pliable textiles and isotropic rigid metal properties, in relation to the self-supporting aspects of MIST.

Reflecting upon what I would approach differently in future research, given the same technical parameters, I would develop in more depth the placing of metal in the weft axis of the weave only, to create a wider range of collapsible structures. I believe that collapsible Samples 1.5 and 2.3 have successfully demonstrated the possibilities of the integration of the properties of the pliable textile and the stability provided by the metal skeleton. Another aspect that I am interested to explore further when customising MIST is an irregular placement of the conductive threads, as demonstrated in Sample 2.3, causing the properties of the structure to be asymmetrical. This would provide more extensive opportunities for refining the properties of the forms in relation to specific design specifications. My future work will seek to identify functional applications for MIST. I intend to build upon the industrial partnerships I have established with [redacted] and [redacted]. Initially I intend to develop bespoke products for interior applications, working alongside designers such as interior architects, acoustic specialists and creative lighting experts.

To extend this research, the parallel processing approach to problem-solving as a weaver could be applied to other finishing process and materials development. My tri-space frameworks could be applied using different research emphases such as sustainability, smart textiles and architecture. Further studies relating to the tri-spaces could include:

- Exploring how novice and expert weavers use my tri-spaces during collaborative research. This would highlight the relevance of a researcher's individual experience and weave knowledge relating to the industrial context selected by the researcher.

- How other design practitioners use adapted versions of my tri-spaces. How their particular knowledge in practice and constants influence the research outcomes within non-routine problem-solving spaces.

- Extending research on how the practitioner and the research innovation evolve as part of the knowledge accumulation life cycle that occurs when using my tri-space frameworks.

- How the use of my tri-space roles approach during situated learning impacts upon the industrial collaborators' knowledge accumulation in the research.

There is scope to extend research to consider more refined potential functional applications for MIST. Examples of areas for future post-doctoral research include:

- Extending my initial research explorations to develop ways of using high and low current density as a means to control the rigidity and pliability of MIST forms. This could include methods of controlling rigidity and pliability to generate complex collapsible/ adaptable forms using weave structures and masking and shielding.

- Jacquard weaving could offer further design possibilities beyond the grid of a dobby loom, if the appropriate conductive threads were compatible with the Jacquard loom's warp technical set up.

- The MIST making approach that uses the precise placement of conductive threads within a textile has scope to be extended to other constructed textile techniques. Knit, crochet, lace and macramé have the potential to offer alternative characteristics and forms. For example, knit's looped thread structure could expand and contract to create net-shaped forms that fit tightly around moulds during finishing. The differences in the types of MIST forms that could be produced through these alternative processes could be compared to structures that can be created using weave.

- Investigating whether, and how, the conductive metal skeleton within MIST could be used for smart textiles applications. The conductive metallised threads within MIST have the potential to be used for Faraday cages (shields to block electromagnetic fields) or as an electrical circuit that could transfer digital data or transmit heat.

- Scale: exploring the practical considerations to discover the maximum scale at which MIST forms can be created. Can MIST structures become self-supporting large-scale architectural forms? This would include testing the compressive strength of MIST structures to establish how they could be used to construct interior walls, screens or ceilings. MIST has the potential to create lightweight forms, in which the rigidity could be tailored to the designer's or engineer's requirements.

Appendix

A1: Background to my textile knowledge

My textile practice focuses upon the application of woven textiles and finishing techniques to achieve design solutions. Throughout my design education and my textile career this approach has become an instinctive way to design. Anni Albers' (1965) philosophy that woven threads can be engineered to create structural forms resonates with my making practice. As identified in Chapter 2, the different qualities of threads and woven structures influence the drape and form of cloth. By interacting with these flexible qualities through textile making processes and materials I have built up a haptic knowledge that informs my methodology (Dormer 1997; Sennett 2009; Ingold 2013).

My previous textile practice considered how the use of traditional handcrafted textile making techniques could be integrated with industrial processes, enabling larger-scale production to be achievable. This included the use of textile finishing processes. During my BA Hons degree (1995-98), I hand-wove metal stitching warps to produce three-dimensional metal and textile fabrics. I encountered practical challenges when weaving with stiff brittle metal wires on a loom, which made the samples time consuming to produce and only suitable for one-off production. Between 2004-2014 I was a senior lecturer in woven textiles and subsequently the Course Leader for the BA (Hons) Textiles for Fashion and Interiors degree at The University for the Creative Arts. This involved teaching students how to construct weave and use finishing processes to alter the texture and form of textiles.

Prior to this research I had begun to explore the electrodeposition of my woven fabrics using conductive paint. Finishing the whole textile with metal caused it to become entirely rigid. I explored selectively restricting the metallisation to specific areas in the weave using sprayed conductive paint to enable the cloth to have flexibility. The results were not satisfactory. It was hard to achieve precise placement of the finishing and the staple fibres within the fabrics produced sharp metal splinters when metallised. I concluded that designing pliable conductive threads within the weave structure, as an integrated conductive base for the electrodeposition, might eliminate these problems. Therefore, the soft and hard qualities within the same metallised piece could potentially be explored more precisely. Consequently, this research explores the electrodeposition of strategically placed conductive threads within a woven cloth after it has been removed from the loom.

A2: Technical weave notation

Warps used in the case studies:

As the warps progressed during this research less detail was required in the threading instructions. This was because as a shared language was established between [redacted] and myself which made communication quicker and more effective. Throughout each case study the weft representations sent to the mill are detailed for each sample using images of the PDF documents sent. The following figures show my representations sent to [redacted]. to weave the warps used in this research.

A2:1: Warp 1

Image redacted.

Figure A2.1: My drawn representation of warp sections for Warp 1.

Figure A2.2 covers 13.5 pages and is inserted below:

Figure A2.2: (below) A text, CAD and drawn representation of warp instructions for Warp 1 created by myself to send to [redacted]

Image redacted.

Image redacted.

Image redacted.

Image redacted.

Image redacted.

Image redacted.

Image redacted.

Image redacted.

Image redacted.

Image redacted.

