The Role of Weaving in Smart Material Systems

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The Role of Weaving in Smart Material Systems

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Abstract

This thesis is an investigation into woven textile structures and weave construction methodologies. The main question at the heart of this research is what are smart textiles and what role/s can weaving play in the creation of such textiles in the future? A critical review of the literature led to a grammatical investigation and interpretation of the term smart textiles, and as a result a key differentiator between *superficial* and *deep* responsivity in textiles is made: the latter is henceforth used to describe the uniqueness of smart textiles (chapter 3). The thesis proceeds to explore the fundamental engineering of textiles as material systems, and by doing so, provide clues as to how fabrics could themselves be considered smart. Through this exploration, an original 'textile anatomy' mapping tool is presented with the aim to enhance and deepen current understanding of textiles and represent them as material systems instead (chapters 4 and 5).

The hybrid research methodology that governed this investigation is unique. It relies on the creative tools of Design while also inherently applies the investigative methods of Science, Technology and Engineering (chapter 2). Weaving is explored through processes of making as an approach to develop smart textiles following an extensive historical review revealing that although methods of weave production have much evolved, the weave structures themselves have not changed at all for thousands of years (chapter 5). A series of experimental case studies are presented, which therefore seek to explore and challenge current limitations of weaving for the creation of a new generation of material systems (chapter 6). As part of this practical work the alternative fabrication technology of additive manufacturing was considered, but its role as substitute manufacturing technique for textiles was accordingly rejected.

This research finds that since weaving has become solely dependent on its machines, the structures produced through these processes of manufacturing are governed by such same specifications and limitations. As a result, in order to step away from current constraints, new assembly methodologies need to be revised. This is particularly applicable within the context of future (smart) material systems, and micro and nano fabrication techniques (chapters 7, 8 and 9).

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I whole-heartedly thank you all.

Declaration

I declare that the work contained in this thesis has not been submitted for any other award and that it is all my own work. I also confirm that this work fully acknowledges opinions, ideas and contributions from the work of others. Any ethical clearance for the research presented in this thesis has been approved [RE21-11-121450, project ID. 1826]. Approval has been sought and granted by Northumbria University Ethics Committee at the School of Design on December 2012.

I declare that the word count of this thesis is 44,889 words.

Name: Lynn Tandler

Glossary

Abrasion: deterioration

Alloy: blend of metals

Amplitude: rise from ground

Aspect ratio: the proportional relationship between width and height

Basketry: the making (weaving) of baskets

Blanket warp (also '**block setting'**): neighboring warps woven with the same weft

Biocompatibility: un-hostile or un-toxic to living organism

Biomimicry: the study of emulating nature

Bobbin: a cylinder or cone wound with threads, yarns or wires

Braiding: plating; multiple strands interlaced to form 3D structure

CAD: Computer Aided Design

Chemical properties: changes in the molecular composition of a material

Chromogenic materials: switchable materials, which are able to change colour

Coatings: a thin layer of polymers applied onto constructed textiles

Cloth (also '**fabric**' or '**textile**'): fibrous architecture of yarns and fibres

Compressive strength: the resistance of a material to break when volume is reduced

CNC: Computer Numerical Control

Corduroy: a woven structure that forms ribs across cotton fabrics

Cover factor: one set of warp or weft threads that cover other threads in given area

Crimp: pleat or crease

Cross-sectional shape: the contour of the diameter

Curvature: the degree of bend

Denier: fineness measurement of yarns, weighting 1 gram for 9000 meters

Dent: gap or space

Drape (also ‘**handle**’): the way in which a piece of fabric falls and hangs

Diameter: a straight line passing from side to side through the centre of a figure

Dimensional stability: maintenance of original dimensions during use

DLP: Digital Light Processing

DMLS: Direct Metal Laser Sintering

EBF^3: Electron Beam Freedom Fabrication

EBM: Electron-Beam Melting

Elasticity: material’s ability to resume its normal shape after being stretched

Elastomers: polymers with distinctive elastic properties (i.e., rubber)

Electrical properties: material’s ability to resist the flow of an electric current

Electroactive polymers: those that react to electric fields by changing size or shape

Electromagnetic properties: material’s response to electromagnetic radiation

Elongation: lengthening

Ends: individual warp units

Energy absorption: the convergence of photons to internal energy

EPD: Ends Per Dent, the number of warp ends led through one allocated reed space

EPI: Ends Per Inch, the numbers of warp-threads across one inch

Fabric (also ‘**cloth**’ or ‘**textile**’): fibrous architecture of yarns and fibres

Fabric density: the ration of warp and weft threads in a squared inch

FDM: Fused Deposition Modeling

Felt: a non-woven textile construction

FFF: Fused Filament Fabrication

Fibre alignment (also ‘**orientation**’): the setting of polymers into a new fibrous form

Fibre migration: the variation of fibre position within a yarn

Filament: long slender thread-like objects

Finishings: processes applied onto fabrics to improve their look, feel or performance

Flexural rigidity: the force required to bend malleable (or non-rigid) materials

Fracture toughness: the ability of cracked materials to resist fracture

Friction: the resistance that a material encounters when moving over another

Glass transition temperature: temperatures where polymers shift from hard to soft

Handle (also 'drape'): the way in which a piece of fabric falls and hangs

Headle (also '**heald**'): wired holes attached to shafts on looms

Headle set: couple of heddles acting as one unit

Hierarchical level: the position of some items in relations to others

Hierarchical design: the use of hierarchical principles to create new phenomena

Hierarchy: structure consisting of multiple levels

Hydrogels: gels made of water

ICD: Industrial Clothing Division

Laminates: layers of plastic or other protective materials

LED: Light Emitting Diode

Length scales: The range of material properties encompasses within a system

Lift: rise

Lift plan (also '**peg plan'**): the raising order of shafts during weaving

Linear density: the measurement of mass or electric charge per unit length

LOM: Laminated Object Manufacturing

Macro-scale: large scale

Mechanical properties: describe how materials react to physical forces

Melting temperature: transition from a crystalline to an amorphous phase

Meso-scale: intermediate or middle scale

Micro: one millionth of a unit length

Mock leno: weave structure applied without leno doups for the creation of open mesh

Model: a systematic description of a material or object

Modeling: physical, conceptual or mathematical representation of materials or objects

Moduli: plural of modulus

Modulus: a constant factor or ratio

Molecular weight: relative molecular mass

Monofilament: a single strand

Monomer: small molecule; the building block of polymers

Motif: a decorative image or design, which forms a pattern

MP3: audio coding format that compresses sound into small files for storage purposes

Multifilament: number of strands used as a single unit

Nano: one billionth of a unit length

Natural-regenerated: organic polymers undergone synthetic processes

Negative space: the space around and between a shape or an object

Pattern: display of reoccurring feature

Peg: a short pin used to control the lifting of shafts on a loom

Pegging: putting pegs in place to form a weave pattern

Peg plan (also '**lift plan**'): the order of raising shafts during weaving to create pattern

pH: the acidity or alkalinity of a solution

Photoactive polymers: those that chemically react to sunlight or ultraviolet radiation

Physical properties: characteristics used to observe a describe a material

Picks: individual weft units

Poisson's ratio: the ratio between contraction and extension

Polymer opals: polymers that demonstrate many small points of shifting colour

Porosity: the extent to which a martials full of holes

PP: Plastic-based 3D Printing

Repeat: reoccurring unit

Resin: flammable organic substance that is insoluble in water

Sample warp: series of woven samples that are created due to a specific warp plan

Shafts: screens that hold headles and used to lift warp ends to form sheds

Shear: break off

Shed: opening between warp ends to allow weft insertion to pass through

SHS: Selective Heat Sintering

Shuttle: an apparatus used for weaving to carry weft yarns from one side to the other

SLA: Strereolithography

SLM: Selective Laser Melting

SLS: Selective Laser Sintering

Specific area: the total surface area of a material per unit length

Spool: a cylinder device (larger than a bobbin), used to wind threads, yarns or wires

Staple fibre: individual fibres, usually of a relative short length

Stimuli: plural of stimulus

Stimulus: something that incites to action

Strain: force

Strand: an individual long and slender unit

Stress: pressure or tension applied onto a material

Structural properties: characteristics used to describe the assembly of a system

Structure unit: base assembly unit

Surface properties: characteristics of the outer boundaries of a material or an object

Surface roughness: a measure of textures

Surface texture (also ‘**surface topography’**): the overall nature of a surface

Surface topography (also ‘**surface texture’**): the overall nature of a surface

Synthetic: chemically engineered

TA mapping: ‘textile anatomy’ mapping

Tappet: a linear motion transmitted through an apparatus

Tensile modulus: the ratio between stress and strain applied to materials

Tensile strength: the resistance of a material to break under tension

Textile: (also ‘**cloth**’ or ‘**textile**’): fibrous architecture of yarns and fibres

Thermal absorption: material’s ability to captivate heat

Thermal conductivity: material’s ability to retain heat

Thermal properties: the behaviour of materials under various temperatures

Thermal resistance: material’s ability to resist a heat flow under specific conditions

Thermal stability: the steadiness of molecules at high temperature

Thread: long, thin strands made of fibres and used for sewing or weaving

Thread count: the number of warps and wefts in one square inch of fabric

Threading: warp plan – the positioning of warp ends across shafts

Treadle: foot pedal

Volume: the amount of space that a substance or object occupies

Warp: vertical threads used for weaving on a loom

Warp rib: weave structure producing a vertical cords effect across the cloth

Wavelength: the distance between one pick of a wave to the next

Weft: horizontal threads used for weaving on a loom

Weft rib: weave structure producing a horizontal cords effect across the cloth

Whug: a third set of threads used for triaxial weaving

Yarn count: a numerical expression that defines the fineness (or coarseness) of yarns

Chapter 1

Introduction

One of the distinctive signs of the early 21st century has been the widespread development of new technologies discreetly embedded into our everyday experience. STEM (Science, Technology, Engineering and Mathematics) is pervasive in contemporary life. Not only do we rely upon it as a tool for greater efficiency but also it increasingly mediates our lifestyle and methods of communication. Throughout the 20th century the integration of STEM disciplines into textiles has been at the heart of the textile industry. Science has driven the creation and synthesis of new polymers. Technology enabled the creation of novel synthetic fibres, filaments and yarns. Engineering – although not a new construction methodology of textile – continue to dominate the industry, mainly through the implementation of weaving and knitting. This also includes the development of various mathematical modeling systems and tools, which until this day, claim to enable the prediction of specific textile properties [figure A.1, p. 194]. As a result, STEM research methodologies are now widely in use for the development of technical textiles, electronic textiles and so-called smart textiles. The latter refers loosely to the research and development of textiles beyond the conventional and away from standard applications.

Although the development of such textiles – technical, electronic and so-called smart - is currently directed mainly by the hands of textile engineers, textile designers have long been taking interest in implementing new advances of textiles into the market place. The divergence between textile designers and textile engineers still persist and this is further discussed in chapter 2. In a response to this, my research had sought to present a new hybrid research methodology. This research methodology is anchored in design thinking and design practice, but it differs from other methodologies in the way in which it also heavily relies on the literature of STEM as well as on the research methods and measuring tools that it offers. It is important to note however that although this research primarily rests on some contributions from the fields of Science and Technology, it primarily relies on methods and research tools offered by the field of Engineering, and although Mathematics plays a role in predicting the behaviour of some textile products, such were not included in the scope of this research.

Through this so-called STEM perspective, taken by a Designer, it quickly has become clear that in spite of much investment in the creation of smart *materials* in recent decades through STEM research and development, smart *textiles* have thus far not realized their expected potential. The distinction between *materials* and *textiles* is an important one, which I discuss in detail in chapters 3 and 4.

The objectives of my research investigation therefore were set as follows:

(1) *To determine what is meant by the term 'smart' when applied to textiles.* Through an extensive literature review, relying on evidence originating in the field of material science, electronics and human ecology I will aim to formulate a greater understanding of what is meant by smart (chapter 3). This understanding will be used to challenge existing definitions of the term 'smart textiles' with practical investigative samples through woven structures (chapter 6).

(2) *To understand and define the detailed logic that directs the creation of woven textiles.* In order to do this, a mapping tool will be developed, which I term 'textile anatomy' (TA mapping). This tool will represent guidelines to the complexities that make woven textiles into material systems with their unique sets of properties – suitable for various applications. 'Textile anatomy' mapping will provide a framework therefore for the various levels of structural hierarchy that are inherent in the creation of woven textiles. It will also examine the inner relationship between each hierarchical level to the next across multiple

length scales. It will be constructed therefore to deepen our understanding of woven textiles as a multi-component material system and to explain how such hybrid research methodology such as presented in this work, can be used to aid and inspire new designs. ‘Textile anatomy’ will be used through the development of original diagrams to emphasize the direct relevance and importance of construction methodologies for the making of new textile systems (chapters 4 and 5).

(3) *To investigate the potential role of weaving as a fabrication tool – today and in the future - for the creation of smart material systems.* Following an investigation into textile architectures (chapter 5) a number of experimental case studies will be devised as part of the practice-led design activity that governs this research. These case studies will set out to explore the character of new woven geometries, i.e. geometries that are responsive and potentially adaptable to changes. The findings from the case studies will then be used to reveal the benefits and limitations of weaving as a method of creating smarter fabrications. Additionally, alternative construction methodologies such as additive manufacturing will also be investigated as potential substitutes for conventional textile making (chapter 6).

1.1 Distinctiveness of this research

The originality of this research is rooted in the development of a new hybrid research methodology, which seeks to find a balance between two very different approaches to research – that of Design vs. that of STEM. In particular, this research deals with the way in which Science, Technology and Engineering (S-T-E) can inform the creative process of Design (chapter 2). This approach builds on the merits of creative design and scientific research methodology in a quest to narrow the gap between the triple helix of design, human centric needs and behaviours, and material systems. It is therefore, by its very nature, an inter-disciplinary study.

The intellectual weight that this research carries owes a factual and interpretive debt to Roderick Lakes' *Materials with Structural Hierarchy* (1993), Brian Culshaw's *Smart Structures and Materials* (1996), and Mukesh Gandhi and Brain Thompson's review and analysis of *Smart Materials and Structures* (1992). These works have illuminated perceptions and ideas regarding material's performance. Their logic and understanding of materials properties and functions have here been applied onto textiles – all of which is discussed in length throughout chapter 3.

Hierarchical design across material length scales is an established methodology in material science and systems biology. The distinctiveness of this research is that it takes the principles of hierarchical design and applied them to the design and production of woven textiles, which, in turn, can provide insights into the development of smart textile constructs.

In an age of open innovation and widespread use of STEM integrated products, it is important to be able to offer sufficient insight into the workings of textile systems, not only for textile practitioners working away from an academic environment but also for a broader audience with the curiosity to explore new developments relating to textiles. This research is relevant to the design field – even away from the specialist area of textiles – because it investigates the principle methods of constructing materials systems and transforming those into new 3D forms. It is therefore aimed at designers from across the fields of textiles, fashion, product and architecture.

Designers in general, and weavers in particular, currently have no access to a straightforward database or mapping system that explains the engineering principles upon which textiles are made. As a response, this research study seeks to present a new understanding of the structural complexities that dictate the construction of textiles in particular. This is visualized through a novel mapping tool called 'textile anatomy' (chapters 4 and 5).

Another point of difference is presented through the practical experimental work in chapter 6. Weavers tend to look for specific properties infused in fibres, filaments and yarns to integrate into new cloths. As a result, such new fabrics may only portray the properties of its components. The originality of this research study steers away from the properties of the fibres and yarns as prime agents for change in textile properties. Instead it focuses on the process of weaving itself as a way of defining smart in the context of deformable woven structures (chapter 6).

1.2 Contribution to knowledge

This research combines the practical experience of a weaver with the application of textile related STEM knowledge and methods. The following practical and theoretical investigations carried out within this research offer an original contribution to knowledge as follows:

- A comprehensive critical review of the literature with regard to smart textiles reveals that smart textiles don't really exist as yet. The discussion of smart textiles also demonstrates critically how perceptions regarding the definition of smart have been distorted in past decades. As a result this research clarifies what smart actually means, and how it relates to textiles for practical benefit.

- The development of 'textile anatomy' mapping as a tool for enhancing our understanding of complex structural hierarchies and their relevance to the performance of constructed textiles in general and woven textiles in particular. This mapping is unique not only because of the sub-division on each of its hierarchical scales, but also in the way in which it ties the various levels of hierarchy together into one material system – from the molecule to the architecture of fibres and yarns. It integrates process and production methodology with the structure of each individual component as well as the materials system as a whole.

- Visualization of the structural complexity of textile systems, through a series of multi component diagram formats, reveals how woven geometries can be used to enable or enhance textile performance.

- Through a series of experimental case studies, and based on an extensive review of evidence based literature, not only the advantages but also the limitations of weaving, currently existing on the macro scale, are revealed and discussed as a crucial hindering mechanism for the creation of genuinely smart textiles. Furthermore, my research reveals the reasons why additive manufacturing cannot yet play a role in replacing conventional methodologies for the construction of textiles.

- Smart textiles are shown not to exist on the macro scale. Current perceptions of textiles – on the macro scale – are revised and a suggestion for new fabrication methodologies is presented, based on the advantages of materials systems through structural hierarchy analysis.

- As an answer to the deep and widespread confusion with respect to the meaning of smart textiles, I propose an original distinction between what I call *superficial* and *deep* responsivity: the former referring to the use of one technological parameter as a sole instrument for responsivity – be it a polymer coating, a fibre or a yarn that changes according to external stimuli. The latter however, refer to a textile material system that is inherently responsive - meaning that each of its components is responsive to an external stimulus or to the mechanical forces applied onto its neighboring components, and together, the system is therefore made responsive.

Chapter 2

Methodology

This research explores the possibility of creating smart textiles with a particular focus on weaving methodologies and woven textile structures. Through the development of a new hybrid research methodology – one that merges Design with Science, Technology and Engineering (S-T-E) - this research seeks to investigate and interpret the evolving role of weaving as a construction methodology for genuinely smart material systems. During this process, common perceptions of textile designers are challenged, particularly with regard to the nature of textiles as materials and the very meaning of smart. In the text below two acronyms are presented and it is worth taking note of their meaning and differences: S-T-E refers to Science, Technology and Engineering, which are the main subjects of investigation and integration into Design as part of a new hybrid research methodology, where STEM stands for the well known acronym for Science, Technology, Engineering and Mathematics.

2.1 The divergence between Design and STEM

For centuries the work of textile designers and that of textile engineers have been defined by a distinctive yet varied set of tools, assessment techniques and research methodologies. Besides the different approaches that can be found through design methods and through that of STEM, designers and engineers use different vocabularies with distinct terminologies, which makes intercommunication between the fields challenging. Additionally, they each operate within significantly different work environments – the studio and workshop serve the designer, and the lab works for the STEM practitioner. It therefore may not come as a surprise that both approaches – that of the designer and the engineer - rarely work jointly in collaboration. From a design perspective, the fundamental problem with this divergence is that the benefits that derive from STEM research into textiles are hidden from designers, which in turn, also limits their understanding of textiles as material systems.

2.2 STEM and textiles

In order fully to understand textile construction and to be able to predict the properties as well as the behaviour of textiles, textile STEM practitioners have created mathematical models based on the principles of structural hierarchy as part of a scientific methodology (Dixit and Mali, 2013; Stig and Hallstrom, 2012; Vassiliadis, Kallivretaki, Provatidis and Domvoglou, 2011; Chen, 2009; Vidal-Salle and Boisse, 2009; Brown, Morgan and McIlhagger, 2003; Tarfaoui and Akesbi, 2001; Komori 2001; Dastoor, Ghosh, Batra and Hersh 1994; Freeston, Platt and Schoppee, 1967; Olofsson 1964; Meredith and Hearle 1959). Some of these modeling systems date back nearly a hundred years (Peirce 1937; Haas, 1918), which goes to show the extent to which some scientific methods of investigating textiles are still relevant – having not changed throughout the 20th and 21st centuries.

According to Antonisamy, Christopher and Samuel (2010), scientific research is described as "systematic, ordered investigation in which the evidences are based on observed facts rather than on personal beliefs" (p. 277). PhD research theses that research STEM subjects follow a distinctive methodology of describing the modeling systems, tools and methods of measurements – such as found in Ruijter (2009) - from which an empirical evidence and verification of the results are produced. In a scientific investigation the empirical data tells the story and defines the success or failure of the research. The models currently used by STEM practitioners in textiles for predicting the behaviour of fibres, yarns and overall fabric structures can be divided broadly into two prime methods: the deterministic and the non-deterministic. The deterministic approach derives from applied physics. Deterministic models are used to explain the relationships between structure and property, and can be used to create textile constructions that meet specific applications. Such models are problem specific and, as a result, when applied elsewhere, can often produce large prediction errors. They require deep expertise, which, at times, can prove hard to access (Behera and Hari, 2010). Types of deterministic modeling techniques include computer simulation models and Finite Element Modeling – also known as FEM.

Non-determinist modeling systems – unlike those discussed above - are known to be more tolerant of imprecision, uncertainty, partial truths and approximations. Those include techniques known as fuzzy logic (FL), artificial neural networks (ANN), genetic algorithms (GA), and hybrid modeling.

However, in the specific case of textiles – unlike the majority of the fields to which Science, Technology, Engineering and Mathematics apply - the STEM routes were found not to be without their issues. In particularly this applies to textile engineering. The main criticism regarding engineering modeling strategies for textiles, such as presented in Vassiliadis, Kallivretaki, Provatidis and Domvoglou (2011), tap into the uncertainty that is associated with average calculations. According to Hearle (2006) conventional engineering techniques have only circumstantial relevance, proving true only under specific conditions. This prevents such findings from ever being used as general rules (Lomov *et al.,* 2001). More specifically, Hearle (2006) claims, the rules that apply for general engineering and those that are relevant for textile engineering are different - although rarely treated as such. In *Engineering Design of Textiles*, he explains: “Textiles are solid materials, but little of direct relevance to textile behaviour will be found in any textbook on the mechanics of materials” (p. 135). He continues: “ In ordinary engineering the development of discontinuities, of porosity, of buckling [etc.] are often taken as signs of failure of the materials… but in textiles their manifestation signals the value of these materials.” (p. 135). In other words, often, the engineering rules that apply to most materials – in this case – don’t always apply to textiles, which makes them not without fault.

2.3 Textiles design in practice and in research

If textile engineers rely on the quantitative characterisation of intrinsic properties of individual materials to describe the function, application or purpose of textile products – in practice, textile designers rely on qualitative measures that derive from their experience as crafts persons, which are often based on cultural references or unique subjective views.

Frayling (1993) outlines three distinct main research avenues employed in design:

- Research *into* design, where design is the subject of investigation.
- Research *through* design, where creative practice is an integral part of the research - which according to Frayling (1993) is also most suitable for collaborative work with the communities of Science (Matthews, 2011).
- Research *for* design, where the final outcome / aspects / effectiveness of the design is investigated.

Throughout the industry, textile designers employ a non-specific and individualistic approach that relies mostly on the creativity and contextual understanding of the designer. Textile design answers an ancient desire of humanity to decorate, ornament and adore the fabrics they have been making, and it precedes that of engineering by thousands years. It relies mostly on visual and textural qualities that together create an experience - that in turn, determines the commercial value and effectiveness of the textile (Fletcher, 1999).

The design process of textiles sees a visual manifestation of an idea by a sketch initially, drawn in pencil or in colour on paper. Alternatively, in recent years many designers have opt to using Computer Aided Design (CAD) softwares, such as Photoshop or Illustrator for the creation of an aesthetic representation of their work. The manipulation and use of colour is key in those developments (Best, 2012): the motif is then transformed into a pattern – where single or various motifs come together to create one image. This is then transformed to form the repeat of the cloth. The advantage of many CAD softwares for weaving – such as Jacquard Designer, Apso, WeavePoint, Weave Maker, Point Carrie, and ProWeave - lies in their ability to incorporate some yarn visualisation, which results in simulations of the aesthetics of the end textile product. These simulations however are only visual. They do not allow an understanding of the behaviour of the cloth and no quantifiable data can be extracted form them. From this perspective, although designers are able to derive much knowledge with regard to the aesthetic of the cloth, they lack a so-called STEM understanding of how this textile is going to behave.

2.4 Design: STEM methodology – anchored in practice-led research

In a quest to narrow the gap between textile design and textile related STEM, I have developed a 'bespoke hybrid research methodology' (Yee, 2010) that seek to find a balance between the merits of textile engineering and that of design thinking. My own personal take on this was to understand the principles, logic of analyzing and methods of evaluation that are used for the characterization of textiles through Science, Technology and Engineering (S-T-E). I used this understanding to re-address the design practice of weaving in order to gain new knowledge into the ongoing evolution of woven textiles. Throughout my research, practice and theory have been co-dependent - informing one another throughout the duration of the work.

It is interesting to note that when Greek philosophers like Plato distinguished between techne and episteme, as two different types of knowledge (Parry, 2014) – the former being practical and experienced based, the latter being pure knowledge – they often used weaving as the characteristic example of techne (Lehmann, 2012). The philosophy of the following methodology is that I have tried to bring together both techne (my own practical experience of weaving) and episteme (in the modern form of the S-T-E disciplines) in order to generate new insights.

The integration of knowledge from the fields of Science, Technology and Engineering (S-T-E) into that of design [figures 2.1 and 2.2] has become key to this new research method and one that has driven me to create an informative and definitive database for designers, resulting in my conviction that there is much to be learnt by adding the perspectives of Science, Technology and Engineering to those of design.

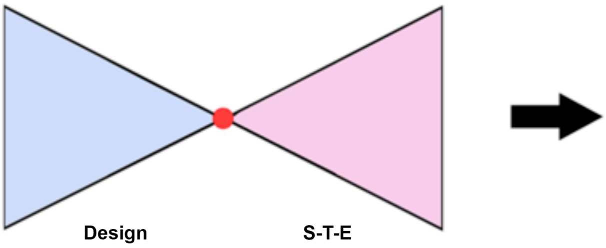


Figure 2.1
The divergence between Design and STEM

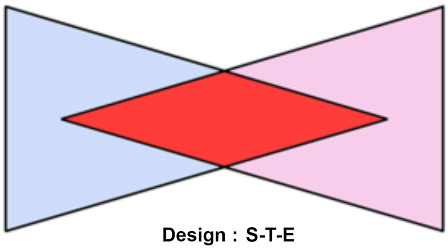


Figure 2.2
Design: STEM integration approach

Lynn Tandler (2015)

Although originally, the focus of textile design was primarily on colour, pattern and print (Aggrey, 1985) - in the course of the 20th century textile designers had begun to also consider the formation of handle and texture through the utilization of various textile structures. Until recently the development of textile structures themselves was dominated by the interventions of textile engineers, however this began to change when textile designers such as Philpott (2011) and Glazzard (2014) embarked on a practice-led research to create new textile structures and performances. Throughout their research, Philpott (2011) and Glazzard (2014) have relied on their specialist knowledge of textile design and expertise in craft and making as textile practitioners: the former through the adaptation of printing techniques and the latter on those anchored in knit.

Similarly, my research is conducted from the perspective of an experienced textile designer, however unlike other design investigations, such as those described above, my research does not focus on the aesthetic value, commerciality or specific application scope to which the research outcomes should apply. Rather, it concentrates on better understating methods of construction for textiles – and weaving in particular – from a hybrid perspective of Design and Science, Technology and Engineering (S-T-E). Here, the newly formed research methodology plays a key role.

In order to apply such new hybrid methodology onto my research I had to find an original way to resolve the persistent tensions that arise between design and STEM investigations – generally speaking, the former anchored in creative thinking and improvisation, and the latter relies on prescribed set of rules that are used as constant parameters for evaluation. My guiding approach for creating this hybrid research methodology was to combine twelve years of practical experience in weaving and design with the academic S-T-E disciplines. In chapter six, for example, I resolved this tension by allowing my investigations to be guided by a long experience of textile design and weaving practise, but then evaluating the results in purely functional terms.

My considerable practical experience in weaving is described here as the application of tacit knowledge. This, essentially, is the product of many years of weaving - referring to the instinctive tools that practitioners adopt through repeated engagement with their forms of practice. Such deep understating of a practice cannot be taught through textbooks or through a prescribed research methods. Indeed, it is often difficult to even explain. And it is precisely the unique qualities of tacit knowledge, which although makes it difficult to justify or discuss, also transformed tacit knowledge into such a valuable and creative research tool. Here, tacit knowledge is not brought to the fore as a prescribed methodology but rather as a tool, which gives an experienced maker the insight to dive deeper into the realm of their practice, and investigate problems that do not appear problematic on superficial inspection.

Relatedly, the knowledge acquired from the literature with regard to textile S-T-E has allowed me to re-evaluate my long-standing understanding of weaving and develop new general concepts regarding smart woven textiles in general. Denscombe (2010) describes such process of evaluation as ‘indicative analysis’. Here it was used to construct theoretical and comprehensive arguments about smart woven structures overall. In an age where fundamental ideas of engineering are changing and making way for new explorations into the realm of nanotechnology and synthetic biology (Drexler, 1990), the indicative analysis of this research was used to draw further conclusions as to how the weaving research community, and industry, should evolve in order to see the relevance of woven textile constructions proving successful for the creation of new material systems.

2.5 Writing in bespoke Design: S-T-E hybrid methodology

One of the challenges of this research – and indeed one of its purposes – is to combine the language of various disciplines, translating the one to the other. The gap between

Design and Science, Technology and Engineering (S-T-E) goes both ways. For example, many S-T-E practitioners consider the ornamental descriptions used by designers to portray some qualities within materials invalid, and therefore inadmissible. Similarly, I found, designers tend to dismiss the technical and detailed attention that derives from the accounts of Science, Technology and Engineering practitioners. The challenge that I faced through conducting my research was not only to gain the ability to understand how S-T-E relate to constructed textiles, but also to translate my understanding of the relevant S-T-E literature into a language that designers could relate to and find useful.

The incorporation of the insights of STEM in general into the field of Design has in itself the potential of generating new levels of understating and also new knowledge. In this instance, in order to emphasize the extent to which some conceptions of textiles have not changed in decades and are still relevant till this day, I cited the earliest publication. In this research, dissatisfaction with current understandings of the term 'smart' in Design is expressed and comprehensively discussed through a critical review of the S-T-E literature, and through a grammatical investigation of the term (chapter 3). The grammatical investigation of the term 'smart' (chapter 3) is an investigation into the meaning and use of the word with respect to textiles. This is not a philosophical investigation that touches on the relevance of artificial intelligence to the development of new synthetic entities, but rather one that inquires into the meaning and definition of smart textiles.

Whilst conducting a critical review of the literature into textile material systems (also in chapter 3), it became apparent that there was no readily available tool, map or database that enabled textile practitioners who are working away from academia, to make conscious design choices in the design of new technological textiles. At present any informative tools regarding textile properties are anchored in STEM and therefore are redeemed as unapproachable for most designers. In order to gain a deeper understanding into textiles as engineered materials systems, a new mapping tool was created in an illustrated and descriptive form - and it was termed 'textile anatomy'. Through the use of an illustrated diagram, this mapping (presented and discussed in details through chapters 4 and 5) explains how textiles differ from other groups of materials. It is offered as a tool for designers across the board who wish to deepen their understanding of textile systems, as well as a tool for better understanding the structural complexity that govern smart material systems.

'Textile anatomy' mapping is the result of on an going exploration into the logic that governs the architecture and structure of textile material systems and which gives them their unique set of properties and hence performance characteristics. One of its unique points of difference is the way in which it is presented to the reader – in a simple and straightforward way. The work carried out to develop 'textile anatomy' mapping had helped shape the experimental practice-led work upon which this research is based. It led to several significant insights - the most important of which is that responsive behaviour thus far only occurs due to the properties of individual textile components and not through the overall structure of the system (chapters 4 and 5). The approach therefore of a Design exploration with scientific and technological understanding, as well as an engineering investigation, into constructed textiles was the backbone for the experimental case studies in chapter 6.

2.6 Processes of making through Design: S-T-E methodology

A number of specific experimental case studies are presented in chapter 6, exploring the limitations as well as benefits of some current weaving methodologies. These studies address questions that have not been asked before, let alone answered. In particular, whether weave structures themselves can be genuinely smart. Primarily, the role of weaving was investigated – through processes of making for the construction of genuinely smart textiles. This approach to weaving design is new and one that has directly stemmed from the unique research platform created by the integration between Design and S-T-E.

Through the investigation of case studies 1 and 2, the limitations that current weaving methodologies have on the creation of new material systems were revealed along with a strong link between apparatus and textile structure possibilities upon which the textile industry heavily relies. Additionally, case study 3 of chapter 6 explores whether additive-manufacturing (AM) technologies – such as 3D printing – could compete with weaving looms for the creation and production of woven textiles in the future. A specific account of the methodology undertaken for each of the case studies is outlined in sections 6.1.2, 6.2.2, and 6.3.3 in chapter 6.

2.7 Analysis through Design: S-T-E methodology

The experimental case study work - presented throughout chapter 6 - involves the gathering and analysis of qualitative data in the form of 'researcher-centered analysis' (Denscombe, 2010). In other words, this refers to a research methodology that relies both on the experience, observation and the unique point of view of the researcher. My 'researcher-centered analysis', has been informed by many years of weaving, design practicing and researching the art of textile construction. In particular, much of the evaluation and analysis of woven structures and their so-called successful adaptation to applicable cloths in chapter 6 was drawn from tacit knowledge.

By assuming the pose of 'humans as instruments' (Maykut and Morehouse, 1994), I was able to evaluate the literature (chapter 3), draw innovative conclusions through the development of an original 'textile anatomy' mapping (chapter 4 and 5) and create a set of unique experimental case studies (chapter 6) from the unique point of view of an experienced weaver. Particularly this was true with respect of the investigation and development of new woven structures, which I was able to contextualize appropriately through process of making and through written coverage (chapter 6).

The designer - unlike most STEM practitioners – locates him/herself inside the research, in the centre of creation. However, as Matthews (2011) comments, at the same time, "it must be acknowledged that challenges arise over objectivity, validity and reliability, which must be addressed through the research methods that are selected" (p. 71).

Lincoln and Guba (1985) inform us that *transferability*, *dependability*, and *confirmability* are important in establishing the criteria for trustworthiness - which in turn determines the credibility of one's findings. To allow *transferability*, the context, aims, objectives, and methods of research have been detailed for each case study separately (chapter 6) in order to allow the reader to draw an accurate picture of the settings that framed each experimental work. The *dependability* of this research, although difficult to achieve in a qualitative research (Shenton, 2004) was established by the same detailed account of each of the works that has been carried out, which will allow others to repeat the case study if they so wish. In order to allow *conformability* in the research, quantifiable data was gathered in two and three dimensional imaging and through various resolution scales – with the aid of UBS microscopy [image 2.1] and stereomicroscopy in both reflective and transmitted light capture [image 2.2] - as a quantifiable visual method of studying and analyzing the properties of individual textile components.

Image 2.1
Dino-Lite USB microscope equipment
Digital photography

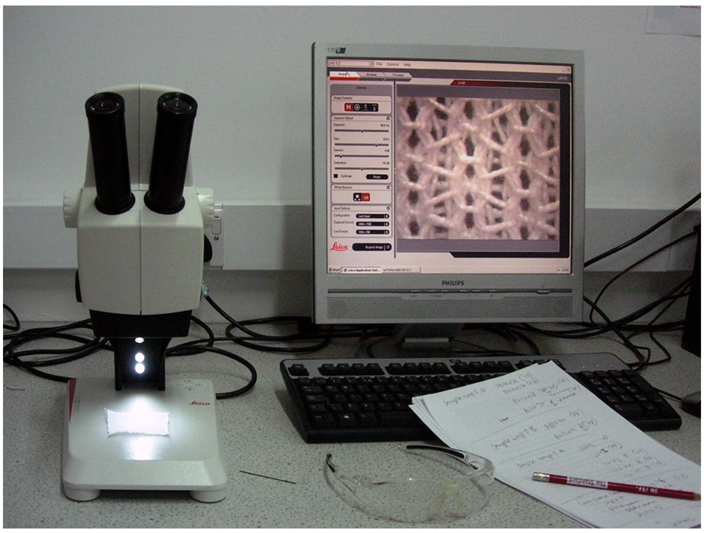


Image 2.2
Stereomicroscope equipment
Digital photography
Lynn Tandler (2014)

2.8 Research methodology: Flow diagram

The diagram in figure 2.3 summarizes the hybrid research methodology between Design and Science, Technology and Engineering as undertaken throughout my research. I divided my research methodology into three main stages. The first stage - marked in pink – identified my research question through a critical review of the literature. Additionally, knowledge about materials properties was acquired and selected components were measured and characterized accordingly (chapter 3 and Appendix A). The second stage – marked in blue – was allocated for building the platform for 'textile anatomy' mapping (chapter 4 and 5) and for a series of experimental case studies, which have derived from the research into the literature (chapter 6). With the knowledge acquired from materials properties, the 'textile anatomy' mapping tool, and results from the experimental case studies, stage three of my research methodology – marked in yellow – examined how well the findings matched the original research question.

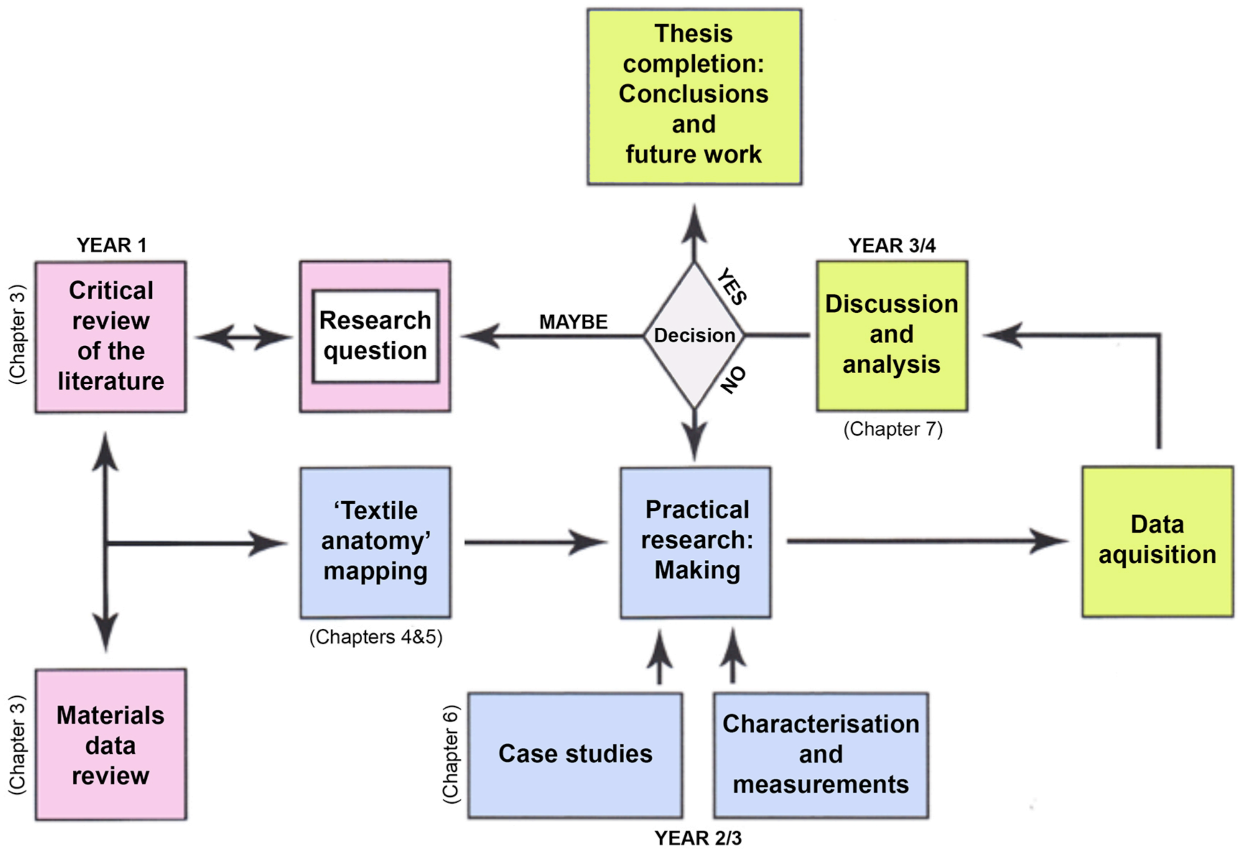


Figure 2.3
Research methodology
Lynn Tandler (2015)

Chapter 3

Literature review

Throughout the 20th century till present day the integration of STEM disciplines into textiles has been at the heart of the textile manufacturing industry - resulting in the development of technical textiles, electronic textiles and the more ambiguous 'smart textiles'.

3.1 Technical and electronic textiles

Technical textiles are non-responsive textiles. According to Mattila (2015) they are aimed at fulfilling a specific function. Such textiles claim no particular aesthetic value. Instead, they rely on technical performance to characterize their worth. Technical textile engineers employ STEM methodologies – such as quantitative measurements, modeling, characterization and analysis – to enhance textile performance. These explorations are often focused on the development of individual textile components, which are emended into the textile or that are applied onto it in later stages of production – such as various coating and finishings. With applications across the fields of agriculture, architecture, footwear, clothing, furniture, filtration, health, automotives, packaging, sport and leisure (Horrocks and Anand, 2000), technical textiles have now become common in our everyday lives. In fact, the ubiquitous use of technical textiles in the environments surrounding contemporary human lives significantly outweighs textiles for fashion and everyday apparel. Electronic textiles, like their technical counterparts, are equally reliant on STEM as a driving tool for the advancement of new textile products. A piece of textile can become electrically conductive through the use of metal alloys, wires, fibres and yarns or through the applications of conductive coatings during the later stages of production (Wilson, 2011a).

Electronic textiles however are not a new phenomena. For example, in the early part of the twentieth century electrical tablecloths were briefly popular amongst the upper classes: bare electric wires ran between two layers of woolen felt cloth, linked to a 12-volt battery. As a result special light bulbs could be plugged directly into the tablecloth and adorn the table with illuminations. At the time, the hazardous combination of bare electrical wires, food and water was not yet fully known. Unsurprisingly, in later years, the electrical tablecloth proved highly dangerous and its reputation and use declined (Field, 2004).

According to Veja (2015), electronic components can be attached onto or into a fabric though processes of binding, knitting or weaving. To date, Veja (2015) claims, all electronic textile samples can be classified into either one of these two groups. This includes the works of CuteCircuit (*Hug Shirt*, 2004; *Galaxy Dress*, 2009; *Twitter Dress*, 2012); Despina Papadopoulos (*Love Jackets* 1995 and 2005); Maggie Orth (*Firefly Dress and Necklace*, 1998; *Electronic Tablecloth,* 1999; *Grace,* 2004); SubTela (*White Wall Hanging*, 2007; *Jacket Antics,* 2007; *Blue Code,* 2008) and Zane Berzina (*E-Static Shadows*, 2009) among others. These works are a display of designers who work with readily available electronic components to create new textile products. This mainly involves the implementation of light-emitting diodes (LEDs) – making such e-textile prototypes open to criticism for their limited use, gimmicky appeal and specific suitability – mostly for younger markets (McCann and Bryson, 2009). In other words, they take little or no account of psychological, emotional or cultural requirements in their implementation.

In an industry report titled *The Future of Smart Fabrics: Market and Technology Forecast to 2021*, Wilson (2011a) writes, “Electronics companies and brands care little whether something is textile or not. Neither, ultimately, does the consumer, as long as the product works” (p. 1). Accordingly he claims, one of the reasons that electronic textiles have not yet become well embedded across western consumers markets – unlike technical textiles for example - is not because electronic cloth isn’t used as an interface for technology but rather because “often when a fabric is employed", he writes, "it may be little more than a carrier for certain electronic components, rather than being an integrated 'product' or containing fibre circuitry of any description" (p. 1). In other words, one of the problems with electronic textiles today is that the construction of weaving or of knitting seems to have no particular significance for the successful construction and operation of electronic cloths.

In practice, textile designers are only able to put together the components that textile engineers develop. And this is where the two methodologies of design and engineering, particularly in textiles, fundamentally differ. In places where designers are aware of the context to which a potential fabric should belong, engineers often think about the function, limitation and performance of individual components, independent from a particular textile to which they are intended to belong.

Building on this point, the failure of electronic textiles to gain acceptance in the marketplace thus far might also relate to a cut & paste effect, for the technology of all electronic textiles is engineered away from the fabric only to be transferred into or onto the cloth towards the end of production. In other words, electronic textiles have not yet become one homogenous and integrated product, but rather they are fabrics with attached electronic components. According to Cork (2015), "electrically functional yarns and fibres should have the same diameters, moduli and strengths as conventional textile fibres" (p. 14) – only then could there be a genuinely discreet integration of electronics with textile substances, and thus become suitable to create comfortable, aesthetically pleasing products.

Research groups such as those led by Prof. Dias at Nottingham Trent University, have been working with a distinct focus to overcome such boundaries and increase the compatibility between electronic components and textile yarns (Dias, 2015). Google too has launched a small research groups who weave conductive threads on jacquard looms for the production of mobile phone interfaces embedded into cloth (Brownlee, 2015). Similarly, an internationally collaborative project that emanated from the University of Exeter presents a conductive, transparent and flexible textile technology through the integration of graphene into textile elements and into the cloth (Onita, 2015). These research groups continue to extend our understanding of the relationship between electricity and textiles.

In some cases, electronic textiles have been referred to as 'smart' textiles – with the term 'smart' representing the cutting edge of textile design and engineering. There is still much ambiguity with regard to the definition and descriptions of the term smart textiles: so much so that it is difficult to clearly understand from the literature what smart textiles actually are and do.

3.2 Smart textiles

"The term smart structures and smart materials are much used and more abused" (Culshaw, 1996, p. 3). This was from twenty years ago. And for most designers, it's just as true today. These days, the word smart has found popular use within the public domain – with products such as smart phones, smart watches, and even smart water reaching our shelves - dominating our consumer expectations and habits with positive promotions associated with everything that is 'smart'.

According to Van Langenhove (2015), smart textiles have been around since 2000 – unlike Culshaw (above) who was writing about smart materials, and not smart textiles. Probably the first attempt to define the term smart in relation to textiles is that of Tao (2001) who classified textiles according to their potential level of smartness. Although not distinguishing between materials and textiles, she described smart materials as those that "sense and react to environmental conditions or stimuli, such as those from mechanical, thermal, chemical, electrical, magnetic or other sources" (p. 2-3) – further classifying them into "passive smart, active smart, and very smart materials" (p. 3). Her descriptions have passed from one publication to the next and her division of smart into active, passive and very smart materials has become widely repeated across the literature - sometimes without acknowledgement of Tao's original publication (Stoppa and Chiolerio, 2014).

Some textile specialists still hold to the belief that any piece of textile, which presents properties over and above those of conventional textiles is worthy of the description smart – particularly for example, the use of electronic textiles (Pailes-Friedman, 2016). Similarly, some contemporary attempts at defining smart textiles have little to separate them from those of responsive textiles per se. For example, Stoppa and

Chiolerio (2014) summarize the term smart textiles as "products such as fibres and filaments, yarns together with woven, knitted or non-woven structures, which can interact with the environment/user" (p. 11958). This is an example that reaffirms a common perception that as long as textile components "interact with the environment/user" they shall be considered smart. The problem with this definition is that, to some degree, every piece of textile changes in reaction to its environment (Morton and Hearle, 2008; Taylor, 2007; Johnson, Wood, Ingham, McNeil and McFarlane, 2003).

Similarly in *Textiles and Fashion: Materials, design and technology*, Mattila (2015) describes smart textiles as those that interact with the environment and "based on information received [they] perform predetermined actions repeatedly and often reversibly" (p. 355). What he seems to have in mind here are examples such as an ICD jacket and an MP3 player jacket. But in the same text, Mattila (above) describes wearable electronics as "textiles where electronic or mechanical components are attached to the textile material, and the textile part does not have any intelligence properties" (p. 355). Meaning, that in electronic textiles it is not the textiles themselves that are being 'smart'. What Mattila does not do is properly differentiate between wearable electronics and smart textiles. In other words, he does not explain how smart textiles differ from any other group of responsive textiles. Thus, in spite of making a clear distinction between smart textiles and wearable electronics in the same text, the examples that Mattila (2015) describes as smart do not differ from those that can be used to describe wearable electronics.

In order to understand where genuine smartness – if such exists - occurs in textiles it is important to understand how textiles are built and what are the foundations upon which they are engineered, both technologically and aesthetically, to meet human centered needs and wants.

3.3 Understanding woven textiles as material systems

In an article for the *Textile Research Journal*, Lomov, Huysmans and Verpoest (2001) describe textiles as "hierarchically structured fibrous materials" (p. 534). Their definition of the term textiles, as adopted by many others in the field, is one that relies on principles of structural hierarchy to illustrate a system which is made out of fibrous materials (Zheng, Zhao and Fan, 2012; Bosia, Buehler and Pugno, 2010; Taylor, 2007; Yao and Gao, 2008; Lomov, Huysmans and Verpoest, 2001; Takano, Uetsuji, Kashiwagi and Zako, 1999; Collier, 1980).

Structural hierarchy refers to the logic that governs complex structures where the elements that form the overall structure themselves have structures (Lakes, 1993). In a much-referenced paper from 1993, titled *Materials With Structural Hierarchy*, Lakes explains the principles of structural hierarchy – for both natural and manmade materials. Lakes (above) defined the hierarchical order of a structure in terms of *n* degrees of scale. Accordingly, "$n = 0$ corresponds to the material which is […] the base material or the base unit block of the overall structure" (Lakes, 1993, p. 511). The number of hierarchical levels (*n*) within a system - as well as the criteria, which is used to link orders together, define the nature of complex hierarchical systems, be they woven materials or the construction of mechanical or structural environments such as the Eiffel Tower, which was the inspiration behind Lakes' work.