Image redacted.

Image redacted.

Image redacted.

The available looms at [redacted] had 12 heal frames which placed restrictions on the weave structures and threading used. Therefore small blocks in between the larger areas in the warps used in Case study 2 were threaded over two shafts. This produced problems with inconsistency of the weft tension when weaving plain weave in these blocks next to 2/2 twill. Due to fewer intersections in the structure plain weave could not be used when weaving 2/2 twill. Half hopsack was used to balance the weft thread build up caused when weaving 2/2 twill next to plain weave. The following distances were created between the single-cloth sections when the fabric was flat:

- [redacted]cm with [redacted] conductive threads each side of the double-cloth pockets.
- [redacted]cm with [redacted] conductive threads each side of the double-cloth pockets.
- [redacted]cm with [redacted] conductive threads each side of the double-cloth pockets.
- [redacted]cm with [redacted] conductive threads each side of the double-cloth pockets.

A2.2: Warp 2

Warp 2 used the same [redacted] dtex polyester and loom set up as the 6cm section from warp, but it was threaded across the total width of the loom. All other factors were the same.

A2.3: Warp 3

As [redacted] dtex polyester had been proved to have suitable properties for the research it was used in Warp 3 to provide continuity with previous warps. Warp 3 was block threaded in two threading blocks with three width sections between the conductive threads across the warp. The left side had 3cm polyester sections with [redacted] conductive threads in between each block. The middle had no metal in the warp. The right section had 6cm polyester gaps between the conductive threads.

Image redacted.

Figure A2.3: My hand drawn representation of the full width of the warp.

Image redacted.

Figure A2.4: My Weavepoint diagram of warp 3 showing sections of threading in detail.

A2.4: Warp 4

Threading for warp 4

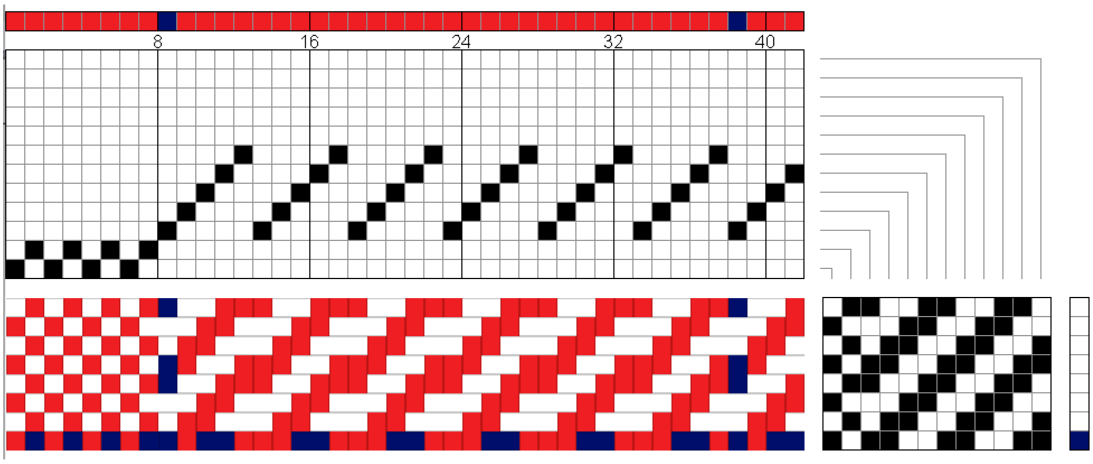


Figure A2.5: My Weavepoint diagram of Warp 4.

A3: Descriptive scales used during haptic evaluation of samples

The following questions were used to evaluate the samples in the cases studies in Chapter 4:

Question 1: Textile handle: What is the level of pliability and rigidity in the textiles within the form?

Question 2: Metal handle: What is the level of pliability and rigidity in the electrodeposited metal within the form?

Question 3: Control of the fabric handle: What is the level of control of the pliability and rigidity of the characteristics of the form?

The tables on pages 242-250 show the 5 different descriptions in relation to each question. These are coded 1-5 and the appropriate number is placed in the table against each sample number which is listed along the top of the table. The bar chart illustrates a visual representation of the results for each sample.

The bar charts for Questions 1 and 2 show there is a variety of levels of pliability and rigidity in both the textile and metal handle of the samples. This demonstrates that the use of the Design-make Tri-space and using the weave and electrodeposition decision flow-diagrams enable the designer to create a range of properties between pliable and rigid when creating MIST[56]. The bar charts for Question 3 relate to the control of the pliability and rigidity. The samples are numbered in the order that they were produced in each case study. The bar charts show that in each case study my ability to control the properties increases over time as my knowledge increases. Figure A3.19 on page 252 shows that in Case study 3 Sample 3.3 has reached code number 5 which is the highest level of control in my coding.

[56] Metal Integral Skeleton Textiles

A3.1: Question 1: Textile handle: What is the level of pliability and rigidity in the textiles within the form?

Textile handle: Case study 1

		Case study sample number				
Code	**Description of fabric handle**	1.1	1.2	1.3	1.4	1.5
1	Malleable and will compress when pressure is applied by hand					1
2	Malleable and drapes with fluid folds within the metal skeleton	2		2	2	
3	Malleable but pulled taught within the metal skeleton		3			
4	Fixed taut between the metal skeleton under low tension. Will distort when pressure is applied by hand.					
5	Fixed taut between the metal skeleton under high tension. Will not distort when pressure is applied by hand.					

Figure A3.1: Textile semantic descriptive scale of the fabric handle used in Case study 1 samples in chapter 4.