The vast majority of woven textiles described in the literature exhibit three levels of structural hierarchy. With Lakes' description of hierarchical systems in mind, in most textile description accounts, fibres appear as the base order within the hierarchy ($n = 0$), yarns represent the architecture of fibres and therefore appear as the first order of complexity within the hierarchy ($n = 1$), and fabric structures, as the architecture of yarns, appear as the second order of complexity ($n = 2$). Other descriptions of textile systems report four or five levels of structural hierarchy such as those described by Chen, Zhao and Collier (2001), which includes finishings and coatings agents as third order, above fabric structure ($n = 3$); and Takano, Uetsuji, Kashiwagi and Zako (1999) and Smith (2010) who specify fabric application as fourth order ($n = 4$) above finishing and coating agents and techniques.

Largely, fibres are described as the building blocks of all textiles (Briggs-Goode and Townsend, 2011; Collier, 1980). Goodman (1968) defines fibres as "solid objects whose lengths are hundreds or thousands times greater than their widths" (p. 1). Throughout the literature many classification of fibres into sub-groups can be found.

Cook (1984) classifies fibres into two main groups: natural and manmade. Collier (1980), on the other hand, divides fibres into three main groups, according to their origin: naming vegetable fibres, animal fibres, and mineral fibres, and Hearle and Peters (1963) classifies fibres into four groups, according to their polymeric origin - naming them as those obtain from animal, vegetable, mineral, or any other chemical source. [A more detailed investigation into the structure of single component fibres and their applications can be found in Appendix A]. Complications arise however when creating fibre composite and multicomponent fibres – in which case the properties of different fibre materials are conjoined together into the one textile product.

Fibre properties such as strength, elasticity, thermal stability and potential responsiveness to external stimuli can be found within the code that is the equivalent of the material's DNA. This can be found through measurements of the properties of the polymers from which specific fibres are made (Hearle, 1982). In the case of most textile components, these refer to the natural and synthetic polymers from which they are formed.

Polymers are large molecules – known as macromolecules - made of small repeating units, called monomers, which are linked together by covalent bonds (Cook, 1984; Hearle, 1982). Because of this, it is inevitable that understanding polymers can enrich the understanding of textile component's performance (Young, 1981). According to Hearle (1982), "As a class, polymers are among the most important of all materials" (p. 19). In 2009, Chen and Hearle reported a textile hierarchy with a new base order ($n = 0$), which they referred to as polymers and not fibres - i.e. the building block of the fibre in the macromolecule that constitutes the fibre.

Polymers are generally divided into natural polymers - or biopolymers – and manmade polymers. In general, biopolymers are water loving, a property that identifies them as hydrophilic due to their evolution through water based environments – either biologic, botanic or aquatic environments. Manmade polymers on the other hand are mainly water repelling, which identifies them as hydrophobic polymers due to the nature and arrangement of the organic molecules of which they are constituted.

According to their origin, biopolymers are further divided into those that originate in plants and those that originate in animals (Walton and Blackwell, 1973; Alfrey and Gurnee, 1967; Goodman, 1967). Similarly, manmade polymers can be further divided into natural regenerated polymers and synthetic polymers. A different group of polymers called responsive polymers is described in by Hu and Lu (2014): these are polymers that "show noticeable changes in their properties with environmental stimulation" (p. 437). Their behaviour is dependent on changes in their chemical and physical structure. Other than polymers, some inorganic and metal elements – such as ceramics, glass and metals – are also in use for making textile fibres. More detail on the different groups of polymers and their inorganic elements counterparts, their sub divisions and unique properties are described in Appendix A.

Once polymers or other inorganic or metal elements are made into fibres, they can then be 'spun' into yarns (Lawrence, 2010; Wilkinson, 1967). In the literature, yarns are mainly classified according to their fibre content and according to their suitability for end-use applications (Gong, 2011; Alagirusamy and Das, 2010). The properties of yarns are largely subjected to the properties of the fibres from which they are spun, and the spinning techniques used to create the yarns. As a result, understandably, a wide range of yarn spinning technologies has been developed (Alagirusamy and Das, 2010; Jing and Hu, 2010; Lawrence, 2010; Nyoni and Brook, 2006; Jiang, Li and Fan, 2002; Wilkinson, 1967) – the general methodologies are summarised in Appendix A.

Yarns, and/or continuous filaments in some cases, are used to form the geometry of the cloth and hence, its structure – most commonly through process of weaving and knitting. For nearly a century, since textiles laboratories begun producing polyamides for making Nylon fabrics, and polyurethane for example, for making Lycra© – the textile industry has relied on the properties of fibres and/or yarns to provide a textile with novel performance (Kapsali, Toomey, Oliver and Tandler, 2013). With advances in chemistry and in engineering, new fibres have been developed and taken to the market. As a result, the structure of the cloth itself – whether woven or knitted – has played a relatively insignificant role in providing novel functionalities to textiles: whether within the field of technical textiles, electronic textiles or that of conventional textiles. With regards to smart textiles, it is now believed that their inception is solely dependent on the development of smart textile components (Stoppa and Chiolerio, 2014; Cherenack, Zysset, Kinkeldei, Munzenrieder and Troster, 2010; Mattila, 2006). And this is precisely the source of so much confusion over the meaning of smart textiles.

Textile materials behave differently to other materials. According to the *Oxford English Dictionary*, the latter is defined as “the substance from which a thing is or can be made” (Waite, 2012, p. 446). Textiles on the other hand, are described in the same text as those made out of many materials - viewed throughout as systems govern by principles of structural hierarchy - see chapter 5. In other words, the word textile itself implies that there is an assembly of many materials into the one form.

3.4 Nanotechnology and textiles

In the groundbreaking paper *There’s Plenty of Room at the Bottom* (Feynman, 1960), the potential of exploring and developing new nano scale materials was presented in its enormity. Nanotechnology and bionanotechnology refer to the study of materials from 100 nanometers down to the atomic level. According to the critical review by Dowling *et al.* (2004), “It is in this range (particularly at the lower end) that materials can have different or enhanced properties compared with the same materials at a larger size” (p. 5). At the nano scale, for example, the chemical reactivity of many materials increase due to a larger surface area, which in turn can dramatically change the properties of the same materials as it exist on the macro scale. This is caused by the fraction of atoms at the surface becoming greater than the atoms in the bulk of the material as the particle size decreases below approximately 20 nanometers.

Indeed, ideas of bulk engineering have been slowly giving space to those of nanotechnology for several decades (Drexler, 1990). The exploration of materials on the nano scale for textile applications is not new, and one that had already proved useful for the enhancement of textile attributes - such as fabric softness, durability, breathability, water repellence, fire retardancy and antimicrobial properties alike (Sawhney, Condon, Singh, Pang, Li and Hui, 2008). In textiles, nano scale techniques have become popular where nano-coated materials such as polymer coatings have been applied onto individual fibres in order to enhance their performance (Bartels, 2011). Today, more companies are involved in fibre engineering, which involve chemical and mechanical intervention on the micro and nano scales. One of the most prominent examples refers to the biomimicry of the Lotus leaf and its adaptation to the development of water repellent textile surfaces (Samaha, Tafreshi and Gad-el-Hak, 2012; Gao and McCarthy, 2006; Marmur, 2004; Patankar, 2004).

Needless to say that nanotechnology research requires special measurement and characterization tools, such atomic force microscopy (AFM) and scanning electron microscopy (SEM), which are used for the study of materials on the nano scale. AFMs are probes able to measure the physical, mechanical and structural properties of nanoparticles and nanomaterials, and simulate these in the format of an image depicting individual atoms within the surface roughness of the object. Similarly, SEM give a microanalysis of solid natural, inorganic and synthetic materials with high magnification rates - up to x 300,000 - able to generate high-resolution pictures, accurately measuring small features and particles within nanofibres or other nanostructures.

3.4.1 Micro and nano scale textile components

Nanofibres are small fibres with diameters smaller than 500 nm. Nanofibres can be made form natural polymers (Ifuku and Saimoto, 2012) as well as from manmade materials (Teo and Ramakrishna, 2009). They have high surface area to volume ratios (Petrulyte and Petrulis, 2011), which provides them with enhanced chemical reactive and physically different properties – an aspect already proven useful in various textile applications (Bartels, 2011; Van der Schueren and De Clerck, 2011; Fleck, 2008). The three inherent properties of nanofibres are their high specific area (surface area/unit mass), high aspect ratio (length/diameter) and their ability to suit a wide range of applications demanding biocompatibility traits. Depending on which, nanofibres can create lightweight, breathable and strong fabrics (Brown and Stevens, 2007). Fibres made of carbon are often used for structural lightweight applications and have been discussed in Paris and Peterlik (2009).

Monofils are single continuous filaments with diameters within the regions of 30-2000 microns thick (McIntosh, 1994). Monofils can be made from natural as well as synthetic polymers. Monofils are much stiffer than conventional multifilament yarns for example: they are known to have high flexural rigidity, good surface release properties and resistance to damage (McIntosh, 1994). They can be created in many cross sectional shapes – see chapter 4 - and their applications vary across agriculture, paper manufacture, industrial brushes and filtration, textile and sport accessories – as shown in figure 3.1.

Applications	Polymers									
	PVC	PE	PP	N	PET	PBTB	PPS	PEEK	PTFE	Diameter/mm
Agriculture and fisheries										
Ropes		✓	✓	✓	✓					0.2–0.5
Nets		✓	✓	✓						0.3–0.6
Strimmer lines				✓						1.0–3.0
Paper manufacture										
Forming				✓	✓					0.1–0.3
Pressing				✓						0.1–0.3
Drying					✓		✓	✓		0.4–0.6
Industrial										
Conveyors				✓	✓		✓	✓		0.4–0.8
Filters			✓	✓	✓	✓	✓	✓	✓	0.03–0.3
Brushes	✓	✓	✓	✓	✓	✓				0.1–1.5
Rubber reinforcement				✓	✓					0.4–1.5
Screening printing					✓					0.03–0.1
Textile										
Zip fasteners				✓	✓					0.4–1.0
Sewing threads				✓						0.1–0.5
Stiffenings				✓	✓					0.03–0.1
Leisure										
Sports racket strings				✓				✓		0.1–0.7
Fishing lines				✓						0.1–0.7

Figure 3.1
The applications of synthetic monofilaments according to McIntosh (1994, p. 367)
PVC = poly(vinyl chloride); PE = polyethylene; PP = polypropylene; N = Nylon
PET = polyester; PBTB = poly(butylene terephthalate); PPS = polyphenylene sulphide
PEEK = poly(ether ether ketone); PTFE = polytetrafluorowthylene.

Sawhney, Condon, Singh, Pang, Li and Hui (2008) describe the diameter of fibres throughout macro- micro- and nano-technology lengthscale [Figure 3.2]. A common example for a class of nano fibres are those made from carbon nanotubes – also known as CNTs. Carbon nanotubes are graphene sheets made entirely of carbon. These are rolled up long tubes with fibre dimensions in the range of 10^{-8} and 10^{-10} (Sawhney, Condon, Singh, Pang, Li and Hui, 2008). The mechanical and thermal properties of CNT's were discussed in length in a paper by Ruoff and Lorents (1995). CNT's have great electrical and thermal conductivity, which made them into a desirable material for the creation of supercapacitors (Dalton *et al.,* 2003). With novel chemical, physical and electrical properties, CNT's are amongst the stiffest and strongest fibres known (Silvestre, Faria and Lopez, 2012; Harris, 2004). The applications of CNT's vary from "aviation and space, car, power, defense, medical, textile and other industries, in information technologies and for environmental protection", so far as that "single-walled CNT's are expected to replace silicon in electronic chips in 10-15 years" (Rakov, 2013, p. 28).

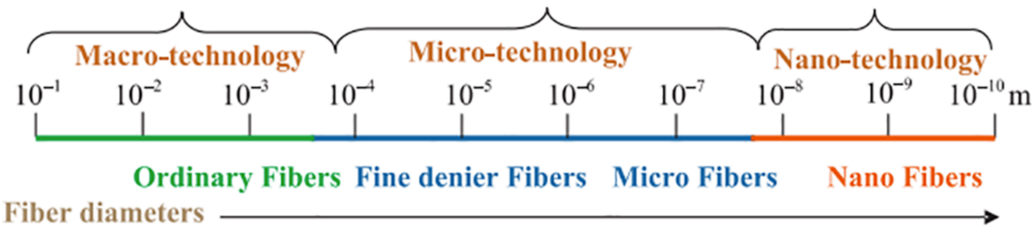


Figure 3.2
Fibre diameter across lengthscale according to Sawhney, Condon, Singh, Pang, Li and Hui (2008, p. 732)

According to Dowling *et al. (*2004) "Nanotechnologies aim to […] create structures, devices and systems with novel properties and functions due to their size" (p. 5). Already, microscopic structures are embossed directly onto the surface of individual synthetic fibres in order to increase the surface texture of the fibres and by that, increase its chemical reaction capabilities (Sawhney, Condon, Singh, Pang, Li and Hui, 2008). But more techniques are being explored across the nano domain in a quest to fabricate new materials into novel material systems (Zhang *et al.* 2012; Tsukruk, Ko and Peleshanko, 2004).

Within the domain of micro and nano materials fabrication, textile methodologies have been used as an inspiration for scientists wishing to draw on textile production methods in order to construct new materials on the nano scale. Examples can be found in the mimicry of yarn spinning techniques that inspired new makings of a nano yarn such as can be seen in Jiang, Li and Fan (2002) and in Zhang, Atkinson and Baughman (2004) and in Rye, Kim, Lee and Hong (2014). Similarly, carbon nanotubes have been spun together with other natural fibres in order to create a hybrid yarns with enhanced properties (Sawhney, Condon, Singh, Pang, Li and Hui, 2008; Iijima, 1991). Images 3.1 and 3.2 show the resembling process that is used to spin yarns form conventional fibres, and spinning yarn from CNT's respectively.

Image 3.1
Spinning wool fibres into yarn
Image adaptation from Flynn (2012)

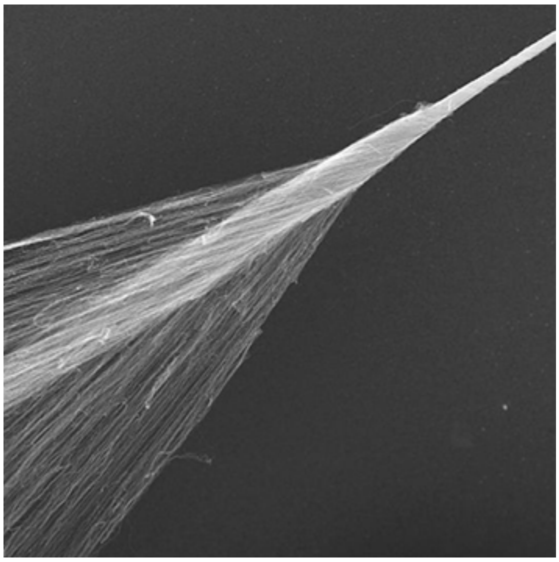


Image 3.2
Spinning CNT fibres into yarn
Image adaptation from CSIRO (year unspecified)

But not only yarn-spinning techniques have inspired the production of new materials on the micro and nano scales. Engineers, further afield from textiles, begun to search for fabrication techniques for the assembly of nano multi structures. Carlson and Kuppurathanam (2008) submitted a patent application for a woven fabric with carbon nanotube strands. Similarly, Zhang *el al.* (2012) reported attempts at weaving carbon nanotube yarns into solar fabrics, and scientists from Shinshu University, Nagano, Japan, developed a theoretical model for a nanoscale weaving mechanism – one that mimics the action of weaving on the macro scale seamlessly (Xia and Hirai, 2013). At present, only first few steps have been taken for the creation of textiles on the nanoscale – all of which are STEM related: conceptualizing the engineering and theological steps needing to take place for the physical fabrication of woven textiles for examples. But little discussion could yet be found regarding the potential design elements, which will be prominent or absent with such inventions (Maclurcan and Radywyl, 2011).

The ways in which we experience and perceive surface roughness depends greatly on the surface topography of our fingertips (Jones and Lederman, 2006). This scale of roughness on average, is approximately thirty microns. Anything finer than thirty microns will be perceived as a smooth texture, while anything above that scale will be perceived as textural.

According to Rakov (2013), "The fabrication of [carbon nanotube] materials is a new stage in the evolution of materials science" (p. 30). In *The New Industrial Revolution*, Marsh (2013) advocates that the new investigation, research and development into nanotechnology is set to be transformative even more so than the original Industrial Revolution - affecting the way we produce and manufacture materials and products. It is therefore not much surprise that scientists, researchers and scholar alike have turned to production methodologies - originated during that time – for inspiration. The works of Xia and Hirai (2013) for example, confirm this: giving way to the relevance of weaving, as a construction methodology for the fabrication of many material systems. With this in mind, let us now return to the question of smart and its relevance to textiles.

3.5 Smart materials – as opposed to 'smart' textiles

Back in 1992, Gandhi and Thompson suggested grouping materials into structural, functional and multifunctional, according to their degree of responsivity. Structural materials, they explain, never change their inner structure but can be manipulated mechanically into various shapes; functional materials can change their physical, chemical or mechanical structure under certain conditions; and, multifunctional materials display an overall behaviour which is the sum of many functions operating simultaneously (Gandhi and Thompson, 1992).

There are currently already over 160,000 new materials available for designers and for engineers - out of which there are more than 45,000 manmade polymers alone, as well as thousands of light alloys and hundreds of high performance composites (Ashby, Shercliff and Cebon, 2014). Figure 3.3, as originally presented in Ashby, Shercliff and Cebon (2014, p. 3), demonstrates the development and occurrence of materials through history from 10,000 BC to current days.

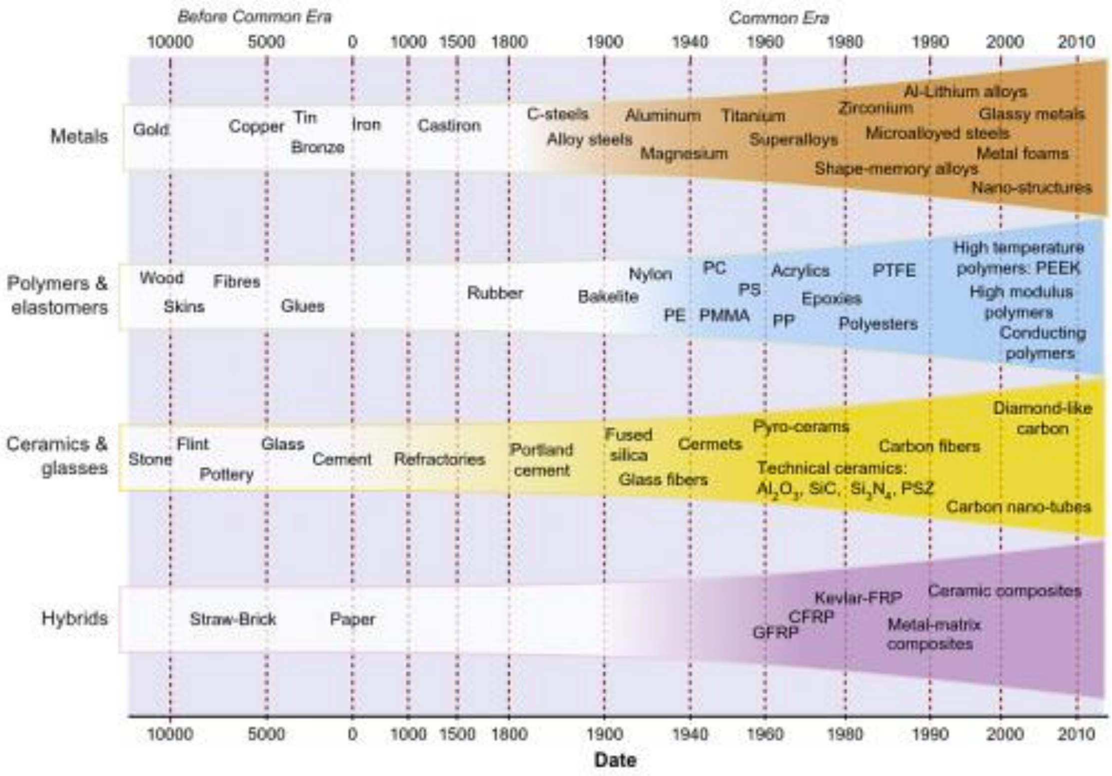


Figure 3.3
The development of materials over time according to Ashby, Shercliff and Cebon (2014, p. 3)

Recent advances in materials and in mechanics now allow the development of organic and inorganic microstructured forms to enable electronic components to compress twist and bend. In doing so new groups of materials such as stretchable electronics has emerged (Rogers, Someya, and Huang, 2010). Among the list of emerging new materials are electroactive and photoactive polymers and elastomers, bio-responsive polymers and hydrogels, chromogenic materials, polymers opal composites, shape memory polymers and alloys, phase change materials, conductive polymers, and stretchable polymers and electronics. Today designers and engineers alike face the expectation of not only familiarizing themselves with the properties of the materials they seek to use but also – due to their diverse selection of materials at hand - inform an optimal choice of materials with regard to properties, suitable for application and cost (Ashby, Shercliff and Cebon, 2014).

Hu and Mondal (2006) define smart materials as those that "can sense changes in their environments and make useful or optimal responses, by either changing their material properties, geometry, mechanical or electromagnetic properties" (p. 106). In the journal of *Smart Materials and Structures*, Hu, Meng, Li and Ibekwe (2012) describe smart materials as stimuli-responsive materials. By applying those to textiles, they explain, an array of smart textile applications are made possible. They give examples of shape memory polymers and fibres that are used for the creation of shape changing textiles, heat and moisture managements within garments, and the development of a verity of skin care products. It is worth noting however, that such definitions do not give a meaning to smart over and above that of responsive behaviour.

It is a well-known fact that some natural textile materials, such as cotton fibres for example, inherently change their properties and behaviour according to changes in their environments (Morton and Hearle, 2008). Cotton fibres expand when exposed to humidity and shrink back when dried (Mattila, 2006), they also become stronger when wet as opposed to all other fibres, which become weaker under the same conditions (Taylor, 2007). Does this, therefore, class cotton as smart? To which, in *Smart Structures and Materials* Culshaw (1996) comments: "All materials are also responsive. Whether or not they are smart materials is a different question" (p. 7). According to Culshaw (above), "No single pure material could ever be construed as 'smart', since all the single material can do is respond to external influences but without any implicit or explicit information-reduction potential" (p. 13).
In which case, what does smart mean?

3.6 What is smart? Finding inspiration for the term smart

Back in 1992, Gandhi and Thompson have defined smart materials as "structures with inherent brains" (p. 34-35) having the "capability to select and execute specific functions intelligently in response to changes in environmental stimuli" (p. 40). A few years later, Wang and Kang (1998) described smart materials as those that can sense the environment and/or their own state, and accordingly, make a judgment in order to change their functions (Wang and Kang, 1998). Similarly, Mann (1998), penned that

"Smart or intelligent materials are materials which respond to environmental changes at the most optimum conditions, and manifest their functions according to changes" (Mankodi, 2000, p. 238). But how can a material make a judgment? Can a piece of material really think for itself?

In 2001 it was demonstrated that the virtue of smartness could exist even in brain-less creatures (Nakagaki, 2001): the *Physarum polycephalum* is one of thousands of types of slime molds. These are self-sustaining single celled organisms – known as amoebas, which have no brains. This type of slime mold duplicates itself to survive by spreading its spores and reproducing as a result. As long as food is abundant, the slime mold exists in its single-celled state, but when food is scares the many individual cells congregate into one single unit – a large organism that is sensitive to airborne chemicals: This large new organism system can detect food and optimize its movement – now as a microorganism - in the most energy effective way (Jacobson, 2012). As soon as food is found, the slime molds return to their individual state of existence. The slime mold, however only made out of one individual cell, is much susceptive to changes in its environment, up to point where it has the ability to "judge and act" (Wang and Kang, 1998, p. 1) "at the most optimum conditions" (Mankodi, 2000, p. 238), and adapt its behaviour accordingly.

Lipton (2005) claims that single cells are smart, due to their sensory ability, adaptability, survival instinct and energy efficient abilities – explaining that "There is not one 'new' function in our bodies that is not already expressed in the single cell" (p. 7) and therefore "It shouldn't be surprising that cells are so smart" (p. 9). Single cells don't have brains – at least not as mammals do. But they do have a sophisticated sensory *system*, which - building on previous definitions of smart textiles – allows them to respond to several external stimuli and adapt they behaviour accordingly. It can therefore be suggested that smartness does not appear in linear forms, but rather as *systems* of many components and responsiveness abilities -all woven into the one form.

3.7 Smart structures

According to Wadhawan (2007), “A smart structure is that which has the ability to respond adaptively in a pre-designed useful and efficient manner to changes in environmental conditions, as also any changes in its own condition” (p. 1). Similarly, according to Tao’s description (2001), smart structures “can sense and react to environmental conditions or stimuli, such as those from mechanical, thermal, chemical, electrical, magnetic or other sources” (p. 2-3) – where the degree of complexity determines the level of smartness. Unlike materials however, textiles are an assembly of many materials bound together within a macro structure. Textiles are in other words – material systems. Smart material systems, according to Varadan, Jiang and Varadan (2001), are able to sense changes in the environment and then respond optimally - either by changing some of their material properties and geometry - or by changing the mechanical or electromagnetic responsivity of the system as a whole (Wadhawan, 2007).

Culshaw’s description of a smart structure refers to a structure that “monitors itself and/or its environment in order to respond to changes in its condition” (Culshaw, 1996, p. 6). This of course was not commented with textiles in mind, but such a structure, he adds, “May be self-repairing, or it may use variable stiffness element to control its response to applied mechanical loads” (p.6).

To date, weave structures have not yet been investigated as potential property changers in fabrics, and the woven interlacements of threads themselves do not yet play a role in making fabrics smart, mainly due to the fact that the properties of fabrics are dominated by the properties of the fibres and yarns that they inhabit (Thomas, 2009). Could a change in the geometry of the weave structure itself therefore ever lead to a change in the properties of a fabric? In other words, and following the title of this research: how smart can weaves structures be? This question is used a guide for the practice-led research undertaken throughout chapter 6.

3.8 Discussion: A new perspective on (genuinely) smart textiles

Culshaw (1996) claimed that: “no single pure material could ever be construed as ‘smart’, since all the single material can do is respond to external influences but without any implicit or explicit information-reduction potential” (p. 13). Therefore, he concluded in this book, “smart materials are always material systems rather than single substances” (p. 186-187). Although Culshaw (above) referred to electronic systems in his book, in textiles too, smartness could therefore be understood to be as not only about the ability of a material system to be responsive but also about the ability of a material system to optimizes its functionality, use, appearance and/or suitability to suit various applications.

The difficulty and confusion with the use of the term smart - in general and within the context of textiles in particular - is not that I want to distinguish between smart and responsive behaviour. But rather, if smart is different to mere responsivity as often suggested (Pailes-Friedman, 2016; Mattila, 2015; Stoppa and Chiolerio, 2014), then what is it? It seems sensible to describe being smart as the ability to manifest appropriate responsive behavior. But it has to be something a little bit more than simply the way a piece of material might respond to changes in moisture or temperature. The problem therefore in the somewhat careless explanation of smart textiles according to Pailes-Friedman (2016), Mattila (2015) or Stoppa and Chiolerio (2014) for example, is that smartness simply occurs on the macro scale and / or on the surface of the materials; either through the attachment of electrical circuits into garments or through the utilization of yarns with specific properties.

I believe, from the evidence, that there is little to distinguish such current ‘smart’ textiles from other responsive textiles, or from organic textiles – to stretch the argument a little further. The distinction that I wish to suggest and examine is therefore between *superficial* and *deep* responsivity - only the latter, I propose, is worthy of the term smart when applied to the material systems themselves.

Similarly, when scholars such as Gandhi and Thompson (1992) or Wang and Kang (1998) suggest that smart materials have some sort of ‘brain’, or are able to make a judgment, this should not be taken to mean that jumpers or table cloths can or should be able to think for themselves. Instead, my understanding and interpretation of the literature has led me to consider ‘intelligent’ behavior in materials as such that would manifest itself mechanically – as a sense of responsivity that is deep and inherent throughout the structure of the systems. Hence in order to be smart, the responsivity of textiles has to be deep and not superficial - and hence, the pursuit towards ‘textile anatomy’ mapping.

What I think makes sense is that the term smart textiles should refer to the very construction of the material system – i.e. the responsivity, which is inherent in the way individual textile components are put together. In other words, smart requires what I call deep – or inherent - responsivity across length scale. The responsivity of smart textiles would have to be prominent throughout the structure of the materials system – in this way no cut & paste effect, nor add-ons, nor MP3 jackets would even in principle be able to make a piece of textile that is smart. In chapters 4 and 5, the hierarchical structure for such a postulate is developed before creating, in chapter 6, evidence to support this view through woven material systems.

Chapter 4

‘Textile anatomy’ process mapping: TA mapping

According to Lakes (1993), hierarchical design principles often lead to further observations about the workings of each of the elements, which belong to the investigated system. Additionally, it can also shed more light on the geometry of the hierarchical system as a whole. As a result, he claims, understanding the hierarchical structure of a material system can guide the exploration and development of new materials - some tailored for specific and unique applications (Lakes, 1993; Sen and Buehler, 2011). This observation is further explored in this chapter with regard to constructed textiles and the creation of genuinely smart textiles.

The divergence between textile designers and textile engineers such as described in chapter 2, is deep and wide: both are different in how they conceive of textile construction and in the domains of discourse they use to describe and communicate it. Engineers employ acquired scientific vocabulary, drawn from research journals, academic publications and technical handbooks; they rely on quantifiable data to inform their decisions and they put their trust in facts in order to justify progression and future aims. Designers on the other hand, rely on more subjective views; their decisions are based on qualitative analysis drawn mostly from practical work and existing production methods found across the industry – and not solely from academia. The language that they use therefore is descriptive, colorful, imaginative and intuitive.

For the creation of new textiles the two disciplines share equal standing. In *The Design of Everyday Things*, Norman (2013) explains, “When we interact with a product we need to figure out how to work it. This means discovering what it does, how it works, and what operations are possible” (p. 10). This, he further explains, happens though the exploration of several fundamental psychological concepts - most important of which is the creation of a conceptual model of the system (Norman, 2013). In other words, it is the conceptual model that provides true understanding of the system as a whole. This notion is further explored through ‘textile anatomy’ mapping (chapter 4 and 5).

Textiles are the only material used by the entire population of the world. This allows textiles to surround us at all the time and it inherently links textiles with a sensorial experience. According to Norman (2013), an experience “is critical, for it determines how fondly people remember their interactions” (Norman, 2013, p. 10). In other words, experience is in the heart of great designs. According to Norman (2013), the solution for optimal use of materials is rooted in ‘human centered deign’ (Norman, 2013). This, he defines, is “an approach that puts human needs, capabilities, and behaviour first, then designs to accommodate those needs, capabilities, and ways of behaving” (Norman, 2013, p. 8). In other words, materials can posses a variety of properties but it is the way in which those materials are put together that truly informs an optimal characterization of new products into the market.

A Design: STEM approach is proposed throughout this research (chapter 2) with an aim to bridge over the long-standing gap between design and STEM. This hybrid research methodology led for the development of a new mapping tool, named by the researcher ‘textile anatomy’ (or TA mapping). This mapping tool outlines the structural complexity and hierarchy that govern all constructed textile systems, including the process links, which tie its various hierarchical levels into a system.

This ‘textile anatomy’ diagram [figure 5.13, p. 91] presents a clear overview of textile hierarchies – from the molecule up to the architecture of the textile - thus providing textile designers with a tool to understand the overall structure and complexity of textile systems. At the same time it also offers textile engineers a broader perspective of textile systems as a whole – beyond the particular limitations and specifications of single components. It is therefore offered here as a form of a Design: STEM mapping tool for the development of new textile systems.

'Textile anatomy' [figure 5.13, p. 91] presents four levels of structural hierarchy, building on the work presented by Chen and Hearle (2009). In 'textile anatomy' mapping however, the properties of each hierarchical order and the links between the levels help explain the properties of the textiles as a whole. In doing so, 'textile anatomy' was developed as an assistive mapping tool and as a way of helping diagnose why it is that modern textiles have failed to yet be properly smart. According to Culshaw in *Smart Structures and Materials* (1996), "the difference between the smart structure and the smart material is essentially one of scale and integration" (p. 14). Through 'textile anatomy' we are able to see more clearly what it is that so-called smart textiles are not doing and what they would need to do in order to become smart.

The 'textile anatomy' assistive mapping tool has therefore been created to:

(i) Enable and enrich a broad and deep understanding of woven textile systems for designers and engineers alike.
(ii) Bridge the gap between Design and STEM disciplines by creating a unified mapping system for both.
(iii) Investigate and understand the reasons that textiles are not yet smart.
(iv) Help indicate what could make them so.

It is different from other accounts of textiles in the way it:

(i) Divides and classifies each level of the structural hierarchy into sub groups based on the unique sub architectures of each of the levels (n=0, n=1, n=2).
(ii) Outlines not only the various hierarchical levels within the system but also the links, which tie their properties together into one homogenous materials system.
(iii) Portrays the complexity of textile inner structures – visually – which inherently connects materials properties and structure to textile behaviour.

4.1 'Textile anatomy' mapping

Fibres are largely considered as the building blocks of textiles (Eadie and Ghosh, 2011). The properties of fibres – their shape, form and behaviour under different conditions – determine their suitability for various textile applications. The structural, mechanical and physical properties of fibres are extensively reviewed throughout the literature (Eichhorn, Hearle, Jaffe and Kikutani, 2009; Scott and Gilead, 1995; Brody, 1994; Hearle, 1982; Walton and Blackwell, 1973; Hearle and Peters, 1963; Nielsen, 1962; Meredith, 1956) and these have been summarized in Appendix A. The properties of fibres are directly linked to the properties of the macromolecules from which fibres are formed (Bartels, 2011; Eichhorn, Hearle, Jaffe and Kikutani, 2009; Hearle and Peters, 1963) (also in Appendix A), however only one relatively recent account of the literature describes these macromolecules, rather than fibres, as the base units and building blocks of textiles (Chen and Hearle, 2009). Accordingly, 'textile anatomy' mapping follows the four predominant hierarchical levels: polymers and macromolecules (marked in red), fibres and filaments (marked in blue), and yarns (marked in purple), presented in this chapter , and fabric architecture (marked in green) – presented in chapter 5.

4.2 Macromolecules and inorganic elements (*n*=0)

Polymers – with their own internal structural hierarchy – are directly linked and informed by the characteristics of their base units, the monomers, as well as by the chemical or physical bonds that tie them together into chains (Hearle, 1982). A detailed account of the mechanical properties of polymers has been given by Alfrey and Gurnee (1967), Hearle (1982), Nielsen (1963), and Young (1981) – among others – with account regarding the physical properties of polymers given by Wolf (1985) and Shirtcliffe, McHale and Newton (2011). Their work was used as part of this research to gain in depth knowledge into the mechanical operations of polymers under specific conditions.

The properties of any macromolecule - and of polymers in particular – depend on their chemical structure and molecular weight (Hearle and Peters, 1963). In other words, it is the structural hierarchy of the polymer itself that determine the properties of the polymer (Meijer and Govaert, 2005). The behaviour of polymers under various conditions is described by their mechanical properties, which explain their behaviour and deformation by applied forces (Nielsen, 1963): such as the measurements of tensile strength, compressive strength, tensile modulus, Poisson's ratio (Nishino, Matsui and Nakamae, 1999; Nielsen, 1963), and the relationship between stress and strain. The mechanical properties of polymers therefore are important when they are intended for use as structural materials, since their use as plastics will be determined by their ability to deform and fuse into shape.

Macromolecules are distributed for the textile industry in powders, granules, pellets, solution or melt based liquids. For the synthetic creation of fibrous materials, the thermal properties of polymers – indicated by the melting temperature (*Tm*) and the glass transition temperature (*Tg*) (Billmeyer, 1984) – are crucial: they are used to inform the production requirements as well as care instructions for fabric applications post-production. Both the *Tg* and the *Tm* are relevant in the main to the synthesis, production and characterization of manmade filaments. Most biopolymers – with the exception of keratin, which demonstrates great fire retardancy properties (Matko, Toldy, Keszei, Anna, Bertalan and Marosi, 2005) - are not tolerant to the same high temperatures that synthetic polymers are able to endure, and this renders them unsuitable for some processes and applications.

In general, the literature at large describes polymers as materials in their own right - without specification or differentiation between probable applications - 'textile anatomy' mapping only includes polymers that can be used for the creation of fibres and filaments, which can later be implemented for the construction of textiles: not only because the definition of textiles is that of "hierarchically structured *fibrous* materials" (Lomov *et al.,* 2001, p. 534) but also because the production methodologies of fibres and filaments are inherently different from those used for the creation of other substrates, such as textile coatings, laminates and thin films.

'Textile anatomy' therefore describes four sub-groups of macromolecules potentially used for the creation of fibres and filaments: (1) biopolymers, (2) synthetic polymers, (3) responsive polymer systems, and an additional group titled (4) inorganic and metal elements. The sub-classification is based on the distinctiveness of each sub-group within the inner architecture of the macromolecules – their polymeric origin - and their unique properties as a result.

(1) Natural polymers, or biopolymers, are derived from living organisms – derived from plants or from animals. Each is comprised of different monomer units and those monomers form into polymeric chains with unique characteristics (Scott and Gilead, 1995; Walton and Blackwell, 1973). Biopolymers form the backbone of fibres through processes of natural growth, and it is interesting to see the great extent to which their geographic origins affect their properties (Hearle, 1982; Young, 1981). Plants, for example, are subject to variations in weather conditions and pesticide treatments, which are rarely regulated on a global scale: this is why cotton plants from across the globe generate different types of cotton fibre – with different properties. Similarly, dieting regulations and nutrition qualities directly affect the animals whose hair we shave to obtain fleece. And therefore the properties of the wool of sheep from Scotland for example, varies dramatically from that of those of New Zealand's sheep.

Unlike biopolymers, natural-regenerated polymers - however derived from natural sources - do not go through process of natural growth but rather, are formed into fibres through manmade mechanical and chemical processes. Different synthesis processes transform biopolymers into manmade natural-regenerated polymers. This affects their properties and commerciality greatly (Cook, 1984). Figure 4.1 outlines the types of natural polymers – both of biopolymers and natural regenerated polymers - used in the creation of fibres.

Natural – plant	Natural - animal	Natural – regenerated
Cellulose I	Chitin	Cellulose II
	Chitosan	PLA (poly-lactic acid)
	Keratin	PLLA (poly-L-lactic acid)
	Fibrin	PGA (poly-glycolic acid)
	Collagen	PLGA (poly-lactic-co-glycolic acid)
	Gelatine	PCL (poly-capro-lactone)
	Alginate	Soy protein
		Casein Micolles (milk protein)

Figure 4.1
Biopolymers and natural regenerated polymers commonly used for textile fibre production
Lynn Tandler (2015)

(2) Synthetic polymers are everything but natural. They are derived from oil: their internal chemical structural and molecular arrangements are crucial in determining the mechanical, thermal, physical and chemical properties of the polymer. An example for the subtleties that the synthesis processes of synthetic polymers can have is found between Nylon 6 (PA6) and Nylon 6.6 (PA6.6). These Nylon polymers differ from one another only in the arrangement of one single atom in their amide groups. This however, according to Cook (1984), results in distinctive variation in their average molecular weight - creating great differences in the mechanical properties of the fibre that they each produce, which in turn effect the end-use of a textile. Figure 4.2 outlines some of the various synthetic polymers commercially used across the textile industry for the production of synthetic fibres and filaments.

PEN (polyethylene naphthalate)	PVDC (polyvinylidene chloride)
PET (polyethylene terephthalate)	PVDF (polyvinylidene fluoride)
PTT (poly trimethylene terephthalate)	PVF (polyvinyl fluoride)
PBT (polybutylene terephthalate)	PVAL (polyvinyl alcohol)
PA (Polyamide)	PTFE (polytetra flouroethylene)
HDPE (polyethylene high density)	PC (Polycarbonate)
LDPE (polyethylene low density)	PS (polystyrene)
HMPE (high modulus polyethylene)	PES (polyethersulfone)
PU (Polyurethane)	PPTA (p-phenylene terephthalamide)
PP (Polypropylene)	MPIA (poly-metaphylene isophthalamide)
PAN (poly acrylonitrile)	LCP (liquid crystal polymer)
PVC (polyvinyl chloride)	TLCP (thermotropic liquid crystal polymer)

Figure 4.2
Synthetic polymers commonly used for textile fibre and filament production
Lynn Tandler (2015)

(3) The third group of polymers in 'textile anatomy' mapping depicts polymers that demonstrate dramatic chemical or physical changes within their architecture when exposed to certain environmental stimuli, such as temperature, moisture, light, pH and/or electricity (Hu and Lu, 2014). Often such polymers are referred to as responsive polymers, but on close inspection into the properties of other 'non-responsive', so-called regular polymers, it became clear that all polymers are responsive to some extent – in particular biopolymers, which naturally respond to change in their environment. Within 'textile anatomy' mapping, therefore, the group of polymers showing dramatic changes in their architecture according to exposure to various external stimuli will be named 'responsive polymer systems' – due to their more complex internal structural hierarchy. Shape memory polymers (Hu, Zhu, Huang and Lu, 2012; Hu and Chen, 2010; Hu, 2007), phase change polymers (Hu, Meng, Li and Ibekwe, 2012; Mondal, 2008 and triple shape polymers (Behl and Lendlein, 2010) are most widely discussed.

Figure 4.3 outlines the names of responsive polymer systems used for the creation of fibres, followed by figure 4.4, which depicts the environmental stimuli to which responsive polymer systems are susceptive, as well as the reactions caused respectively.

TPI (trans-polyisoprene)
poly(styrene-co-butadiene)
Polynorbornene
shape memory polyurethane: SMPU56-90, SMPU56-120, SMPU66-90, SMPU66-120

Figure 4.3
Responsive polymer systems commonly used for the production of textile filaments
Lynn Tandler (2015)

Environmental stimuli	Response within the material
pH change	Colour change
Temperature change	Colour change Volume change (swelling or shrinking) Surface change: i.e. hydrophobic to hydrophilic switching
Light	Volume change Shape change
Applied pressure (mechanical stress)	Colour change Capacitance change
Applied stretch (mechanical strain)	Colour change Texture change Capacitance change

Figure 4.4
The environmental stimuli to which responsive polymer systems are susceptive according to Morehead, Oliver, O'Connor, Stevenson-Keating, Toomey, and Wallace (2016, p. 3)

(4) Metal elements and inorganic macromolecules - such as ceramics and glass - play a significant role in the textile industry. Inorganic elements that are used for the making for textiles fibres include mainly ceramics and glass. The specific polymers and macromolecules included in each sub-group are outlined in figure 4.5.

Silica PMMA (poly-methyl methacrylate) PEEK (poly-ether-ether-ketone)	Copper Silver Gold Aluminium Carbon Titanium Steel

Figure 4.5
Inorganic polymers commonly used for the production of textile filaments (left) and metal elements commonly used for the production of wires for textile applications (right)
Lynn Tandler (2015)

Groups 1, 2, and 3 of hierarchical order (n = 0) of 'textile anatomy' mapping are all thermoplastic polymers (Young, 1981). They can be manipulated into various forms and shapes through processes of extrusion, postdie processing, forming and injection molding (Baird and Collias, 1995). The process however that is ascribed to fibre formation is fibre spinning – and this process is based on polymer extrusion, which will shortly be outlined.

The originality of this new perspective nonetheless is that it builds on the properties of the materials and portrays the properties of polymers, fibres, and filaments and yarns as the building block of a potentially smart textile system – one whose behaviour is governed by physical, chemical and mechanical laws. The properties identify as well as inform what a potentially smart textile system would be able to do and which materials could be paired up in order to enhance its behaviour and extend its functionality.

4.3 From polymers to fibres: the technologies that govern the making of fibres

Biopolymers go through processes of natural growth to make fibres. These depend on the plant or animal According to the unique properties of some polymers, various fibre-spinning techniques have been developed for the creation of fibres and continuous filaments – predominantly falling into four methods, naming: dry spinning, wet spinning, melt spinning and electro-spinning. The mechanical and thermal properties of polymers inform a suitable fibre spinning process. Those - as well as the molecular weight of the polymer - play key role in determining the formation and subsequent properties of the fibres (Bartels, 2011; Eichhorn, Hearle, Jaffe and Kikutani, 2009; Hearle and Peters, 1963). The properties of individual fibres are widely discussed across the literature (Majid, 2012; Thomason ans Carruthers, 2012; Senthilram, Mary, Venupogal, Nagarajan, Ramakrishna and Dev, 2011; Lewin, 2006; Gruszka, Lewandowski, Benko and Perzyna, 2005; Rwei, Lin and Su, 2005; Stamoulis, Baillie and Peijs, 2001; Pan et al., 1997; Greaves and Saville, 1995) - together giving an detailed overview to the way fibres behave under certain conditions.

Fibre spinning, according to Robinson (1980), is the process of extrusion of polymer solution through fine spinnerets to produce long continuous filaments (Morton and Hearle, 2008). The molten polymers are pressed through fine holes under pressure to form long continuous filaments – which can be chopped into shorter length as manmade staple fibres (Kadolph and Langford, 2002). The properties of polymers used remain prominent in the newly formed filaments however, the molecular structure of the new filaments is realigned. The methods of fibre spinning are briefly outlined below:

(a) Dry spinning: after extrusion of molten polymers through fine spinnerets, the filaments are set into their fibrous form during a cooling process, where excess solution liquid is extracted through air jets only to leave a formed solid filament.

(b) Wet spinning: after extrusion of molten polymers through fine spinnerets, the newly formed filaments are passed through a solution bath during the fibre formation in order to rid itself from excess solution liquid and complete the molecular alignment.

(c) Melt spinning refers to the process by which polymers are heated to reach their melting temperature (*Tm*) and then are forcibly extruded though micro scale spinnerets (Hearle and Peters, 1963) to form continuous filaments. This method is solely applied onto synthetic polymers for the creation of synthetic fibres and filaments.

(d) Electro-spinning: applied to generate nano-fibrous scaffolds, where an electrical charge is applied onto the spinnerets in order to draw out very fine fibres from a melt liquid.

Not only polymers but also the various metal elements from which wires are drawn have great effects on the properties of the fibres and henceforth on the properties of the cloth that they in turn, make. My previous experience in weaving with metals – also showcased in the upcoming publication of *Designing with Smart Textiles* (Kettley, 2016) – revealed, though a series of experimental work, that the properties of metals play a key role in their successful adaptation to different fabrication processes. Copper wires and copper based alloys, for example, (with diameters of 0.1mm and 0.2 mm) – due to their softness and relative fine diameters – could withstand the stress and strains inflicted by the weaving process with relative ease.

Stainless steel wires of similar thickness on the other hand, are stiff, hard and brittle and therefore proved difficult to weave. Brass – which is essentially a mixture of copper and zinc – was similar to stainless steel, however slightly softer due to the presence copper, which made it tolerable for hand weaving but still unsuitable within industrial production techniques [image 4.1].

Image 4.1
The effects of metal wire properties of the drape of woven textiles
0.1mm copper / polyester blend (top left), 0.1mm tinned copper / polyester blend (top right)
0.2mm bronze / polyester (bottom left), 0.2mm tinned copper / polyester (bottom right)
Lynn Tandler (2010)

Throughout all fibre-spinning processes, the spinneret – from which molten polymers are extruded – plays a key role in determining fibre properties: the shape of the spinneret determines the cross-sectional shape of the filament or the fibre (Rusu, Morseburg, Gregersen, Yamakawa and Liukkonen, 2011). Various shapes can be produced – as shown in the diagram of figure 4.6 - and in doing so the physical properties of the fibres are consequently enhanced, which goes to show how fundamental and important is the inherent link between polymers properties and fibre properties. Moreover, although often filaments are spun from single component polymers, sometimes more than one polymer or substance is used for the creation of new filaments or fibres. Bi-component filament and tri-component filaments may be produced to tailor specific applications. The properties of such filaments depend on the properties of the polymers used for extrusion. Additionally, the ways in which the two or three components are bound to form the filament affect the characteristics and applications of the filaments.

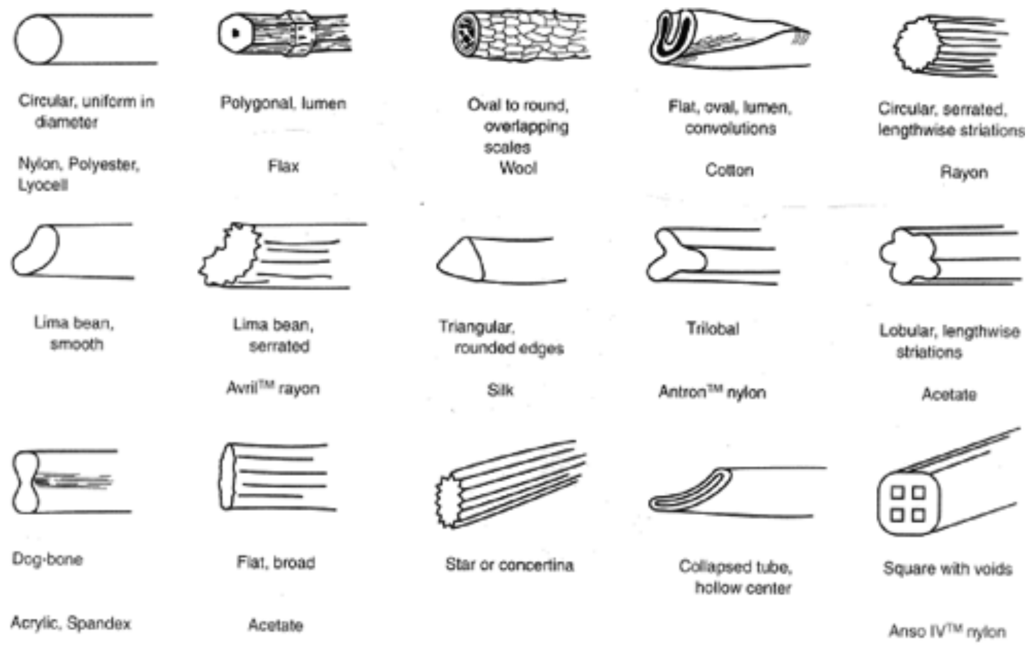


Figure 4.6
Various fibre cross sectional shape according to Lawrence (2010, p. 159)

Three main methods of forming bi-components and tri-component filaments are commonly found across the textile industry. These are termed: (1) side-by-side, (2) sheath-core, (3) island-in-the-sea, and (4) segmented / conjugate / pie – as illustrated in figures 4.7 – 4.10. Like other manmade fibres, these too can be cut into specific lengths towards the end of the process to form short staple bi-constituent and tri-constituent staple fibres.

The link between polymer properties and the way in which they are processed or spun into fibres is central to their classification throughout 'textile anatomy' mapping. Consequently, fibres and filaments (n=1) are classified in TA mapping according to their physical properties - referencing the macromolecules from which they were spun, the production methodologies used in the process, and the various processes they undergo in order to turn into yarns (n=2). In particular, the lengths of the fibres are used as an indication to their structural and mechanical properties. Fibres and filaments (n=1) are therefore classified into four predominant groups: naming (1) short staple fibres, (2) long staple fibres (3) single component continuance filaments, and (4) multi-component continuance filaments.

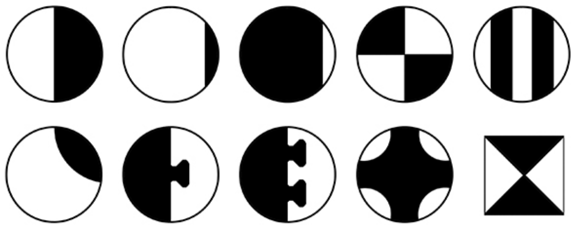


Figure 4.7
Cross sectional shape of side-by-side bicomponent fibres
Illustrated by Lynn Tandler (2015) based on Hedge, Dahiya and Kamath (2004)

Figure 4.8
Cross sectional shape of core-sheath bicomponent fibres
Illustrated by Lynn Tandler(2015) based on Hedge, Dahiya and Kamath (2004)

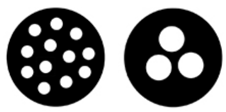


Figure 4.9
Cross sectional shape of island-in-the-sea bicomponent fibres
Illustrated by Lynn Tandler (2015) based on Hedge, Dahiya and Kamath (2004)

Figure 4.10
Cross sectional shape of segmented / conjugate / pie bicomponent fibres
Illustrated by Lynn Tandler (2015) based on Hedge, Dahiya and Kamath (2004)

4.4 Fibre and filaments and filaments (*n*=1)

Not all existing fibres and filament are mentioned in TA mapping: commercial names given by the textile industry to various fibres make the task of tracking every single fibre into a time consuming and difficult one. Instead though, a representative list of fibres and filaments has been gathered and characterized from the reports of Brody (1994), Cook (1984), Eichhorn, Hearle, Jaffe and Kikutani (2009), Morton and Hearle

(2008), and Taylor (2007). Instead of outlining those in a list, selected fibres and filaments were added on and inserted into 'textile anatomy' mapping – alongside the polymers from which they are made and the process that these had undergone.

The $n = 0$ and $n = 1$ of 'textile anatomy' mapping are therefore present in figure 4.11.

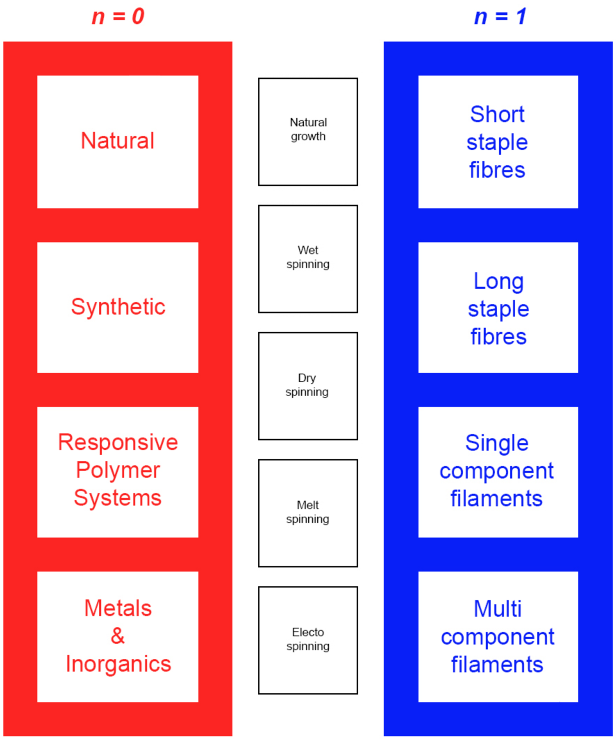


Figure 4.11
TA mapping: macromolecules and polymers (red) and fibre and filaments (blue)
Lynn Tandler (2014)

4.5 Yarns (*n*=2)

In order to from fabrics, fibres are often spun into yarns. Just as fibres are affected by the properties of the polymers and their spinning process (Briggs-Goode and Townsend, 2011) - the properties of yarns are determined by their fibre and filament content, their respective properties and the yarn spinning process applied (Alagirusamy and Das, 2010): fibre type, fibre properties and fibre migration, as well as the applied yarn spinning process, all affect the properties of yarns (Lawrence, 2010). Yarns, therefore, are the sum of many variables that together help determining the properties of fabrics - and this is because they are in themselves encapsulating complex structural hierarchy of macromolecules, fibres and / or filaments arrangements. At this point, therefore, the structural hierarchy of yarns is already considered complex. Due to that, their constituents and their individualist set of properties - i.e. fibres or filaments - play a center role in determining the properties of the yarns. [More detail on the yarns' structure and properties is shown in Appendix A].

In 'textile anatomy' mapping therefore, yarns have been divided twice into two main classification groups, according to their structure and physical properties. These are summarised as first and second divisions.

4.5.1 'Textile anatomy' mapping of yarns: first division

In the first division, yarns have been grouped according to their contents, identifying: (1) multi-component yarns and (2) single-component yarns. This classification links the architecture of yarns firstly to the macromolecule level ($n = 0$) and the first level of fibres within the structural hierarchy ($n = 1$) – both of which are crucial components in determining the physical and mechanical properties of yarns.

4.5.2 'Textile anatomy' mapping of yarns: second division

The second division sees yarns being classified into five sub-groups according to the production methodologies and yarn spinning techniques used to construct the yarns. These too, reflect heavily on the mechanical and physical properties of the end product yarns. They are: (1) non-spun yarns, (2) spun yarns, (3) compound yarns, (4) textured yarns, and (5) fancy yarns. Each is briefly described overleaf.

(1) Spun yarns group fibres or continuous filaments into a twist and bind them into a single continuous form. Even though both spun yarns and spun continuous filament yarns are produced often through very different types of machines, their architecture is similar: a single twist along the axis hold the fibres or the filaments in place.

But issues with regard to spun yarn engineering have arisen in the literature. In the field of textile engineering, spun yarns are all considered to be comprised of continuously unified filaments: ones with regular – often round - cross-sectional shape and a constant linear density along their lengths (Dastoor, Ghosh, Batra and Hersh, 1994; Freeston, Platt and Schoppee, 1967; Olofsson 1964; Peirce 1937). The problem however with such an assumption is that factors such as fibre migration and fibres alignment are not taken into account, and as a result, the predictions made regarding the performance of such yarns are often misleading or easily proven wrong. Meredith and Hearle (1959) and Komori (2001) have all developed yarn analysis modeling tools with awareness to the issue above. However only Ozgen and Gong (2010) suggested a model, towards a more realistic rather then idealistic representation of yarns, with variable cross-sectional shapes based on fibre type, yarn count, yarn twist and cover factor (Vassiliadis, Kallivretaki, Provatidis and Domvoglou, 2011).

Image 4.2
Spun silk yarn
Dino-Lite microscopy
Lynn Tandler (2014)

(2) Compound yarns - also known as core-spun yarns (Chen, 2011) or wrap-spun yarns - are those which have a central core of either a group of staple fibres, a single or a multifilament core: the core is wrapped with a layer or sheath of fibres or filaments (Gong, 2011). Compound yarns can be either single component yarns or multicomponent yarns – meaning that all the fibrous constituents are from the same or from a different source, respectively.

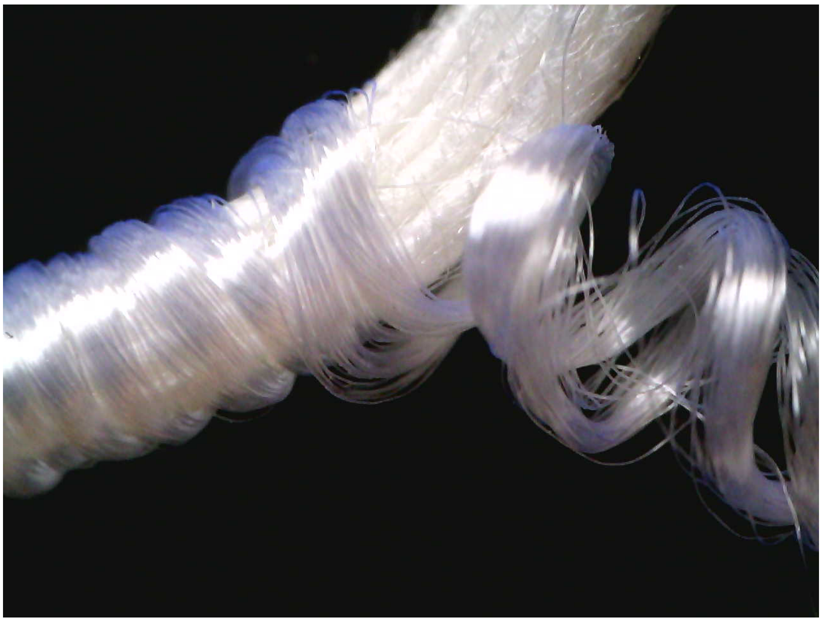


Image 4.3
Compound yarn
Dino-Lite miscroscopy
Lynn Tandler (2014)

(3) Textured yarns and Fancy yarns are included in the same group of TA mapping. These are yarns have been deliberately introduced with irregularities or intermittent effects along their length, in order to create an interesting visual effect or texture (Wright, 2011). These yarns undergo various spinning processes – some with an addition process of heat setting either by liquid or by air - in order to improve their structural and mechanical properties. This process is usually carried out by the insertion of loops and snarls (Taylor, 2007; Collier, 1980): snarl, loop, chenille and boucle are amongst the most popular yarns in use – mainly across the fashion textile industry.

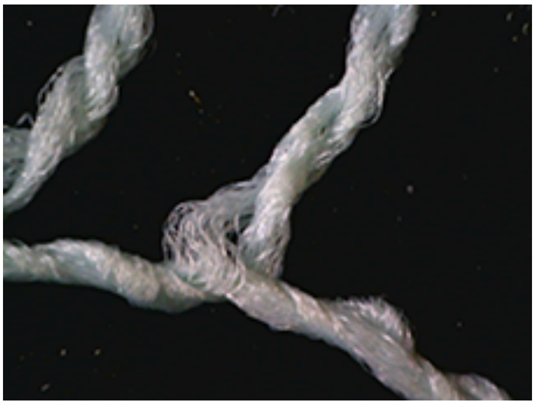


Image 4.4
Snarl yarn
Dino-Lite microscopy


Image 4.5
Loop yarn
Dino-Lite microscopy


Image 4.6
Chenille yarn
Dino-Lite microscopy


Image 4.7
Boucle yarn
Dino-Lite microscopy

Lynn Tandler (2014)

(4) Unlike any of the former yarn examples, yarns that do not undergo any process of spinning are called non-spun yarns [Image 4.8]. This group of yarns embodies single, often synthetic, continuous monofilaments, tapes or strips from extruded films. In a way, non-spun yarns are the results of fibre-spinning processes rather than of yarn spinning process, and hence, sometimes create confusion among practitioners - when a single component monofilament is described as a yarn.

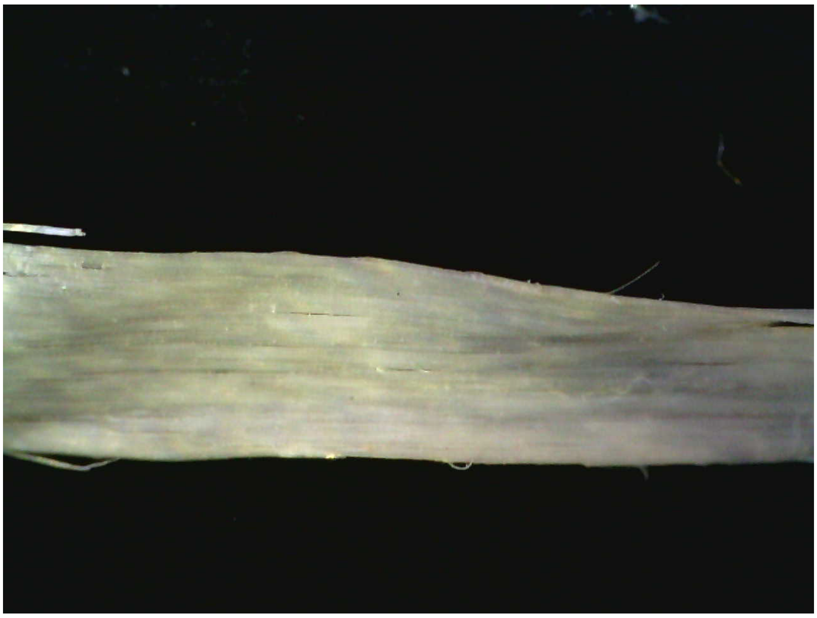


Image 4.8
Non-spun yarn (paper)
Dino-Lite miscroscopy
Lynn Tandler (2014)

As a result of this investigation ‘textile anatomy’ is proposed overleaf in figure 4.12, as a tool to better understand the inherent structural complexity of textile components. Through TA mapping, individual fibres and yarns can be traced back to their molecular origin and the processes applied for their making can be revealed too. The structural hierarchy of individual textile components can inform designers and engineers alike towards the potential performance of the textiles that they are intended for constructing. This way, individual textile components can be fitted into TA mapping and within one illustration reveal their history of making and inherent structural complexity.

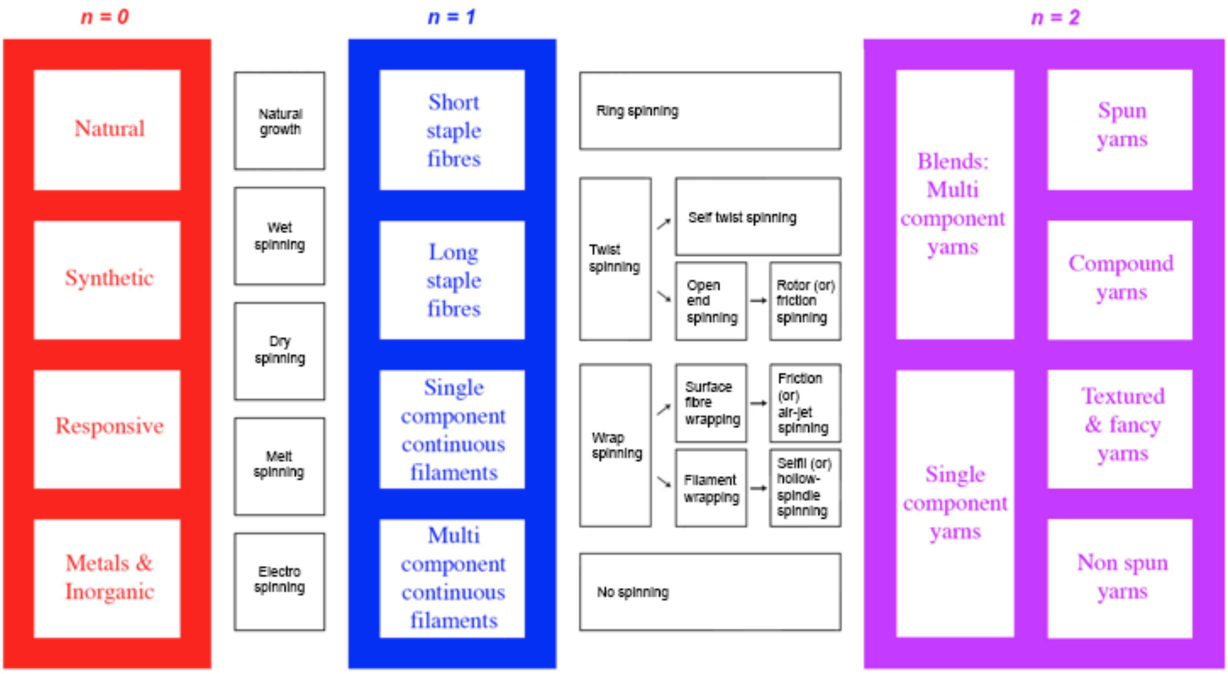


Figure 4.12
TA mapping: macromolecules and polymers (red), fibre and filaments (blue) and yarns (purple)
Lynn Tandler (2014)

4.6 TA mapping as an assistive tool for the creation of new textile systems

As an example of the benefits that the TA mapping tool can bring to the understanding of yarn origin and properties, four fine white yarns are presented below. All four yarns were deliberately chosen due to their similar aesthetics – meaning that they are all white and spun out of fibres. Each of the yarns has been observed through a USB Dino-Lite microscope and a tailor made TA mapping were attached to suit. The results are outlined through images 4.8 – 4.11 and figures 4.13 – 4.16 (p. 60 - 63).

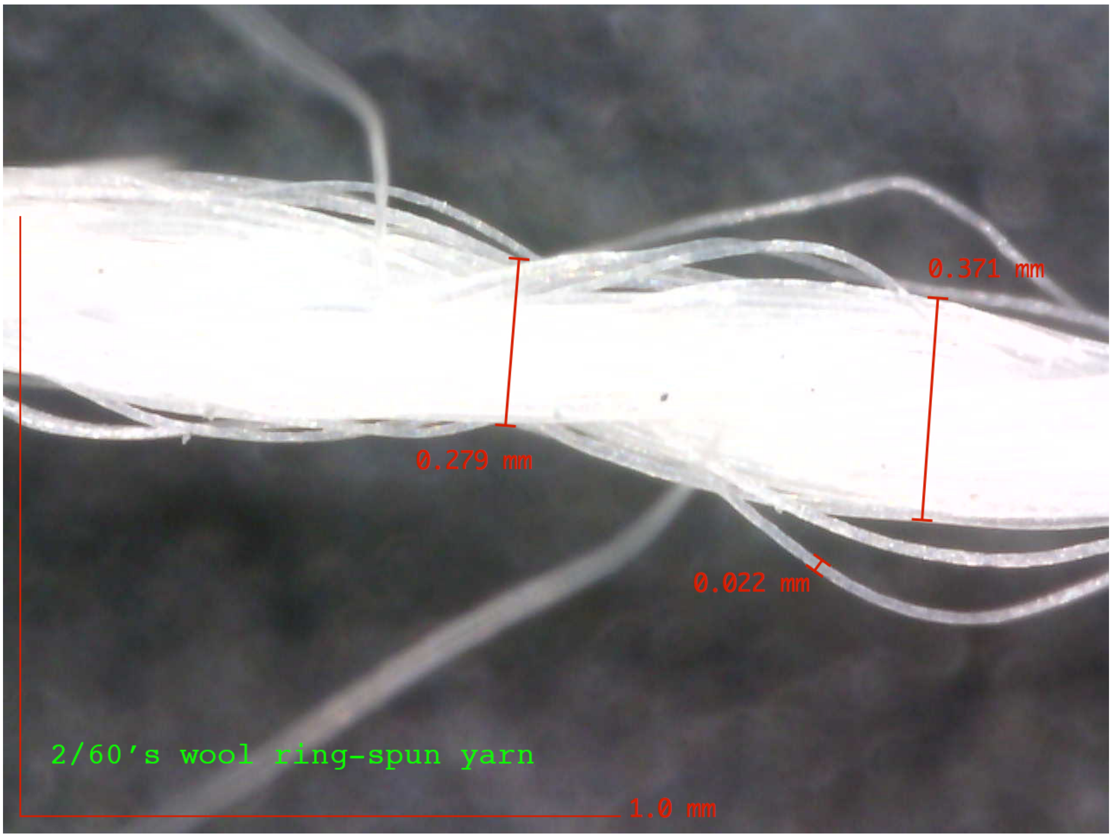


Image 4.9
2/60's wool ring spun yarn
DinoLite microscopy

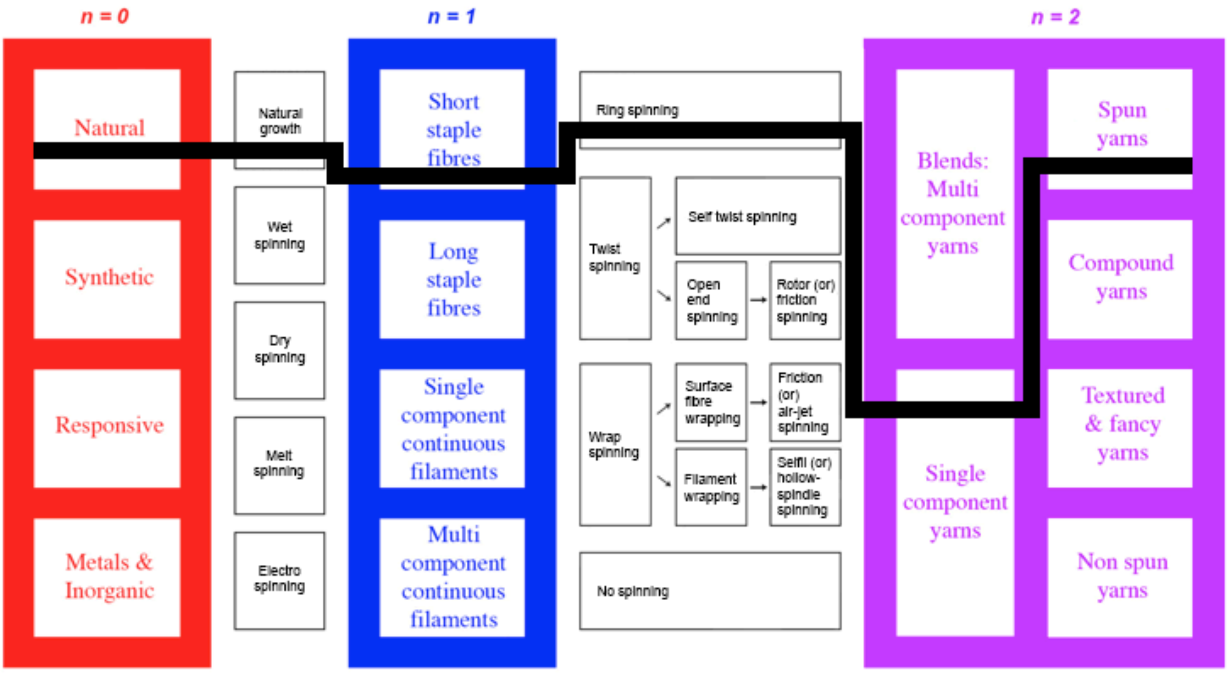


Figure 4.13
Description of the yarn through TA mapping
Lynn Tandler 2015)

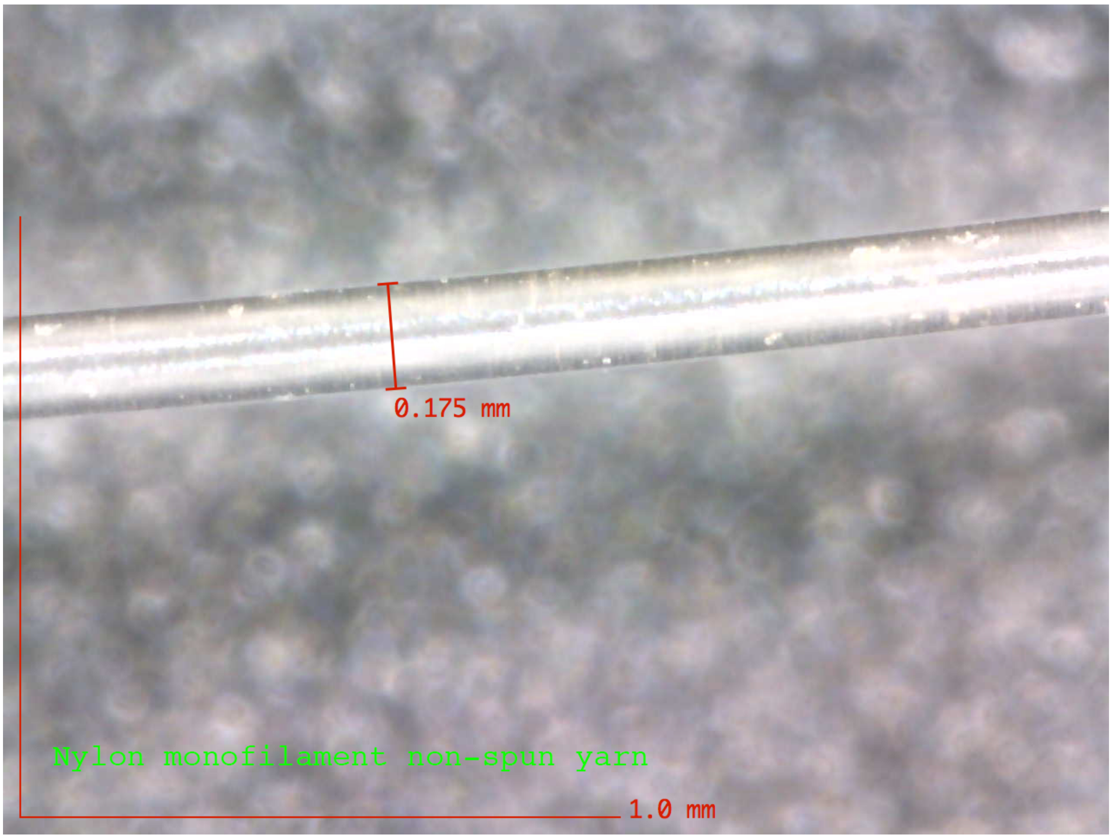


Image 4.10
Nylon monofilament non-spun yarn
DinoLite microscopy

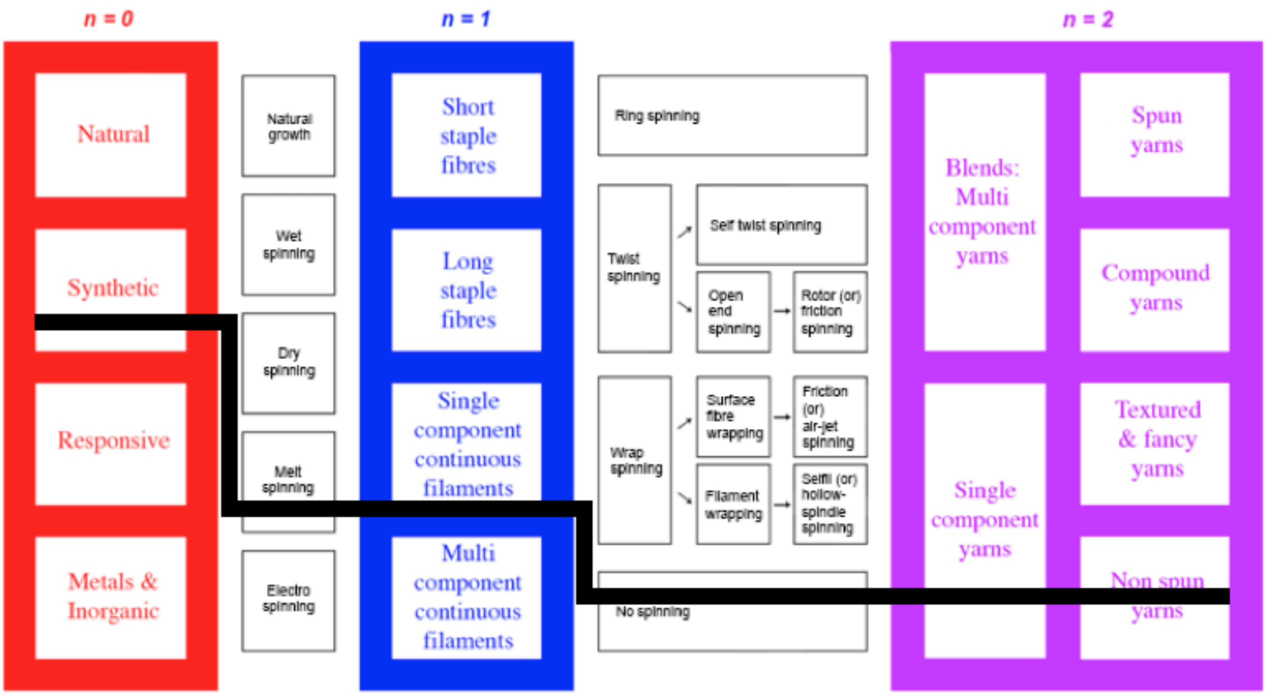


Figure 4.14
Description of the yarn through TA mapping
Lynn Tandler 2015)

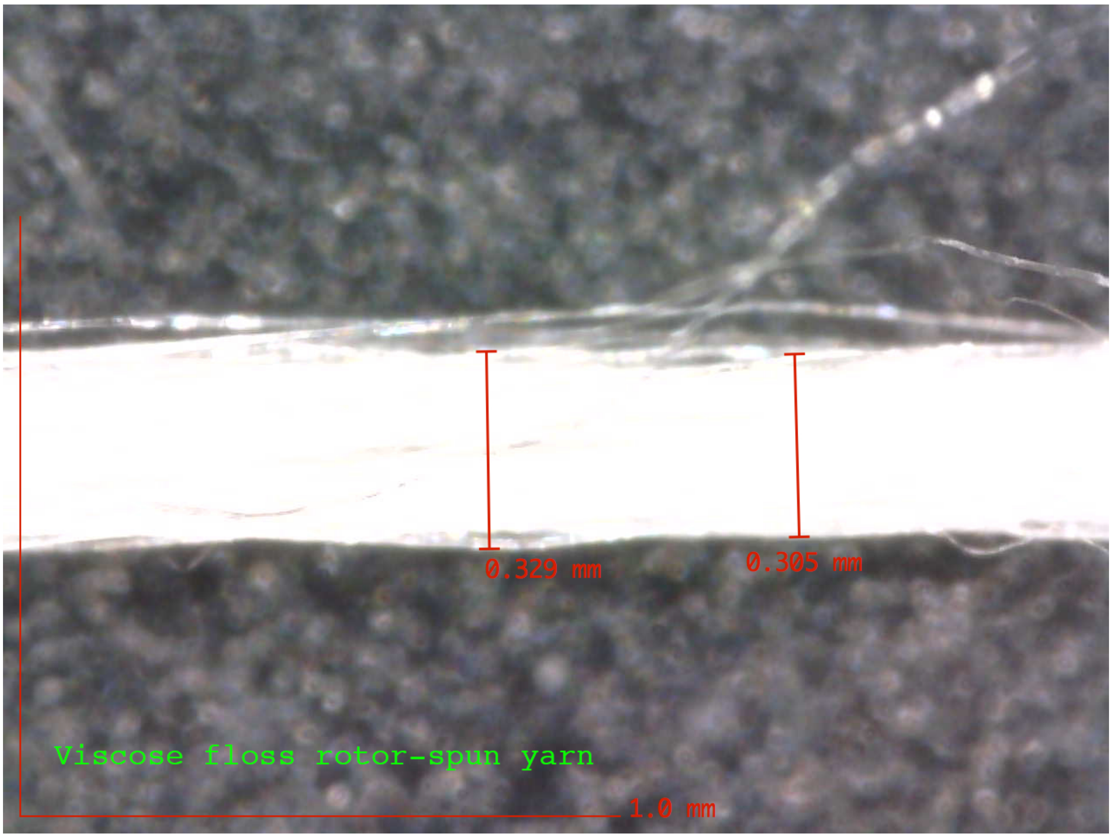


Image 4.11
Viscose floss rotor-spun yarn
DinoLite microscopy

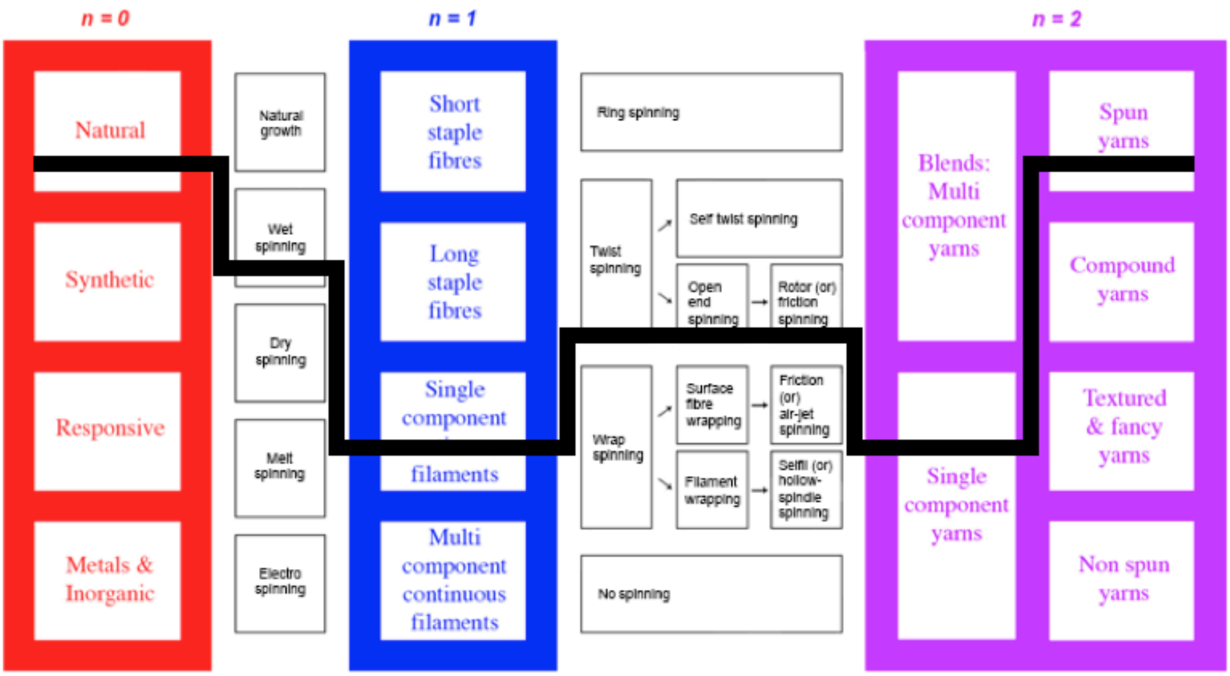


Figure 4.15
Description of the yarn through TA mapping
Lynn Tandler 2015)

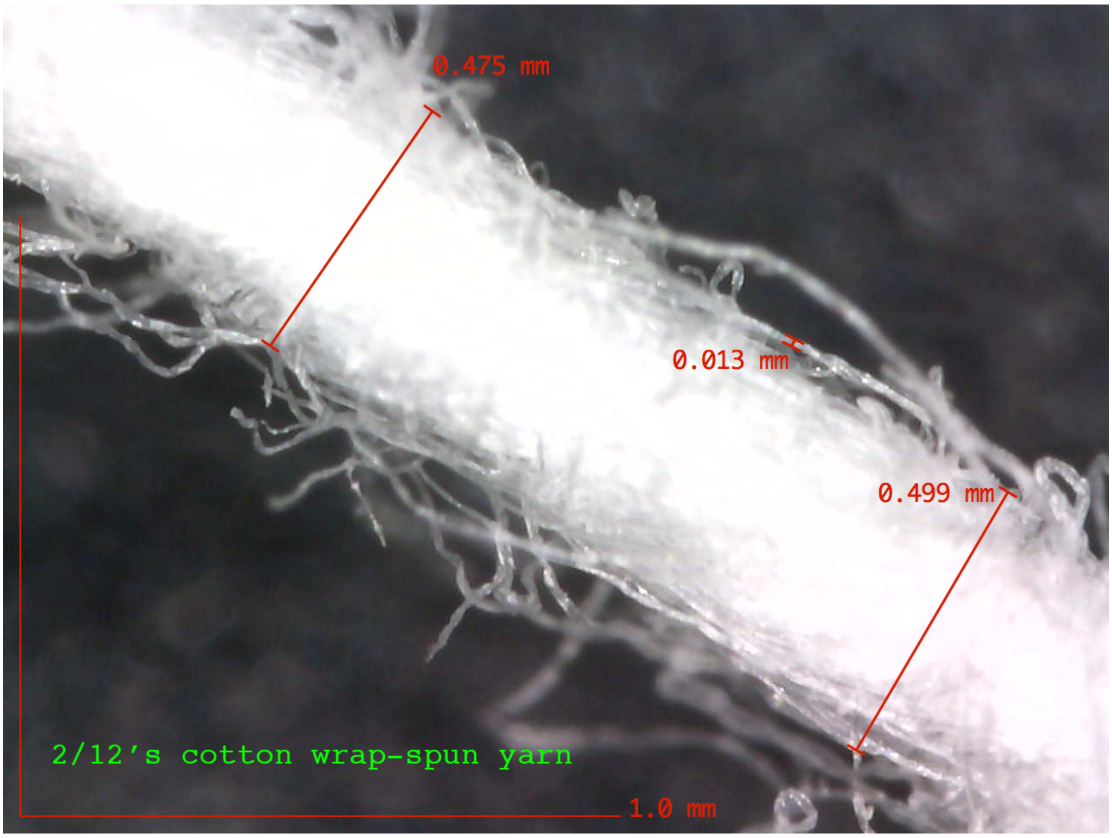


Image 4.12
2/12's cotton wrap-spun yarn
DinoLite microscopy

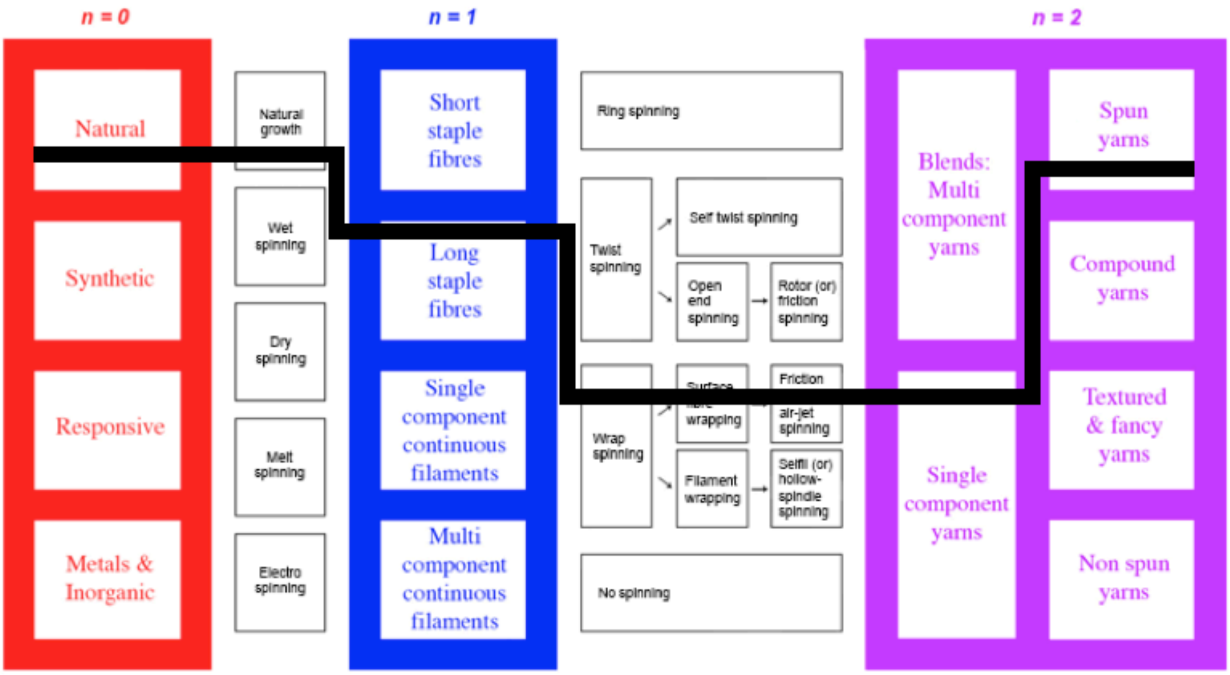


Figure 4.16
Description of the yarn through TA mapping
Lynn Tandler 2015)

4.7 Summary

'Textile anatomy' mapping is a diagram meant to illustrate in a straight forward way the structural complexity that governs all constructed textile systems, by encompassing within itself the properties of polymers (n=0), fibres and/or filaments (n=1) and yarns (n=2), as well as the process mapping to how these elements link together to form one piece of textile. TA mapping identifies the areas where responsive behaviour may occur in textile systems as well as the areas that are most commonly exploited in the pursuit to enhance textile performance. Currently, these are achieved through the synthesis of polymers, the creation of fibres and the development of yarn spinning technologies. The next chapter will discuss the role of yarn assembly methodologies - such as weaving, knitting and lace making - for the creation of textiles. These will be investigated as potential agents for aiding the creation of genuinely smart textiles.

Chapter 5

The anatomy of constructed textile structures

According to Vincent (2008), fabrics are considered to be an assembled structure rather than a material. This emphasizes the point that textiles are in fact material systems and not just materials. Indeed, it may be concluded from practical evidence that what makes textiles different from other materials is the structural and mechanical relationships that are created from the assembly of the many individual components.

Emery (1994) presents a distinction in the classification of fabric structures between "those composed of felted fibres, and those composed of interworked elements" (p. 17). By which she means to distinguish between constructed fabrics - such as weave or knit, which dominate industrial textile production – and non-constructed fabrics such as those bonded or felted. Similarly, Vassiliadis, Kallivretaki, Provatidis and Domvoglou (2011) classify fabrics according to their "manufacture process as knitted, woven and non-woven" (p. 42).

According to Kapsali, Toomey, Oliver and Tandler (2013), in the design process of synthetic materials designers and engineers rely on the properties of materials to create the product – or the system. In other words, both designers and engineers rely on individual properties of some materials to be implemented into a different context and enhance the behaviour of the product or the system accordingly. This, it's claimed, leads us to "operate in a space where the needs of the *system* inform the selection of *material*" (p. 378). Biomimicry is a research field that seeks to find deep and insightful inspirations in the natural world to inform new designs. Nature relies on the way in which molecules come together with inherent varying structures to form new systems with minimum energy. Such variations in the assembly of individual polymeric units are responsible, through natural occurrences, for a vast range of properties. In other words, in such instances "*materials* are used to form the *system*" (Kapsali, Toomey, Oliver and Tandler, 2013, p. 378).

This strongly implies that not only the properties of single components are important in determining the characteristics of material systems, but also the way in which those components are put together - i.e. the overall structure that holds them in place - is equally as important. In other words, the assembly methods that are used for constructing textile systems affect the properties and behaviour of textiles. This is also important in allowing a material system the potential of becoming smart.

The first part of 'textile anatomy' mapping – presented in chapter 4 – demonstrates how textiles are material systems built on the principles of structural hierarchy: the properties of macromolecules inform the formation of fibres, and various processes are used to transform those into yarns. The second part of 'textile anatomy' – which is examined in this chapter – discusses the various ways in which fibres and yarns can come together to form a piece of textile: the processes, methodologies and machines applied are reviewed. Below, the various structures that can be used to bring yarns together into cloths are described – through knitting, lace making and weaving methodologies - and the strong link between existing construction methodologies and the machines by which they are formed is also discussed.

5.1 Fabric architecture (*n*=3) in representation throughout TA mapping

Two new columns are added to 'textile anatomy' mapping describing the process methods and the textiles that they produce, marked in white and green respectively (Figure 5.1, p. 68). The white column is divided into two main production methodologies: the first described as hand techniques or bespoke production, and the second as industrial production. The main difference between the two techniques rests in their dependence on machine specifications; whereby with hand there is potentially greater freedom for manipulating the structures, through industrial production techniques there is much less tolerance for specific modifications. The products of these manufacturing methods (marked in green) are described as woven textiles, knitted textiles and other constructed textiles – referring to lace making, braiding, etc.

The majority of this chapter focuses primarily on weaving as a construction methodology for material systems. In addition however, it includes brief accounts of knitting and lace making technique as a comparison.

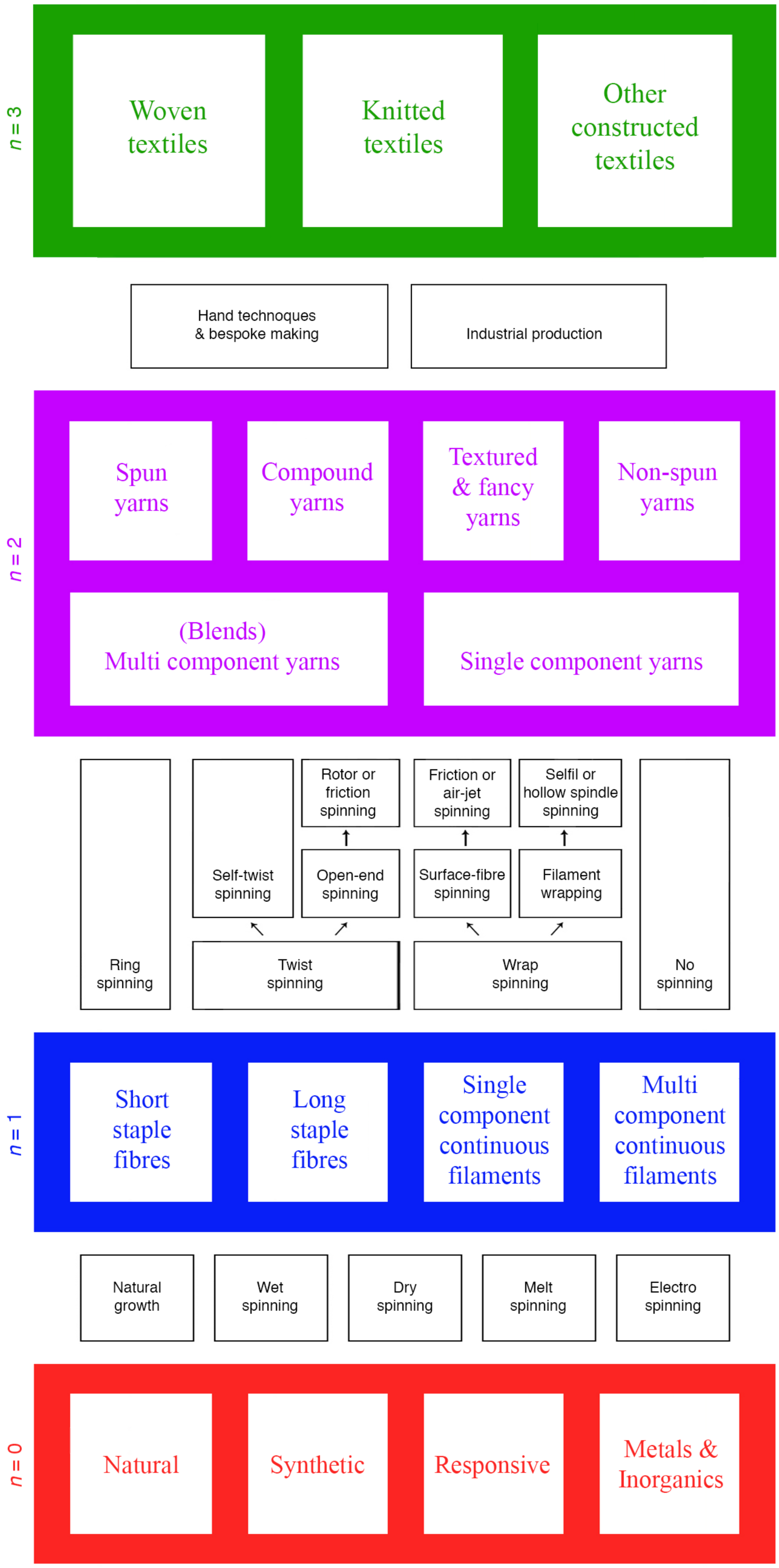


Figure 5.1
TA mapping: macromolecules and polymers (red), fibre and filaments (blue), yarns (purple), and textile construction (green)
Lynn Tandler (2015)

5.2 Knitting

The action of knitting can be done by hand or by machines. By hand, knitting is the formation of intertwined loops that together form a cloth. Various stiches can be knitted by hand with the most common known as the plain and pearl stiches (Collier, 1980). Knitting on machines – across the industry – is done predominantly on weft knitting machines, where a single yarn is passed horizontally across the fabric to form rows of loops [figure 5.2], or through warp knitting, in which case sets of yarns pass vertically and simultaneously across the fabric, interlocking parallel rows of loops together [figure 5.3]. Both production principles can be done on flat bed or circular machines.