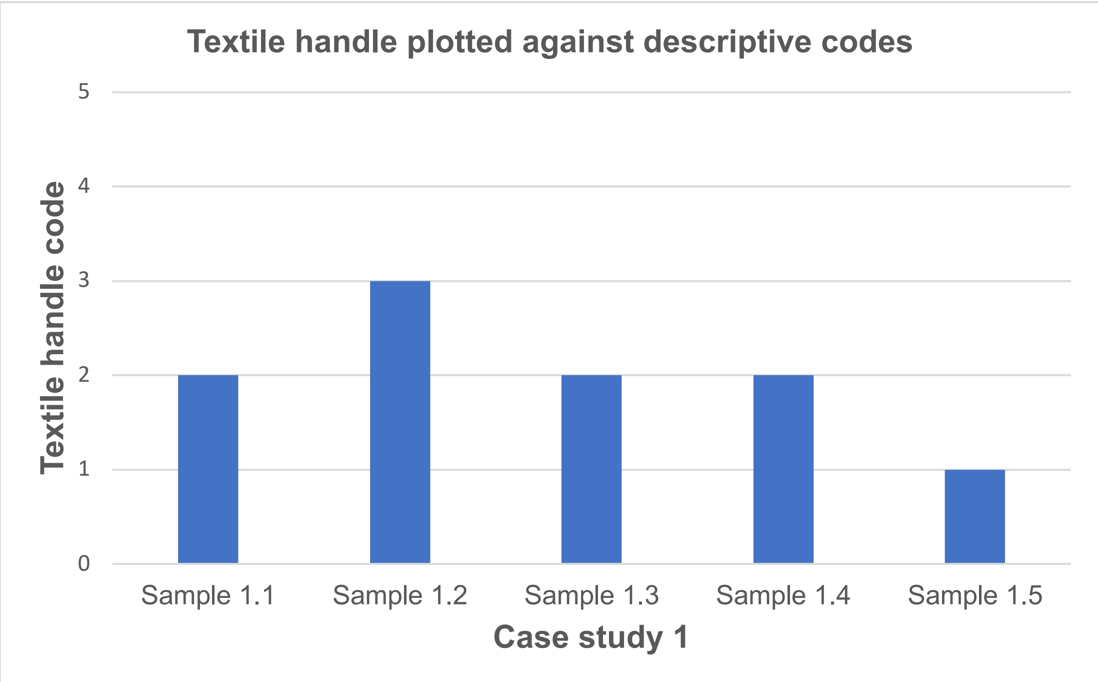


Figure A3.2: Diagram of the textile semantic descriptive scale of the fabric handle used in Case study 1 samples in chapter 4.

Textile handle: Case study 2

		Case study sample number				
Code	**Description of fabric handle**	2.1A	2.1B	2.1C	2.2	2.3
1	Malleable and will compress when pressure is applied by hand					1
2	Malleable and drapes with fluid folds within the metal skeleton					
3	Malleable but pulled taught within the metal skeleton					
4	Fixed taut between the metal skeleton under low tension. Will distort when pressure is applied by hand.		4			
5	Fixed taut between the metal skeleton under high tension. Will not distort when pressure is applied by hand.	5		5	5	

Figure A3.3: Textile semantic descriptive scale of the fabric handle used in Case study 2 samples in chapter 4.

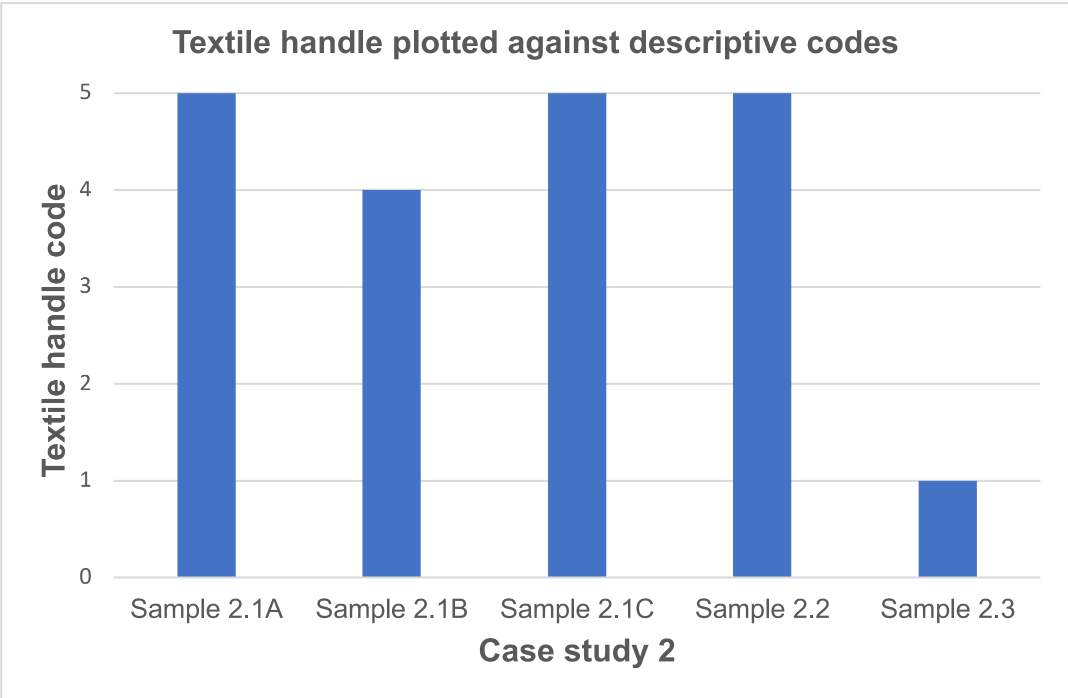


Figure A3.4: Diagram of the textile semantic descriptive scale of the fabric handle used in Case study 2 samples in chapter 4.

Textile handle: Case study 3

		Case study sample number			
Code	**Description of fabric handle**	3.1	3.2A	3.2B	3.3
1	Malleable and will compress when pressure is applied by hand				
2	Malleable and drapes with fluid fold within the metal skeleton				
3	Malleable but pulled taught within the metal skeleton				
4	Fixed taut between the metal skeleton under low tension. Will distort when pressure is applied by hand.		4	4	4
5	Fixed taut between the metal skeleton under high tension. Will not distort when pressure is applied by hand.	5			

Figure A3.5: Textile semantic descriptive scale of the fabric handle used in Case study 3 samples in chapter 4.