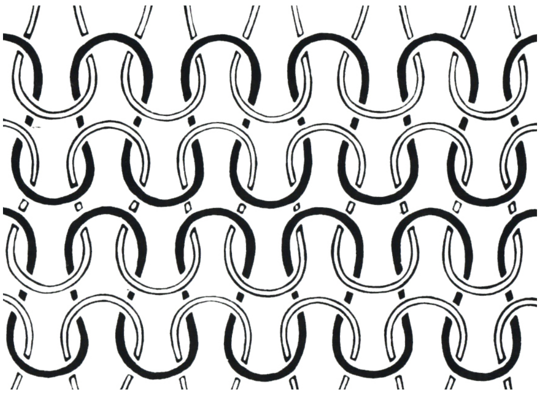


Figure 5.2
Weft knitted structure

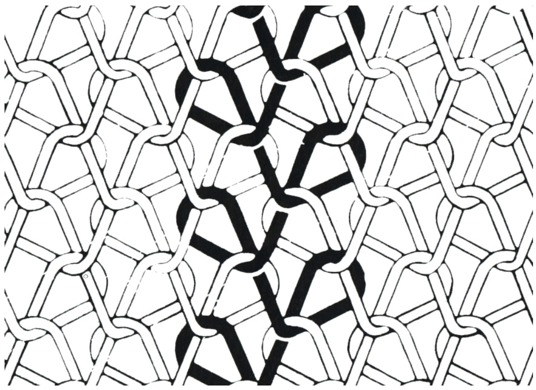


Figure 5.3
Warp knitted structure

Illustrations from Collier (1980, p. 104-105)

Further advancements in the field of knitting have been the introduction of 3D knitted fabrics such as multiaxial warp-knitted fabrics and space fabrics (Guo, 2011). In the former, many parallel yarns create interlocked layers often with varying yarn densities to enhance fabric performance. In the latter, two layers of either warp or weft knitted fabrics are attached through crossing strands that hold the two layers connected at a predetermined distance usually between 3-10 mm (Guo, 2011).

Since knitted fabrics are essentially made out of loops, they tend to be very extendable - conforming easily to changes in shape and form. Which is also why knitted fabrics have found such wide reaching application scope within hosiery and the apparel sectors. However, the elasticity of such constructions also yields fabrics with very limited dimensional stability, which limit their application scope dramatically.

Although hand-knitted textiles and machine-knitted textiles are different in manufacturing speed and volume of production, they do not differ much in the principle that governs their intricacy: both are comprised of a single yarn twisted and looped on and around of itself to create a fabric. In other words, in knitting, always only one continuous yarn is used at any given time: a stitch is made when a loop of yarn is drawn through a preceding loop to form the textile construction.

'Textile anatomy' mapping colours, as shown in figure 5.1 (p. 68), were implemented into a knitted textile structure in order to emphasis the importance of the structural hierarchy [figure 5.4 and 5.5]. The richness of the TA mapping colour code is a reminder of the structural complexity of individual constituents, such as single yarn strand – as shown throughout chapter 4. Similarly, all textile production methods can be analysed through TA mapping.

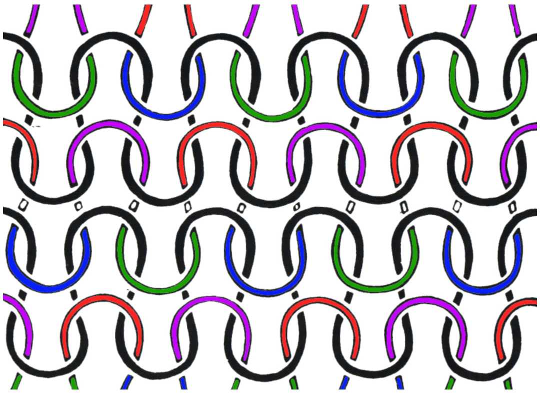


Figure 5.4
Weft knitted structure coloured with TA mapping

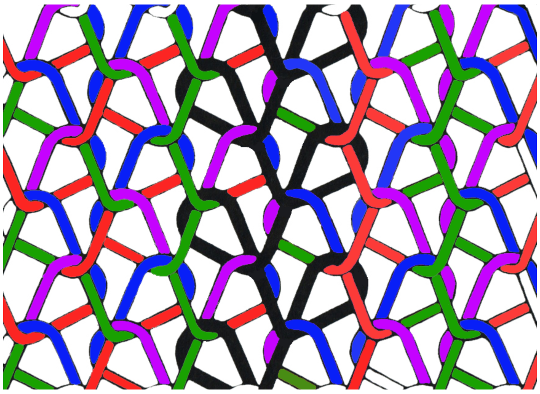


Figure 5.5
Warp knitted structure coloured with TA mapping

Illustrations modified from Collier (1980, p. 104-105)
Lynn Tandler (2015)

Through the process of machine knitting only one yarn is used to create loops and knots at any given time. That is not to say that only one type of yarn can be used throughout production, but rather that the structural unit of knitted fabrics gets its integral complexity from one sole agent.

5.3 Lace making and Bobbin lace

A description of lace from *The Encyclopaedia Britannica* (1929) describes it as "An ornamental openwork fabric formed by looping, interlacing, braiding or twisting threads" (p. 563). Accordingly, it is reported, lace making can be achieved through different processes such as knitting, weaving or braiding: looped lace is traditionally made with a crochet hook; interlaced lace or woven lace is constructed on a weaving loom and braided or twisted laces can be made with bobbins and pins, or with a needle – stitched over an open net weave.

The construction principle behind lace in general, and bobbin lace in particular, is that two groups of threads – a so-called warp and a crossing weft – are employed. Only here, the threads upon which the lace is created – the so-called warp - is not stationary but mobile: threads wound onto bobbins are used as wefts to cross over and under the warps, twisting around neighboring threads to create a similar interlacement of threads as can be found in weaving. In bobbin lace, fan-shaped laid threads cross over and under one another at a sequence, forming a wide multi-end plat. In this technique, it is this exact multiplicity of thread direction- and their mobility – which allows the unique and versatile weaving of the lace.

5.4 Weaving

Weaving is the most prominent textile construction methodology currently employed by the textile industry worldwide. It refers to the action of systematically interlacing two separate textile elements such as filaments or yarns into cloths (Emery, 1994; Forbes, 1964; Watson, 1946). Weave structures are known for their unique ability to create stable structures. They are the architecture that binds threads in a geometric form into fabrics. As a result, weave-structures have been used as a platform for fibres, filaments and yarns properties. At present, weave structures do not, in and of themselves, contribute to the smartness of textiles. Thus, an inevitable question arises: if weave structures are only a framework that enables the responsive behaviour of its elements – can the woven architecture of textiles itself be smart?

5.4.1 The evolution of weave structures

The past is often a helpful guide to the future. The following sub-chapter will therefore review the history of basic weave structures – namely plain weave, twill and satin. It will examine how they evolved throughout time and what made the textile industry – throughout history – rely on them so heavily.

According to Broudy (1979), "No one knows nor is ever likely to know how weaving began, but the idea of weaving clearly preceded the loom by many thousands of years" (p. 9). He explained that "the farther back we go, the less likely it is that fibrous materials would survive; and from times before the use of clay became common (in the Neolithic), we don't find impressions on clay" (p. 79).

But what is known from the earliest archeological textile imprint evidence is that the oldest textiles already displayed more than one weave structure. Which goes to show that over 8000 years ago weavers had already developed some sort of library of weave structures to make cloths. As Barber (1991) put it, "right from the beginning of our evidence we discover that weavers were already aware of more than one possible way to bind threads together" (p. 126). Weavers used this so-called library of weave structures creatively in order to attribute unique ethnographic signatures of cultures and geographies throughout the world.

According to Barber (1991), the first weave structures were found to be constructed by threads being passed over and under each other to form a simple fabric, known as plain weave fabric or plain cloth: the warp referring to the vertical threads and the weft to the horizontal [figure 5.6]. This fundamental form of weaving - from at least 8000 years ago (Barber, 1991) - has lasted through the years and is still commonplace across the weaving industry around the world. The earliest variations of plain weave that were found included two-thread basket weave in which two warp threads pass between to weft threads [Figure 5.7] and three-thread basket weave in which three warp threads pass between three weft threads (Barber, 1991).

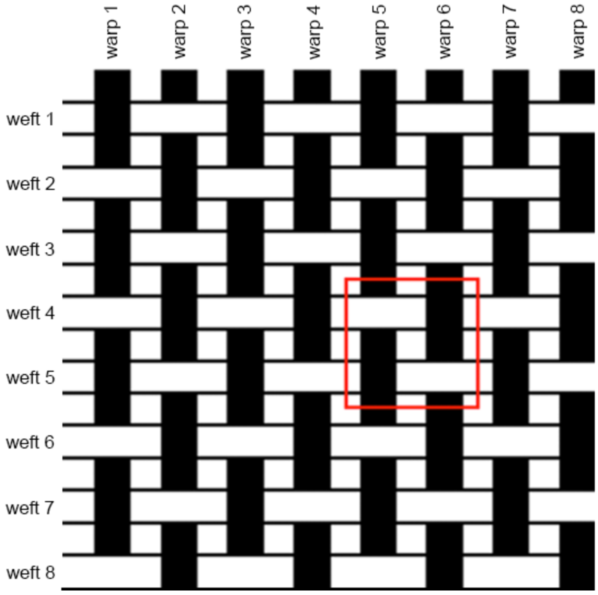


Figure 5.6
Plain weave (8-ends weave structure)

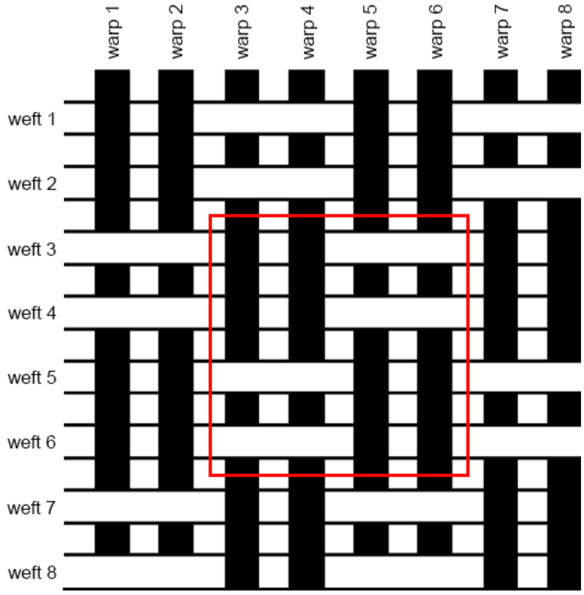


Figure 5.7
Hopsack (8-ends weave structure)

Warps (black), wefts (white) structure unit (inside red frame)
Lynn Tandler (2016)

Today, plain weave structures expend beyond the basket weave. According to Straub (1977), version of plain weave may exist in several forms: (1) through the creation of warp or weft rib structures; (2) through basket or hopsack weaves; or (3) by altering the tension of the warp and hence creating seersucker fabrics. This goes to show that however the geometry of plain weave is considered simple, it still lends itself to a wide verity of textures, effects and design motifs.

The next stage of development following the discovery of fabrics with various plain weave structures came when fabric threads were passed over and under each other but at stages would miss out and skip over a number of threads. These non-interlacing threads are known as floats. In a warp float, the warp thread might pass over a number of weft threads, where in a weft float, the weft might pass over a number of warp threads. Weave floats, according to Emery (1994), refer to “any position of a warp or weft element that extends unbound over two or more units of the opposite set on either face of the fabric” (Emery, 1994, p. 75).

Evidence from around 3000 BC shows the innovative introduction of floats into weave structures. Barber (1991) described: “the idea that one thread can skip or float over two or more threads in the opposite system, instead of being bound in by every second warp or weft thread, is developed far beyond the regular passing of warp threads over and under pairs of weft threads in the borders" (p. 137). This at the time was a hugely innovative addition to the design and construction of fabrics.

Technically, a twill – a weave structure with small floats - exhibits precisely this architecture. As does a satin, which has longer floats [Figure 5.8 and 5.9 respectively]. The main difference between a twill and a satin, as far as the float is concerned, is that the twill generally has a float of two to four threads, and a satin a float of between five to twelve threads.

What is remarkable is that from this point onwards – from the development of plain weave, its variations, the weave floats, the twills and the satins - some 3000 years ago – weave structures have changed very little. This basic structural architecture is still very much in use today and remains the building block for most woven fabrics.

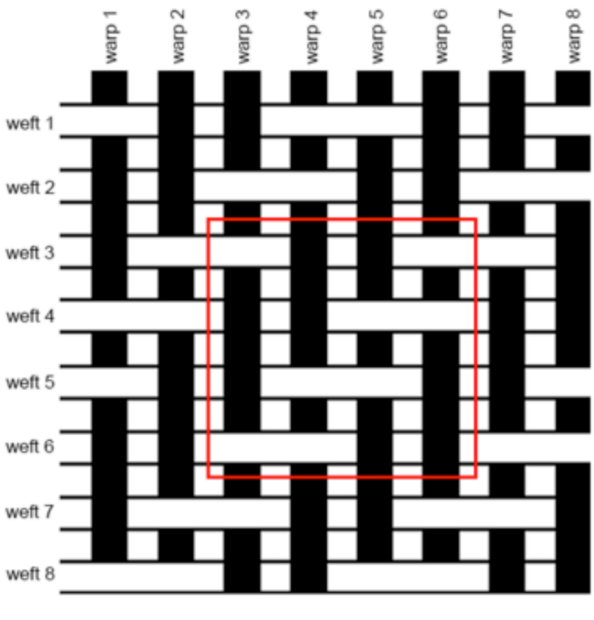


Figure 5.8
2/2 Twill (8- ends weave structure)

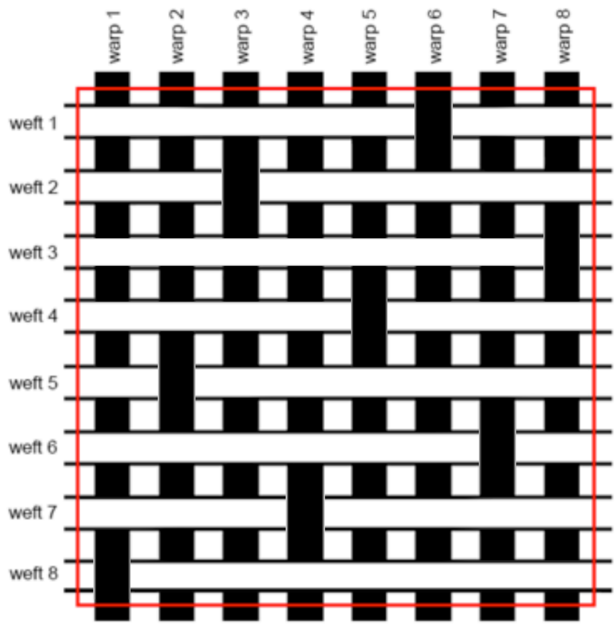


Figure 5.9
8-ends Satin weave structure

Warps (black), wefts (white) structure unit (inside red frame)
Lynn Tandler (2016)

In comparison to knitted constructions where only one type of yarn is looped in and over itself to create a structure, in weaving a minimum of four different agents (in plain weave construction) or more (in twill or satin constructions) can be used to create a woven assembly. These filaments or yarns may be identical – as often they are – but more importantly they can also be different. From the perspective of ‘textile anatomy’ mapping this means that multiple sets of yarns with their unique set of properties can be used to create the structure. The symbolic colour code of TA mapping is illustrated in the weave structures below [Figures 5.10 and 5.11] as a reminder of the structural complexity of individual constituents.

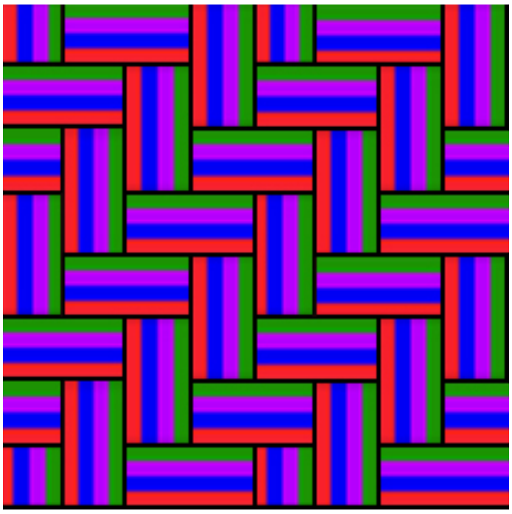


Figure 5.10
2/2 Twill (tight structure)

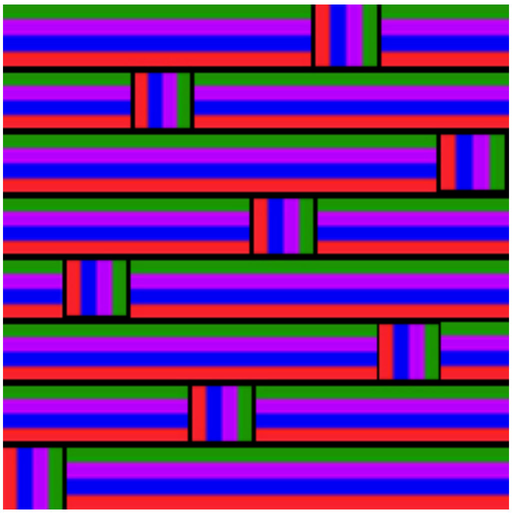


Figure 5.11
8-ends Satin (tight structure)

Weave structures illustrated through TA mapping: warps (vertical), wefts (horizontal)
Lynn Tandler (2016)

5.4.2 Weave structures vs. fabric structure

The difference between weave-structures and fabric-structures may not appear obvious but it is nonetheless fundamental. Weave structures relate to the geometry that is formed between a warp and a weft in a given repeat unit. Fabric structure on the other hand refers to the sum of the properties of the cloth or the overall design of multiple weave structures measured as one architecture. But in spite of this, specialists within the field still confuse the fundamental difference between weave structure and fabric structure, and by doing so often propose suggestions based on inaccurate assumptions (Veja, 2015).

Weave structures are the geometrical shapes that are created when a warp and a weft interlace. They relate directly to fabric properties such as handle and drape.

Fabric properties such as weight, permeability to airflow and moisture are more directly linked to characteristics of specific fibre and yarns – and not the geometry upon which the fabric is made.

5.4.3 Weave construction methodologies

Weaving can be divided into two main types: flat weaving and pile weaving (Redmore, 2011). According to the dimensional fabric volume that they produce – flat weaving refers to 2D fabrics, and pile weaving to 3D constructions. Gandhi (2012) however, divides weaving into three main groups[1]:

(i) Fabrics in which warp yarns and weft yarns intersect one another at right (90 degrees) angles.
(ii) Fabrics in which certain warp yarns interweave to the right and/or to the left of neighboring warp ends creating a stable open weave such as leno or gauze.
(iii) Fabrics in which portions of the threads (either warp or weft) project away from the foundation of the cloth creating loops and piles on the surface.

This classification into types of woven cloths can also be viewed as a classification of fabrics according to the looms that they are produced by (more on this later in this chapter). From the perspective of the machines upon which weave structures are made, woven fabrics could also be classified according to:

a) Fabrics in which warp yarns and weft yarns intersect one another at right angles can be woven on tappet, dobby or jacquard looms.
b) Fabrics such as leno and gauze, which require unique assistive tools to be fitted onto the loom in order to achieve the unique weave.
c) Fabrics such as terry towel, velvet and corduroy, which require an entirely different loom all together.

[1] Originally this classification of weaving into three groups was outlined in Watson (1946) - only this was not referenced in Gandhi's text (2012)

In the past, weaving looms were classified based on the way they used to insert the wefts, for example in air-jet, rapier and water jet looms (Redmore, 2011). But the insertion of the weft has no bearing on the properties of the cloth and therefore such developments are not discussed in this work. Today, the vast majority of weaving is done on dobby and Jacquard looms. The differences between the two types of looms do not manifest themselves through the weave structures that they employ but solely on the size of their repeat. Meaning that dobby and Jacquard looms vary mainly in the fabric structures that they are able to create and the size of motifs rather than the weave structures that they are able to employ – which in fact, remain the same.

From a machine perspective, looms fundamentally vary from one another in the mechanism employed to control sets or individual warp ends. Today, the majority of textile production worldwide is done through the mechanical operation of dobby and Jacquard looms.

5.4.3.1 Dobby looms

Dobby looms operate four to forty-eight shafts, which in turn control the lifting of predetermined groups of warp ends. The number of shafts in dobby looms informs the pattern type and size that can be created. Jacquard looms on the other hand, have a mechanism that is able to control individual warp ends and in doing so create larger and more intricate patterns across the design of the cloth. Principally however, in weaving, regardless of the looms used for the construction the hierarchical complexity is fundamentally greater from any other textile construction methodology – mostly due to the fact that two different sets of textile elements, namely the warp and the weft, are involved in creating the architecture at any given time: warp and weft yarns can be identical but they can also vary dramatically in appearance, property and handle and in turn, also affect the properties of the cloth. Although the weaving of a plain cloth can be made on looms as limited as two shafts, many weaving looms in industry today employ a minimum of four shafts. As the number of shafts increases, so does the complexity of potential interlacement arrangements.

Double cloth constructions can occur on a minimum of four shaft looms, which can produce two layers of plain cloth at once; each through the application of two allocated shafts. Hence, eight shaft looms can weave more elaborate structures as a double cloth, meaning that two individual four shaft sets fabrics can be woven simultaniously. Similarly, sixteen shaft looms can be divide into two groups of eight shafts, four groups of four shafts, or eight groups of two shafts for the simultanuous weaivng of a various layered cloths: the allocation of shafts does not have to be equal, meaning that on a sixteen shaft loom for example, two groups of four shafts can be woven simultanously with an additional gorup of eight shafts.

5.4.3.2 Jacquard looms

Jacquard looms are not controlled by shafts, but by the lifting of individual warp ends in accordance to a prescribed lift plan. The fact that Jacquard looms are so-called free from shaft space restriction does not make them without limitation for the structural weave unit remains with the same merit as that which is woven on dobby looms. With Jacquard however, the arrangement of weave unit side by side is virtually unlimited. In other words, a plain weave structure unit, for example, can be woven next to a type of twill, next to a section of satin and/or a honeycomb construction – all within one inch. Even though on the macro scale these variations may not be visible to the naked eye, structurally they are made possible on Jacquard looms.

Some Jacquard looms are laid out in the form of circular looms, which allows them to weave tubular seamless cloths. These are types of Jacquard looms operating to a wave-shed principle (Adanur, 2000). This form of weaving differs from other methods mainly due to its unique weft insertion principle, which although may also exist in flat bed looms, can often be found on the circular loom: wefts travel across the cloth in circles, simultaneously, through changing shed openings that move like a wave.

5.4.3.3 Dobby and Jacquard looms and the weaves they produce

It is often assumed that because the Jacquard loom picks up individual threads, as opposed to pre-determined groups of threads spread across shafts as on a dobby - the weave structure is limited only by the size of the Jacquard loom itself. One of the reasons this is not true is because weave structures do have limitations. For example, floats have a limited reach. In order to achieve successful stable weaves, it is a common practice amongst weavers not to exceed floats that are bigger than 12 threads across whether as warp or weft float. Depending on the weave structure, a ratio of 1:12 is just about enough to hold the threads securely, without distorting the form of the cloth. Anything beyond this proportion leads to loose warp ends or weft picks that migrate away from the structure center of the cloth. This rule of thumb restricts the size of weave structures to twelve ends / picks structure unit repeats. It is therefore a misperception to think that any shape or size of weave structure could be invented and further employed. Regardless to the type of loom on which textiles are woven - whether tappet, dobby or jacquard looms the maximum weave-float size cannot exceed twelve threads across. So with twelve shafts, a dobby loom can weave any architecture that a Jacquard loom can. Which is why dobby looms remain the dominant form of production for modern textile materials.

The number of shafts of dobby loom indicates the maximum size of a weave structure that could be woven or in other words, the size of its repeat. For example, with two shafts, the tappet loom could only weave structures that are no bigger than two warp-ends units. Similarly, a dobby loom with eight shafts could only weave structures with up to eight warp-ends repeats. A dobby loom with twenty-four shafts on the other hand, could also weave two unit structures, each with twelve warp-ends wide; three unit structures, each repeat with no more than eight warp-ends wide; or four unit structures with no larger than six warp-end repeat size in each.

The principle difference between the dobby and the Jacquard looms therefore resides in the size of their repeat – meaning that dobby looms could weave, small repeat unit determined by the number of their shafts, while Jacquard looms could potentially employ many structural repeats across the width of the cloth and in doing so produce large and complex motifs.

Jacquard looms however do differ quite dramatically to dobby looms in the way in which they allow the bigger and more articulate motif to be woven. On a Jacquard loom, the size of the repeat does not refer to the size of the weave structure unit but the size of the artistic motif that can be woven as a whole. Artistic motifs can be woven with one or several weave structures at the same time. For example, in a floral design, one petal could be woven with a plain weave, while another petal within the same flower, regardless of its position on the design, can simultaneously be woven with a twill (Watson, 1946).

In that style of weaving, weave structures are used to create visual effects within the artistic design of the cloth: Light refracts differently on threads that run vertically - in the warp, and threads that run horizontally in the weft. And these basic principles have been used by textile designer for generations to create shadow effects on the cloth and to allow an entire image to be woven from just the one colour thread by manipulating the warp/weft structure ratio.

5.5 Alternative weaving technologies

In order to step away from conventional cloth constructions, unique weaving tools and looms were developed and implemented into the textile industry. They are briefly described overleaf.

5.5.1 Leno weaving and leno doups

Leno weaving is the twisting action that allows some warp ends to loop around other ends to form empty spaces, gaps and holes with the cloth. Through the process of leno weaving two types of textiles can be created: leno fabric and gauze. Leno fabrics are fabrics made out of separate segments of leno twisting, which are introduced into the cloth to form of a pattern (Straub, 1977; Muller, 1991). Gauze, on the other hand, is a term used to describe a fabric that is woven with leno twisting throughout (Gandhi, 2012).

Leno weaving allows much greater spaces between warp and weft threads due to its unique twining system that locks warp threads in place through twisting around other ends. The uniqueness of leno weaves resides in the fact that large gaps are created between the threads without jeopardizing the structural stability and integrity of the cloth (Straub, 1977; Taylor, 2007) meaning that in spite of the large holes created as a result of leno weaving, the woven structures hold their shape without distortion or fraying. Leno weaving creates durable fabrics with excellent dimensional stability. Leno-weave fabrics are in fact stronger and firmer than other conventional woven textiles (Chen, 2011). Its open structure geometry creates a fabric with much negative space, meaning that from a design perspective the holes become a visual feature in its own right.

Leno fabrics are woven on conventional looms such as dobby looms, with the help of specially fitted headles, also known as doups. The principle behind leno weaving reveals two sets of warp threads: a set of "stationary ends" and a set of "crossing ends" (Chen, 2011, p. 118). The crossing ends are carried through the doups, which allow them to twist and wrap around the stationary ends according to a predetermined pattern (Best, 2005). Due to their unique weaving method, leno fabrics have become known for their stable construction they are lightweight and open, breathable, strong and firm. Also, leno fabrics have reduced yarn slippage and reduced distortion (Thomas, 2009).

5.5.2 Velvet looms

Velvet fabrics are woven on special looms - where an individual loom produces two separate pieces of woven cloths simultaneously. In velvet weaving individual fibres or yarns are caught within a base fabric construction of plain weave. Velvet can be done on a single or double bed velvet weaving looms. Single velvet looms are types of Jacquard looms that – with the help of metal rods – weave loops of yarns into the fabrics. These loops, if kept in tact, are also known as terry towel weaves. Otherwise, they can be cut - with fine knives running across the width of the cloth – in order to produce a cut pile fabric.

Double bed velvet weaving machines are more expensive to run. These are special looms that weave effectively two cloths at the same time – facing one another and interlinked throughout. In other words, the wefts of cloth no.1 are also the wefts of cloth no. 2. The base cloth of each of the cloths is plain weave, but he angle in which the wefts are inserted can be altered, to produce straight or angular velvet. Once woven – and locked to one another – a knife runs through the weft insertions and splits the double cloth into two individual single cloths – each wound onto a separate cloth beam.

The properties of velvet fabrics are greatly affected by the density of the warps and the type of yarn used for weaving. Pile weaves – which are woven on special looms – are durable, firm, dense and insulating (Thomas, 2009). In velvet, more so than any other woven fabric, the applied finishing techniques dramatically change the appearance of the fabric as well as its end use. These finishing techniques involve the application of great forces pressing onto the piles, wrinkling, creasing and embossing them into shape – but rather than affecting their mechanical characteristics, these techniques are used solely for aesthetic values.

5.5.3 Tapestry weaving and basketry

Tapestry weaving is weft-faced weaving, meaning that all the warp threads are hidden in the completed work, and the weft threads solely create the motif on the cloth. In tapestry weaving, weft yarns are typically discontinuous, and they are tied to one another to form small pattern areas. It is mostly artistic and never mass-produced in continuous lengths. Essentially, tapestry involves tying on knots and creating an intricate visual image. It is done on a frame loom and therefore is referred to as weaving, but unlike other methods of weaving, tapestry does not require the know-how of operating a loom. It is free hand production – a bit like painting with threads.

Basketry weaving is thought to be the oldest form of weaving (Broudy, 1979). It is a versatile handcraft, done by hand – and until present day, not in a loom. In its making, basketry is similar to bobbin lace making: a set of mobile strands travel over and under a predetermined skeleton shape.

5.5.4 Triaxial and tetra-axial weaving

Triaxial weaving is a modernization of an old basketry technique dating from about 710 AD (McCarty and McQuaid, 1998). Like many ancient art forms, it too was done by hand (Tyler, 2011) until mechanized by Dow in the 1970's (Kulczycki, 1977, Kulczycki and Darsie, 1977; Kulczycki and Darsie, 1976; Kulczycki, Darsie and Dow, 1976; Townsend and Trumpio, 1976; Dow, 1974; Dow, 1969). Triaxial weaving uses three sets of threads - instead of just two as used in conventional weaving: warps, whugs and wefts (Tyler, 2011). Conventional weaving - also known as biaxial weaving - sees the warp and the weft interlace at a 90 degrees angle. Triaxial weaving on the other hand, includes all three sets equally at 60 degrees interactions, where tetra-axial weaving employ four sets of warps and wefts inclined at 45 degrees intersections. Like leno, gauze and lace, triaxial and tetra-axial fabrics too have holes in them. Only unlike the formers, triaxial and tetra-axial fabrics are very regular and isotopic (Tyler, 2011). Currently however, only triaxial weaving is produced commercially: tetra-axial weaving is done by hand.

The prime advantage of triaxial fabrics resides in their ultra lightweight properties, good resistance to damage and an ability to withstand tear: a triaxial weave fabric "typically has about half as many structural elements per unit area as a rectangular woven fabric made using the same elements" (Tyler, 2011, p. 141). Due to their superior mechanical properties, triaxial weaves are used in industrial construction – being added to cement to create stronger concrete - also in automotive production, sport accessories, and even bulletproof vests (Mooney, 1984).

Even though it was claimed that triaxial weaves were developed by Dow in the 1960's (Mooney, 1984), mechanical triaxial weaving was first discussed in Stewart (1921). In this patent – submitted in the U.S. – Stewart describes a weaving method in which the warp turns into wefts and vise versa, in order to create a multi directional weave. In the past similar methodology was applied for the making of baskets in basketry making. Soon after the publication of his patent Stewart drew the first machine for the creation of a multi directional weave (Riley, 1926). Dow on the other hand developed a special loom on the very same principle of 60 degrees interlacing intersections, but one that use different sets of warps, wefts and whugs. According to

Dow, triaxial weaves can vary according to yarn thickness and proportion with regard to the other sets of threads – each in turn results in different fabric construction (Dow, 1969). Triaxial weaves, according to Thomas (2009) have high tear and shear resistance, are very strong, stable, lightweight and breathable.

5.5.5 3D weaving

The definition of 3D weaving is unclear (Hearle, 2015). The construction of all cloths in general describes a structure along the X and the Y-axis, but also on the direction of the Z-axis. Badawi (2007) explained: "Fibres or yarns are intertwined, interlaced or intermeshed in the X (longitudinal), Y (cross), and Z (vertical) directions" (p. 92). It has been suggested in the past that a third dimension in the thickness layer of the cloth – the so-called Z axis - creates 3D woven textiles (Badawi, 2007; Behera and Mishra, 2008). Hearle (2015) therefore described "a structure that has yarns crossing in three mutually perpendicular W, Y and Z direction or, at least, with components through the thickness (Z axis)" (p. 2). At the same time however he also noted that Ko (1989) used this definition of 3D weaving to describe a non-woven cloth: in this instance threads were crossing one another – but not interlacing.

As we saw when describing the differences between dobby and Jacquard weaving "Any loom is limited by the size of the weave repeat it can produce, and this is governed by what is known as the shedding motion, which controls the lifting and lowering of the heald shafts" (Taylor, 2007, p. 92). The shedding mechanism of 3D weaving technology is therefore different to that of 2D weaving techniques (Gokarneshan and Alagirusamy, 2009), which enables the creation of bulkier 3D architectures.

According to Ko and Pastore (1985), "A 3-D fully integrated structure is formed with yarns intimately interlaced together to assume various net shape structures" (p. 429). 3D weaving can happen through 2D weave construction – in the form of a multi layered woven cloth as shown by LaMattina and Parvizi-Majidi (1992) - or through manipulation and additives that can be fitted onto conventional looms in order to genuinely weave 3D shapes. This involves the utilization of a dual shedding mechanism (Hearle, 2015; Behera and Mishra, 2008). This, in other words means that the motion of interlacement need to take place in the X, Y and Z axis, all within the same unit cell. Due to their multiple directional interlacements, 'true' 3D woven fabrics (Behera and Mishra, 2008, p. 275) display great structural integrity, which turns their construction to be strong, stable and reliable: "The integrity of such a structure arises due to the intense interlacement of three perpendicular series of yarns" (Gokarneshan and Alagirusamy, 2009, p. 5).

Traditional methods for increasing the volume of textiles and inserting bulk have been taking place through multi-layer weaving and double clothed manipulations on both dobby and jacquard looms in the past. As well as through the use of velvet weaving and towel looping techniques. In an attempt to step away from the boundaries and limitation of conventional 2D weaving, Gokarneshan and Alagirusamy (2009) describe a methodology that enables a three-dimensional weaving process for the generation of 3D woven fabrics. They differentiate between what they called a "three-dimensional woven 3D fabric" and a "two-dimensional woven 3D fabric" (p. 1): the former governed by a mono-directional shedding system and the latter by a dual-directional shedding system. In the text they described a method previously described by Fukuta, Onooka, Aoili and Isymuraya (1982) that "causes interlacement of three perpendicular sets of yarns so as to form a completely interlaced 3D fabric" (p. 5).

5.6 The formation of the woven textile industry as we know it today

Whilst studying the various looms (above) and understanding how machine specifications affect the cloths currently produced by the textile industry, the way history had shaped our methods of production today has come into question, which is why it is useful to examine some of the patterns in the history of textile development that have led up to the present situation.

As mentioned before, the first recorded documentation of textiles dates back to the Stone Age and the early Bronze Age (Lord and Mohamed, 1982; Barber, 1991). The majority of this long period of history witnessed the slow, steady and evolving use of natural fibres and yarns such as cotton, linen, flax, wool and silk and their adaptation into various textile forms. But it was over the last 250 years that, through developments in mechanization and industrialization, textile production evolved at formerly unimaginable rates and into its current form. The importance of the years of the Industrial Revolution will be discussed in this chapter in detail with an aim to discover why the weaving industry shaped itself the way that it did and why have we come to rely on some technologies over others.

5.7 The evolution of weaving technologies

The weaving of cloths have always been done on a loom. And the mechanisms that operated looms evolved and changed throughout the centuries slowly during thousands of years, and in an accelerated speed during the past 250 years. What will become apparent from this review is that in spite of these changes, the principle of weaving has not changed at all.

The first known loom from around about 7000 BC was the vertical loom, or the warp weighted loom. This loom had an upright warp stretched between two cloth-bars assisted with weights, which had been tied to the bottom of individual warp bundles (Broudy, 1979). Throughout thousands of years this principle of weaving had not changed. Around about 560 BC headles were introduced to the weaving process (Broudy, 1979). According to Broudy (1979) this ”was not a minor but a major technological advance that overcame the greatest problem of textile production its tediously slow pace” (p. 26). Heddles allowed a more efficient way of weaving - now instead of lifting warp repeatedly ends one by one, groups of threads could be decided upon in advance and lifted at once.

The vertical loom evolved into the horizontal loom - which allowed weavers to sit rather than stand whilst weaving, but more importantly weavers were able to have longer warps and consequently greater design and production opportunities. During the 2nd century pedals, known as treadles, were introduced to the vertical loom – and in doing so the vertical loom had transformed into a treadle looms, where pressing onto pedals did the lifting of the threads.

The horizontal loom and the treadle loom themselves later evolved into the 'draw loom' around the sixth century. Draw looms were operated with the help of a draw boy, which gave them their name: this used to sit on top of the loom and lift the shafts by hand according to the pattern given to him by the master weaver. Draw looms dominated the textile industry and Britain's cottage industry throughout the Middle Ages and right up until the Industrial Revolution. From that point onward, as Broudy (1979) put it: "how the loom developed was to a large extent dependent on what fibre was used for the warp" (p. 14).

5.8 Textile innovations in Britain during the Industrial Revolution: Leading to the automation of the weaving process

Kay's flying shuttle speeded up the process of weaving to such an extent that it created a need for more yarn (Lord and Mohamed, 1982). As a response, in 1738, Lewis Paul (Lawrence, 2010), or Louis Paul (Chapman, 1967), developed the first mechanism to replace the manual skill of yarn spinning. But it wasn't until 1764 that a British weaver, James Hargreaves, invented the spinning jenny that dramatically increased the speed of yarn production.

In 1769, the same year that Hargreaves had patented the spinning jenny, Richard Arkwright also patented a similar spinning machine and called it the water frame (Singer, Holmyard and Hall, 1958; Lawrence, 2010). This was the first yarn-spinning machine, which was operated by the power generated by a water wheel. Arkwright's spinning frame was based on Paul's mechanism, developed some 30 years prior. Arkwright applied Paul's mechanical success with that of the factory system and in doing so he turned the spinning frame into a commercial success (Chapman, 1967).

Arkwright was a barber by trade, with no qualification or training within the textile world. Despite this, he became to be one of the most prominent men of his time – a leader of textile. His significance was in the way he demonstrated the profitability that was made possible by mechanization, earning him the name of the "father of the English factory system" (Chapman, 1967, p. 67). His story therefore does not celebrate innovation for the sake of newness, but innovation within context, driven by the need for financial success: his is one of the first stories of entrepreneurship, and one of the first examples to link mass production of textiles with financial gain, and even more so, with fame.

Regardless of the validation of their patents, both the spinning jenny and the water frame mechanized the process of yarn spinning, which was previously carried out by hand. But each of the machines was able to produce different yarn qualities: the water-frame produced strong, well twisted yarns that were mainly aimed at cotton warps, and the spinning jenny spun more fragile yarns, suitable for wefts (Mann, 1958). Yet the yarn-spinning machines of the late 18th century were still crude and the yarns that they produced were imperfect: machines that could spin cotton would not spin wool or linen, and vice versa, and it was often necessary to alter a machine in accordance to the needs of different yarns (Mann, 1958). Soon thereafter it became evident that in order to spin different yarns, different machines parts had to be modified and separately patented.

In 1779 Compton's spinning mule was introduced, although never patented. It differed from the water frame and the spinning jenny in the way it was made to offer and spin larger variety of yarn counts (Mann, 1958): the mule spun fine yarn counts as well as course, both from cotton and from wool - in doing so it quickly rose to dominate the British market. As more specialist machines developed they enabled greater versatility, and specifically the creation of yarns of different thicknesses, which in turn created a demand for unique textile products for specific applications. The need for greater efficiency drove technological innovation that itself generated the possibility of new products. This is one of the first links we can find of the relationship between the specifications of machines and the final product properties they yield. In other words, its not so much that demand generated supply but that supply stimulated demand.

5.9 The mechanization of the weaving process

According to Broudy (1979) in *The Book of Looms*, "All handlooms, no matter how primitive or sophisticated, involve four processes that are subject to varying degrees of complexity or mechanization: (1) a system for holding the warp threads parallel, (2) a means of forming alternate sheds, (3) a process for inserting the weft, and (4) a manner of pressing it home" (p. 102). In general terms this refers to (a) the threading of warp ends through small heddles, (b) the mechanism that lifts the headles and creating a gap through which (c) the weft can be inserted, and (d) a reed is used to beat the weft into place.

Inspired by Arkwright's yarn spinning machine from 1769, Edmund Cartwright sought to mechanize the weaving process, and in 1784 he produced the first power loom prototype (Barlow, 1878). In 1792, Cartwright's power loom became widely used as a means of production, mainly within the regions of Doncaster and Manchester. This loom was operating according to a mechanism known as a tappet. Tappet looms could operate on as little as two shafts, and up to five. The number of shafts used on the tappet informed the weave possibilities that could be employed and could therefore also inform the size and type of patterns that could be created. Outside Britain, in 1801, a French weaver and textile merchant named Joseph Marie Charles Jacquard invented the Jacquard loom. Similar to the Lancashire loom, the Jacquard loom was based on earlier French innovations (Lord and Mohamed, 1982). The Jacquard loom differed from Cartwright's power loom in the way that it controlled the lifting of individual threads, rather than shafts, which controlled groups of threads, producing intricate patterns by separately lifting the warp ends (Lord and Mohamed, 1982). Jacquard looms allowed the mechanization of imagery weaving and motif based fabric construction, previously only achievable through processes of tapestry weaving and embroidery. But his was developed in France, whereas in Britain, until the 1820s, all mechanized looms were designed to weave plain fabrics alone.

In Britain, due to further modifications that dramatically speeded up the action of weaving (Singer, Holmyard and Hall, 1958), between 1813 and 1820 the number of power-looms increased from 2,400 to over 14,150 (Mann, 1958; Hill, 1993) – an increase of over 600% in less than 10 years.

In 1822, Richard Roberts adapted the acclaimed power loom and allowed it to raise different sets of warp threads at any given time (Mann, 1958). His looms became known as the Roberts looms, and they were able to produce fancy weaves and twills - previously only achievable through processes of hand weaving. The popularity of the power looms increased even more in spite of objections and rebellious actions taken by hand weavers at the time, fearing to lose their livelihoods. In fact, the popularity of the new power looms - the Roberts looms - was so great that by 1833 there were over 100,000 power looms operating in Britain – a staggering expansion from the modest 2400 working power looms in 1803 (Hills, 1993).

By the mid 1800s, power looms with plenty of shafts, such as the Roberts looms, came to be known as dobby looms. Before the name dobby was fully anchored, dobby looms were also called “a witch”, “a wizard”, or “the index-machines” (Fox, 1922, p. 82-83). Dobby looms were, and still to some extent are, shaft looms on which chains of wooden bars with multiple pegs and holes control the lifting and dropping of specific shafts in a sequence. The rotating action of the dobby mechanism defined the repeat of the design as “the number of ends and picks required to produce one complete pattern” (Collier, 1980, p. 92). To this day, dobby looms are widespread across the woven textile industry throughout the world operating according to the exact same mechanism.

5.10 'Textile anatomy' mapping – discussion

This chapter clarifies and emphasis the advantage of weaving over other textile construction methodologies such as knitting. Rather than a single strand forming a geometrical structure as found through the process of knitting, in weaving, at all times at least two strands are involved in forming the structure - although often, and for the creation of most weave structures at least four ends are required (for the vast majority of weave structures eight warp ends are preferable). This gives weaving constructions superiority over other textile construction methodologies for through the process of weaving many more materials and therefore properties could be introduced through a single structure unit.

Above all, chapter 5 reveals that weaving and knitting are in fact processes undertaken for the construction of textiles. They are not the *materials* per se, but rather the *method* applied to achieve the production of textile systems. Within the investigation regarding the creation of smart textiles – and smart textile structures – the structures themselves are subject to machine specifications. 'Textile anatomy' mapping was therefore revised. The structures of weave, knit, and other 3D assemblies previously (marked in green) were realised to be more fitting as processes of construction since the structure of the material system is controlled by the specification of the machines on which it is created.

Additionally, it is through the processes of weaving or knitting, and the machines specifications of industry or hand production techniques, that three types of textiles can be formed. These are here mentioned as: non-responsive textiles, responsive / reactive textiles, and smart textile systems [figure 5.12, p. 92].

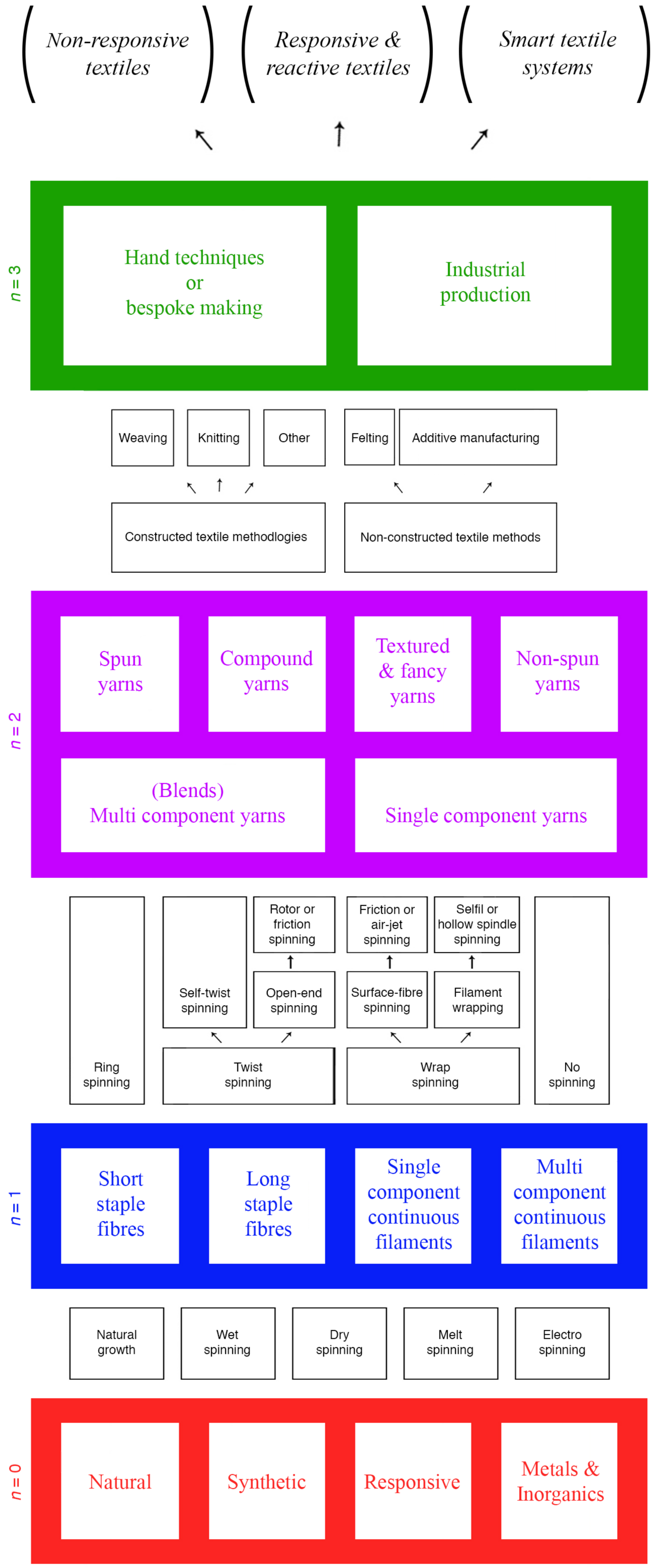


Figure 5.12
Revised TA mapping
Lynn Tandler (2015)

Chapter 6

Experimental studies

So far, designers and engineers alike have been using the unique properties of polymers, fibres, filaments and/or yarns, to extend the physical and mechanical properties of cloths (Thomas, 2009). As shown in chapter 5, a woven textile structure is an assembly that, like any other structure, serves an engineering purpose (Wadhawan, 2007). But although woven fabrics have been induced with responsive elements and components - such as those displayed in some fibres and yarns - no clear evidence is yet to have been found to prove that responsive behaviour in textiles can occur due to changes within the architecture of the fabric – in the weave structures themselves ($n = 3$).

In chapters 4, the contribution of individual textile components to the enhancement of textile properties was reviewed. As a result it was revealed that textile construction methodologies such as weaving, to date do not yet contribute to the enhancement of textile properties – meaning that although single components are commonly used to attribute textiles responsive properties, weaving has thus far not been applied in such a way. As opposed to changes that tend to occur on the microscopic level - for example in shape changing polymers, phase change polymers, alloys, and technical fibres or yarns - the geometry of weave structure, on the macroscopic level, i.e. the design of the weave structure itself, has not yet been studied in detail as an agent for the creation of smart textiles.

Further applying the hybrid research methodology described in chapter 2, a series of case studies is therefore presented in this chapter, which sets to explore whether a new weave structure could react to "changes in its own condition" (Wadhawan, 2007, p. 1)

- be it changes within its own geometry or within its mechanical state (Varadan, Jiang and Varadan (2011). In other words, the following chapter examines the possibilities of woven architectures taking part in converting a piece of textiles into smart.

The three case studies presented in this chapter are anchored in practice-based activities. Case study 1 challenges the limitations of leno weaving from design and engineering perspectives. Case study 2 explores double cloth weaving structure techniques in a similar way and in doing so it challenges their contributions and reveals their limitations for the creation of novel weave architectures. Finally, case study 3 explores whether additive-manufacturing techniques could offer more possibilities in creating reversible weave structures, by comparing the technology, structure and properties of weaving to that of Additive Manufacturing (AM).

Each case study is presented with its own introduction, background and context to the overall exploration of my research as well as each of their aims and objectives and the methodology undertaken. A documentation of the findings is presented through digital photography and microscopic observations, along with a discussion of the results of each of the case studies – leading to further explorations.

6.1 Case study 1: investigating leno weaving as a method for creating novel mobile geometries in textiles

The first case study was set out to explore whether shape change in textiles could occur solely within the geometry of a weave structure – independent of the properties that filaments or yarns may have. According to Meredith and Hearle (1959), it is not only the properties of the yarns, but also the spacing of the threads, which contribute to the mechanical stability and properties of woven structures (Meredith and Hearle, 1959). This is determined by the reed. A reed is a tool in the shape of a comb, which is used to fan out warp ends and hold them in place whilst weaving commences [image 6.1]. In plain cloth weaving for example, the warp ends are often cramped to maximize the density of the cloth creating a closely woven textile. Reversely, in leno weaving, large gaps are often introduced – creating woven textiles filled with gaps and holes.

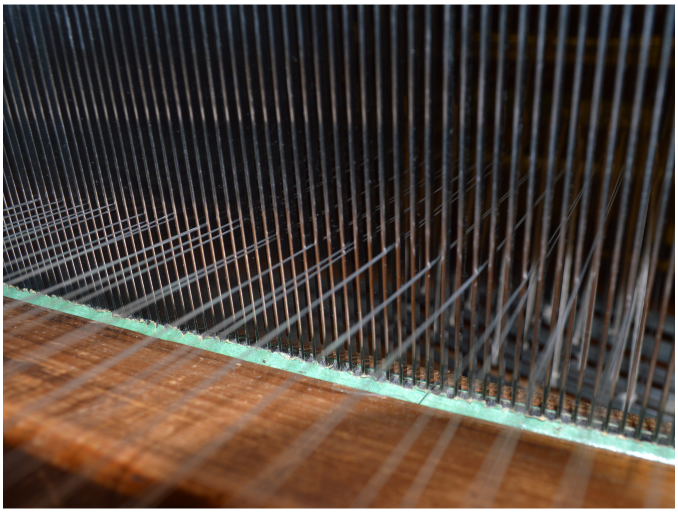


Image 6.1
Warp ends spaced through a reed
Lynn Tandler (2013)

A manipulation therefore of the negative space within a weave structure – such as that which is created in lace and / or leno weaving - could potentially introduce a woven geometry with more possibilities for change in shape. In other words, by utilizing the space between the threads and within the weave structure the intention here is now to produce a woven geometry, which upon manipulation is able to retrieve its original state.

6.1.1 Case study 1 – Aims and objectives

The aim of the first case study is to examine whether leno weaving is a suitable weaving construction for the development of a reversible weave structure – one with changeable geometric states.

The objectives are outlined as follows:

(i) Investigate and understand the operating mechanisms of leno weave structures in order to acquire sufficient knowledge of leno weaving; including the construction of bespoke leno doups and sourcing of suitable yarns for warp and weft weaving.

(ii) Manipulate leno weaving to create novel weave constructions that enable a reversible geometric and mechanical movement within the weave structure.

6.1.2 Case study 1 – Method and machine

This is a practice led research, one that relies on the specialist knowledge, experience and know-how of weaving through its potential modifications and achievable adaptations. This task requires an experienced weaver – one who is familiar with the process of specific weaving techniques in order to find technical and creative solutions to problems as they arise through the process of developing new woven architectures. The weaving in this case study was done by hand in order to understand and illustrate the process in detail, pick-by-pick, and in doing so to allow a deep appreciation of not only the logic behind leno construction but also the way in which such constructions could potentially be altered.

In weaving, the creation of a successful weave structure refers to the development of stable thread geometry; one that does not slide, fray, or disintegrate upon manipulation. Here therefore, experience and the use of tacit knowledge – as explained in the paragraph above and in chapter 2 – is crucial. One the one hand, the new leno geometries needed to be reproducible, 'successful' and mechanically stable. On the other hand, they also needed to demonstrate how two different sets of geometries could reversibly appear within the one structure. To tackle this, I turned to the principles of engineering to draw inspiration for how to create mechanically reversibly structures. The main inspiration I had in mind was the simple action of opening and closing a door: the adjacent elements – linked with a form of locks and hinges – were able to move reversible when mechanical forces were applied. In order to translate this into weave I first needed to visualize how one geometric shape changes to another (figure 6.3, p. 101).

With that in mind I sought to apply my practical knowledge of the weaving process to novel and experimental leno threading techniques. Weaving mostly generates square geometric shapes, and one of the main challenges that unfolded throughout this case study was to create a triangular shaped thread travel. That is to say, that the interlacement of warp and weft threads should produce a 45 degrees alignment of the threads rather than the common 90 degrees angle.

The analysis of the findings that arose from this case study were therefore done with the objective of creating the potential for two different yet stable woven architectures within the one structure that do not fray, migrate or disintegrate when pulled or manipulated.

The George Wood dobby loom upon which case study 1 was conducted [images 6.2 and 6.3] is a peg loom, where a series of wooden bars approximately twenty centimeters long are dotted with holes, linked horizontally to from a chain [image 6.4]. Each hole on these wooden bars is meant to host a wooden or a plastic peg. These pegs, in turn, create 3D shaped pattern of the woven structure where individual pegs control individual shafts: for example, hole number one is connected to the first shaft at the front, hole number two connected to the second shaft, and so on.

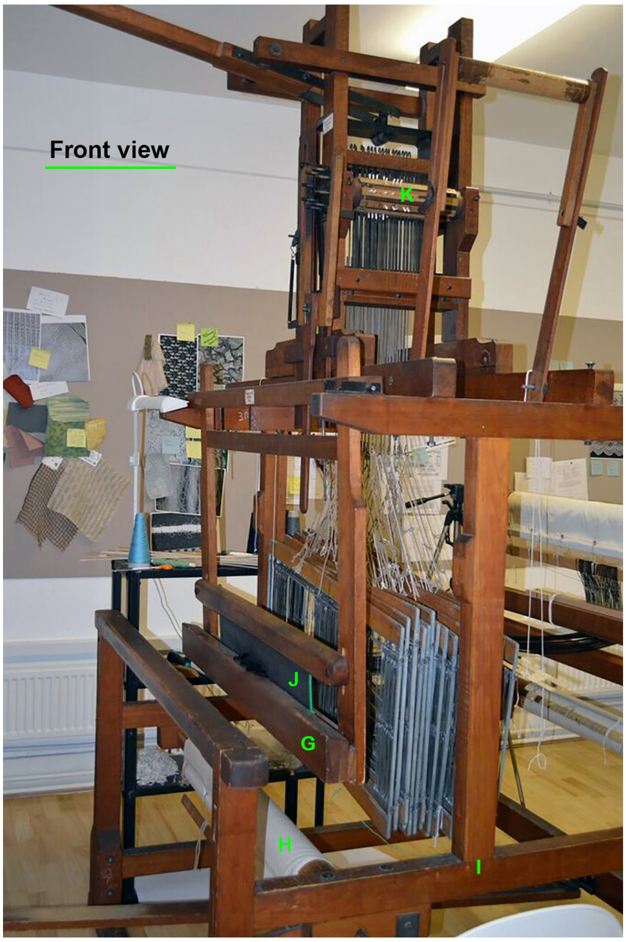


Image 6.2

Image 6.3

Front and rear view of George Wood dobby loom used for case study 1
A – top warp beam; B – bottom warp beam; C – warp; D – shafts; E – dobby mechanism; F – pedal; G – batten; H – cloth beam; I – loom frame; J – reed; K – weave pattern pegged into bar chains
Lynn Tandler (2013)

Image 6.4
Plastic and wooden pegs hammered into bar chains in preparation for weaving
Lynn Tandler (2013)

This mechanical dobby loom has wooden bars with 24 holes - meant to control up to 24 shafts. In this particular instance the working loom has 20 shafts. Wooden or plastic pegs are hammered into specific holes on the bars in order to create a unique repeating sequence, which in turn identifies the weave structure by lifting specific shafts on demand. In this way for example, the pegging of a plain weave structures (on a 20 shafts loom) repeats itself as follows: First lift – 1, 3, 5, 7, 9, 11, 13, 15, 17, and 19; Second lift – 2, 4, 6, 8, 10, 12, 14, 16, 18, and 20; Third lift (repeating first lift) - 1, 3, 5, 7, 9, 11, 13, 15, 17, and 19; Forth lift (repeating second lift) - 2, 4, 6, 8, 10, 12, 14, 16, 18, and 20 [figure 6.1].

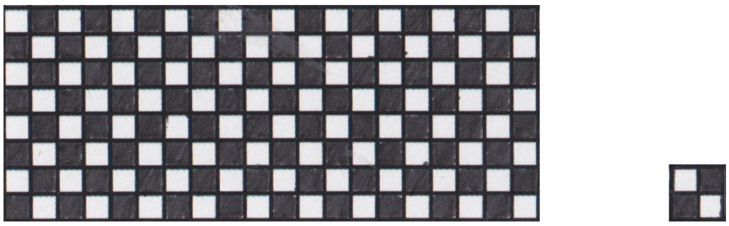


Figure 6.1
Plain weave structure unit (right), and plain weave pattern for 20 shafts looms (left)
Lynn Tandler (2013)

Similarly, on a 20 shafts loom, 1/3 Z twill will repeat as follows: First lift - 1, 5, 9, 13, and 17; Second lift - 2, 6, 10, 14, and 18; Third lift - 3, 7, 11, 15, and 19; Fourth lift - 4, 8, 12, 16, and 20; Fifth lift (repeating first lift) - 1, 5, 9, 13, and 17; Sixth lift (repeating second lift) - 2, 6, 10, 14, and 18; Seventh lift (repeating third lift) - 3, 7, 11, 15, and 19; Eighth lift (repeating fourth lift) - 4, 8, 12, 16, and 20 [figure 6.2].

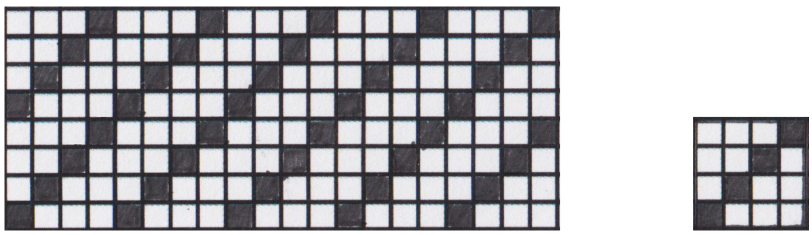


Figure 6.2
1/3 Z twill structure unit (right), and 1/3 Z twill pattern weaving for 20 shafts looms (left)
Lynn Tandler (2013)

In order to set the loom up for leno weaving, special loops were made from a cotton cord (2.2 Nm) for the creation of leno doups. Those have been measured, cut and tied into loops to form identical sized rings: 40 cm long cotton cords were folded in half and tied 1 cm off the edge of the cord into approximately 17 cm round loops [image 6.5]. Once tied into a circle, the loops were attached onto a set of allocate shafts - which had now become the leno shafts – and threaded through neighboring headles: the leno shafts control the leno effect by lifting the doups and twisting the leno warp ends around their neighboring ends. Warp ends were then threaded through normal headles and trough the leno doups according to specially designed plan.

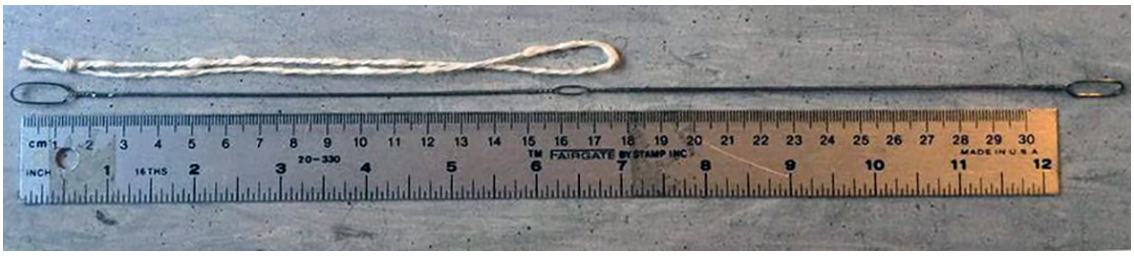


Image 6.5
Leno doups made to measure for case study 1
Lynn Tandler (2013)

Basic principles of mechanics were introduced into the design process as an inspiration for new construction of leno weaves. Locks, hinges and tracks were identified as mechanical actions that - if applied onto leno structuring could lead for shape change behaviour within the geometry. The idea behind this was to re-think the design and action of leno weaving but infusing it with a different design methodology one that is based on the laws of mechanics: while creating an open woven structure, locked and held in several anchor point (leno), it was hypothesized that several geometries could be introduced to the woven structure to come to play under various tensile load conditions as well as those of stretch and strain.

Depending on the direction of interlacement and the tightness of the twist, leno weaving of specific warps ends in allocated spaces were to be used as locks securing the geometrical shape in place; the travel of the wefts horizontally was to create an angle with a hinge at its meeting point with the warp; and lastly, idle warp ends and wefts were to be used as tracks for the sliding of twists and knots along their axis [figure 6.3].

In order to prove any change in the geometry of the weaves, it was important to set the parameters of evaluation, and conclude how much change would suffice to attribute the case study with success. Much has been written about cloth's measurements methodologies (Meredith and Hearle, 1959): the diameters of a piece of cloth could be measured with a ruler, a 'grab test' or with a 'strip test' (p. 232).

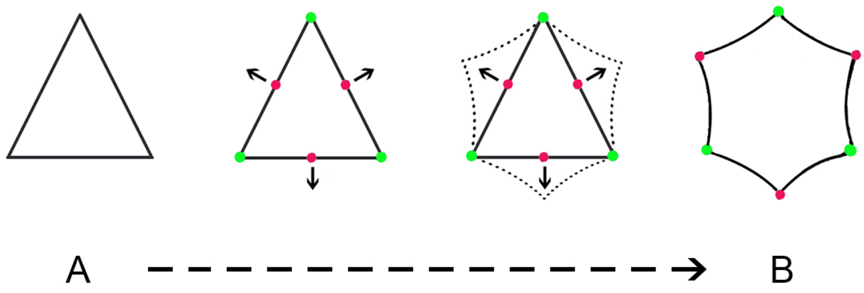


Figure 6.3
Potential geometric change within a single structure unit through the use of static anchoring points (green) and leno twists (pink) that upon stretch transform the shape of the structure from triangle to a star
Lynn Tandler (2013)

A considerable change is that which is noticeable and large enough to reckon with, without the aid of specialist equipment. In other words, if the change is obvious to the naked eye it should suffice as noticeable. Because weaving exists on the macro scale, the manipulation of its structures is done by hand and the assessment and analysis of its mechanical stability and so-called success is largely done by eyesight. It was therefore decided that the shape change in the geometry of the new leno weaves should also, first and foremost, be visible to the naked eye.

For the purpose of this case study, I chose a 2/12's mercerized cotton yarn due to its strength and elasticity, which in turn allowed it to twist into a leno structure in spite of the high tension of the warp [image 6.6]. Because the prime premise of this case study was to develop a new shape memory weave structure, or to assess the integrity of the weave structure at best, it was important to eliminate the influence of yarn performance on the structure. As a result the same yarn was used both within the warp and within the weft. The methodology that governed this case study was that of creative design, loom set-up, weaving, analysis, and conclusion for each of the sample warps. Each experiment was derived from the previous findings: drawing on strengths that have been revealed, eliminating any disadvantages that surfaced along the way.

Throughout case study 1, eight separate sample warps were made – each with a unique threading, set up requirements and weaving specifications. Each sample warp had a minimum of two sections, which were woven simultaneously according to the same peg plan (or lifting plan) as blanket warps: each section in the warp however was threaded differently in order to explore various structuring potential at any given time.

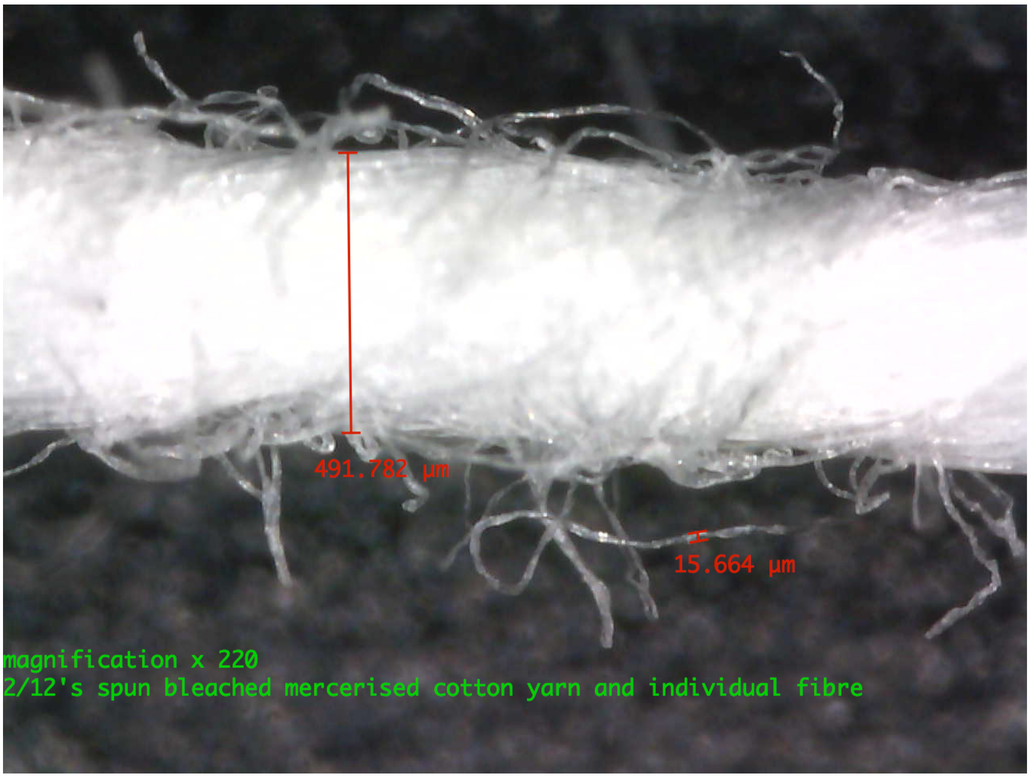


Image 6.6
2/12's spun mercerized cotton yarn measurements
Dino-Lite microscopy
Lynn Tandler (2013)

6.1.3 Case study 1 – Warp plans and weaving

A total of eight sample warps have been designed throughout case study 1. The breakdown of each weaving plan is presented in the following pages.

6.1.3.1 Sample warp 1.1

Sample warp 1.1 was the first experimental warp to be created. Divided into six sections [figure 6.4], it was formed in order to understand the operating mechanism of leno weaving. A warp was made with 2/12's mercerized cotton yarns, and the same yarn was also wound up for use as weft insertions of sample warp 1.1.

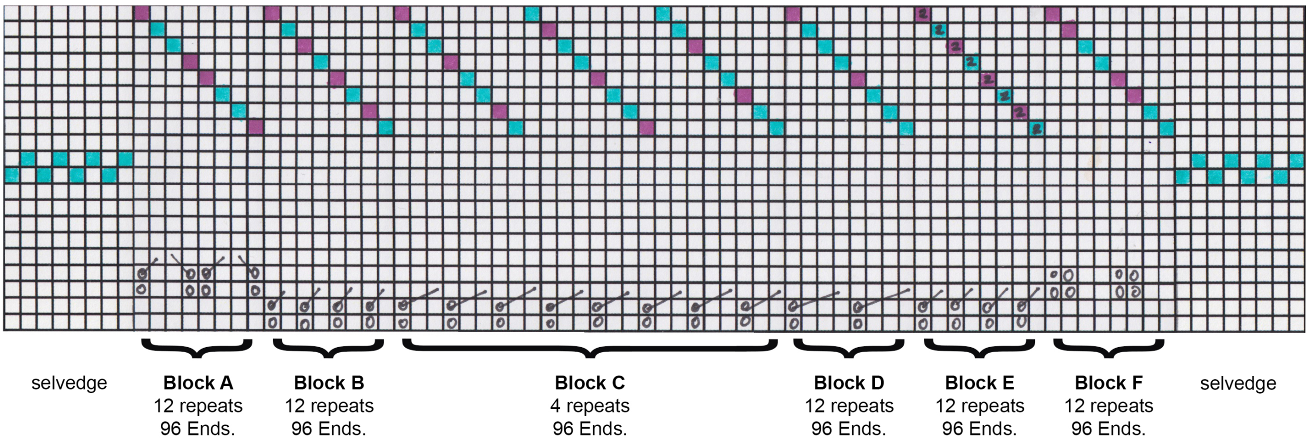


Figure 6.4
Sample warp 1.1 – threading plan
Lynn Tandler (2013)

Four variations of plain weave were inserted into the lifting plans to weave - while controlling the lifting of the leno doups differently in order to create different woven structures although plain weave structure was applied onto all the samples, variations of leno lifting were applied too, which in turn created different weave structures all together, as shown throughout images 6.7 – 6.10. In the following images, the unit structure of each woven sample – meaning the minimum number of warp-ends (marked in pink) and weft-picks (marked in yellow) used to create the woven structure - is marked in the red frame, below the lifting / peg plan of each of the samples. At the bottom of each image a graphene rod was placed to give an indication of size and scale. The rod measures 0.9mm in diameter.

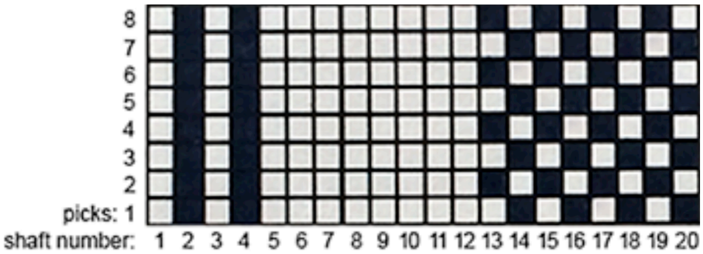


Figure 6.5
Plain weave (shafts 13-20) and leno lift (shafts 1-4)
Lynn Tandler (2013)

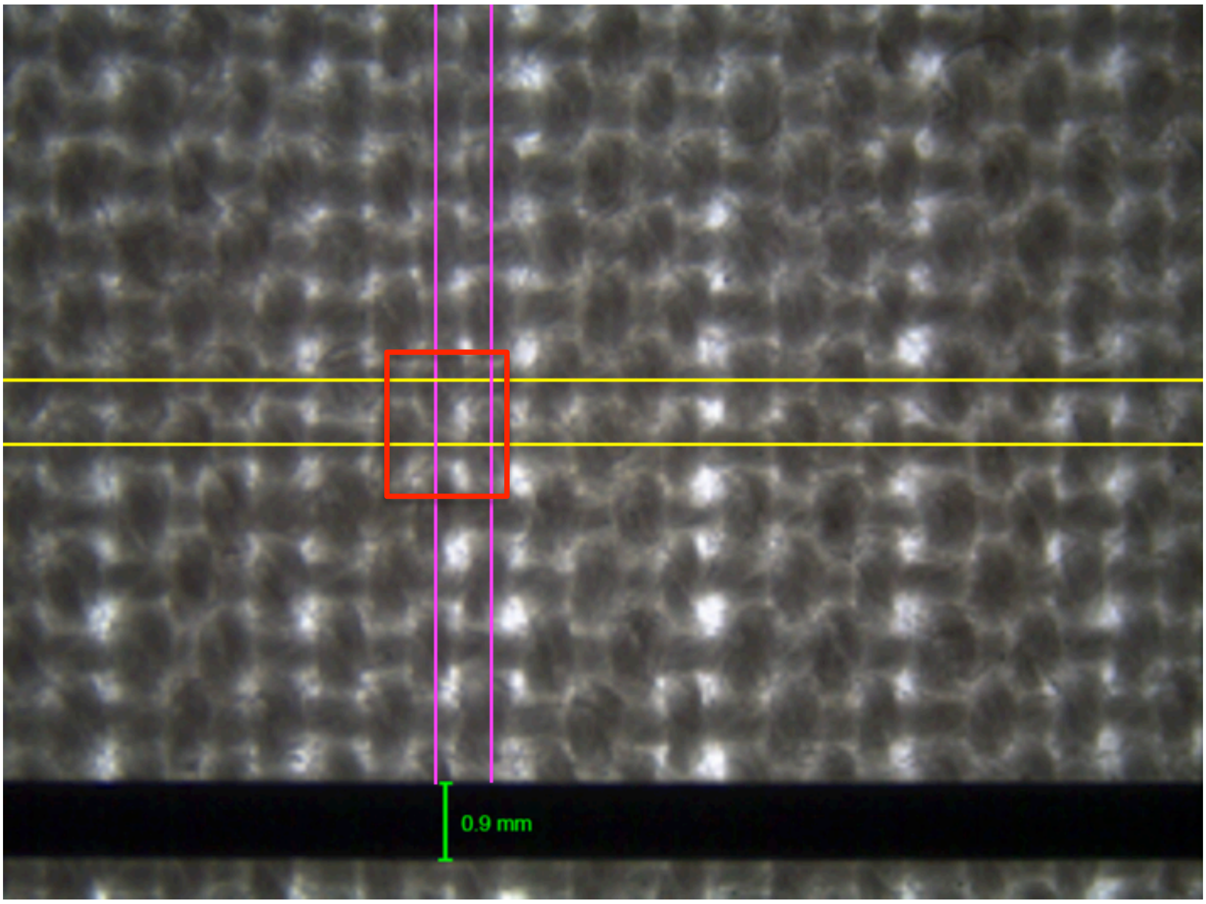


Image 6.7
Section D: Plain weave (a)
Stereomicroscopy – transmitted light
Lynn Tandler (2013)

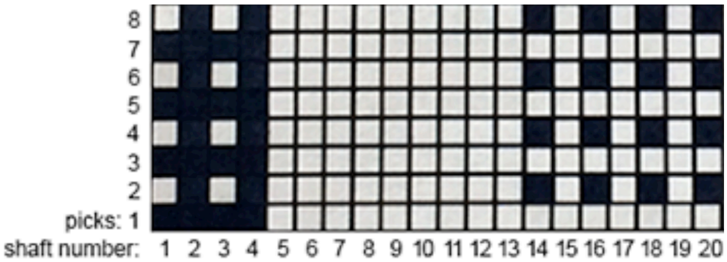


Figure 6.6
Plain weave (shafts 13-20) and leno lift (shafts 1-4)
Lynn Tandler (2013)

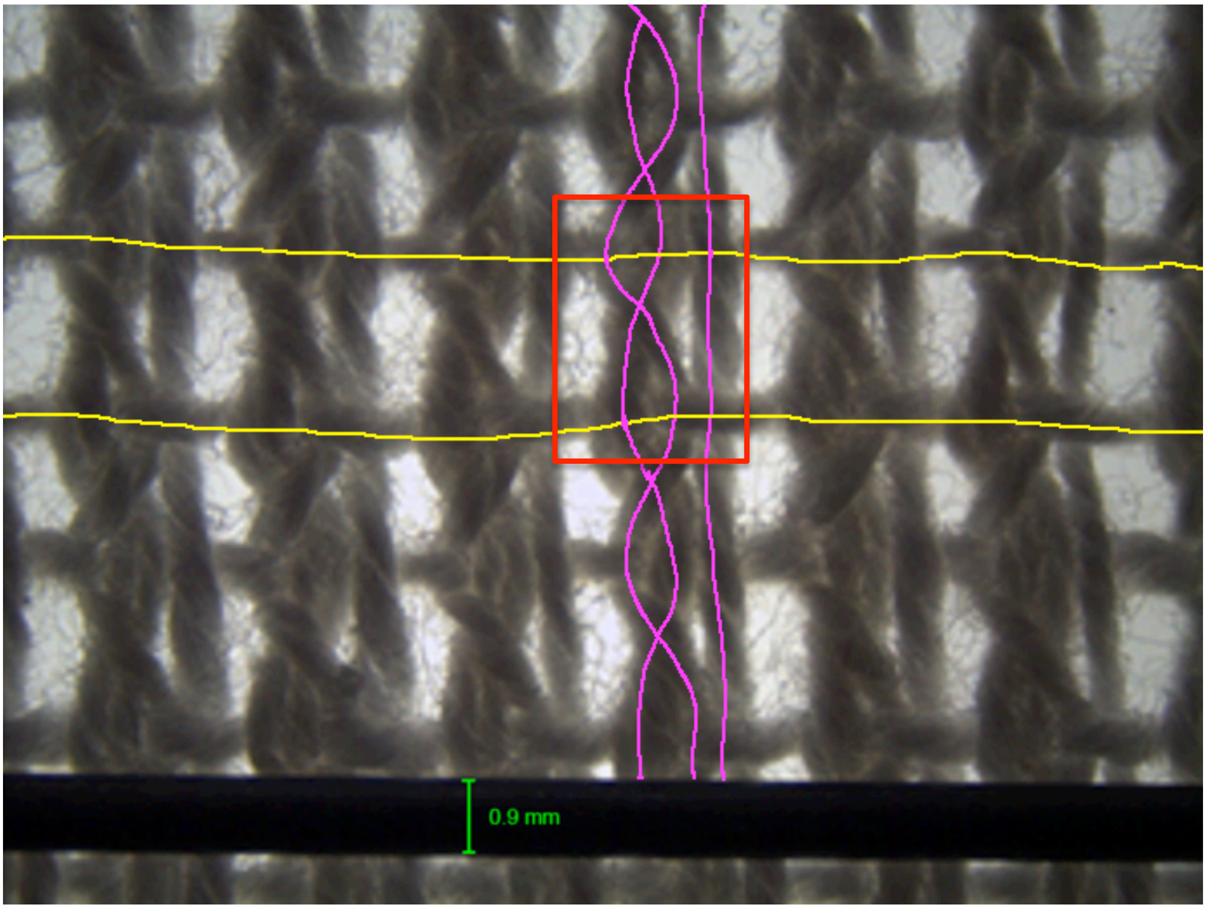


Image 6.8
Section D: Plain weave (b)
Stereomicroscopy – transmitted light
Lynn Tandler (2013)

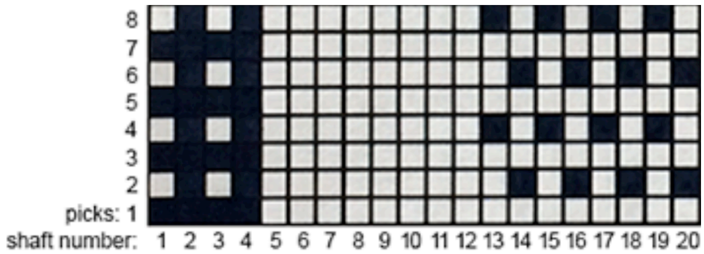


Figure 6.7
Plain weave (shafts 13-20) and leno lift (shafts 1-4)
Lynn Tandler (2013)

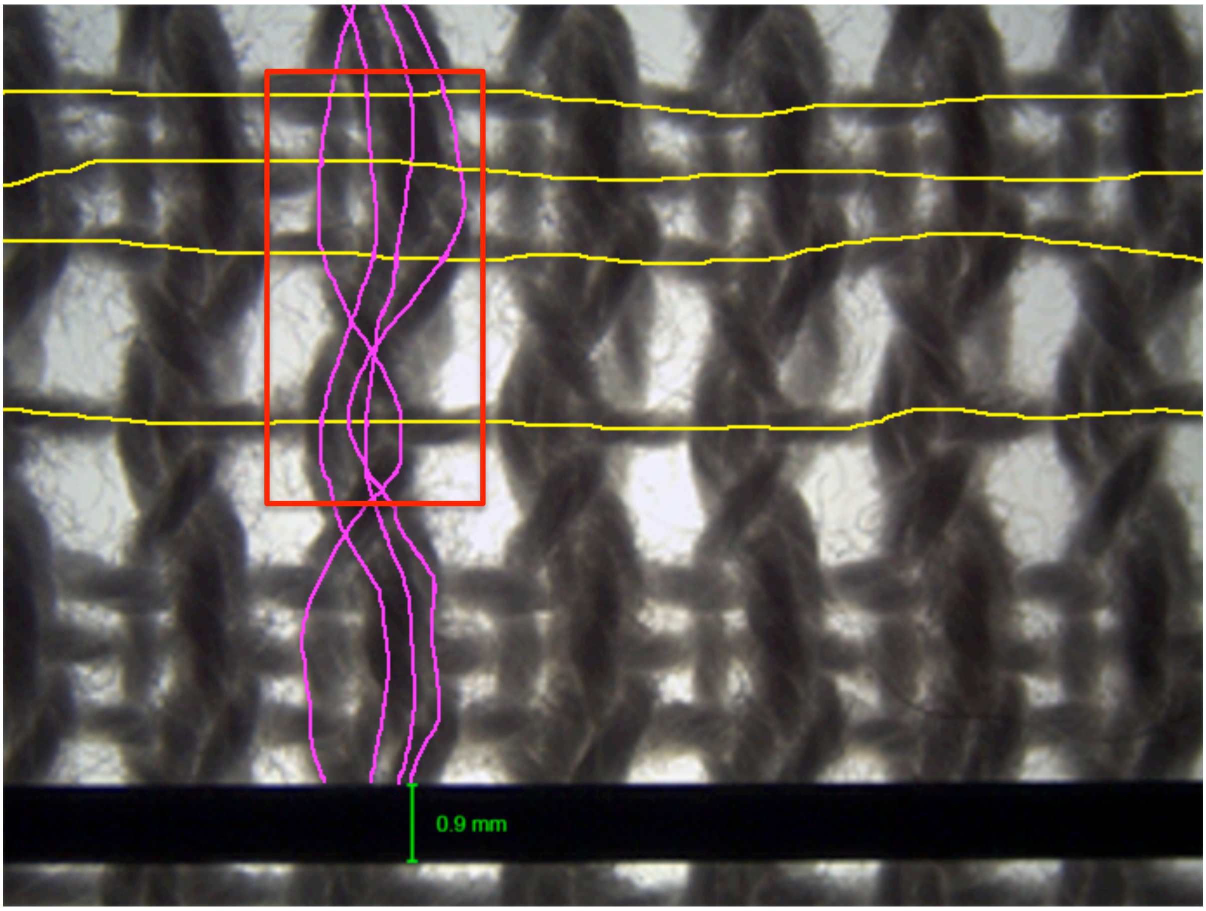


Image 6.9
Section D: Plain weave (c)
Stereomicroscopy – transmitted light
Lynn Tandler (2013)

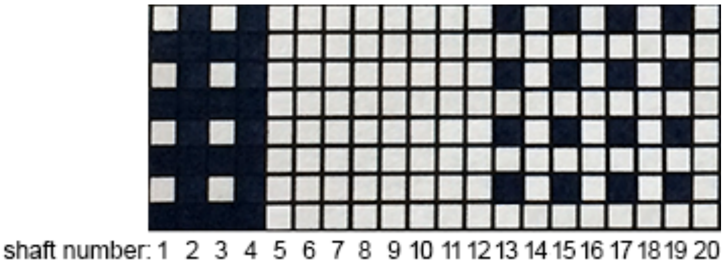


Figure 6.8
Plain weave (shafts 13-20) and leno lift (shafts 1-4)
Lynn Tandler (2013)

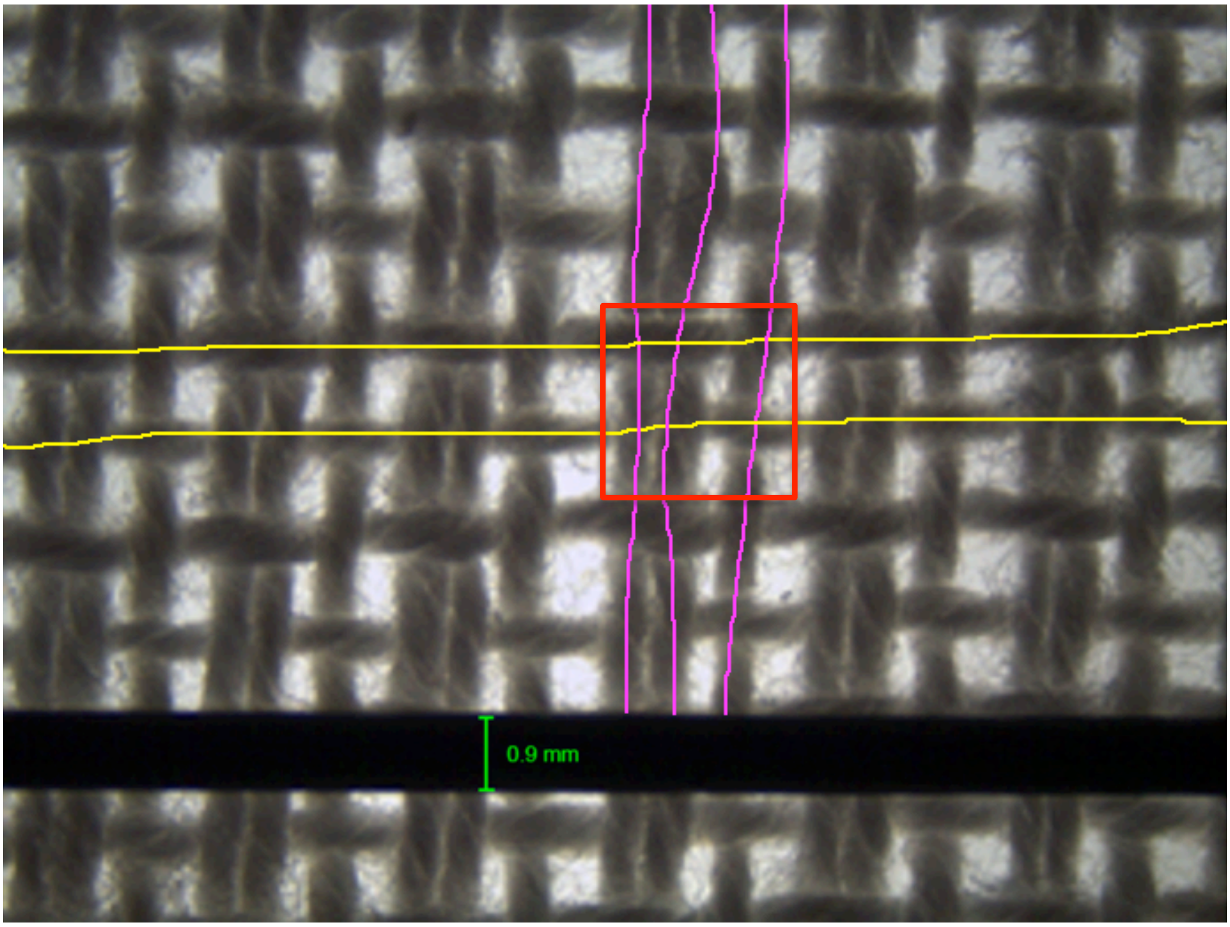


Image 6.10
Section D: Plain weave (d)
Stereomicroscopy – transmitted light
Lynn Tandler (2013)

Following this, eight weave structures were woven into the blanket warp – according to the threading plan of blocks A, B, C, D, E and F (figure 6.4, p. 103) - in order to challenge and compare the structure of plain woven leno geometries with other leno construction and hence to identify the most suitable structure for further exploration. The aim here was to explore how leno weaving can create intricate geometries with room for potential geometric change. The structures tested were a hopsack, 2/2 warp rib, 1/3 weft rib, 1/7 satin, 4/4 Z twill, 1/3 S twill, 1/2/1 warp rib, and 1/7 Z twill structure [images 6.11 - 6.18]. As a result, sample warp one yielded a total sum of 72 woven samples – out of which, eight samples are presented below from blanket warp section C as an example - demonstrating the operating mechanism of leno weaving and allowing further insights into the very elements that produce a leno twist. The weave structure units are marked below inside a red frame.

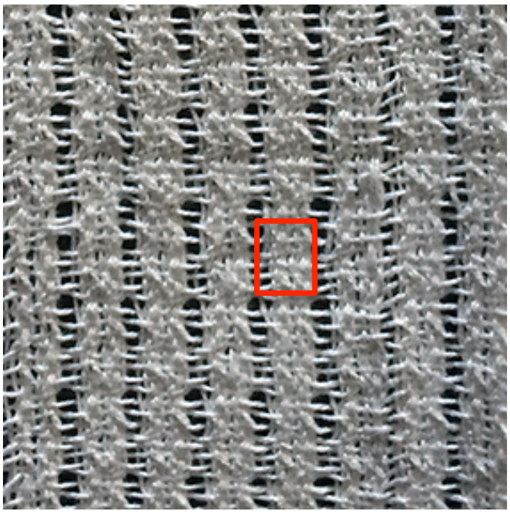


Image 6.11
Hopsack peg plan woven with leno lifting

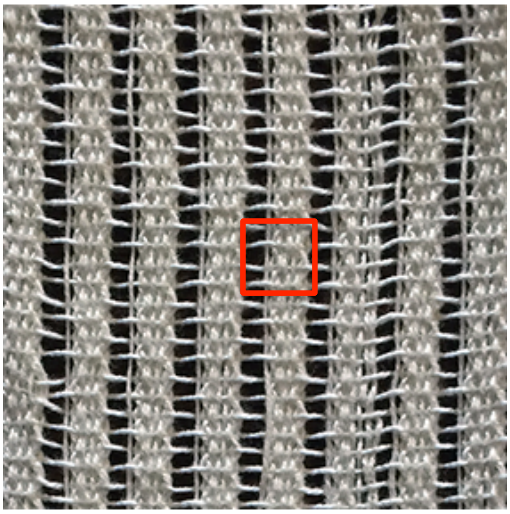


Image 6.12
2/2 warp rib peg plan woven with leno lifting

Digital photography
Lynn Tandler (2013)

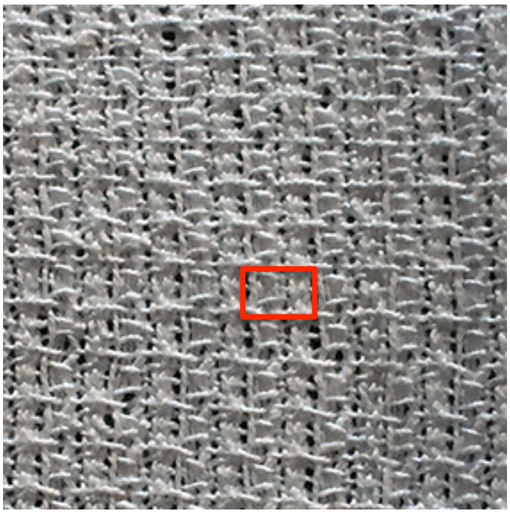


Image 6.13
1/3 weft rib peg plan woven with leno lifting

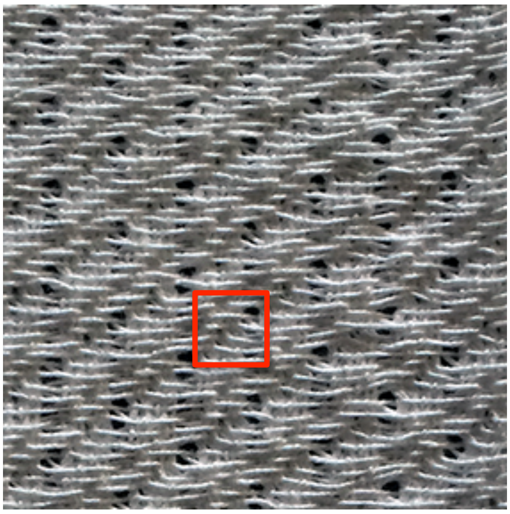


Image 6.14
1/7 satin peg plan woven with leno lifting

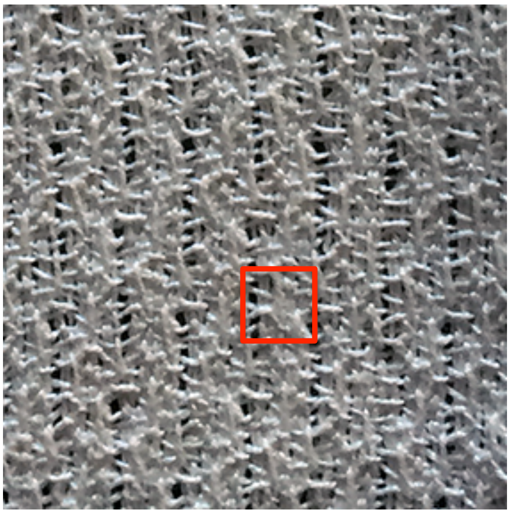


Image 6.15
4/4 Z twill peg plan woven with leno lifting

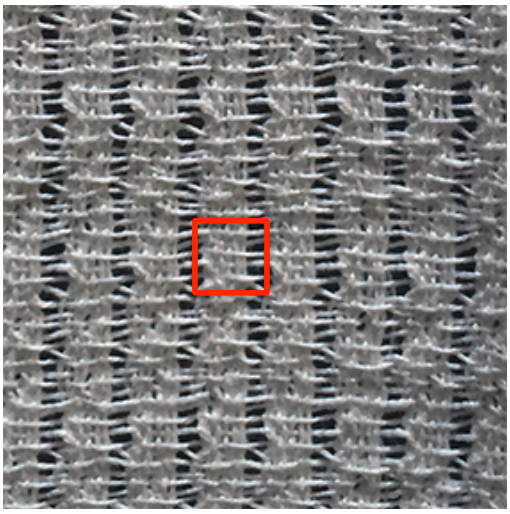


Image 6.16
1/3 S twill peg plan woven with leno lifting

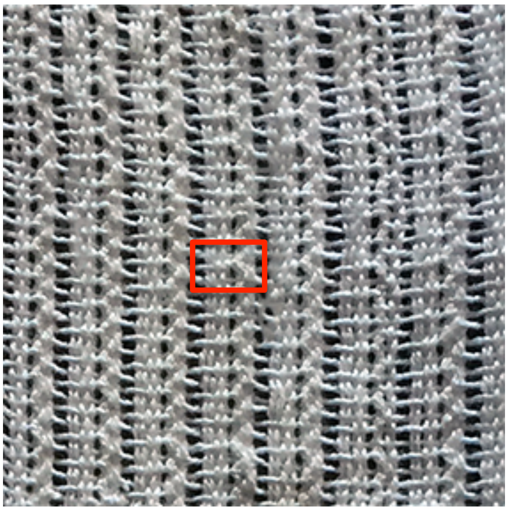


Image 6.17
1/2/1 warp rib peg plan woven with leno lifting

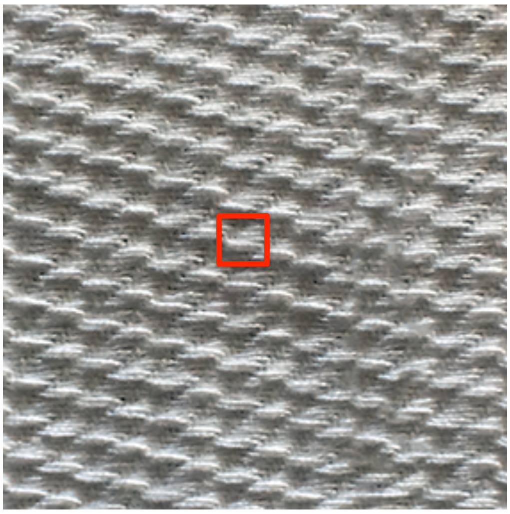


Image 6.18
1/7 Z twill peg plan woven with leno lifting

Digital photography
Lynn Tandler (2013)

Once woven, the samples were taken off the loom to be washed, steamed and pressed – a common practice by weavers – in order to release the building tension that was put on the warp ends throughout the duration of the weaving, following which the structures were analyzed. Upon analysis of the results only two sections out of the six – section C and D [figure 6.9] - demonstrated a good leno effect by creating both a stable geometry and an open weave structure, which potentially, upon further development, could generate a reversible movement within the structure. Sections A, B, E and F had mostly generated very tight woven architectures. This meant that there was very little room for movement to occur in a quest to create a novel reversible weave structure. Mostly, sample warp 1.1 proved successful with a lifting plan of plain weave, uneven 1/3 S twill, and 1/7 satin: these samples were investigated further in the following sample warp 1.2.

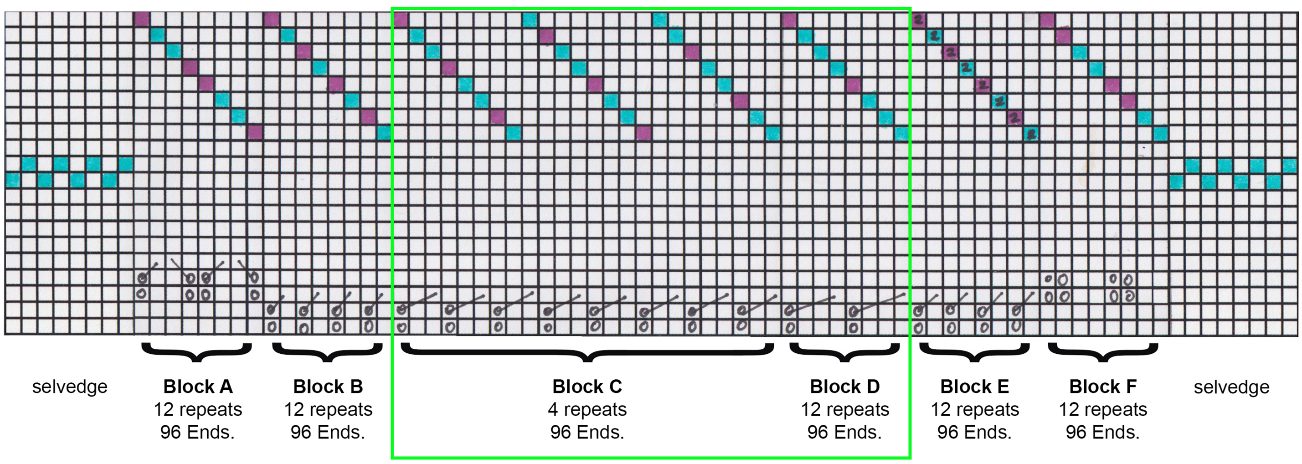


Figure 6.9
Sectins C and D from the original threading of smaple warp 1.1
Lynn Tandler (2013)

6.1.3.2 Sample warp 1.2

The aim of sample warp 1.2 was to further explore the potential for shape change movement in selected samples from sample warp 1.1. The objective was to repeat the warp threading of sections C and D from sample warp one, only this time also to increase the negative space inside the weaves and in doing so to accentuate the effects of the leno and stretch its boundaries.