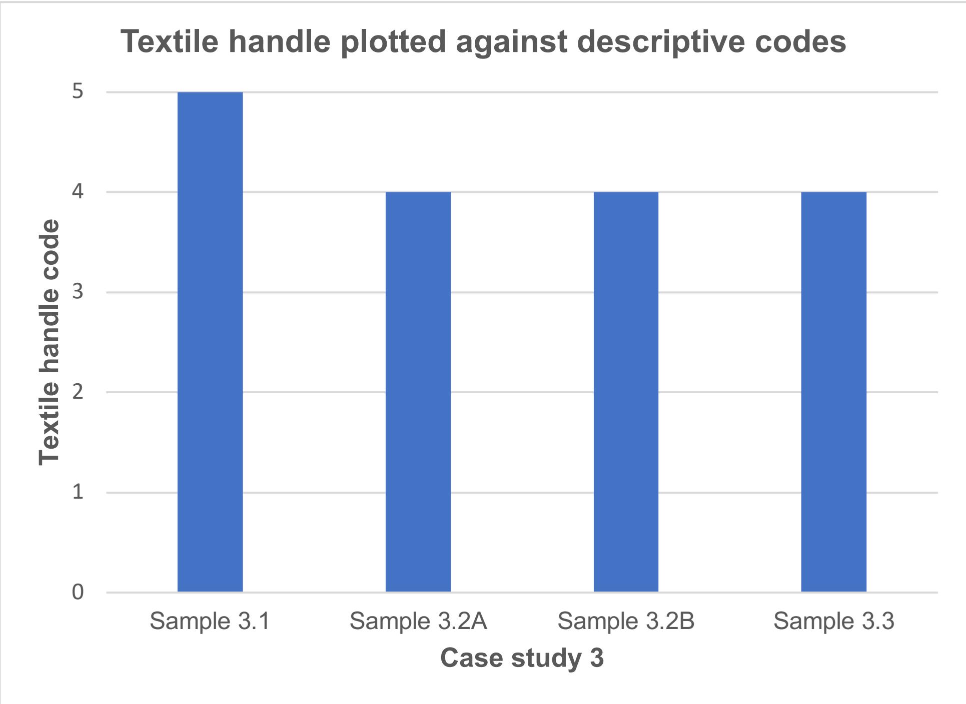


Figure A3.6: Diagram of the textile semantic descriptive scale of the fabric handle used in Case study 3 samples in chapter 4.

A3.2: Question 2: Metal handle: What is the level of pliability and rigidity in the electrodeposited metal within the form?

Metal handle: Case study 1

		Case study sample number				
Code	**Description of metal handle**	1.1	1.2	1.3	1.4	1.5
1	Holds a form. Pliable in both axis		1			
2	Holds a form. Conductive threads in one axis only. Pliable in one axis, rigid in the other axis					2
3	Holds a form. The form is pliable and will expand if pulled in one axis and the from will recover its shape	3				
4	Holds a form. Rigid in both axis but can be flexed by hand			4	4	
5	Holds a form completely rigid in both axes					

Figure A3.7: Metal semantic descriptive scale of the fabric handle used in the Case study 1 samples in chapter 4.

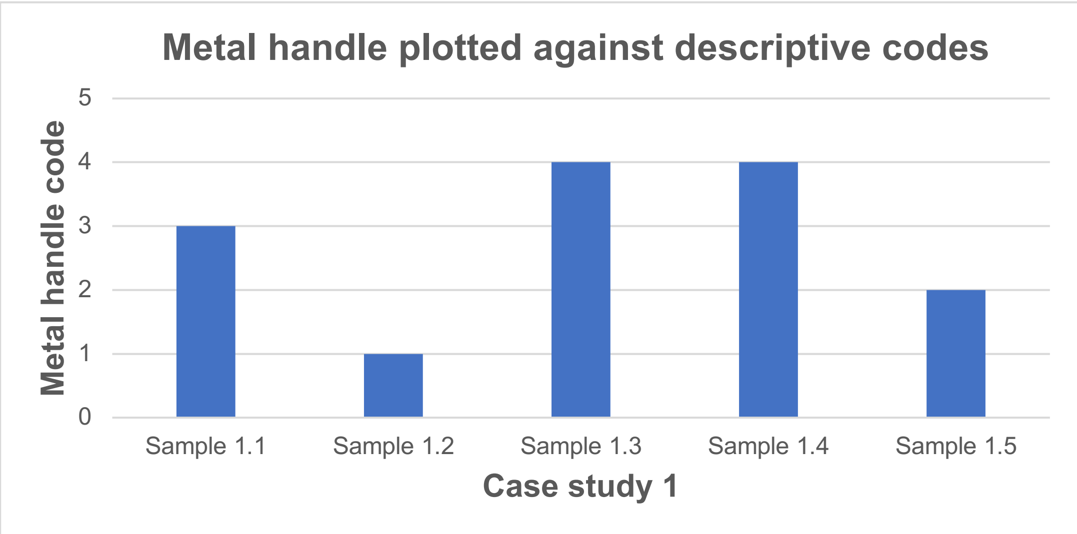


Figure A3.8: Diagram of the metal semantic descriptive scale of the fabric handle used in the Case study 1 samples in chapter 4.

Metal handle: Case study 2

		Case study sample number				
Code	**Description of metal handle**	2.1A	2.1B	2.1C	2.2	2.3
1	Holds a form. Pliable in both axis					
2	Holds a form. Conductive threads in one axis only. Pliable in one axis, rigid in the other axis					
3	Holds a form. The form is pliable and will expand if pulled in one axis and the from will recover its shape					3
4	Holds a form. Rigid in both axis but can be flexed by hand					
5	Holds a form completely rigid in both axes	1	1	1	1	

Figure A3.9: Metal semantic descriptive scale of the fabric handle used in the Case study 2 samples in chapter 4.