A new warp was made from the same yarn used in sample warp one - 2/12's mercerized cotton yarns – repeating only the threading and loom set-up of sections C and D from the previous experiment. This time however, the warp ends were led through an open spaced reed - creating a different density across the warp with a total increase of 60% in warp width. Several weave structures were applied – each creating different alignment and density of threads: 1/3 S twill, 8-end sateen and two variations of plain weave (a and b).

The main variable on this sample warp was the density of the warp: an empty dent space was inserted between each group of warp ends. Images 6.19 – 6.26 show a microscopic documentation of two of the weave structures tested – 1/3 S twill and 8-end satin – both from sample warp 1.1 and sample warp 1.2 for purposes of comparison. At this stage the aim was only to increase the size of the structure unit and as a result to create more space for movement within the weave. The empty spaces within the structure unit were measured and the figures of their dimensions are presented in red lettering. Instead of using a red frame to indicate the structure unit of the weave samples, the images were taken at a higher resolution (magnification x 50) and therefore the images themselves capture the structure unit of the indicated samples.

While re-threading the warp ends through a more spacious reed setting it was expected that since the fabric width increased in width so also would the spaces within the structure unit expand and widen respectively. Contrary to this, the spaces within the structure unit of the 1/3 S twill, in section C, have decreased and halved in size from a close setting of the threads in sample warp 1.1 (image 6.19) to a specious setting in sample warp 1.2 (image 6.20). Through the same 1/3 S twill weaving in section D, the spaces within the structure units although increased in width have decreased in height between sample warp 1.1 (image 6.21) and sample warp 1.2 (image 6.22). Through a satin weaving in section C no significant change was notable between the tight setting of the warp in sample warp 1.1 (image 6.23) and that of sample warp 1.2 (image 6.24). And although no change was noticeable in width through a satin weaving in section D, the spaces within the structure unit had tripled in size between the setting of sample warp 1.1 (image 6.25) and sample warp 1.2 (image 6.26).

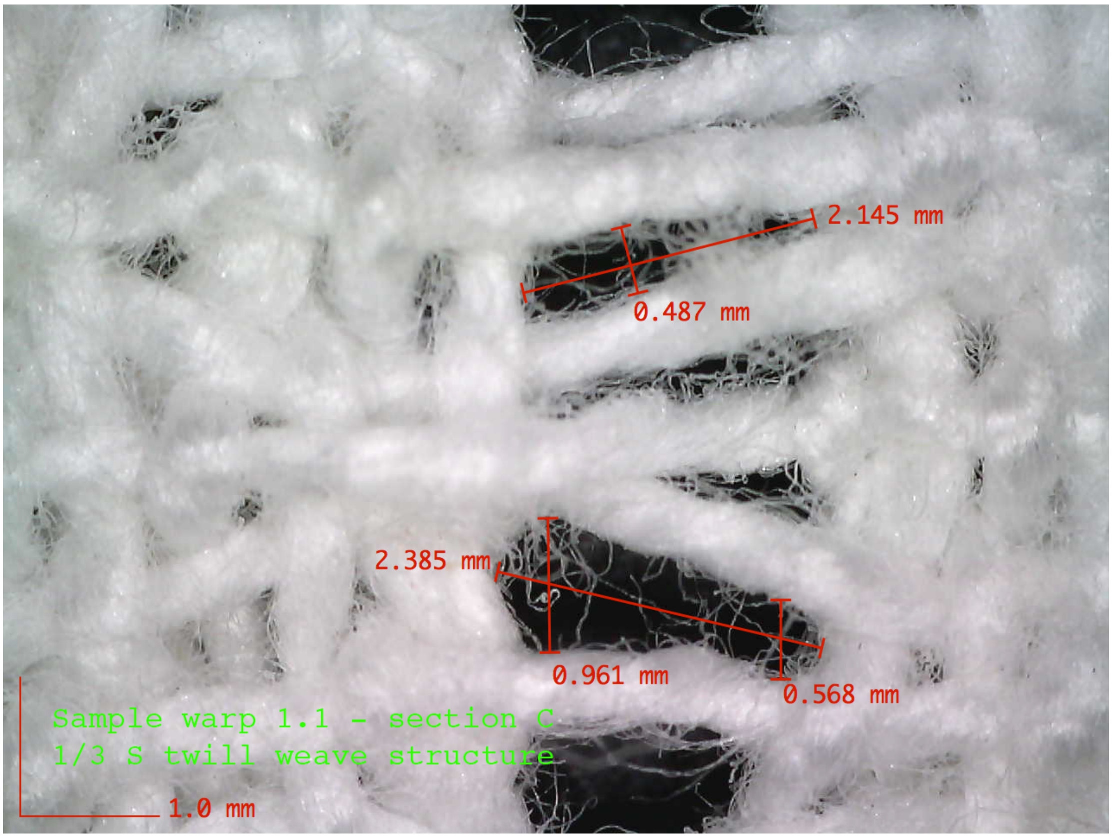


Image 6.19
Samples warp 1.1, section C, *1/3 S twill*
Dino-Lite USB microscope

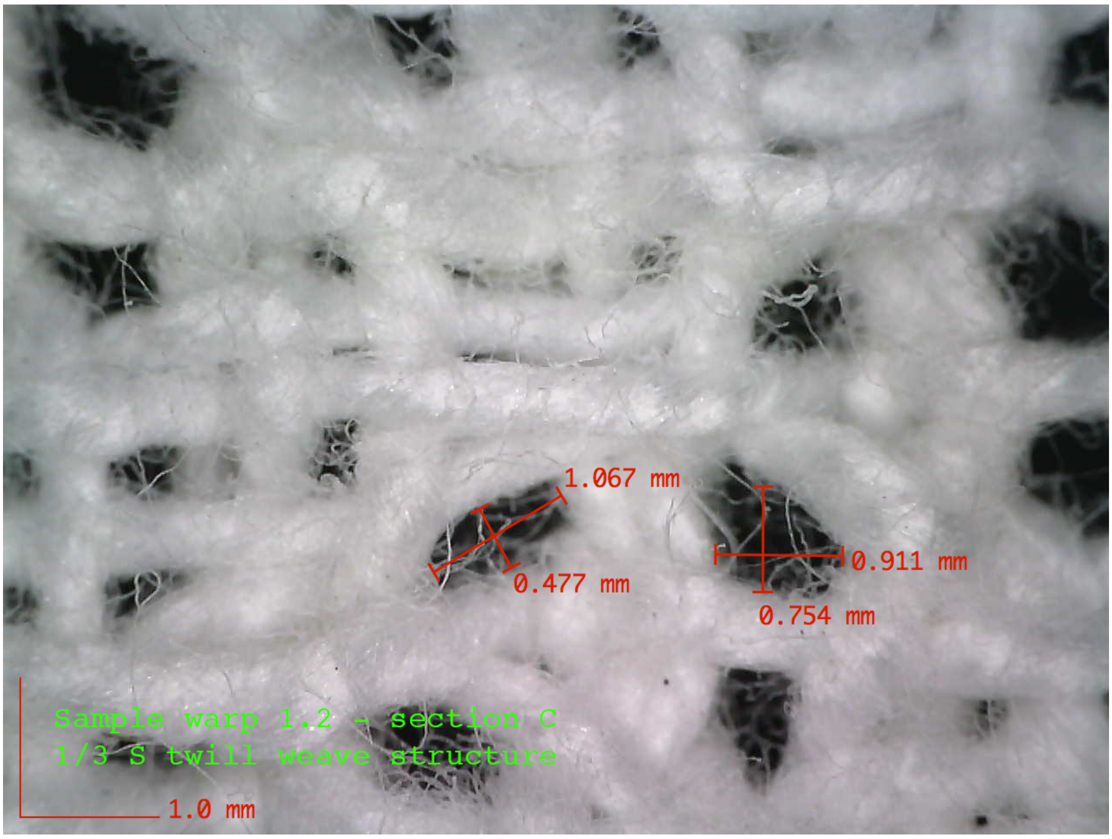


Image 6.20
Samples warp 1.2, section C, *1/3 S twill*
Dino-Lite USB microscope
Lynn Tandler (2013)

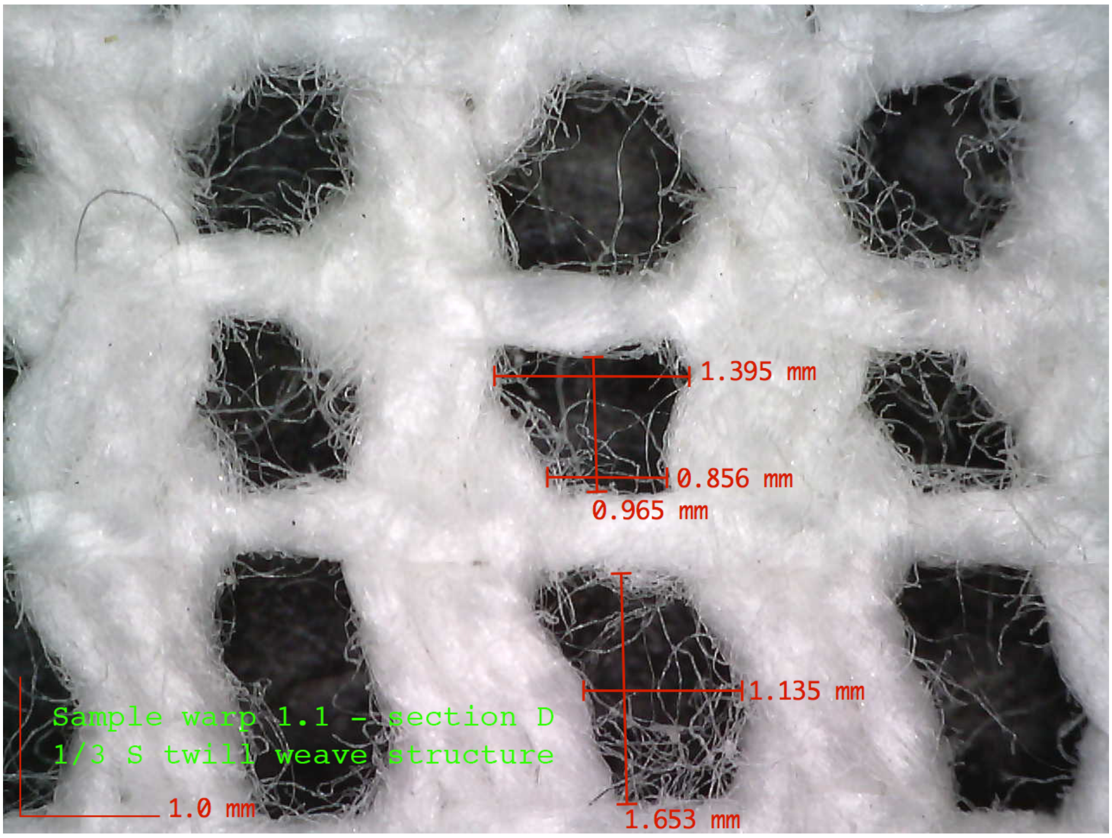


Image 6.21
Samples warp 1.1, section D, *1/3 S twill*
Dino-Lite USB microscope

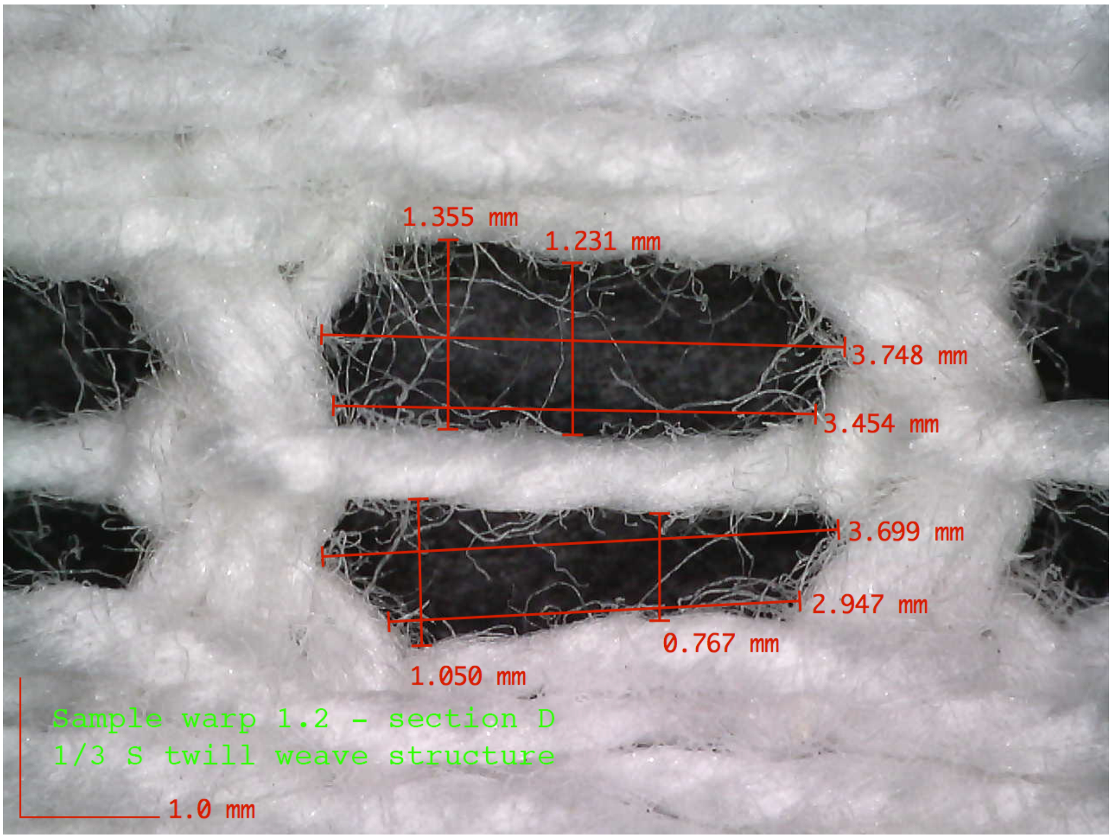


Image 6.22
Samples warp 1.2, section D, *1/3 S twill*
Dino-Lite USB microscope
Lynn Tandler (2013)

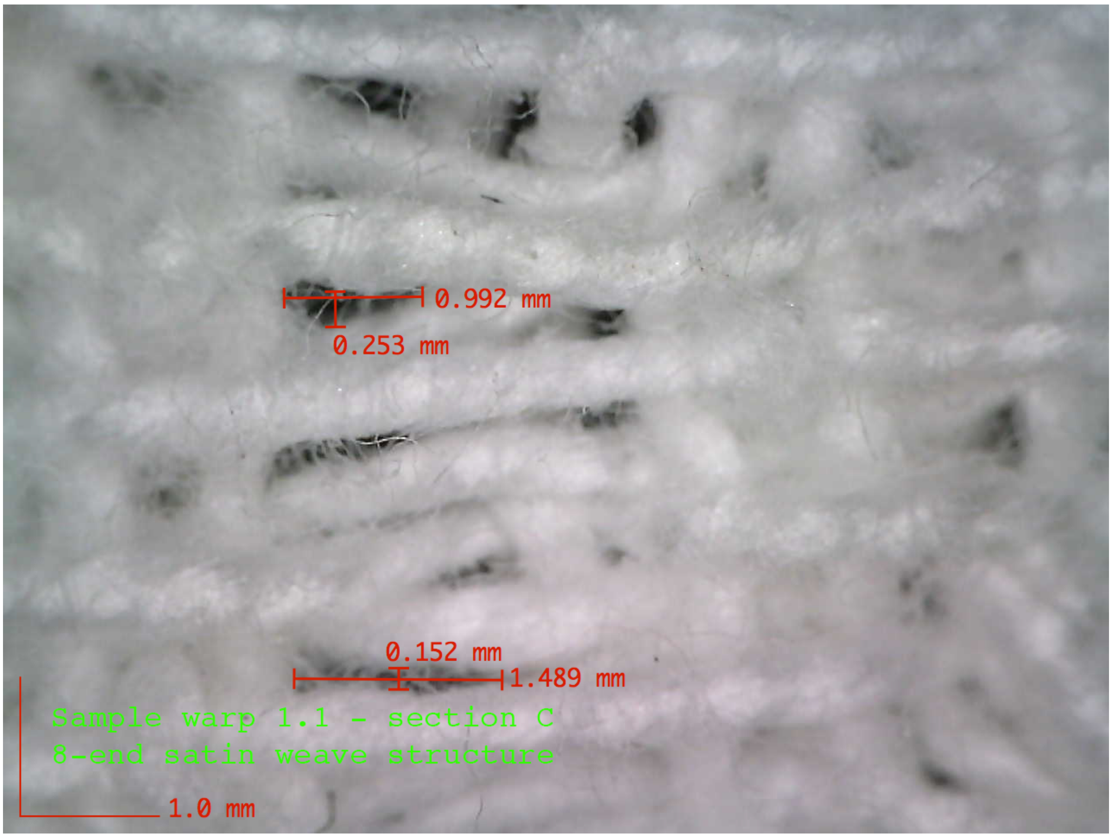


Image 6.23
Samples warp 1.1, section C, *8-end satin*
Dino-Lite microscope

Image 6.24
Samples warp 1.2, section C, *8-end satin*
Dino-Lite microscope
Lynn Tandler (2013)

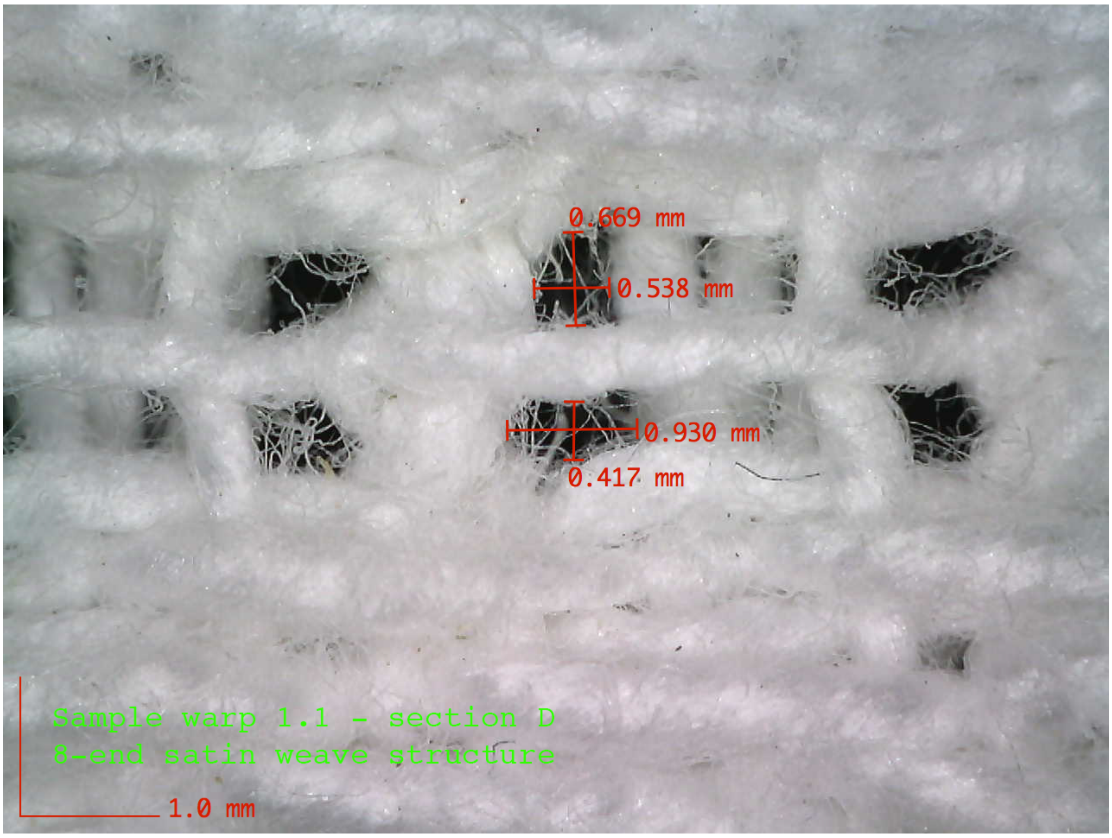


Image 6.25
Samples warp 1.1, section D, *8-end satin*
Dino-Lite microscope

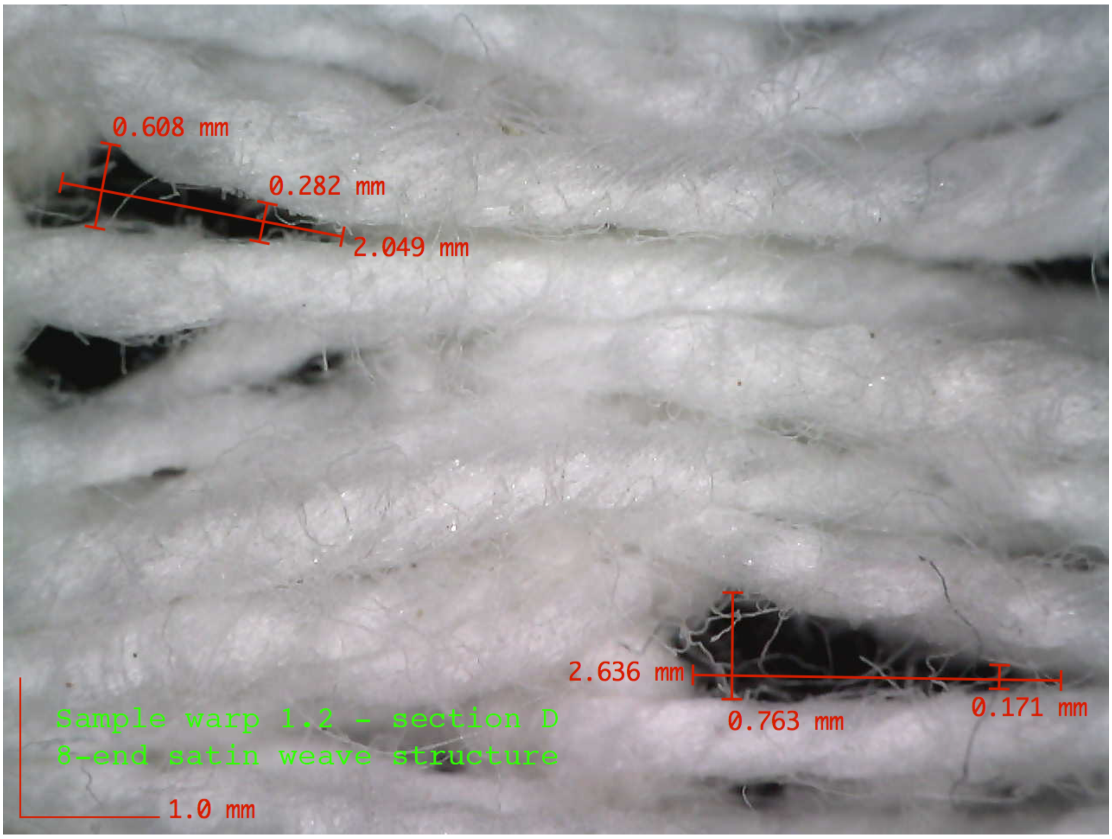


Image 6.26
Samples warp 1.2, section D, *8-end satin*
Dino-Lite microscope
Lynn Tandler (2013)

What this shows is that the reconfiguration of weave structures is not solely dependent on the setting of the warp and the density of the reeds. On the contrary, in such cases although the unit structure settings were expected to increase in size, the spaces within the structure unit actually decreased.

In order to explore both the possibilities and the limitation of leno weaving for enlarging and extending the structure units of some weaves, originally the warps in both case study 1 and 2 were wound onto the same beam - with no differentiation between leno and stationary warp ends. However, at this stage of the experiment the process of leno weaving was beginning to prove too strenuous on the warp. The tension that was applied onto the leno warp ends was too high, and the process of inserting the weft and weaving the samples gradually became more demanding. The leno warp ends had to ‘travel’ much further – with the added twist action on top of their interlacement resulting in the accumulated tension ending up creating an unbalanced warp with dramatic changes in the stress that was applied on various warp ends of the same cloth. This required continuously cutting the warp ends off and re-tying them in order to equalize and reset the tension. And although this was expected it also created much unwanted waste.

6.1.3.3 Sample warp 1.3

The aim of sample warp 1.3 was now to examine whether leno can be used as an elements within a larger – more complex – structure. Two objectives therefore were set out: (1) to overcome the difficulty within warp tension that arose through the process weaving of previous sample warps, and (2) to explore the minimum threading arrangements required for the production of a leno effect – reducing the amount of allocated shafts down from eight. In showing that leno can be used on only two shafts for example, leno structuring - it was hypothesized - could be used only as an additional element within a more complex structure.

The same yarn – 2/12’s mercerized cotton – was used in sample warp 1.3. This time the warp was wound onto two separate beams: the base cloth was wound onto the bottom beam of the loom, and the leno doups onto the top beam. The division of the warp ends onto two separate beams was done to control the individual tension of each group of threads, according to their unique motion of travel. The warp was divided into three separate sections - A, B, and C: in each section – unlike previous attempts – the design was only threaded through two shafts (section A), four shafts (section B) and additional two shafts (section C), as can be seen below [figure 6.10]:

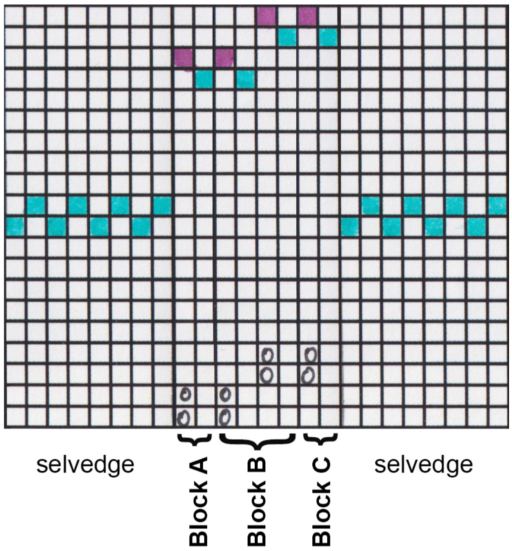


Figure 6.10
Sample warp 1.3 – threading plan
Lynn Tandler (2013)

Two variations of plain weave and a mock leno structure were woven, only this time none had created a leno effect: in all three weaves, each section was weaving a variation of a plain weave structure regardless of the difference in warp threading. Mock leno - which is usually used for the insertion of small holes to any standard weave – without the need for special leno doups to be fitted on - did not do so in this instance. And neither did any of the plain liftings. As a result no woven samples were considered successful: the combination of unique threading plan with a mock leno lifting and that of plain weave did not yield any lifts and / or leno fabric structures.

6.1.3.4 Sample warp 1.4

The aim of sample warp 1.4 was to attempt to control the effect of leno through the manipulation of headle repositioning: controlling the density, size and structure of the weave by verifying the number of ends led through each of the headles. By doing so, the aim presented in the description of sample warp 1.3 was kept in mind - where leno structuring could be identified and used as an individual element within what could be much bigger and more complex structuring system. However in sample warp 1.4 the threading of the loom and the action of weaving were spread over eight shafts. The ends in each repeat were threaded through only two headle sets. Therefore, even though the action of weaving occupied more shafts, and as a result was bigger in size, effectively only two shafts were working to form the weave. This was in line with the aim to establish the way in which the elements of leno weaving could be formed into an overall pattern.

Sample warp 1.4 was divided into two separate warps and wound onto two separate beams. The warp was divided into two sections - A and B [figure 6.11]: in section A, two warp ends were led through the same leno doup, which was placed on the right hand side to the repeat, followed by an additional seven warp ends were threading in a straight drafting motion. However, all seven warp ends – threaded across seven shafts – were led through a single dent space within the reed. In section B, three warp ends were led through the same leno doup, followed by additional three warp ends from the bottom beam threaded across three consecutive shafts and led through a single reed dent space. Two variations of plain weave as well as a mock leno weave structures were woven. However, in this case too, no new leno geometries were produced.

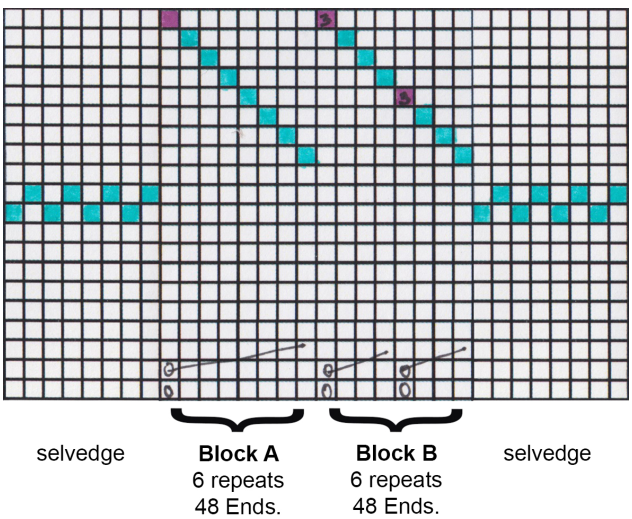


Figure 6.11
Sample warp 1.4 – threading plan
Lynn Tandler (2013)

6.1.3.5 Sample warp 1.5

The aim of sample warp 1.5 was to revisit the original notion of case study one, which was to create a mobile geometry through a novel use of leno weaving. This time however, sample warp 1.5 was set to explore whether and to which extent such possibilities exist within a point draft threading - rather than the previously explored straight draft threading.

The major difference between a straight threading and a point threading is in the type of pattern received in the weaving. In straight drafts [figure 6.12] the warp-ends are led through the shafts in a repeating increasing or decreasing order (1,2,3,4,5,6,7, and 8 or 8,7,6,5,4,3,2, and 1). As a result, any shape, introduced through the peg plan, repeats itself across the width of the cloth – according to the number of repeating shaft orders. Point threading [figure 6.13] on the other hand produces symmetrical shapes. The warp point threading order sees warp ends led through the shaft in an increasing and a decreasing order (1,2,3,4,5,6,7,8,7,6,5,4,3,and 2 or 8,7,6,5,4,3,2,1,2,3,4,5,6,and 7) – creating an arrow shape when drawn. Instead of complete motif shapes, only half shapes are drawn out and inserted into the lifting plan. Upon weaving, the point threading mirrors the lifting and in doing so creating a complete symmetrical shape as a result.

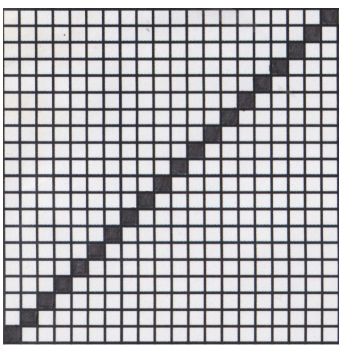


Figure 6.12
Straight drafting on twenty shafts

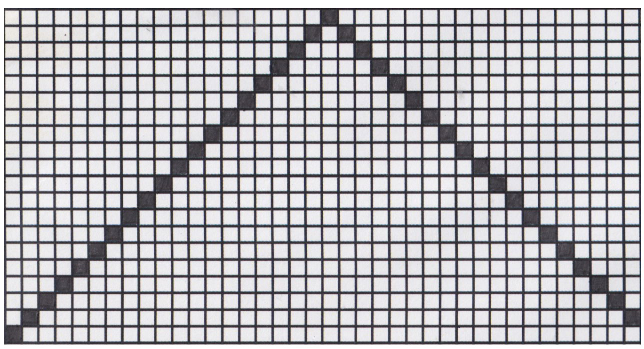


Figure 6.13
Point drafting on twenty-shaft setting

Lynn Tandler (2013)

In sample warp 1.5 two directions of leno twists were introduced simultaneously into a point draft threading where different shafts controlled different directional leno doup group [figure 6.14].

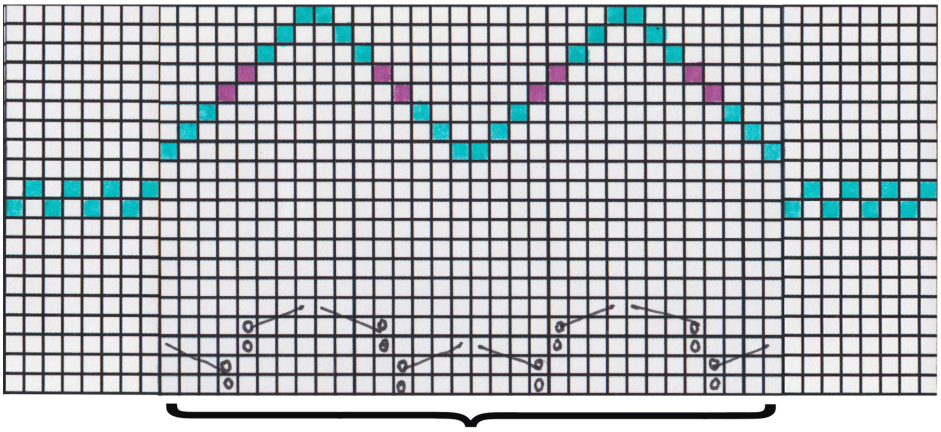


Figure 6.14
Sample warp 1.5 – threading plan
Lynn Tandler (2013)

Repeating the warp set-up presented through sample warp 1.3 and 1.4, sample warp 1.5 was too divided into two beams in order to better control the tension and the weaving of leno structures. The warp ends were led through an 8-size reed, with four ends in a single dent leaving one spaced dent empty between each insertion.

Five different weave structures were selected and used based on their thread arrangement and density, for the purposes of comparison: two variations of plain weaves, two variations of 8-ends honeycomb structures, and one basket weave. The aim here was to challenge the extent to which the leno woven geometry changes in response to the mirroring of the threading plan.

A total of five woven samples were produced, out of which only two samples - weave sample no. 1 and no. 5 [images 6.27 and 6.28] - showed some good potential for creating reversible weave structures. While demonstrating a stable and successful woven alignment (p. 96), both samples also showed large negative spaces within the woven structure units and diagonal angles, created by the traveling threads with a potential for creating more elaborate shapes, such as shown in figure 6.3 (p. 101).

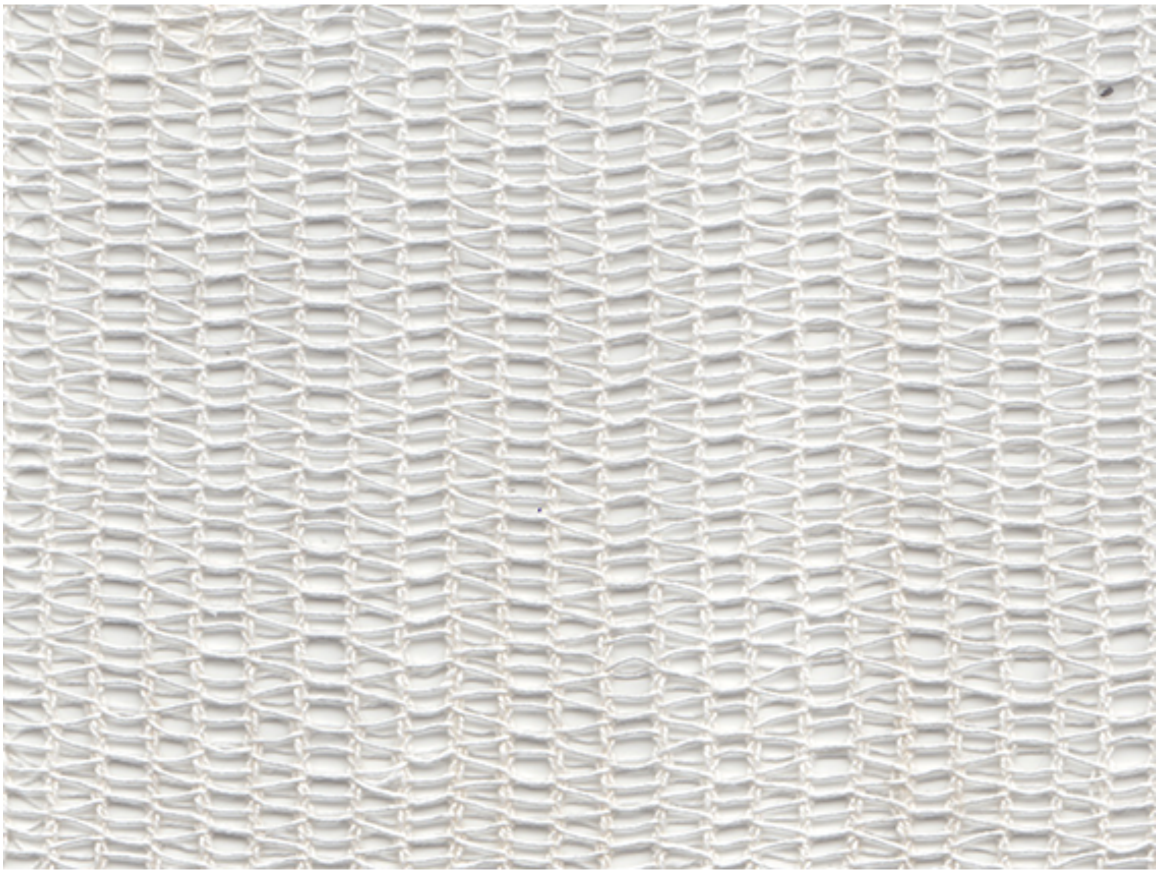


Image 6.27
Sample warp 1.5 – leno plain weave

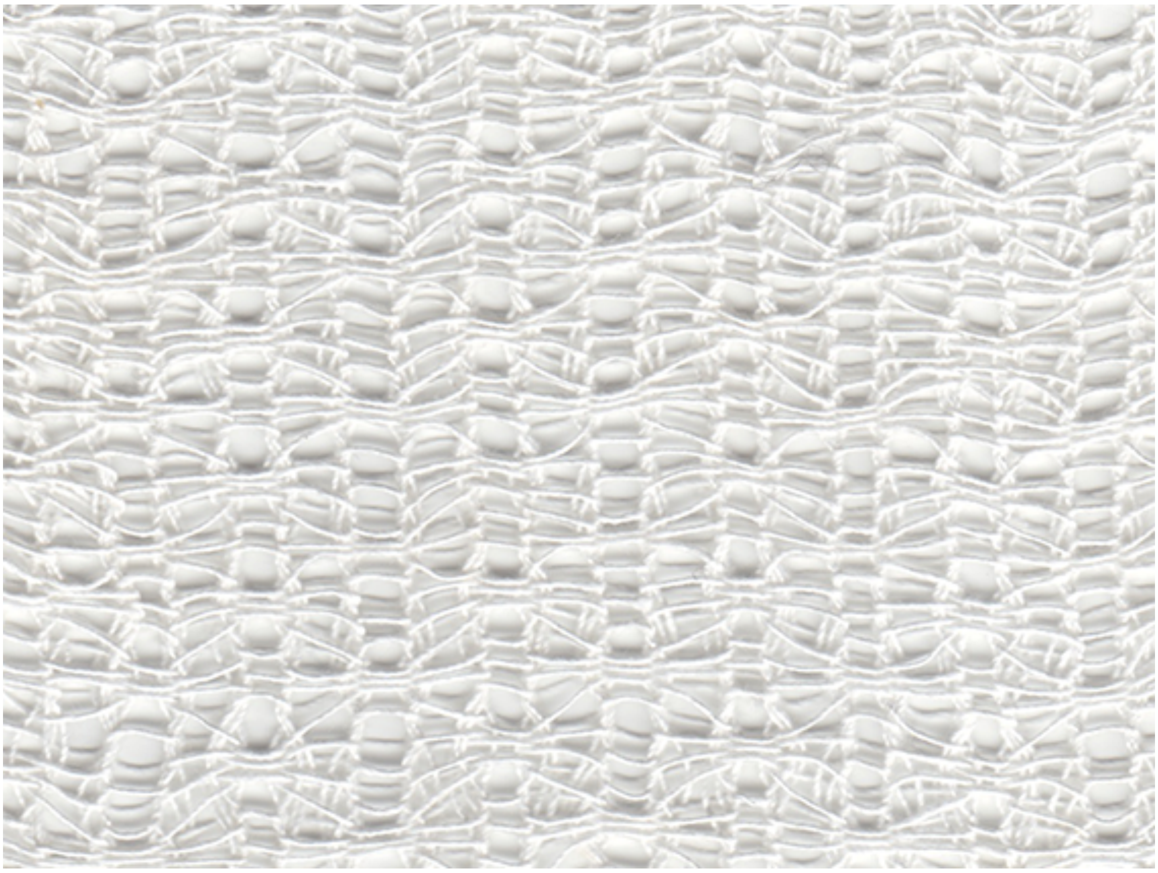


Image 6.28
Sample warp 1.5 – leno basket weave
Digital photography
Lynn Tandler (2013)

6.1.3.6 Sample warp 1.6

The aim of sample warp 1.6 was to further explore the geometry of sample no. 1 (image 6.27, p. 121) and that of sample no. 5 (image 6.28, p. 121) from the previous sample warp (sample warp 1.5). To do so, the gaps in the reed have been removed and as a result, the warp became denser. Four structures were woven in the form of a basket weave and three variations of leno weft ribs. As a result, four hand-woven samples with complex yarns arrangements were produced [images 6.29 - 6.32].

Image 6.29
Sample warp 1.6 – leno basket weave
Digotal photography
Lynn Tandler (2013)


Image 6.30
Sample warp 1.6 – leno 2/2 weft rib (a)

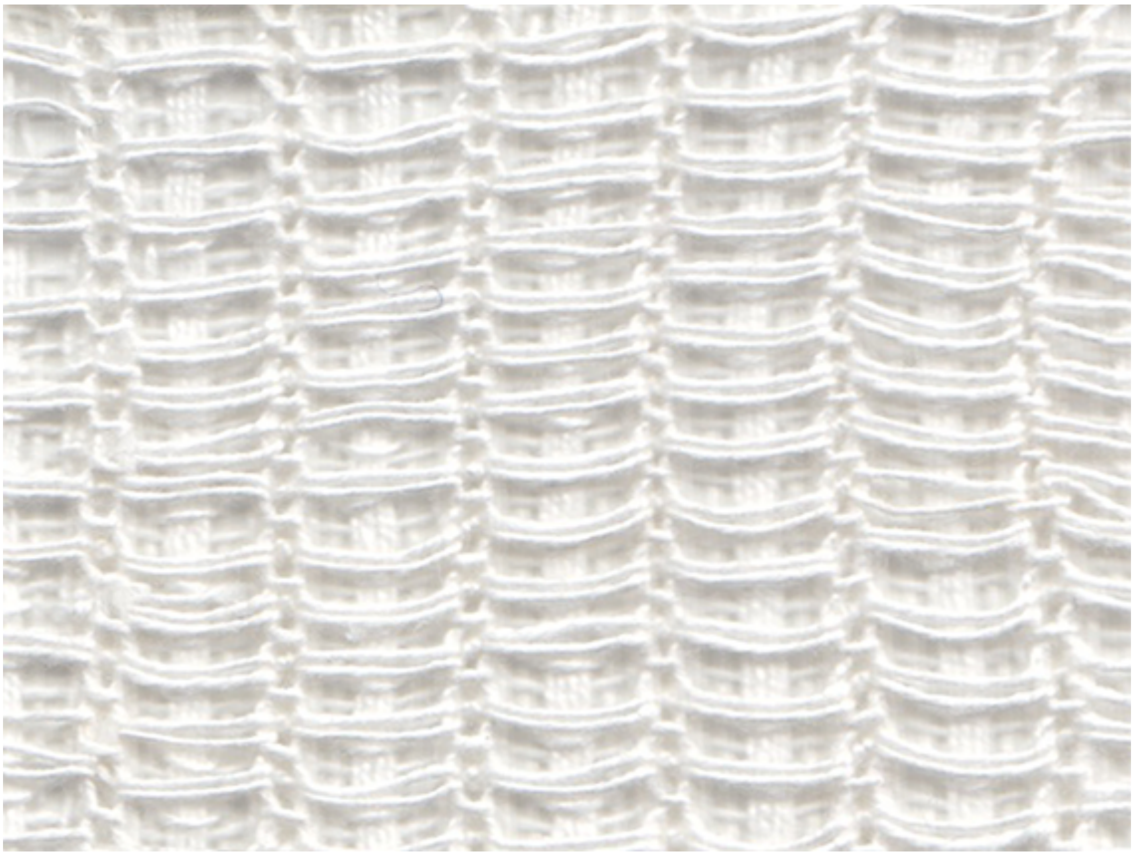


Image 6.31
Sample warp 1.6 - leno 2/2 weft rib (b)
Digotal photography
Lynn Tandler (2013)

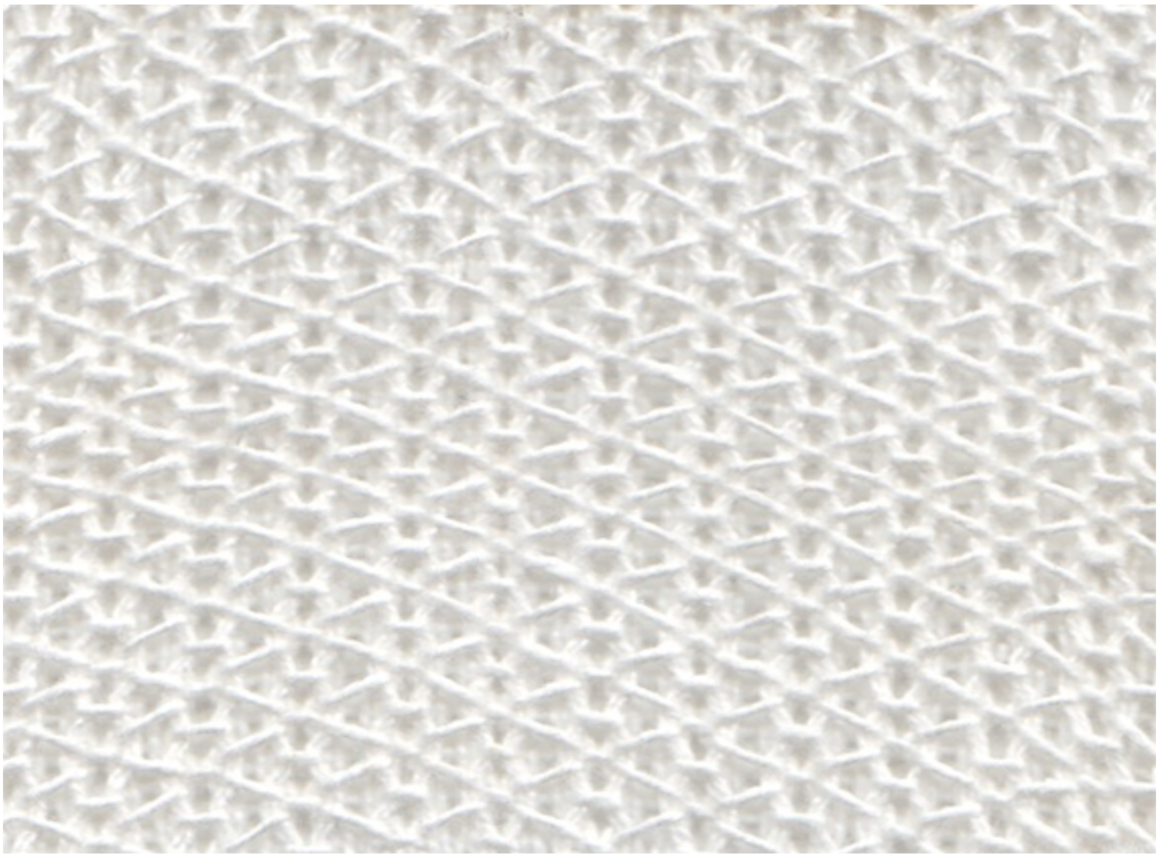


Image 6.32
Sample warp 1.6 - leno 2/2 weft rib (b)
Digital photography
Lynn Tandler (2013)

With the decrease in warp width and increase in warp density, the geometry of the weave structures and their structure units had changed. The creation of a 45 degree angle in travel movement of the threads was now beginning to establish and manipulations of the structure as a whole were starting to take shape.

6.3.1.7 Sample warp 1.7

Investigating the structures further, the aim of sample warp 1.7 was to analyse a single weave from sample warp 1.6 in order to understand in greater depth the operating mechanism of the leno weave structures and isolate the movement of each individual thread within the system. In order to do so, selected warp ends were coloured in black, blue and brown according [figure 6.15]. Woven sample no. 7 from sample warp 1.6 was used as an example, and woven again with the new yarn colour code installed in place.

This weaving shows the travel movement of each thread within the repeat: two black threads were placed in the position of leno ends twisting to the left, two blue threads were placed in the position of leno ends twisting to the right, and four additional brown threads were placed at the edges of the point draft threading as static weaving warp ends. All coloured yarns - which were added onto the weave - were 2/12's mercerized cotton threads.

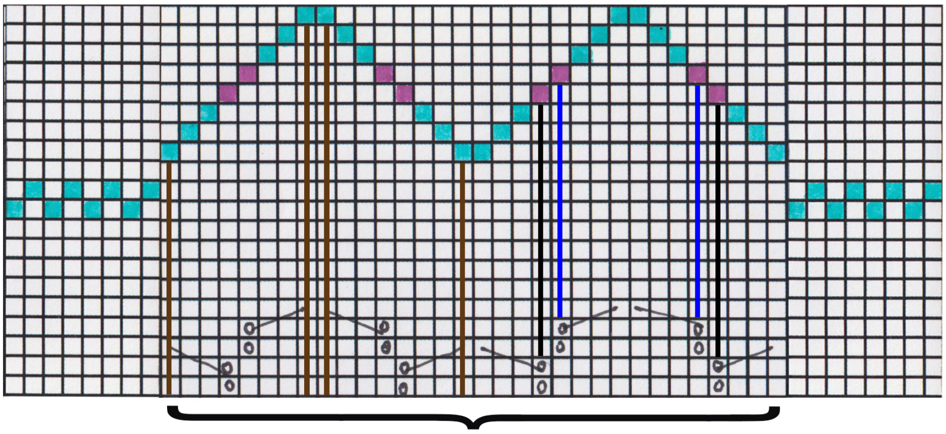


Figure 6.15
Sample warp 1.7 – threading plan
Lynn Tandler (2013)

One long sample was woven to allow a close inspection of the precise travel movement of each of the component threads: a 2/2 weft rib weave structure was woven normally for four picks and a 2/2 weft rib leno (a) – such as shown in image 6.30 (p. 123) - was then woven for four picks after [image 6.33].

Apart from distinguishing the movements of selected warp ends across the sample, the coloured threads were also used to track the exact movements of some wefts. Selected unit structures were examined closely with coloured wefts [images 6.34 and 6.35]. Here, the same weave unit structure is shown from the front and from the back. As shown before, at the bottom of each image a graphene rod (0.9mm in diameter) was placed to give an indication of size and scale.

Image 6.33
Colour indication of leno weaving
Lynn Tandler (2013)

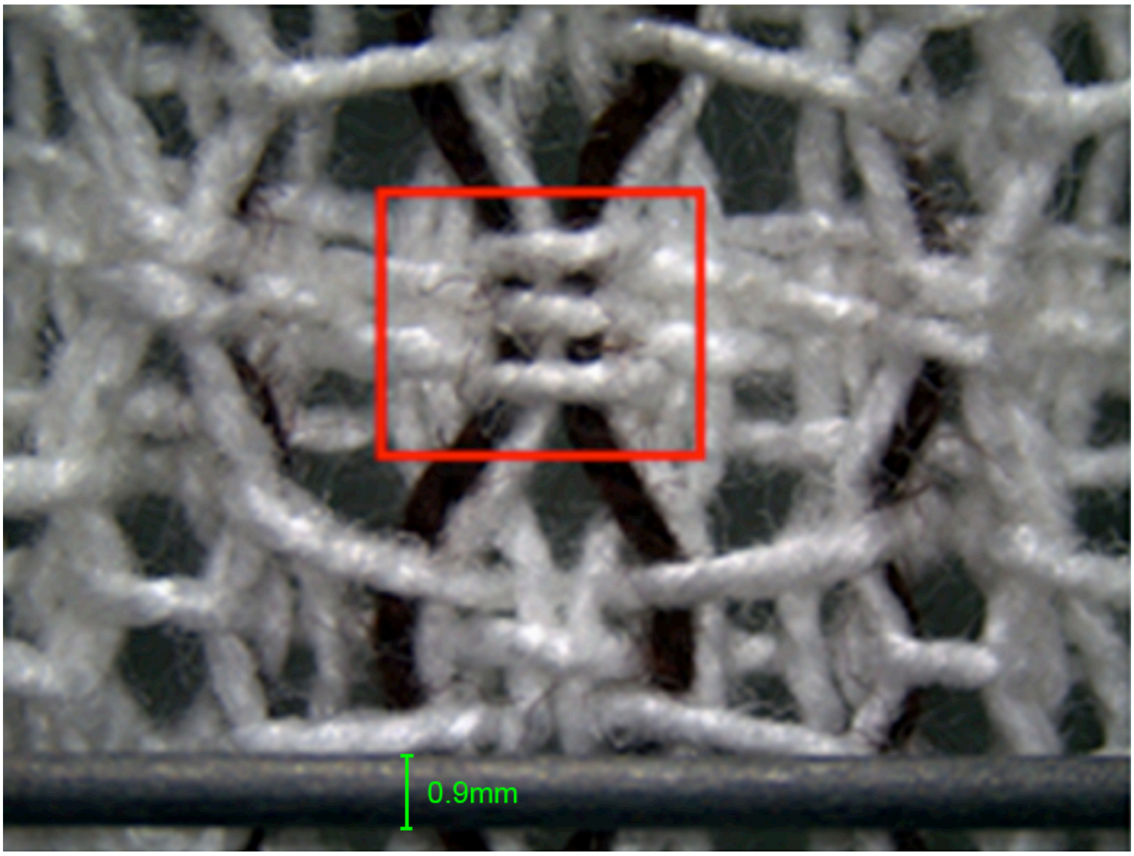


Image 6.34
Woven sample E (front) – stereomicroscopy (reflective light)
Examined structure unit in side red frame

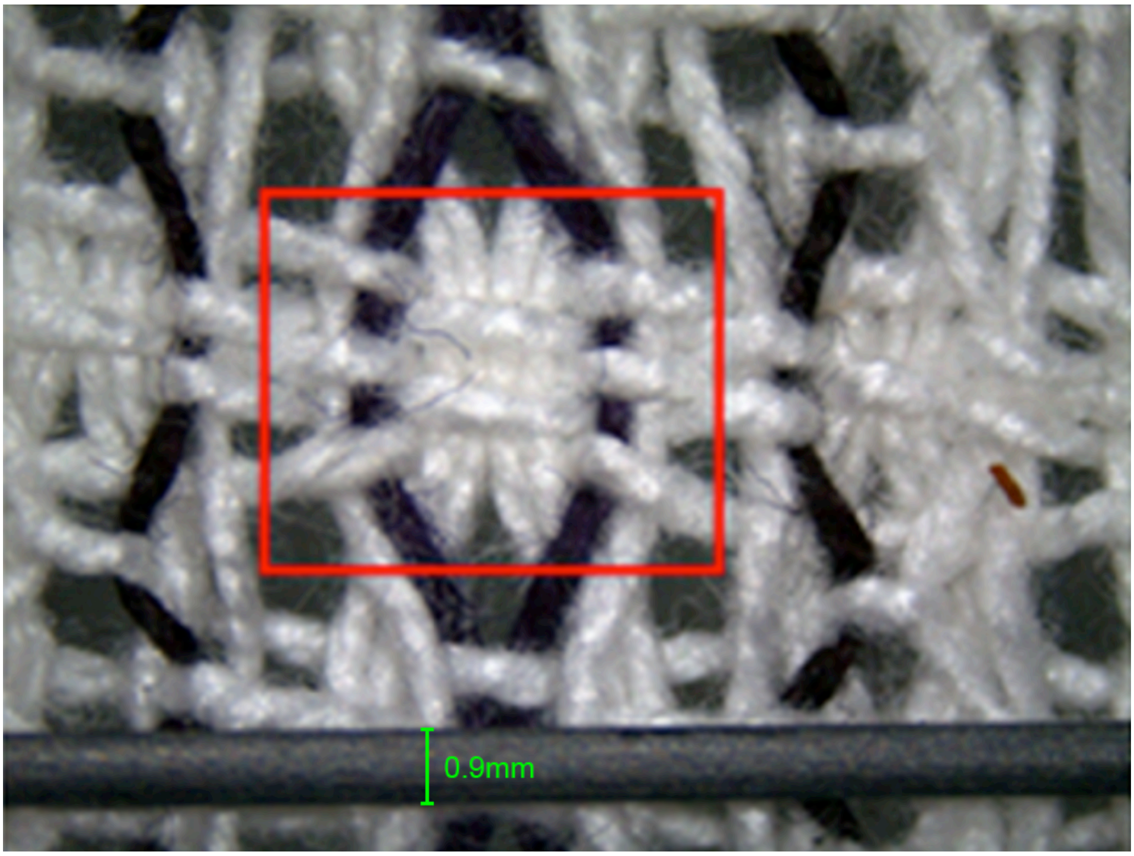


Image 6.35
Woven sample E (reverse) – stereomicroscopy (reflective light)
Examined structure unit in side red frame
Lynn Tandler (2013)

While examining and analyzing the woven sample from sample warp 1.7 (image 6.33, p. 126) the movement of the threads was established but at the same time, no movement was occurring within the structure unit itself. At this stage, it was still unclear whether the structures was not altering due to (a) the pressure that the leno twists applied onto the adjacent warp ends, or (b) whether it was down to the choice of yarns that were applied to the setting of the warp: the yarns were meant to be sliding over one another when pulled, using the length of the yarn when tensioned and stretched, as tracks.

The secured twists created by the application of leno weaving were important to the creation of new woven structures. Only with the aid of leno twisting such new woven shapes were able to retain their integrity and mechanical stability. With that in mind, it appeared to have not been the stress of the twists but rather the lack of sliding movement across the tracks. The hairiness of the 2’12’s cotton yarns and course surface roughness had caused any mobility within the structure to cease.

6.3.1.8 Sample warp 1.8

Lastly, the aim of sample warp 1.8 was therefore to test the role that yarn type and structure have on the working mechanism of leno weaves, and in particular how the properties of different yarns affect the behaviour of leno woven structures. For this purpose, a stiff monofilament Nylon was chosen instead of the 2/12’s mercerized cotton yarns previously used in sample warps 1.1 till 1.7. This particular monofilament yarn [image 6.36] was selected due to its distinctively smooth surface roughness, its homogenized thickness and equally round cross-sectional shape throughout its length.

Nylon monofilaments are known for their unique mechanical properties: they have very high tensile strength and relatively low modulus, which makes them strong and stiff textile components for weaving. Due to their high stiffness they also have a low drapability, which ensures that the fabric sample will have high structural integrity, and the structures will not deform once taken off the loom. The smoothness of the

Nylon monofilaments could potentially, it was thought, allow some structural stability whilst allowing at the same time for some sliding movements to take place.

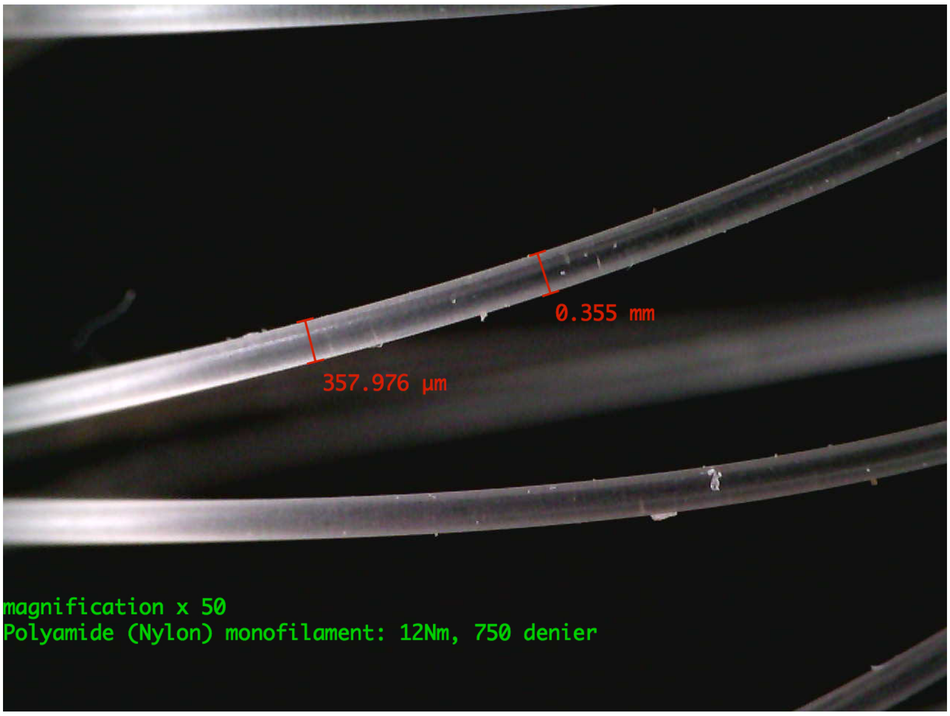


Image 6.36
Clear Polyamide (Nylon) monofilament
Dino-Lite microscope
Lynn Tandler (2013)

The monofilament warp was made out of clear 750 denier (Nm 12) monofilament yarns, threaded in a point draft over eight shafts [figure 6.16]. This threading is identical to the threading of sample warp 1.5, which thus far held the most prominent results due to its dual twisting direction and creation of open mirrored structures. The warp monofilaments were spread out in relatively large spaces: two monofilament warp ends were threaded through the same reed dent in half an inch spaces from one another.

Two samples were woven: the first as a plain weave leno, and the second only as a repeating leno weaving only lifting the even picks of 1, 3, 5, and 7. But even after removing the samples from the loom the leno twisting were too tight to travel along the monofilament axis, and the net-like structure - even though somewhat flexible due to the empty spaces, holes and gaps - had yet no mobility in its weave structure.

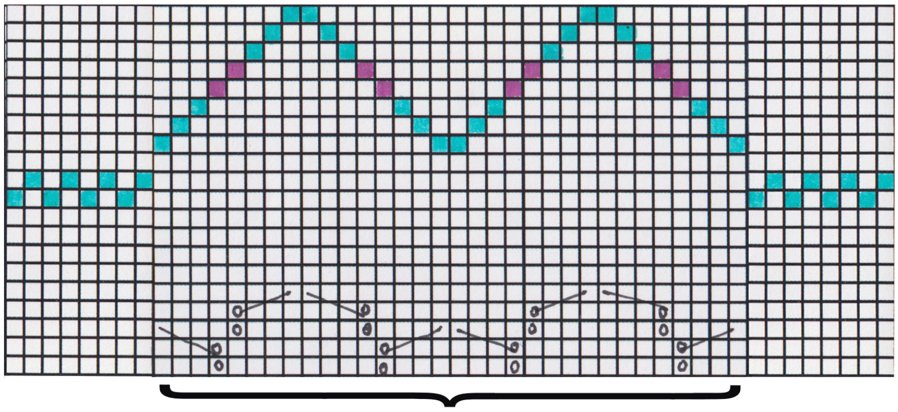


Figure 6.16
Sample warp 1.8 – threading plan
Lynn Tandler (2013)

6.1.4 Case study 1 – Discussion of results

In total, 90 hand woven samples have been produced throughout case study 1. During the initial investigations the basic operating mechanism of leno weaving were examined through the weaving of 72 different samples - out of which 22 samples showed a noticeable leno effects and 6 woven samples showed a degree of promise for further investigation into the creation of reversible weave structures.

The aim of case study 1 was to examine leno weaving as an outlet for geometric and mechanical change within weave-structures. Once sufficient knowledge into leno weaving was established (sample warps 1.1, 1.2 and 1.3), creative drafting took place in order to manipulate leno weaving and explore their operation beyond conventional norms. Some general principles from mechanics were taken as an inspiration for the design thinking that ended up governing the planning of the sample warps - and the elements within conventional leno weave-structures were converted into 'locks, tracks and hinges'.

Through processes of creative design, drafting, loom set-up and weaving - and based on my established experience as a weave practitioner – the investigation of case study 1 into the creation of novel woven geometries through the adaptation and modification of leno weaving revealed that even the smallest of changes in the positioning of the leno doups and static warp ends could dramatically change the structure of a fabric. Changes in warp density too, had dramatic repercussions on the geometry of the weaves and their mechanical behaviour across the cloth. Different shapes and sizes of 'holes' – such as those seen through the negative space within the structure units of some weaves - were created through the weaving of different structures where only equal lifting of both odds and even leno picks had produced a successful leno structure.

The leno structures produced through this case study were stable and secured, meaning that the geometry of the weaves was not distorted through process of handle and manipulation. Although this shows how new weave structures can be developed, the premise of this case study was to introduce mechanical movement within the structure unit of the weaves in order to make way for creating a reversible weave structures – ones with dual mechanical states.

On the cotton warps, the leno twists have proved useful as locks by securing the twists tightly in place and creating angular yarn travel movement within the structure units. However, on these warps the surface roughness of the cotton yarns, with the tights twists, did not generate any sliding movement. By changing the yarn into a smooth Nylon monofilaments, the aim was to loosen the grip and yarn friction and in doing so allow the structure unit to shift. Nonetheless, in this instance too, no movement within the structure unit of the weaves was generated. The leno twists applied onto the structure were not tighter than those applied to the cotton warps however they still proved too secure to allow any travel along the adjacent axis. It was therefore concluded that because the grip level of the leno twists is hard to repeatedly control leno interlacements cannot be used as so-called 'levers' to reversibly slide open the angular points within the structure.

6.1.5 Case study 1 - Further investigation and tool making

Yarn count, as shown before, defines the fineness or coarseness of a yarn. Furthermore, reeds are used to arrange the warp threads and keep them aligned throughout the weaving process – allowing a constant pre-determined warp width.

The numerical name of the reed corresponds with the number of dents it holds per cm or inch unit length. The most common is a straight reed, but other reeds with more elaborated spacing designs can be found in order to insert various fabric densities across the cloth. Curved weft hand-woven fabrics for example, were reported by Thomas (2009), as a production methodology for new woven shoes (Thomas, 2009).

Throughout case study 1 the effect of the spacing of the threads across the warp had shown to have a great impact on the geometry of the leno weaves. And these have been determined by the size of the reed. Reeds not only influence the density and the weight of a cloth, but with different shapes and various distributions of dents across its width, according to Thomas (2009), reeds can also affect the bias stretch of the cloth. Their shape and dent distribution therefore have great effects on the physical and mechanical properties of the cloth.

Reeds come in various densities – usually through the identification of number of dents (i.e. space bars) in centimeter or per inch. For examples, warps with a total width of one hundred ends could be threaded through several reeds in order to achieve different fabric widths. These are illustrated in figure 6.17, below:

Total warp ends	**Reed number**	**Ends per dent**	**Ends per inch**	**Total width of fabric**
1000	10	2	20	50 inches
1000	10	4	40	25 inches
1000	20	4	80	12.5 inches
1000	25	4	100	10 inches

Figure 6.17
The effects of reed count on the density and width measurements of warps
Lynn Tandler (2013)

Case study 1 has demonstrated that although some threading and lifting plans do effect the formation of leno weaving the density of the reed is crucial. And as a result, only so much can be changed in leno weaving and conventional weaving technologies to allow the creation of new weaving geometries.

To overcome this, I designed a new headle – one that can change its position and travel across the width of the cloth. The new headles – presented in figures 6.18 and 6.19 - developed specifically for the purposes of this research are effectively half heddles: they are designed to only attach to the bottom of the shaft. Their top part is situated in warp height half way through the height of the shaft and is attached to a rotating arm, which allows it to travel from one side to another. The length of the arm was designed to be altered, and depending on its size it can create various hole-spaces [figure 6.20].

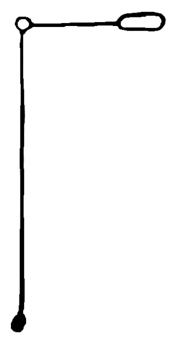


Figure 6.18
New proposed headle
Lynn Tandler (2013)

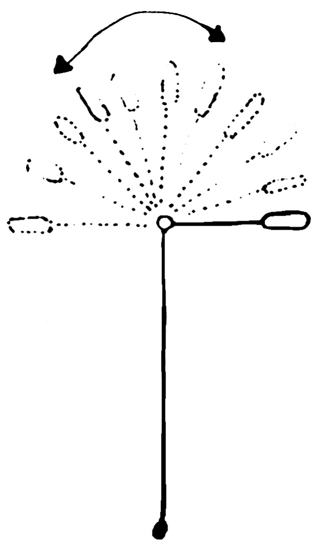


Figure 6.19
Movement of new propose headle
Lynn Tandler (2013)

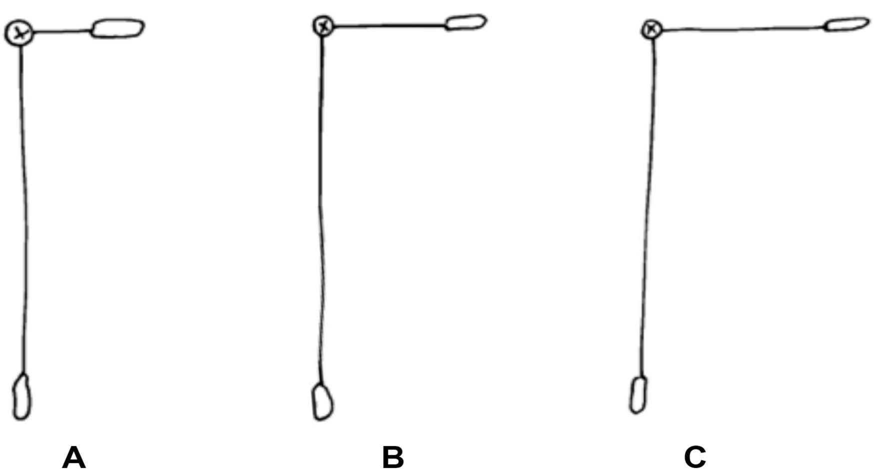


Figure 6.20
Different arm sizes could be fitted onto the headle to enable various woven architectures
0.5cm arm (A), 1cm arm (B), and 2cm arm (C) create travel movement of double their length
Lynn Tandler (2013)

To accommodate the movement of the headles, a new reed also needed to be designed with specifically calculated tracks to allow the movement of the yarns across the width of the warp [figure 6.21]. Unfortunately however, the bespoke production of such a reed was beyond the forms of this research and alternative weave architectures and woven geometries were sought after throughout case study 2 for the development of novel reversible weave structures.

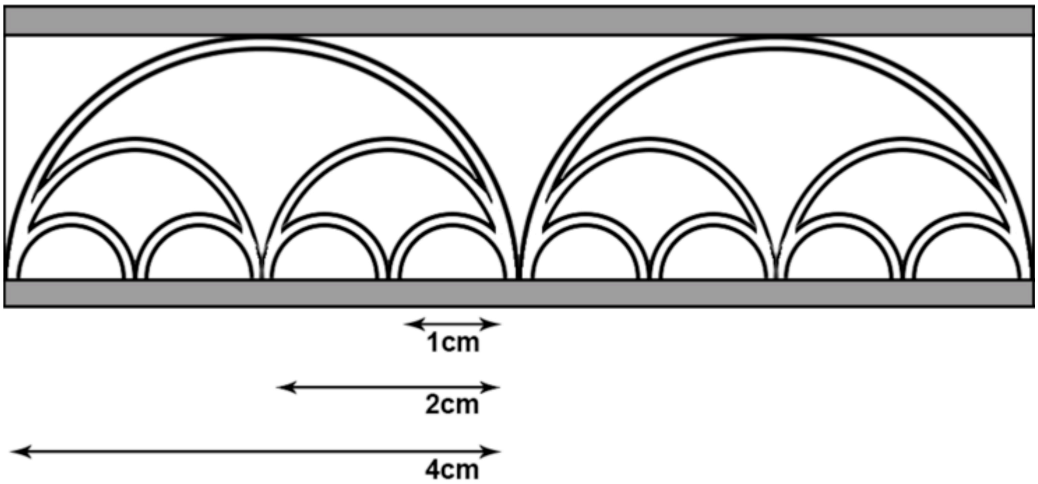


Figure 6.21
New reed: small, medium and large arches allow the travel motion of warp ends threaded through the movement of headles A, B and C respectively (as demonstrated in figure 6.54)
Lynn Tandler (2013)

6.2 Case study 2: Investigating the role of weaving as a method for creating auxetic textile structures

Woven textiles designers are trained to understand the various construction geometries of weave structures and use this knowledge to tailor specific structures for desirable affects (Thomas, 2009) - both mechanically and aesthetically. The potential therefore for exploration and investigation of weaving techniques and its possible adaptations have yet to be fully explored with regard to the design and creation of genuinely smart textiles.

The previous case study investigated leno weaving as potential woven construction methodologies for the creation of a geometrically reversible weave structures. Mechanical laws of engineering were used as a part of a hybrid research methodology that seeks to narrow the gap between design and engineering (chapter 2). The principles of leno weaving were investigated in case study 1 but was also concluded to be unsuitable for the creation of reversible weave structures: the twisting of the leno ends was too tight that no other movement such as sliding of yarns into new geometrical state for example could subsequently occur. Although a reversible movement was not achieved throughout the first case study, its results were key to construct a second case study, still in the quest to explore the potential development of a reversible weave structures: now a new weaving technique needed to be identified and explored in order to examine whether weave structures could be an agent for smartness in textiles.

The mechanical properties of any woven textile are governed by four elastic constants: Young's modulus [E] - which measures stiffness; Shear modulus [G] - which measure rigidity; Bulk modulus [K] - which measures compressibility; and Poisson's ratio [v] - which measures elasticity. But as highly anisotropic material systems (Hu, 2004), the mechanical deformation of textiles often occurs disproportionately and unevenly on all dimensions.

Most textile materials have Poisson's ratio [v] values between 0 and 1: auxetic materials however are identified by a negative Poisson's ratio. These are materials such that their geometrical construction can increase in volume and/or size simultaneously and counter-intuitively when pressed or otherwise stretched [figures 6.22 and 6.23]. In other words, auxetic behaviour allows materials to expand in its width and its length simultaneously – unlike conventional materials where an increase in the dimensions of one axis results in the decrease of another: the higher the negative value [v], the more dramatic the counter-intuitive effect of the auxetic construction. The significance of auxetic materials lies in their unique counterintuitive properties, high volume change, double curvature, energy absorption, fracture toughness, and porosity variations (Evans and Alderson, 2000). Today, auxetic behaviour can be found in human skin, some polymers, fibres and yarns, and in some fabric structures such as knit - but rarely in weave.

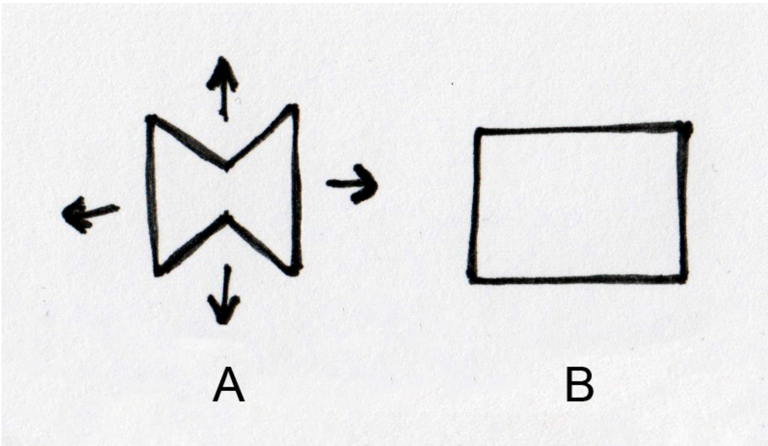


Figure 6.22
Auxetic behaviour in single unit structure
Lynn Tandler (2013)

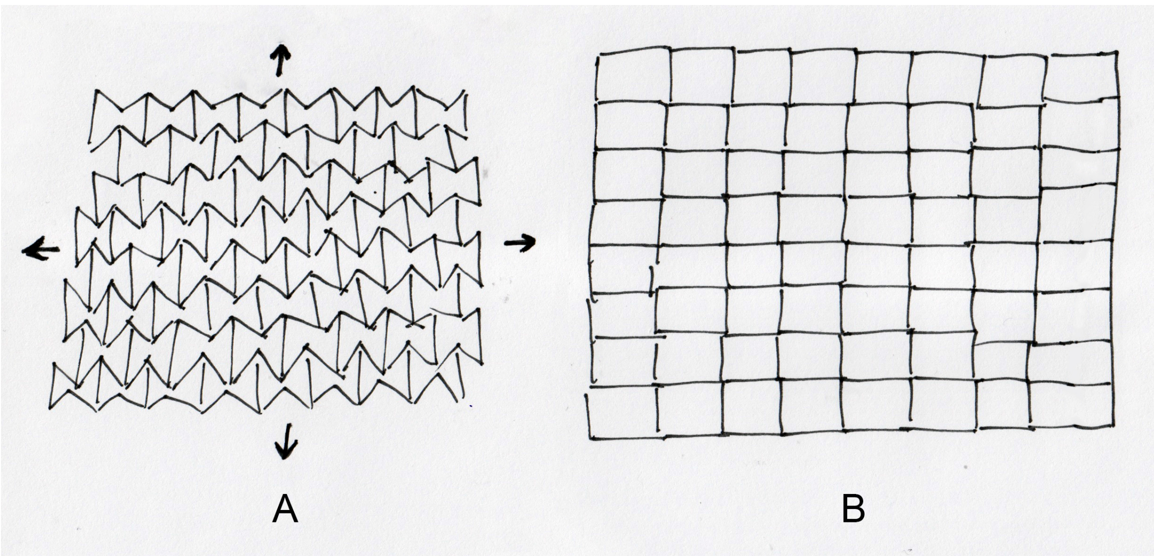


Figure 6.23
Auxetic behaviour in macro structures
Lynn Tandler (2013)

Following the foundation of 'textile anatomy' mapping (figure 5.12, p. 92), auxetic natural and manmade polymers have been research and their properties outlined (Alderson and Evans, 1997; Alderson and Evans, 1995; Gunton and Saunders, 1972). Synthetic polymers such as polypropylene, polyester and Nylon have been used to create auxetic continuous monofilaments (Ravirala, Alderson, Alderson and Davies, 2005), based on a unique extrusion methodology - developed at Bolton University (Alderson, Alderson, Smart, Simkins and Davies, 2002). In this method of extrusion, the physical and mechanical behaviour of the filaments are controlled by the drawing ratio, the thermal processing technique, and the microstructure properties of the fibres themselves: auxetic monofilaments that are made from auxetic polymers, have an internal honeycomb structure. As long as there is no tension in the drawing process of the monofilaments the polymers do not stretch out completely and as a result they are able to form miniature bow-tie shapes within the filament (Chinta and Veena, 2012). This bow-tie geometry attributes the filaments with an auxetic behaviour. Additional attempts to developing auxetic monofilaments were published (He, Liu, McMullan and Griffin, 2005; Grima and Evans, 2000; Evans, Alderson and Christian, 1995). The interesting thing in all these experiments is that the governing concept had been one focusing solely on geometrical play - whether in attempts to create structural shapes from polymers or to allow bow-tie movement.

Auxetic yarns just like their polymeric monofilament counterparts are built on engineering and geometrical principles. Such yarns can be made out of high-stiffness polypropylene filament spaciously wrapped around a thicker low-stiffness filament: in this instance none of the constituents filaments are themselves auxetic, but the geometry created by the elements, together allows an auxetic behaviour to take place due to the difference in thickness between the core filament and that which is wrapped around it - once pulled, the twisted thick yarn bulks allowing it to increase in volume whilst extending in length. Most commercially available are the helical auxetic yarns - also known as HAYs (Wright, Burns, James, Sloan and Evans, 2012; Sloan, Wright and Evans, 2011). But additionally, semi-auxetic yarns have been reported by Lim (2014): these yarns are too made out of non-auxetic filament elements, but here the elements are not twisted but rather are sewn together to create some auxetic behaviour within the yarn.

Geometry therefore appears to play a key role in the creation of auxetic behaviour in materials; from the micro, through the meso and to the macro scales. The exploration of auxetic fabric architectures therefore is also studied through the development and application of various geometries onto the structures. Such shapes include squares (Attard, Manicaro, Gatt and Grima, 2009), a combination of triangles and squares (Grima *et al.*, 2011), a type of a chiral geometry (Grima, Gatt and Farrugia, 2008), and various honeycomb structures (Gasper, Ren, Smith, Grima and Evans*,* 2005; Wan, Ohtaki, Kotosaka and Hu*,* 2004).

The vast majority of auxetic fabrication attempts can be found in knitted textiles (Glazzard and Breedon, 2014; Alderson. Alderson, Anand, Simkins, Nazare and Ravirala, 2012; Ugbolue *et al.,* 2011; Liu, Hu, Lam and Liu, 2010; Ugbolue *et al.,* 2010) - and applications of knitted textiles had already found benefits both in healthcare and in fashion. Aside from the difference between knit and weave constructions, as previously discussed in chapter 5, a prominent distinction between the two is the angle that weft yarns create and upon which the overall geometry of the structure is formed: woven geometries are based on vertical and horizontal arrangements of threads, since in most cases the weft will be traveling at a 90 degrees angle to the warp. In knitting however, diagonal weft travels are commonplace, which makes the creation of triangular shapes far easier. And since diagonal lines and angular shapes are critical for the creation of auxetic behaviour, it is no great surprise that the majority of experiments thus far occurs within knit.

To date, auxetic woven fabrics have been produced only with the use of auxetic filaments and yarns (Wright, Burns, James, Sloan and Evans, 2012; Miller, Hook, Smith, Wang and Evans, 2009) – meaning that mostly conventional weaving techniques are used, while the auxetic properties come form auxetic filaments and/or yarns, which are employed within the woven structure. In other words, the vast majority of auxetic weaves are so due to the auxetic properties of its components and not due to the woven architecture of the fabric itself. A couple of attempts has been made to develop auxetic weave structures (Hook, 2011; Ge and Hu, 2013), however none of which was ever attempted within the restraints of a weaving loom: both of which were conducted on a specially designed apparatus and frame – specially built for this purpose. The concern here is that in order to create auxetic weave structures a new weaving paradigm needs to be engaged, for without the special machines no special weaving can take place. What case study 2 of this research examines is the creation of a woven auxetic structure on conventional dobby looms - one that could potentially be adopted by weaving mills across textile industry.

6.2.1 Case study 2 – Aims and objectives

The aim of case study 2 was to explore alternative weaving techniques as an outlet for mechanical change within weave-structures. More specifically, auxetic structures were used as an inspiration for the creation of novel reversible weave structures.

The objectives of the second case study are summarised below:

(i) Acquire knowledge into the development of auxetic geometries: identify what shapes could potentially cause an auxetic behaviour.
(ii) Translate auxetic design work in to weaving.
(iii) Weave a novel auxetic structure on a George Wood dobby loom.

6.2.2 Case study 2 – Method and machine

The adaptation of auxetic shapes into new geometries that could potentially be translated into weave was primarily done through drawing and with the assistance of Solidworks CAD software. The same engineering principles of 'locks, hinges and tracks', as presented throughout case study 1, were used here only instead of concentrating on the locking of some of the elements in place, the transitioning of the structure - i.e. its sliding from geometry A to B - was used as the focal point, such as illustrated in figure 6.3 (p. 101). In other words, the emphasis in this case was the development of mechanical movement through the so-called 'tracks', rather than securing the 'locks' in place and instigating movement through the 'hinges' as investigated throughout case study 1. My experience and understanding of weaving allowed me to generate and further explore new geometrical shapes that could fit the revised objective through the development of modular diamond shapes. In order to then translate my drawings into weave plans, I chose the layered cloth construction as the weaving methodology for this case study. This technique, I felt could elevate my designs and transform them into woven auxetic structures.

Layered cloth weaving is known to be the weaving of multiple separate pieces of cloth simultaneously on the same loom, which can be linked together into one piece through interruptions within the repeat of the weaves that it employs. Respectively, a double cloth construction is the weaving of two-layers of cloth, as triple cloth construction is the weaving of three-layered cloth.

Most weave structures can be woven into a double cloth, where the sole restriction on construction resides in the maximum size of the repeat, or in other words, in the number of shafts. The drafting of a double cloth will see the weave structure double in size: the maximum number of shafts available on the loom for weaving will be divided in half; each half will be allocated for the weaving of individual layers of cloth. For example, a plain weave with four warp ends and four weft picks would increase to eight ends and eight picks. The expansion in repeat size occurs due to having to weave two cloths at the same time [figures 6.24 – 6.26]: odd warp-ends and odd weft-picks (in blue) are designated for the weaving of the top cloth; and even warp-ends and even weft-picks (in yellow) are designated for the weaving of the bottom cloth for which all top cloth warp-ends are at all times lifting.

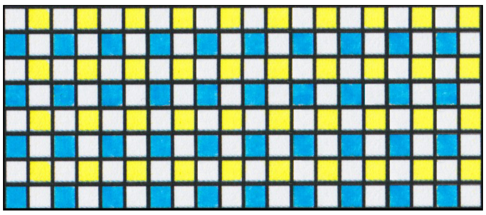


Figure 6.24
Double cloth design – step 1

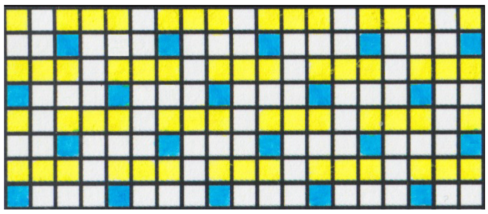


Figure 6.25
Double cloth design – step 2

Odd warp-ends (blue) for top cloth weaving
Even warp-ends (yellow) for bottom cloth weaving

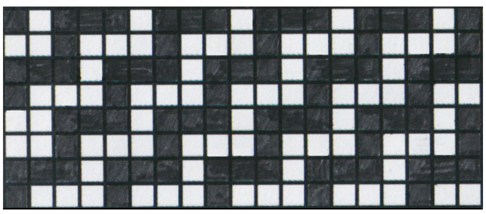


Figure 6.26
Double cloth design – step 3
Plain weave double cloth pattern
Lynn Tandler (2013)

Building on the work from case study 1 and following the same hybrid research methodology, the principles of mechanics were used as an inspiration for the creation of novel auxetic double weaves: the points of intersection between the layers - when top cloth becomes bottom and vice verse – were now envisaged as the locking points; elements of the geometry of the design itself were used as hinges; strong yarns were used both in the warp and wefts to allow the enforcement of applied tensile strength in order to allow the layers to slide into a new geometric position without breaking on the so-called tracks.

To create an auxetic weave structure both the width and the length of the fabric sample needed to counter-intuitively increase in size. To measure this, a 'before and after' measurements of the woven sample were taken with a ruler and documented in photographs accordingly. Additionally, a visual change has to be noticed too when stretched.

6.2.3 Case study 2 – Warp plans and weaving

A novel weave design was invented to suit the purposes of this case study, in which two layers of cloth were to cross one another in designated spots [figures 6.27 and 6.28]. The majority of the design work in case study two was done on paper through sketching, on Solid-Works software and through the manipulation of angular geometries with an aim to create double cloth weave structures that create a mechanical system of tracks, locks and hinges, as discussed in the methodology of case study one. Only two layers were introduced to the structure. This was based on the belief that a basic double cloth structure only has two layers of cloth, and if auxetic behaviour could be found to occur between two layers of cloth it could also occur between, three layers, four layers, or more.

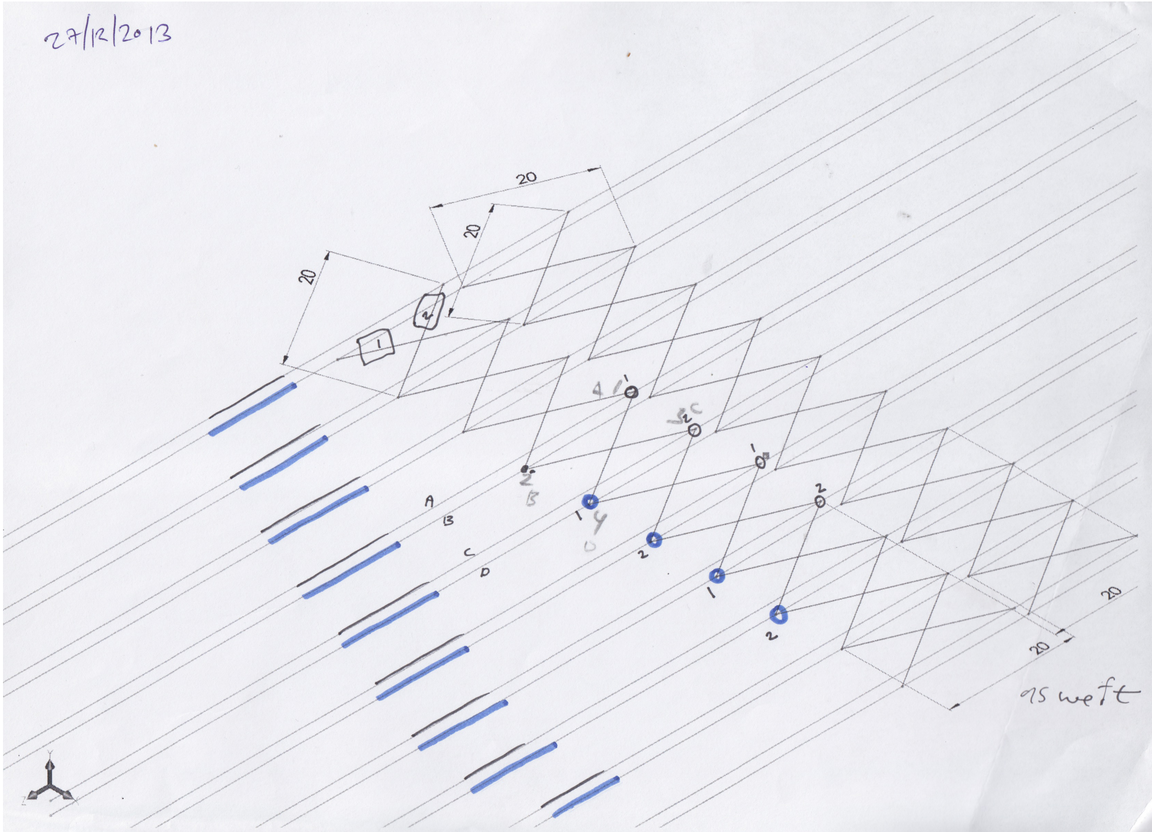


Figure 6.27
Design development (Solidworks) for the creation of auxetic double cloth weaves
Lynn Tandler (2013)

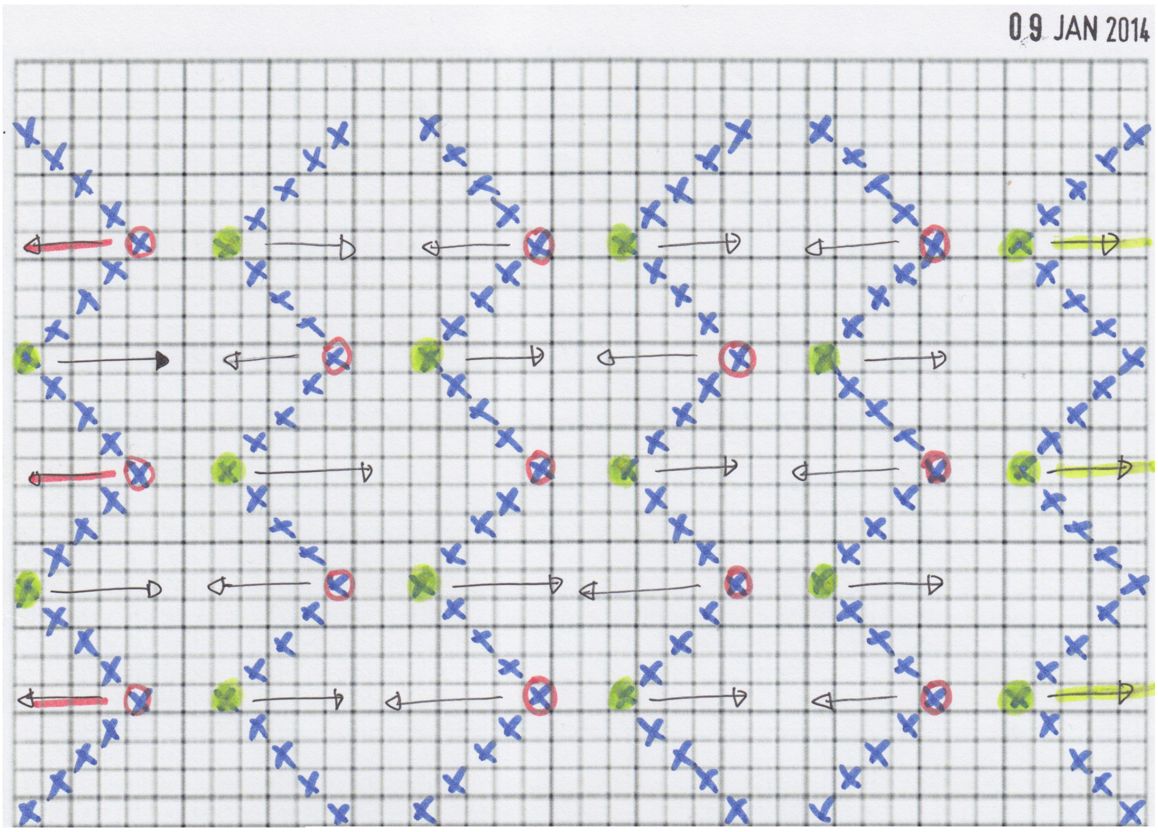


Figure 6.28
Design development (drawing) for the creation of double cloth weaves
Lynn Tandler (2014)

The design work for producing an auxetic weave structure was done by hand and on Solidworks CAD software. The drafting of the auxetic weave structures, i.e. the translation of the design work into a weave was done by hand as well but also, in later stages, with the aid of ProWeave weaving software, provided by the School of Design at Northumbria University. After much experimentation in drawing, drafting and weaving a candidate weave structure was developed. The overall structure-repeat comprised of 64 picks [figure 6.29, p. 144].

Each weft insertion needed to be pegged in and hammered into place individually and by hand to fit the weaving methodology of the George Wood looms upon which case study one was woven too. Quickly it appeared that there was not enough pegs available to complete a single repeat due to its extensive length. The manufacture of pegs for George Wood looms - done only by a few production houses in the UK - is limited, which makes the manufacturing of relatively small quantities even more difficult to come by. Consequently, additional pegs were made by hand from a three-millimeter diameter wooden rod, which had then been cut into 2.2cm peg length to match the proportions of the plastic pegs [image 6.37, p. 145].

The pegging of long repeats was followed by an even slower weaving process due to some inaccuracies done through the pegging process as described in the methodology undertaken in the first case study: wooden pegs that were hammered too tightly into the bar could not reach the dobby mechanism and press their allocated shafts, resulting in keeping those idle, without lifting. Pegs, on the other hand, that were not hammered deep enough kept on pressing the dobby mechanism for an additional pick or two after their intended position in the repeat has passed, distorting the lift of the shafts and the weave structure as a result. Even though it was common practice among weavers to check the opening of the shed at least during the few runs of their repeat, in this instance due to the complexity of the weaving plan and the bespoke production of additional pegs, the process was even more time consuming, and needing of many alterations.

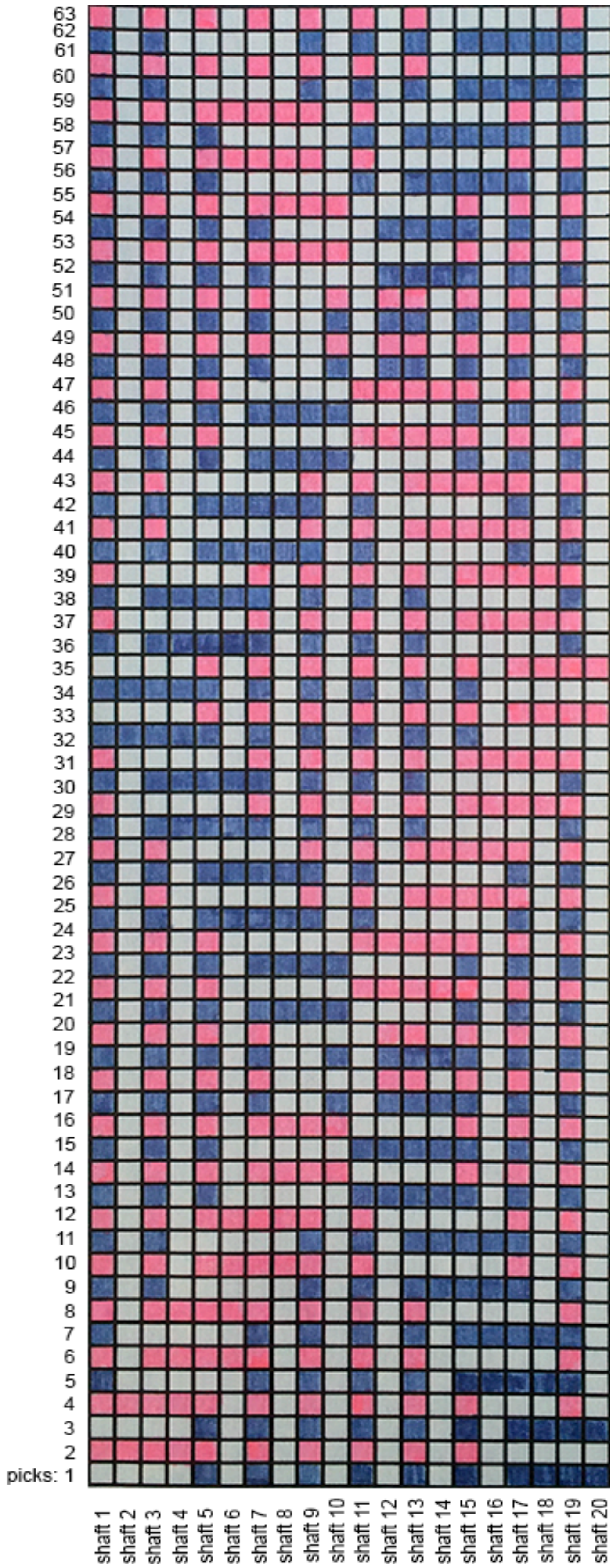


Figure 6.29
Novel weave-structure for the creation of auxetic double-cloth construction woven with two wefts (marked here in blue and in pick)
Lynn Tandler (2014)

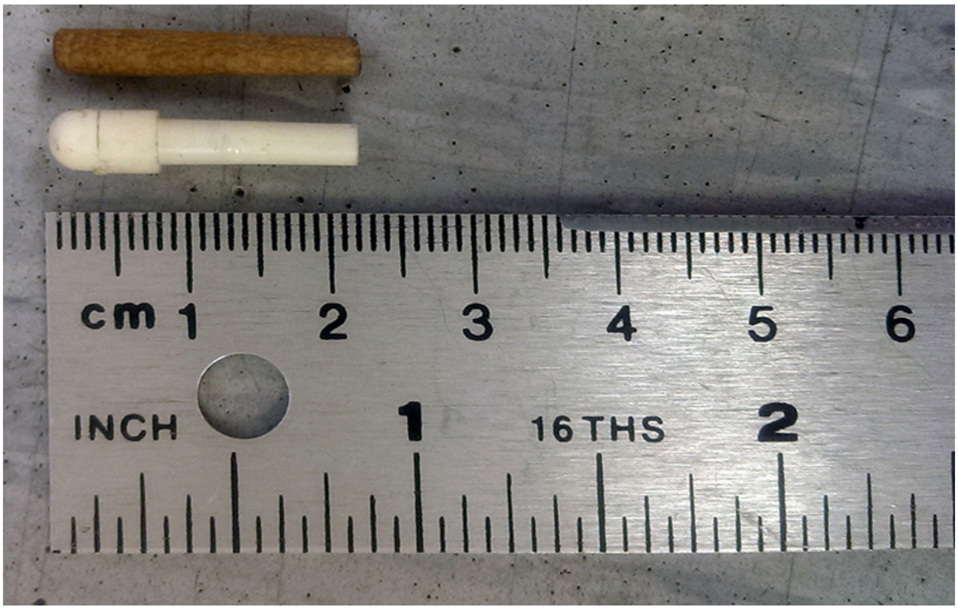


Image 6.37
New hand made wooden pegs in comparison with original plastic pegs
Lynn Tandler (2014)

The first attempt at waving the auxetic double cloth construction was done with spun 2/12's mercerized cotton yarns both in warp and in weft. However the use of spun cotton yarns created much friction once force was applied during pull in order to open the structure, and this made sliding of the yarns difficult. Also, when stretching was attempted the fabric sample curled over with no sliding of any of its threads. Because it was important to establish movement only within the geometry of the weave - and not due to movements within the structure of threads themselves - Nylon monofilament threads were introduced to the weaving due to their stiffness and minimum degree of elasticity.