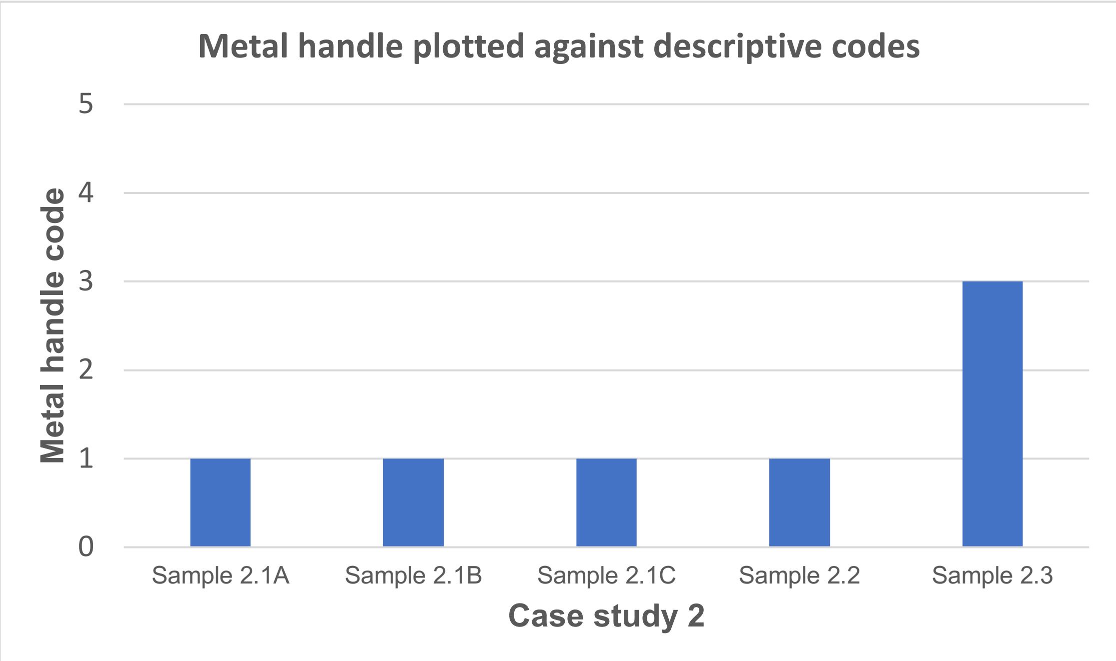


Figure A3.10: Diagram of the metal semantic descriptive scale of the fabric handle used in the Case study 2 samples in chapter 4.

Metal handle: Case study 3

		Case study sample number			
Code	**Description of metal handle**	3.1	3.2A	3.2B	3.3
1	Holds a form. Pliable in both axis				
2	Holds a form. Conductive threads in one axis only. Pliable in one axis, rigid in the other axis				
3	Holds a form. The form is pliable and will expand if pulled in one axis and the from will recover its shape		3	3	3
4	Holds a form. Rigid in both axis but can be flexed by hand	4			
5	Holds a form completely rigid in both axes				

Figure A3.11: Metal semantic descriptive scale of the fabric handle used in the Case study 3 samples in chapter 4.

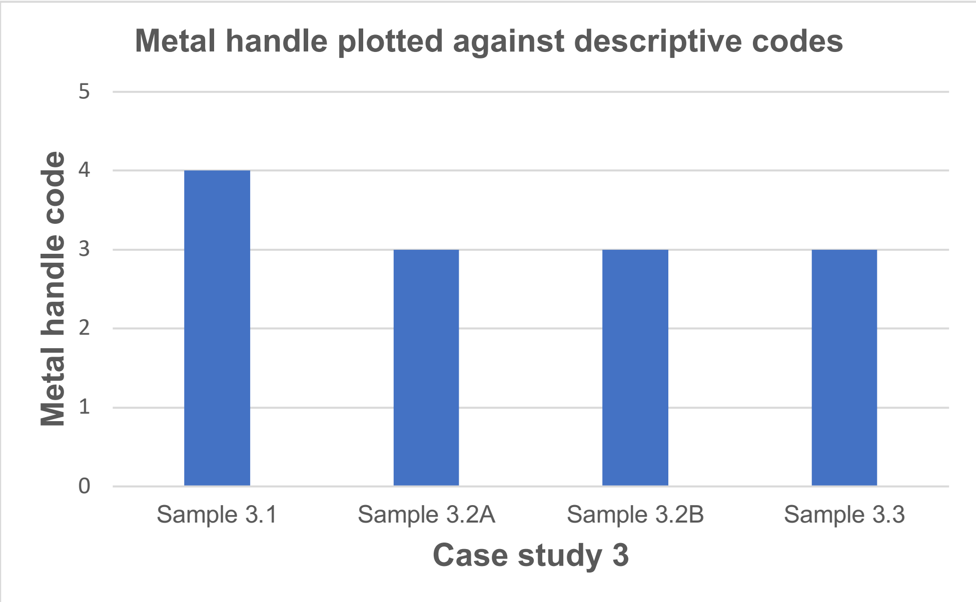


Figure A3.12: Diagram of the metal semantic descriptive scale of the fabric handle used in the Case study 3 samples in chapter 4.

A3.3: Question 3: Control of the fabric handle: What is the level of control of the pliability and rigidity of the characteristics of the form?

Level of control: Case Study 1

		Case study sample number				
Code	**Description of metal handle**	1.1	1.2	1.3	1.4	1.5
1	No control					
2	Limited control	2	2			
3	Moderate control			3	3	
4	Significant control					4
5	Refined control					

Figure A3.13: Level of the control semantic descriptive scale of the fabric handle used in Case study 1 samples in chapter 4.

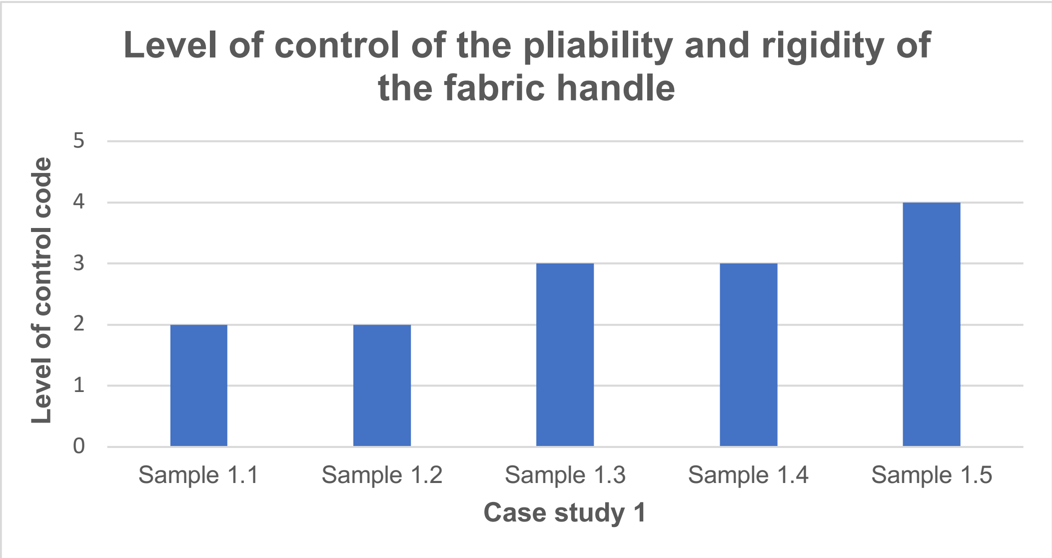


Figure A3.14: Diagram of the level of control semantic descriptive scale of the fabric handle used in Case study 1 samples in chapter 4.

Level of control: Case Study 2

		Case study sample number				
Code	**Description of metal handle**	2.1A	2.1B	2.1C	2.2	2.3
1	No control					
2	Limited control					
3	Moderate control	3	3	3		
4	Significant control				4	4
5	Refined control					

Figure A3.15: Level of control semantic descriptive scale of the fabric handle used in Case study 2 samples in chapter 4.

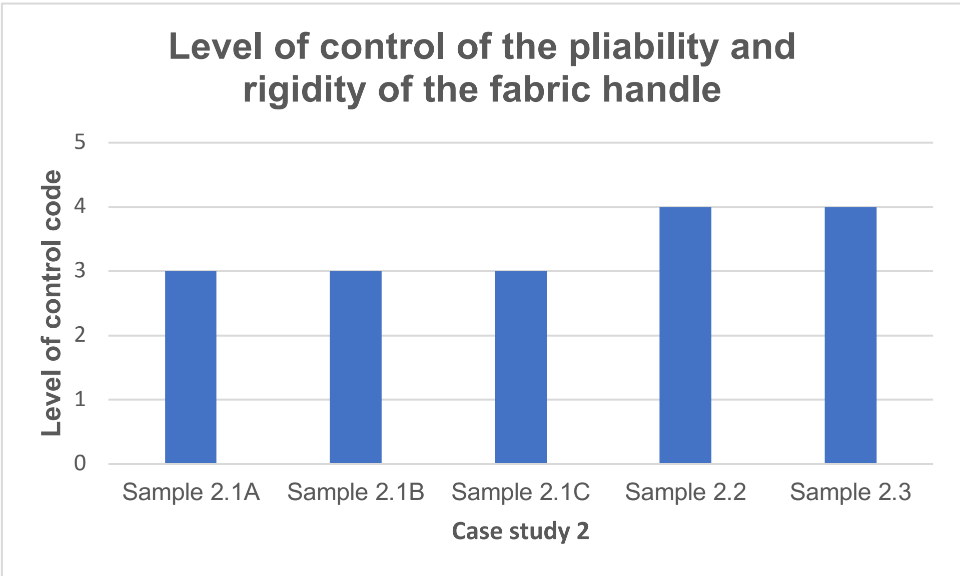


Figure A3.16: Diagram of the level of control semantic descriptive scale of the fabric handle used in Case study 2 samples in chapter 4.

Level of control: Case Study 3

		Case study sample number			
Code	**Description of metal handle**	3.1	3.2A	3.2B	3.3
1	No control				
2	Limited control				
3	Moderate control	3	3		
4	Significant control			4	
5	Refined control				5

Figure A3.17: Level of the control semantic descriptive scale of the fabric handle used in Case study 3 samples in chapter 4.

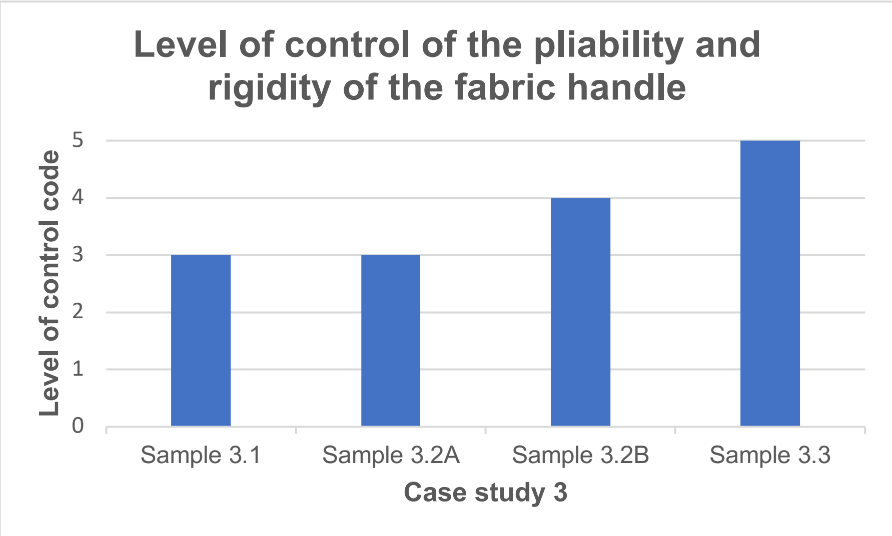


Figure A3.18: Diagram of the level of control semantic descriptive scale of the fabric handle used in Case study 3 samples in chapter 4.

Glossary

Action research:	Action research is prevalent in human centred research (Crouch and Pearce, 2012:157). It involves experiential learning cycles (Kolb, 1984) which use an iterative looping process that builds new knowledge to refine solutions to an identified problem.
Active threads:	Threads that alter when a finishing process is applied or when the fabric is released from the loom. Natural active threads such as wool or silk shrink and move position within the fabric when moisture or heat is applied.
Anisotropic:	A material that has different properties in different directions.
Annealed metal:	Annealed metal is heated and cooled to increase its ductility and reduce its harness. This allows it to be formed into shapes and cut more easily. The crystalline structure of the metal recrystallizes during the process and this can reduce the metal's original compressive and tensile strength.
Anode:	An anode is the metal that forms onto the object during electrodeposition.
Apprenticeship:	A method of learning which involves hands-on-experience to gain new skills from an experienced practitioner.
Bespoke jig:	A bespoke jig is a support that is specifically designed to support the mandrel during electrodeposition.
Blanket-warp:	Using different threading blocks across a warp used when sampling designs.
Calendaring:	A finishing process where fabric is passed under high pressure between metal rollers to smooth the surface.
Codified knowledge:	Knowledge that has been made explicit and translated into written rules, instructions and procedures.
Cognitive:	Relating to the mental process of creating, storing and accessing knowledge.
Collective tacit knowledge:	Domain-specific knowledge shared by a group of specialised people.
Composite:	Composed from more than one material.
Concrete:	A building material made by mixing cement and stones/gravel with water. When it is dry it sets hard to create a solid hard material.
Conductive threads:	Threads that enable an electrical current to pass through them.

Covering power:	The term covering power is used to describe the ‘extent to which an electrodeposition electrolyte can cover the entire surface of an object… with reasonably uniform thickness, including at least some deposition in the recesses and cavities’ (Kanai 2006:73).
Crimp:	In industrial weaving terminology refers to an uneven tension across the woven fabric.
Crystalline:	A structure composed of crystals.
Current density (CD):	The measurement of electric current flowing across a material per cross-sectional area.
Designable Materiality:	The term used by Menges and Knippers (2015) to describe when the characteristics of the materials, combined with the means of production, directly affect a structure’s characteristics.
Double-cloth:	Two warps woven as one cloth on a loom.
Dye:	A substance that is used to colour textiles by mixing it with an aqueous solution.
Electrodeposition:	Electrodeposition is a process that deposits metal onto another conductive surface using an electrical current passing through a tank of electrolyte.
Electroforming:	Electroforming deposits a thicker layer of metal onto a conductive form called a mandrel and produces self-supporting forms.
Electrolyte:	A liquid that contains ions.
Electroplating:	Deposits a thin layer of metal onto the surface of a conductive material. The base material remains within the final piece and the metal deposit is not self-supporting.
Embedded tacit knowledge:	Deep know-how and learning that is rooted in the mind through context-specific experiences and actions.
Embodied tacit knowledge:	Relating to knowledge linked to the body or practical experience and actions.
Endoskeleton:	Rigid internal bone structures that support animals or humans from within their bodies.
EPI:	‘Ends per inch’ in weaving terminology: describes the number of threads per inch in the warp within a woven textile.
Exoskeleton:	Supports and protects a living form by means of an external rigid shell.
Explicit knowledge:	Knowledge that can be communicated through written, drawn or spoken instructions: it is easy to transfer to another person.
Fabric Formwork:	A construction technique that uses flexible fabric moulds as an alternative to rigid formworks to reinforce prestressed concrete.

Fabric hand:	Fabric hand is a qualitative term to describe the tactile properties of the fabric in the hand.
Finishing:	In the context of this thesis finishing refers to a process that is applied to a material as means to alter the final characteristics of the material.
Form-finding:	The shape of form-finding structures is not predetermined but is generated by the characteristics of the materials used to create it, combined with active forces.
Frame-jig:	The supporting frame which the samples are attached to during electrodeposition.
Geodesic dome:	A spherical shaped structure constructed from a complex network of triangles.
Haptic:	'Relating to the sense of touch, in particular relating to the perception and manipulation of objects using the senses of touch' (Oxford Dictionaries, 2018) and bodily movement.
Hydrostatic:	Relating to or denoting the equilibrium of liquids and the pressure exerted by liquid at rest.
Intersections:	The points within a weave structure where the warp and weft threads cross.
Isotropic:	The properties of the material are the same in all directions.
Iterative:	A process of repeating a process several times.
Jacquard weaving:	A type of weaving loom that enables complex figurative patterns to be woven into textiles.
Jig:	A former or frame to support the textile during finishing: this is described further in Section 3.9 of this thesis.
Kinaesthetic actions:	Hands-on interaction with materials and equipment.
Knowing-in-practice'	Schön's term that describes the use of a practitioner's previous knowledge and experience of a task.
Legitimate peripheral participation (LPP):	Lave and Wenger' s theory which relies upon an engagement in social practice in which learning is an integral part.
Mandrel:	The object onto which the metal is deposited during electroforming.
Metal Skeleton:	In the context of this research it is metal framework within a woven fabric.
MIST:	An abbreviation for Metal Integral Skeleton Textiles which is the term used to describe the hybrid forms in this research.
Net shape form:	A structure made from one single piece of material that is not cut or joined to create the form.

Orthogonal:	The order and intersection of two groups of interlacing lines at right angles.
Parallel processing:	A term to describe problem-solving in more than one thinking space simultaneously.
Passive threads:	Threads that remain unchanged or stable when a finishing process is applied.
Physical vapour deposition (PVD):	Sputtering and electron beam evaporation are two types of PVD that deposit airborne atoms or molecules onto a surface within a vacuum chamber (Boone, 1986).
Pick:	A line of weft thread in a woven fabric.
PPI:	'Picks per Inch' in weaving terminology describes the number of threads per inch in the weft within a woven textile.
Prestressed structure:	Structures that are made stronger by the use of tensile stress applied to structural supports such as cables or wires.
Qualitative evaluation:	Is evaluation that uses primarily exploratory research that is not bounded by statistics and numerical data. It uses experiences as insights to create hypotheses.
Quantitative evaluation:	Evaluation that is structured and uses statistics and numerical data to be able to generalise results to create hypotheses.
Rapier Dobby loom:	A loom that uses mechanised finger-like grasping to transfer the weft across from one side of the loom to the other.
Reflection-for-action:	Uses previous experiences to inform future problem-solving iterations.
Reflection-in-action:	Involves evaluating past events and gaining new insights by interrogating past actions.
Reflection-on-action:	Involves responding to circumstances, thinking and acting in the moment and reflecting on previous knowledge to inform the present situation.
Reflective practice:	When a practitioner reflects upon their experiences to evaluate the outcomes.
Representations:	A written or drawn set of instructions or ideas that are used to communicate a designer's thoughts to another person.
Resin:	A soft solid or highly viscous substance of plant or synthetic origin 'usually containing prepolymers with reactive groups' (IUPAC, 2014).
Screen-print:	A textile print process that uses a mesh stretched over a screen. Pigment or dye is pressed through the screen using a squeegee to transfer a pattern onto textiles.
Semantic descriptive scale:	A scale that rates the samples based upon descriptive extremes, such as pliable and rigid.

Shibori:	A textile technique where the fabric is tightly bound, dyed and then unfolded to create patterns.
Single-cloth:	A woven fabric that is constructed from one layer of woven threads.
Single-filament structures	Structures that are composed using fibres that are produced by extruding material to produce single thread that is not spun or twisted.
Situated Learning:	Lave and Wenger's theory maintains that the act of doing is essential to fully understanding a task and focuses on the impact that social and environmental contexts have upon learning. Like Schön's, their theory centres around the idea that cognition and action are interconnected.
Situated Theory (SIT):	Greeno and Moore (1993) developed Lave and Wenger's Situated Learning, creating the term Situated Theory (SIT), which combines situated cognition (thinking) and situated action (action). It relies upon the context of the situation to inform problem-solving and learning.
Smart Textiles:	Textiles that react to environmental conditions and stimuli.
Soft Constructivism:	Lars Spuybroek's (2009) term to describe 'softness and flexibility building structure' (Ludovica Tramontin, 2006: 53).
Somatic tacit knowledge:	Knowledge gained through the body and mind interacting with materials and processes.
Stainless steel	A form of steel containing chromium that is resistant to rust and tarnishing.
Stitching warp:	Threads that are under high tension in the warp on a weaving loom that pass through from the front to the back of a multi-layer weave to join the two layers together.
Structural Integrity:	'The ability of the structure to retain its strength, function and shape within acceptable limits, without failure when subjected to the loads imposed throughout the structure's service life' (Al-Sherrawi, 2016).
Tacit knowledge:	An individual's knowledge that is gained through physical interaction or experiences with materials or tasks. It cannot be communicated through written, drawn or spoken instructions but has to be experienced.
Tenacity (from a woven textile perspective):	The measurement of strength of a yarn at breaking point when force is applied. It is usually measured in denier or tex.

Tensegrity:	Combines the characteristics of tension and integrity to create self-supporting structures composed of rods under tension at the points that do not have any fixed joints. The structure is stable when forces push the component parts against each other to create a rigid form.
Textile Computing:	Lars Spuybroek's (2009; 2011) term for architectural structures inspired by textile processes such as macramé, crochet, braiding and knitting,
Warp:	The vertical threads that are tensioned on a loom to form the base for the weft thread to enable the construction of woven cloth.
Weave:	The textile construction process that uses threads interlacing at right angles to create cloth.
Weavepoint software:	A computer aided design (CAD) software program that creates written weave designs and notations.
Wet-finishing process (textiles):	A finishing process that uses liquid, usually water, to change the characteristics of a textile: examples are steaming, hot water agitation or shrinking.
Weft:	The thread that passes horizontally across the warp threads on a weaving loom.
Young's modus:	The stiffness of a material and its ability to resist tension in lengthwise direction.

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R3: Conferences/ Lectures

Association of Architectural Educators (AAE) Conference, 7-9 April 2016, Bartlett School of Architecture, UCL, London.

Biomimicry and design (symposium), 17 June 2016, V & A Museum, London.

Coxon, A. and Fer, B., *Anni Albers curators' talk,* 17 October 2018, Tate Modern, London.

Craft connecting architecture, architecture connecting craft, 24 November 2017, The Building Centre, London.

Crafts Council, *Manufacturing workshop*, February 2017. University for the Creative Arts, Farnham.

Ellen, A., Richards, A. and Wood, D., '*Textiles taking shape', artist talks*, 17 January 2018, Winchester Discovery Centre, Winchester.

Samanidou, I., *Anni Albers exhibition tour with Ismini Samanidou*. 14 January 2019, Tate Modern, London.

The Crafts History Conference, 15 March 2017. Crafts Study Centre/ University for the Creative Arts, Farnham.

The Matter of Material (symposium), April 2017. Turner Contemporary in collaboration with the International Textile Research Centre, University for the Creative Arts, Farnham; Turner Contemporary, Margate.

Trafas White, Z. '*Ove Arup and the philosophy of total design, part of the engineering the world season'*: *V&A Lunchtime Lecture*, 28 September 2016, V & A Museum, London.

R4: Exhibitions

Anni Albers, 11 October 2018 – 27 January 2019, Tate Modern, London

Entangled: Threads and Making, 28 January – 7 May 2017, Turner Contemporary, Margate.

Festival of Textiles, 11 March – 17 April 2016, Fashion and Textile Museum, London.

Fortuitous Circumstances: Recent Textiles for the Crafts Study Centre, June 2018, Crafts Study Centre, Farnham.

Ove Arup and the Philosophy of Total Design, 18 May – 6 November 2016, V& A Museum, London.

Peter Collingwood woven: unwoven, 2nd January – 11th August 2018, Craft Study Centre, Farnham, Surrey, England.

Soft engineering: textiles taking shape, 13th January – 18th February 2018, Winchester Discovery Centre, Winchester, England.