A total of nine samples were woven on two double-cloth settings: first on 2/12's mercerized cotton warps and then on Nylon monofilament warps. They are each briefly summarized through the descriptions of sample warp 2.1 and 2.2.

6.2.3.1 Sample warp 2.1

Sample warp 2.1 was made out of two warps: a top warp and a bottom warp, which were both threaded in alternating order and in a straight draft. Both warps were made of 2/12's mercerized cotton yarns; the top warp was white (marked below in blue) and the bottom was black (marked below in yellow) in order to create a visual distinction between the two [figure 6.30].

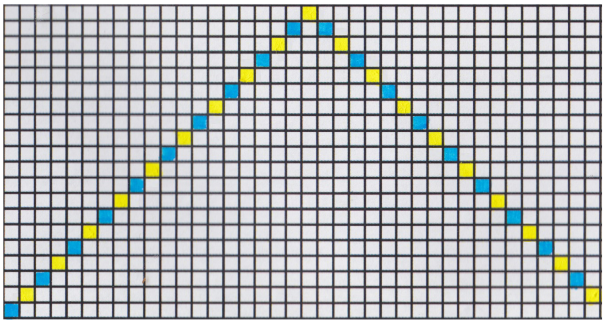


Figure 6.30
Sample warp 2.1– threading plan
Lynn Tandler (2014)

Four woven samples were made to validate the design and assure the successful weaving of the auxetic structure. Firstly, with alternating white and black weft insertions only this weave structure produced a tight and squashed pattern. Secondly, two samples were woven with thick pink and blue cotton cords, but even though the geometry of the structure was successful and true to the design on paper, the weaving was too tight and dense to allow any movement to occur. Thirdly, wooden sticks were introduced to the weaving process in addition to the weft yarns in order to insert more space into the density between each pick and in doing so allowing more space for movement within the structure. The woven samples were then taken off the loom and the sticks removed. The woven samples were washed, steamed to release the tension that was applied onto the warp ends during weaving. As a result, upon inspection, movement occurred between the layers while the geometry remained stable at the same time. This, it was thought, could have been because of the thick cotton cords that were used to establish the correct geometry: not enough room was allowed however between the threads to allow movement [image 6.38].

Image 6.38
Woven sample no. 4 – digital photography
Top cloth (right) and bottom cloth (left)
Lynn Tandler (2014)

Extra yarns were left unwoven on each side on each of the warps, and more space was kept unwoven on the top and the bottom of the sample. This was made to allow the structure to move without fraying. But once bound, it was very difficult to move the cotton threads across. No sliding between the layers occurred. This was then considered to have happened due to the high friction created by the spun cotton yarns and stray fibres, which migrated away from the main yarn axis.

6.2.3.2 Sample warp 2.2

Building on the work done on sample warp 2.1, the aim of sample warp 2.2 was to create movement between the layers and eliminate the obstacles of yarn friction. Nylon monofilaments were chosen to replace the 2/12's mercerized cotton yarns due to their smooth surface roughness as well as homogenous round cross sectional shape and consistent thickness dimensions throughout its axis.

The monofilaments - 750 denier (12 Nm) - were chosen in two colours; clear for the top warp and grey for the bottom warp in order to distinguish their travel movement across the weave. The loom was set-up identically to the way it was threaded in sample warp 2.1. A total of five samples were woven on sample warp 2.2 under two different loom settings.

The first two samples were a replicate of the third and fourth samples from the previous warp: sample no. 1 was woven without any sticks [images 6.39] and sample no. 2 with the aid of gap sticks [images 6.40]. They were both woven by alternating two wefts – clear and grey coloured monofilaments – both identical to the same monofilaments used on the warps. Both samples were woven according to the same peg plan (figure 6.29, p. 144). As soon as the sticks were removed however, some of the monofilament wefts got caught on the sticks and hence removed due to the close tension that was applied to the fabric structure during the weaving process. This showed that weaving this unique structure with Nylon monofilaments results in a close textured interlacement with little friction - meaning that it was now no longer considered to be the case of having to eliminate friction entirely, but rater needing to find suitable abrasion that will allow grip and sliding in different areas of the design.

As a result, two new weave structures were developed. New threading plan was applied and the warp was re-set accordingly into a 3-block setting. But in this instance too, the weaving proved too dense [Image 6.41 and 6.42].

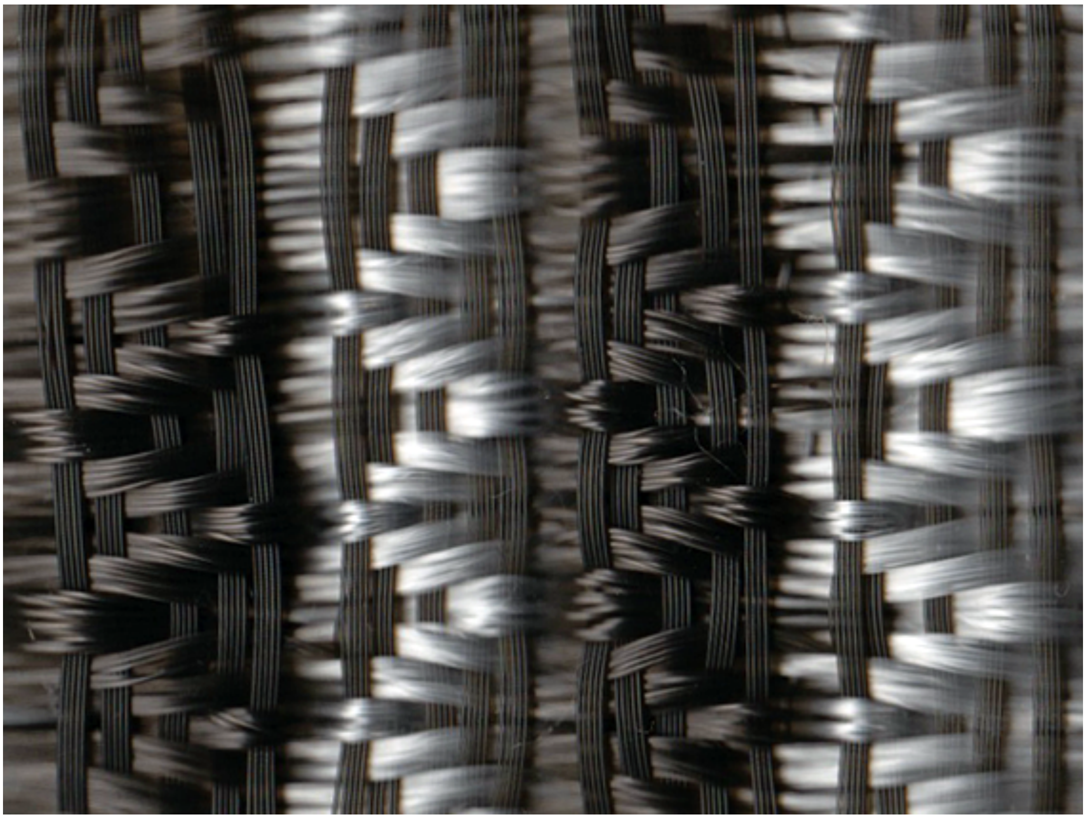


Image 6.39
Sample warp 2.2 - woven sample no.1: woven without sticks
White and grey monofilaments woven according to pink and blue lifting plan (figure 6.29, p. 141)
Digital photography

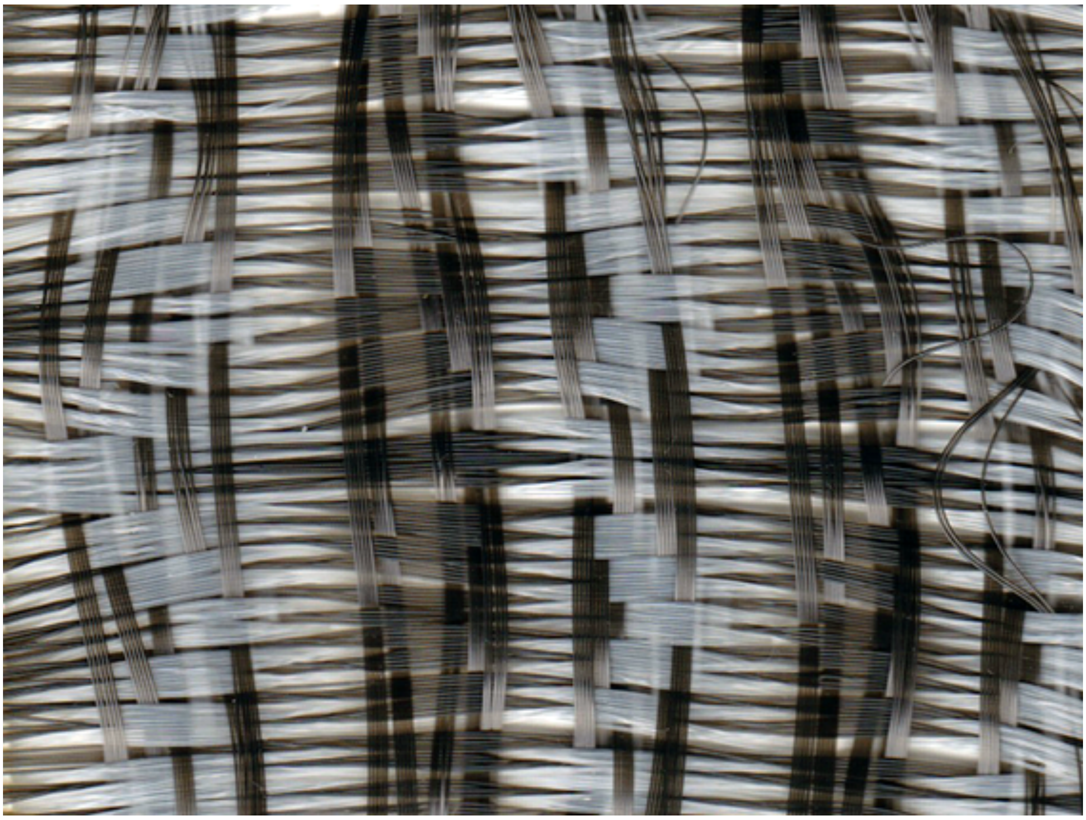


Image 6.40
Sample warp 2.2 - woven sample no.1: woven with sticks, which have been removed
White and grey monofilaments woven according to pink and blue lifting plan (figure 6.29, p. 141)
Digital photography
Lynn Tandler (2014)

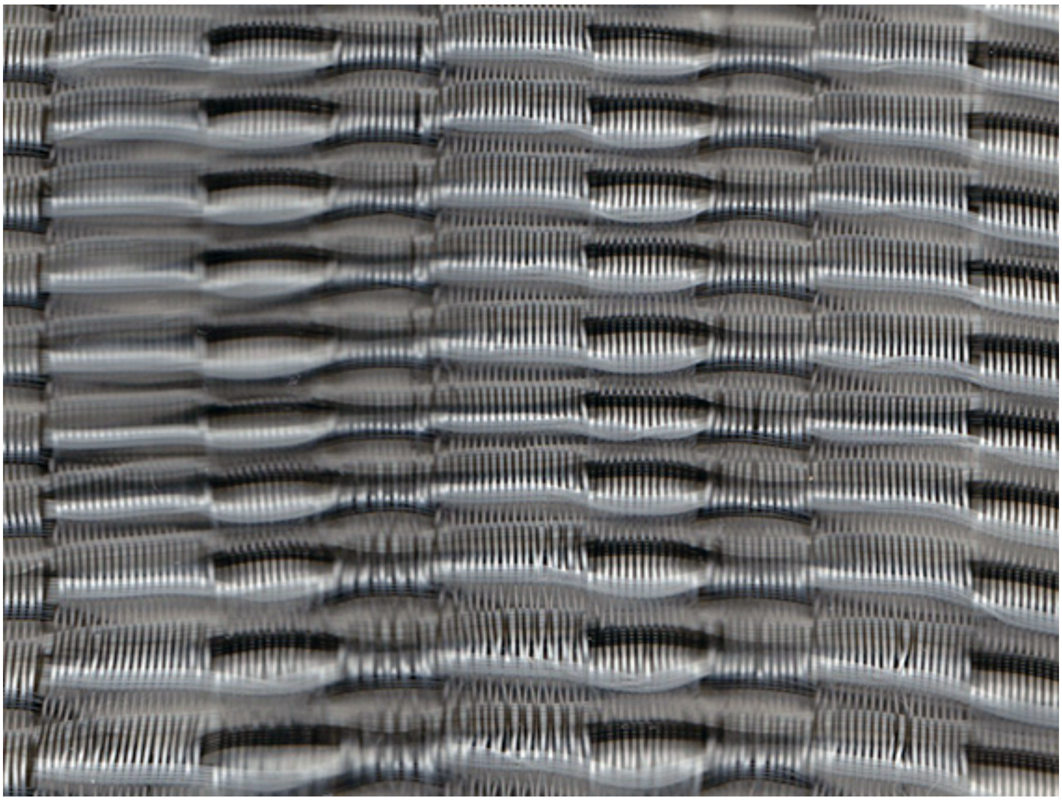


Image 6.41
Woven sample no. 3
Digital photography

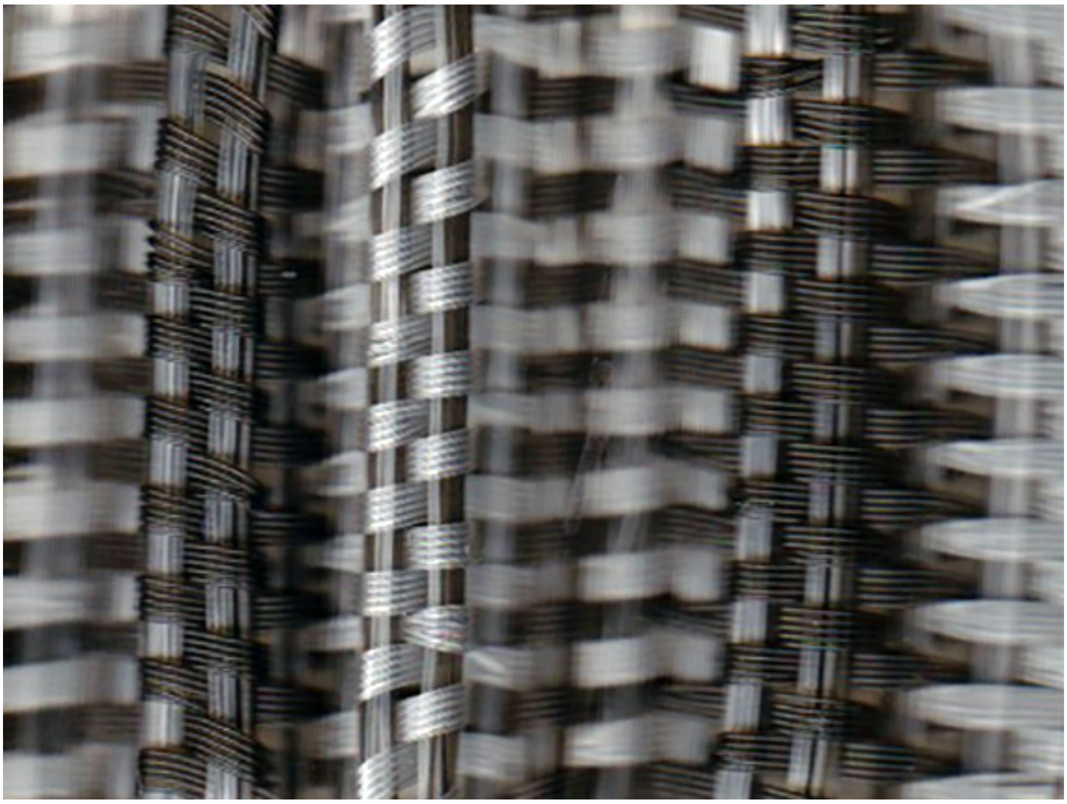


Image 6.42
Woven sample no. 4
Digital photography
Lynn Tandler (2014)

Lastly, a sample of the original angular double cloth peg plan was woven - as it was woven in sample warp 2.1 - only this time it was woven with a mixture of cotton and monofilament: the warps were of clear and grey Nylon monofilaments and the wefts were of white and black 2/12's mercerized cotton. Auxetic behaviour was observed and established. Upon stretching the woven sample horizontally, its dimensions increased vertically too. The dimensions of the woven sample before stretching, as it came off the loom, measured as 27.69 cm wide and 41.31 cm long. Post stretching it measured 33.23 cm wide and 43.60 cm long [image 6.43].

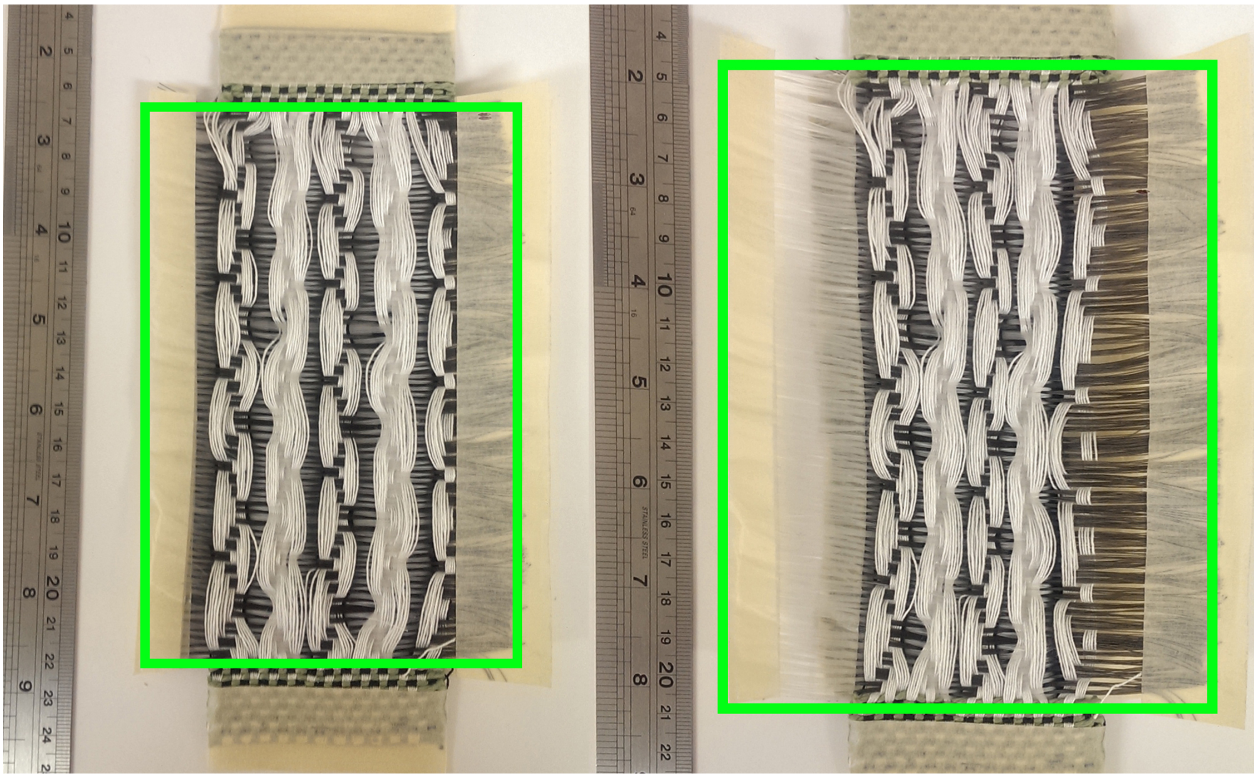


Image 6.43
Sample warp 2.2 – woven sample no. 5
White and grey monofilaments woven according to pink and blue lifting plan (figure 6.29, p. 141)
Pre-stretch dimensions (right) and post stretch dimensions (left)
Lynn Tandler (2014)

With this combination of Nylon monofilaments and spun cotton yarns some auxetic movement was noted and the structure proved successful creating a counter intuitive motion within the cloth solely due to the unique weave construction of its constituents.

6.2.4 Case study 2 – Discussion of results

The aim of case study 2 was to use alternative weaving techniques such as double cloth weaving for the developments of novel reversible weave structures. And due to its unique geometrical shape change, which is solely based on mechanical movement, the creation of auxetic behaviour through weave was chosen as an aim.

During the experimentations of case study two a total of nine samples were woven, out of which only one demonstrated auxetic behaviour: when the fabric sample was pulled to expand its width, it did so in its length. A novel woven structure was therefore created - enabling some auxetic behaviour to occur though the mechanical movement if the weave itself. Upon stretching on the other direction to reverse the movement the fabric sample returned to its original dimensions. Specifically, when the width of sample no. 5 from sample warp 2.2 grew in 5.54 cm: from 27.69 cm to 33.23 cm. At the same it its length grew in dimensions too from 41.31 cm to 43.60 cm: a total increase of 2.29 cm counterintuitively in length. This change in size however was, in relative terms, only minor.

But through the experimental work of case study 2 it also became apparent that the properties of the yarns could not be isolated and detached form the behaviour of the geometric weave. The most prominent proved to be the surface roughness and friction of the yarns and filaments used: for with high friction levels no movement could take place and under these conditions therefore, no shifting between geometries could be made possible. The experiment also showed that not as expected different types of yarns and therefore different friction ratios react best to sliding and movement. In this particular case, the best movement was with a monofilament Nylon warp and spun cotton yarn wefts: a 100% Nylon monofilament sample in fact yielded very similar results in terms of movement to a 100% spun cotton yarn sample regardless to their differences in surface roughness and friction ratios.

What also became clear was that the fabric would not increase in size beyond the limitations of its yarns. In other words, because Nylon monofilament yarns do not stretch the structure would not exceed the given length of the yarn: either in the warp or in the weft. This way the limitations of the yarn become the limitations of the weave structure and the auxetic movement consequently. Therefore, the conclusion drawn from case study 2 is that geometry of weave structures strongly depends on the properties of its constituents. Even though some publications along the years had looked into the link between yarn structures and the properties of the woven cloth from which they are made (Lord and Mohamed, 1982; Richards, 2012), no publication to date was found to discuss the link between the *structure of yarns* and their effects on the development of new weave structures.

Thus far, the experimental work from case study 1 and case study 2 showed how machine specifications and materials properties respectively, are linked with the workings of a woven structure. In other words, if one was to invent a new weave structure away from the restraint of present day machines with the intent to construct a new 3D geometry they must not do so without considering the properties of the textile constituents form which they intend on using.

This case study links the weave structure (*n*=3) to the remaining hierarchical levels in TA mapping. Case study 2 has shown that weaves are strongly dependent on the yarns and / or filaments from which they are created. Similarly throughout chapter 4, TA mapping has shown that the properties of yarns are informed by those of the fibres from which they are made, and these in turn, are derived from specific polymers – taking shape in accordance to their properties. This anchors an understanding that the processes of making are inherently embedded into the properties of the textiles as a whole. As a result, the implementation of different yarn assembly methods should be considered in relation to the components that make the systems and their unique sets of properties.

6.3 Case study 3: Additive manufacturing vs. weaving

In a report for the London College of Fashion, titled *3D Printed Textiles and Personalized Clothing*, Delamore (2004) discusses the relevance of rapid prototyping as a method for producing textiles, on which he comments that "there is no need to knit or weave the raw materials as the structure is printed in 3D" (p. 5). In this article, Delamore (2004) suggests that in the future, current textile production methodologies such as weaving and knitting will gradually become redundant making room for an ever-increasing 3D printed clothes-manufacturing industry.

Rapid prototyping – also referred to as rapid manufacturing (Levy *et al.,* 2003) or additive manufacturing (Kruth *et al.,* 1998) – is a set of technologies that uses CAD files for the creation of 3D products. The way in which 3D-printers work depends on the particular technology that operates it (Barnatt, 2013). Today, additive-manufacturing (also known as AM) technologies can create 3D prototypes through process of extrusion, layer deposition or heat adhesion - all follows the pre-designed tracks of a 3D digital design. The past decade saw a rise in the popularity of AM technologies due to lower costs of machines and the affordance of a variety of raw materials. Some of the commonly used technologies are listed in figure 6.31.

Type	Technology	Acronym
Extrusion	Fused Deposition Modeling	FDM
	Fused Filament Fabrication	FFF
Wire	Electron Beam Freedom Fabrication	EBF[3]
Granule	Direct Metal Laser Sintering	DMLS
	Electron-Beam Melting	EBM
	Selective Laser Melting	SLM
	Selective Heat Sintering	SHS
	Selective Laser Sintering	SLS
Power Bed	Plastic-based 3D Printing	PP
Laminated	Laminated Object Manufacturing	LOM
Light polymerization	Strereolithography	SLA
	Digital Light Processing	DLP

Figure 6.31
Additive manufacturing technologies currently available
Lynn Tandler (2014)

In a book chapter, titled *Designing for a New Fabric Generation*, Herald (2000) gives an account of smart textiles as textiles that can so-call design themselves, and in doing so she raises concerns regarding the future role of designers in light of the increasing integration of technology into the field of textiles. The appearance of such smart fabrics, she explains, "Does not necessarily depend on the intervention of a 'textile designer', but on another creative expert who designs the conditions in which the textile operates" (p. 114). For which she refers to the machine, the technology or the science. Naturally, she consequently asks: "Does this make the textile designer redundant?" (p. 114).

Herald's text (2000) not only acknowledges the changing role of the textile designer in a reshaped working environment of changing expectations and new so-called digital inventions that take over colour, texture and shape but also, she points out towards a profound difficulty, which questions the role of the designer all together in a so-called changing manufacturing realm. "Today we are seeing a return to a new sort of cottage industry" (Anderson, 2012, p. 51). But is this true? Could a new world of additive manufacturing take over the production of textiles?

Recently, in 2013, Iris Van Herpen launched a womenswear collection of 3D printed garments (Materialise, 2013). In a collaboration with Stratasys Ltd., Van Herpen had used thermoplastic polyurethane (TPU) materials to 3D print her garments. She refers to the construction of some of her fabrics as weaves, but on a close inspection it reveals that Van Herpen mainly used 3D printing techniques to adorn ready-made fabrics as well as printing garment segments. In other words, none of her 3D printed weaves were actually woven.

Similarly, in 2014, Oluwaseyi Sosanya, a design product student from the Royal College of Art, presented a "3D weaving machine" (Dezeen, 2014). According to Dezeen's report, "Oluwaseyi Sosanya has created a loom that can weave in three dimensions". The machine, according to the article, "weaves interconnected layers of straight warp threads and intertwining weft patterns at different heights, providing the third dimension". But on close inspection Sosanya's "interconnected layers" are in fact individual trails of yarns, which are laid up in vertical layers. The layers don't interlace at any point through the process of so-called weaving: the silicon coating, which is added on at the end of the process, binds the layers of thread together to hold the overall structure in place also allowing it to be squeezed and stretched. Even though Sosanya claimed that his inspiration was drawn from sewing machine and industrial knitting machine, he claims to have invented a 3D weaving machine – but in reality, as just explained above – he has not.

Later in the same year, a similar machine was demonstrated by a group of students from the California College of Arts in San Francisco presenting a prototype machine, which they have called "Space Weaver: A Seven Foot Tall 3D Weaving Machine" (Thimmesch, 2014). The machine holds twelve spools on top of a downward moving bed: a CNC motor operates the machine - allowing a hook to move across and grab the threads from the spools. One at a time it changes its position, leading different threads from different spools according to a pre-programmed software trail: but instead of weaving, the machine in fact braids or plaits.

In 2015, Disney Research launched their "Layered Fabric 3D Printer for Soft Interactive Objects" (Peng, Mankoff, Hudson and McCann, 2015). Their machine laser cut felt fabrics and uses adhesive glue to bind the shaped layers together to form soft 3D objects. But their machines too, do not print in 3D – as they suggest.

These examples reveal a widespread distortion of the terminologies of weaving, knitting and even printing currently within the academic and public debate, away and removed form the textile community. For non-textile practitioners the distinction between weaving, knitting and even printing may be irrelevant and one that only suggest a form of construction. But as a result new production technologies are given names that they cannot justify; such as the 3D weaving machines that do not weave. At the same time, it appears that the emergence of such machines come to play and receives its popularity only due to their so-called newness. They are considered novel and yet unexplored, which adds to their mystique and appeal as a result. However, none of these machines have yet investigated whether they produce prototypes that are actually better than conventional textiles. Indeed, they are different, but are they better than textile production methodologies currently employed by the industry?

6.3.1 Case study 3 – Preparation and design methodology

Case study 3 was set to explore the relevance that some AM technologies may potentially have on the production of woven textile structures and whether 3D printed textile structures could express any advantage over traditional woven textile structuring methodologies, such as those currently available across the textile industry. In an attempt to step away from the limitations of yarn specifications and existing weaving methodologies, as demonstrated through case study one and case study two, the aim of case study three was set to challenge whether other manufacturing methodologies, such as some AM technologies, could compete with traditional methods of weaving in producing alternative cloth constructions.

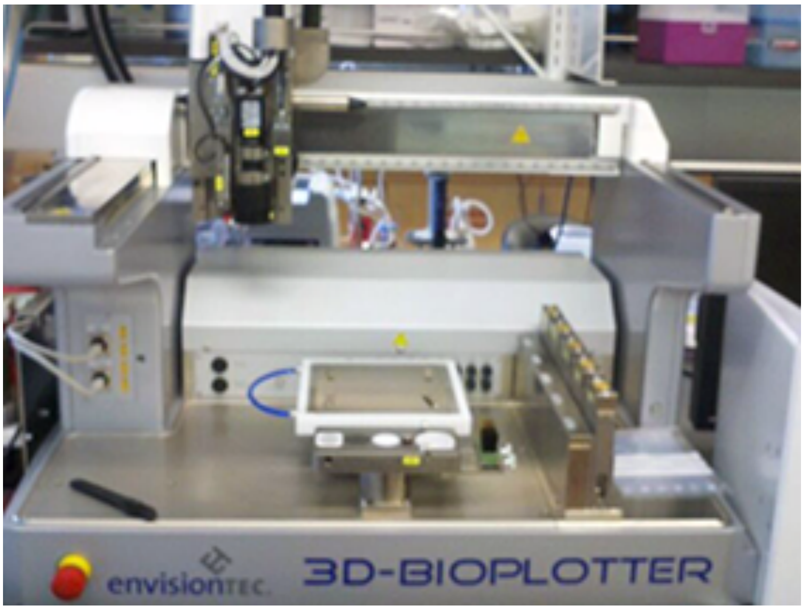


Image 6.44
EnvisionTech 3D bioplotter machine
Digital photography
Lynn Tandler (2015)

Originally the *EnvisionTech 3D bioplotter* machine [image 6.44], which extrudes viscous polymers, gels and molten liquids, was chosen for this case study. The original aim of case study 3 was therefore to 3D-print sample of basic plain weave and to compare it with a hand woven sample made from the same material. The textile laboratory SGS, Leicester, was identified for its characterization and measurement tools. The input that the team at SGS, Leicester, shared with regard to the specifications of their machines helped establishing the required dimensions of the samples both the woven samples and the 3D printed samples. In order to compare 3D printed "weaves" to hand woven architecture and in doing so compare the construction methodology between conventional textile construction methodologies and textile additive manufacturing (AM) methodologies - identical parameters had to be established for a like-with-like comparison.

In order to be able to assess and analyze the effectiveness of additive manufacturing technologies onto woven architecture assemblies, the margin of variables that dominated the constructions – such as the material's type, properties and shape - was to be reduced to a minimum. In other words, (1) the shape of the woven strands and (2) the base material itself should have been identical in order to create an experiment in which only the production methodology has been changed.

(1) The strands
As shown in chapter 5, spun yarns are governed by the structure and type of the fibres that they bind, as well as fibre migration and the spinning methodology used for the spinning of the yarns. The inner architecture of spun yarns is therefore complex. For that reason, as first attempt, it was decided to mimic the shape of a continuous filament meaning that one homogenous dimensions and shape was to follow through and remain consistent throughout the length of the filament. This shape was also thought to be relatively easy to mimic through additive manufacturing and in particular through the *EnvisionTech 3D bioplotter*.

In order to match filament diameter to machine, I concluded that the thickness of the extruder's nozzle – which could not be altered – would inform the thickness of the sourced filament for the weaving. This was determined at 0.3mm.

(2) The base material
The base material or polymer intended for the use of 3D printing needed to be identical to the polymer used to form the filaments for the weaving. If the base materials were different, for example, with a Nylon printed weave structure and a cotton cellulose woven structure, it would have been impossible to detect whether the performance of the macro structure was due to the properties of the polymers from

which they were made or from the fabrication methodology applied. Polymers used for 3D printing – and for fibre extrusion - have to have both the optimum thermo-physical and mechanical properties appropriate for stable wearing test. In other words, in order to compare the construction methodologies for the creation of woven materials, the same polymer needed to be found in the form that would be suitable both for 3D printing and for woven textiles.

Commonly found polymers used for additive manufacturing include ABS (acrylonitrile butadiene styrene), PLA (polylactic acid), PC (polycarbonate), PPSU (polyphenylsulfone), HDPE (high density polyethylene). PLA can be printed but is only produced as a spun yarn and not as a continuous filament. Similarly, chitosan and gelatin, fibrin and collagen could be extruded into filaments on a 3D bioplotter but, just like PLA, they too do not exist as textile manufactured continuous filament. Following an extensive search and analysis of machine specifications and the data sheets of their materials, only one polymer was found suitable for 3D printing and for filament extrusion, i.e. for weaving, which was Nylon 12.

Unfortunately however, after technical issues repeatedly failed the bioplotter from being installed, case study 3 had to be entirely modified. This meant that new AM technologies needed to be identified. The costing of the case study too needed revising and new funding had to be applied for. The use of Nylon 12 had to be reviewed and accustomed to the specifications of the newly allocated AM technologies some of which without the ability to process polyamides. The filament diameters too had to be adjusted for a new work frame respectively.

6.3.2 Case study 3 – Aims and objectives

The aim of case study 3 remained to challenge whether other manufacturing methodologies - such as some AM technologies - could compete with traditional methods of weaving in producing alternative cloth constructions. And the newly amended objectives of case study four have been set as outlined as follows:

(i) Create a library of digital CAD files for printing ‘weaves’.

(ii) Print samples of plain weave structure in FDM (fused deposition modeling) and SLA (Stereolithography) technologies.
(iii) Conduct characterization and measurements of the printed "weaves" samples and assess their mechanical performance.

6.3.3 Case study 3 – Methodology

Two alternative machines were identified to replace the *EnvisionTech 3D bioplotter*: (1) *dimension st1200* – which builds up molten substances layer by layer, and (2) *FormLabs 1+* Strereolithography SLA machine, which set resins into shapes in slices through processes of light setting with the help of scattered laser beams – both of which were available in the Experimental Workshops of Northumbria University's School of Design. The main differences between the two technologies are briefly summarised in figure 6.32.

The FDM *dimension st1200* [image 6.45] and Strereolithography *FormLabs 1+* [image 6.46] are both technologies that use the deposition of materials in layers in order to build a 3D object. But the problem with both these machines was with the materials that they were able to process. Firstly, there was no commonality between the machines' specifications to allow them to process the same materials. And secondly, both *dimension st1200*'s ABS plastic and the resin used by *FormLabs 1+* were not manufactured as continuous filament by the textile industry – meaning that no machine monofilament could be sourced either for the purpose of comparison weaving.

	Dimension st1200	**FormLabs 1+**
Technology	FDM	Strereolithography
Max build volume	254 x 254 x 305 mm	125 × 125 × 165 mm
Layer thickness	254 or 330 microns	25, 50, 100, 200 microns
Material types	ABS	Resin
Binding mechanism	Heat fusion (with support material injection)	Light fusion

Figure 6.32
Product specifications of FDM and SLA machines
Lynn Tandler (2015)

Image 6.45
FDM dimension st1200

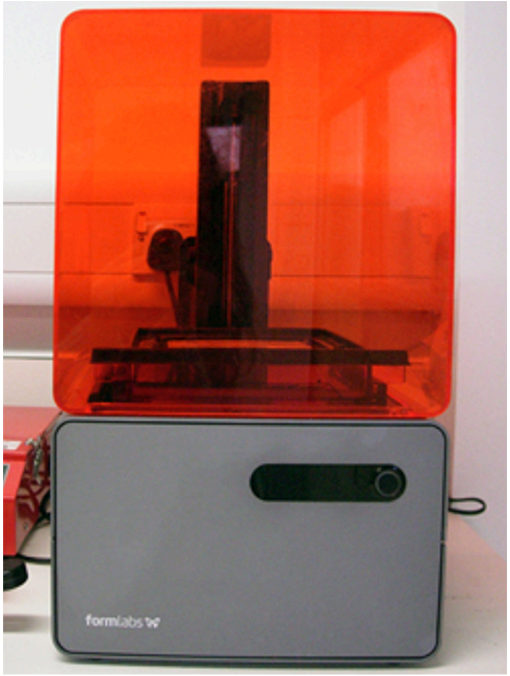


Image 6.46
SLA FormLabs 1+

Digital photography
Lynn Tandler (2015)

In an attempt to narrow the margin of error, the raw ABS filament materials used to feed into the FDM for printing was chosen to also perform as a thick continuous monofilament for weaving. This way, it was believed, a printed 3D weave and the hand woven lattice could be used in comparison. The width of the raw ABS material was measured as 1.75mm thick, and so this was set as an anchoring point of reference in the design of all prints and weaves.

Instead of relying on imagination, a sample of ABS raw material filament was to be hand-woven and the dimensions of the new woven interlacements were to be mimicked and translated into a digital CAD file. But the thickness of the ABS filaments was too great to be woven. The physical and mechanical properties of the ABS raw material made the filaments brittle and much prone for snapping, and as a result, the ABS raw filaments could not be wound into a warp and onto the loom. Instead, individual filament lengths - of 30cm each – were laid down and attached to a flat surface. A second set of filaments of the same length was then woven through the static set of filaments to form a woven sample of ABS raw material filaments.

This woven sample however quickly bounced into disorder once taken off its ‘frame’ and could not be fixed into the shape of a cloth. As a result it was deemed a failure. Consequently, the design of the CAD file for 3D printing of weaves did not have a tangible woven reference to mimic. And as a result case study 3 has critically morphed into an investigation of the usability of two AM technology for the production of woven lattices and architectures.

With the restraints of the *dimension st1200* machine specification, and minimum layer thickness of 254 microns, although it was no longer crucial to maintain a filament diameter thickness of 1.75mm, too few layers, it was thought, would increase the already brittle qualities of the ABS. And so it was decided to keep the 1.75mm thickness parameter, which was to be formed of seven layers of ABS through the FDM machine.

All weave structures were designed in Solidworks[2]. Since ABS material have no stretch or bendability, the curvature and travel movement of the monofilament needs to be designed within the digital file in advance. The so-called digital monofilament unlike in its physical form is therefore determined by three factors: its wavelength (WL), amplitude (A), and filament diameter (D) [figure 6.33].

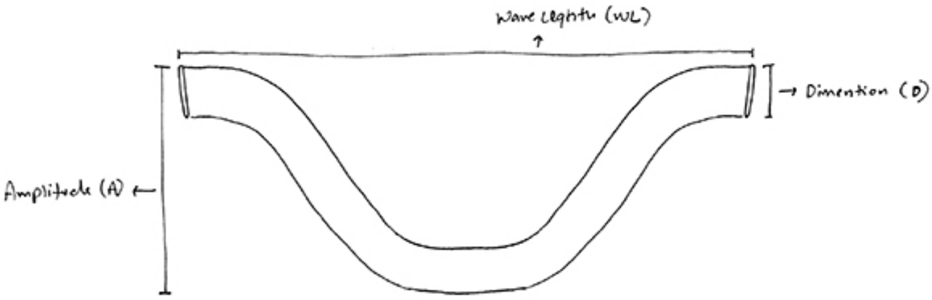


Figure 6.33
Illustration of filament measurements
Lynn Tandler (2015)

[2] At this point of the research this case study had greatly benefited from the support and knowledge contribution of James E. Thomas, who has been the mastermind behind the programming and the coding of the all the CAD work – see appendix B - working closely with myself and creating a novel digital library of 3D printed weaves.

6.3.4 Case study 3 – Findings

Various CAD files were developed as part of the experimental work in case study four – all of which are summarized in figure 6.34, below:

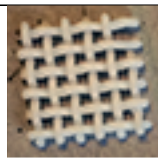
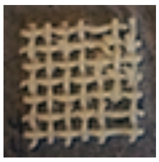
Sample no.	Technology & machine used	Design dimensions (WL x A x D) in millimeters	Object dimensions (L x W) in millimeters	Picture
1 (original samples)	FDM - *dimension st1200* [ABS]	9 x 2.25 x 1.75	30 x 30	
2 (original samples)	FDM - *dimension st1200* [ABS]	4.5 x 1.125 x 0.875	15 x 15 (50% scale down from sample no.1)	
3 (original samples)	FDM - *dimension st1200* [ABS]	12 x 2.925 x 2.275	39 x 39 (30% scale up from sample no.1)	
4 (second batch)	FDM - *dimension st1200* [ABS]	9 x 2.25 x 1.75	30 x 30	
5 (second batch)	FDM - *dimension st1200* [ABS]	10.35 x 2.5875 x 2.0125	34.5 x 34.5 (15% scale up from sample no.1)	

Figure 6.34
FDM weave structure printing – findings
Lynn Tandler (2015)

In order for the 3D printed filaments to still retain some independent movement within the woven architecture, a gap of about 1/100th of an inch was included in the CAD files. The *dimension st1200* was using its 'soluble support technology' to create a scaffold to support the so-called floating filaments: this was later dissolve in an alkaline solution.

Although the ratio between the wavelength, amplitude and filament diameter remained constant, various sizes and scale were measured throughout the experimentation above: Sample no. 1 was used as the base ratio for 3D printed weaves, and this ratio was scaled up or down to test its effectiveness. Sample no. 2 was reduced down to half the size of sample no.1, resulting in a rigid sample of fused mesh. Sample no. 3 was made bigger than sample no.1 by 30% - and more movement was made possible between the printed filaments. The ABS however, proved very brittle and some of the filaments as a result because there was not much support fell apart and broke very soon after removed from the machine.

Sample no. 4 and sample no. 5 were printed together in one go and as one batch – in order to check the production repeatability of the *dimension st1200* and explore a scale up of the manufacture. Sample no. 4 was repeating the ratio and dimensions of sample no. 1, as a control sample; at the same time, sample no.5 was enlarged by only 15% from the original set dimensions of sample no.1 (and sample no. 4). Building on the findings of sample no.3, sample no.5 was designed to create more breath amongst the filament, but also without compromising the support that their interlacement brings to the structure. The printing however of sample no. 4 and 5 together in one batch proved disastrous when the molten ABS had gradually accumulated in the deposition nozzle compromising the integrity of the rest of the printing.

The *FormLabs 1+* technology was then tested for the 3D printing of woven architectures only this time the base ratio of sample no.1 was upset and distorted. The same CAD files that were used for the FDM *dimension st1200* were used for this part of the experiment too; only some of the variables have changed to examine the effects of filaments proportions – wavelength (WL), amplitude (A) and diameter (D) – on the mechanical performance of the printed woven architecture. Five samples were produced, and these are presented in figure 6.35.

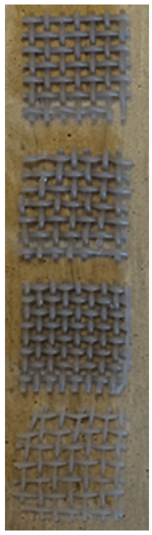
Sample no.	Technology & machine used [material used]	Design dimensions (WL x A x D) in millimeters	Object dimensions (L x W) in millimeters	Picture
6	SLA - *FormLabs 1+* [resin]	9 x 2.25 x 1.75	30 x 30	
7	SLA - *FormLabs 1+* [resin]	9 x 2 x 1.75	30 x 30	
8	SLA - *FormLabs 1+* [resin]	9 x 2.5 x 1.75	30 x 30	
9	SLA - *FormLabs 1+* [resin]	7.5 x 2 x 1.75	30 x 30	
10	SLA - *FormLabs 1+* [resin]	9 x 1.5 x 1.25	30 x 30	

Figure 6.35
SLA weave structure printing – findings
Lynn Tandler (2015)

Sample no. 6 was printed out with the same ratio and dimensions of sample no. 1 and 4. The results of this sample, unlike its FDM equivalents, it that a loose printed sample with enhanced drapability, movement and curvature was created. In this particular case, the FormLabs 1+ SLA technology proved superior to the *dimension st1200* FDM machine. But when the amplitude was reduced, in sample no.7, only by a minor 0.25mm, the woven interlacement had much restriction in movement, and the printed filaments were tightly laid out on top of one another. On the other hand, when it was slightly increased from 2.25mm to 2.5mm in sample no. 8, more movement was again made possible. In sample no. 9 the parameters were set in a way that both the wavelength and the amplitude were reduced, and this as a result, created a densely printed woven architecture. Lastly, sample no. 10 saw a reduction in filament dimensions as well as in amplitude - while maintaining a constant 9mm wavelength. This sample was considered the most successful creating a woven lattice that is bendable and flexible, yet stable in structure and in its interlacements.

The *FormLabs 1+* SLA technology uses laser beams to heat set the resin into its 3D form. Unlike the FDM *dimension st1200*, which deposited layers of materials from the bottom up, the *FormLabs 1+* heat set the layers in a reverse order from the uppermost to its lowermost. Then, the technology of the *FormLabs 1+* printed out a 3D scaffold to support the structures [figure 6.36]: the same scaffold was also used to support the so-called floating filaments within the woven architecture. The 3D printed weaves had then needed to be dismantled from the scaffold support and this was done with a pair of pliers. Although the separation was done with much care, still some scaffolds' remains could not be avoided.

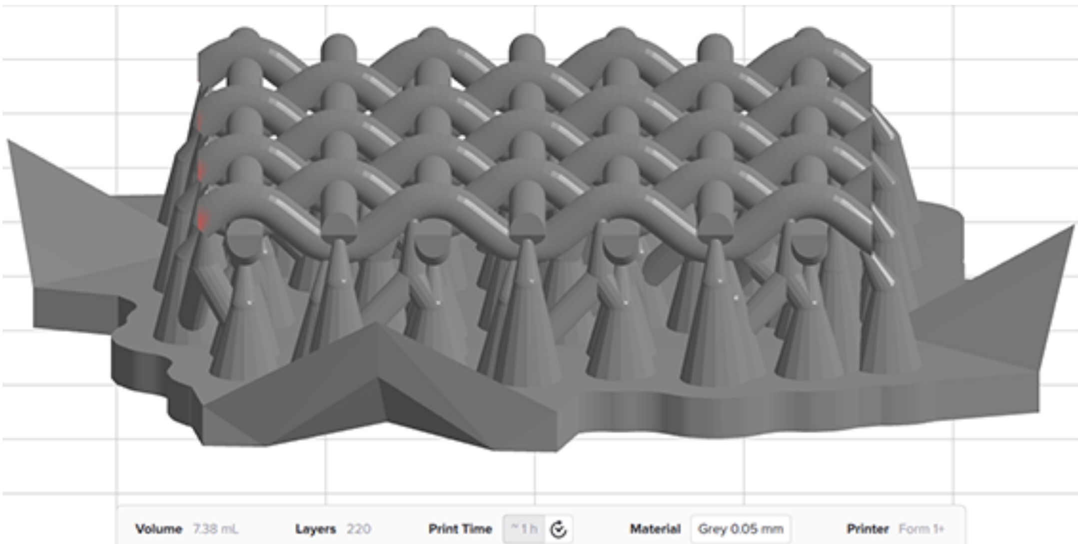


Figure 6.36
Scaffolds of SLA printed weave structures
James E. Thomas (2015)

More so, on a close inspection through the lens of a stereomicroscope – the surface roughness of the 3D printed product become prominent. Images 6.47 and 6.48 (p.167) demonstrate a plain weave structure, printed by the FDM dimension st1200 machine. The indication bar attached is 0.9mm wide. Images 6.49 and 6.50 (p. 168) demonstrate the same woven plain weave structure, printed through a SLA FormLabs 1+ machine. The indication bar attached is 0.9mm wide.

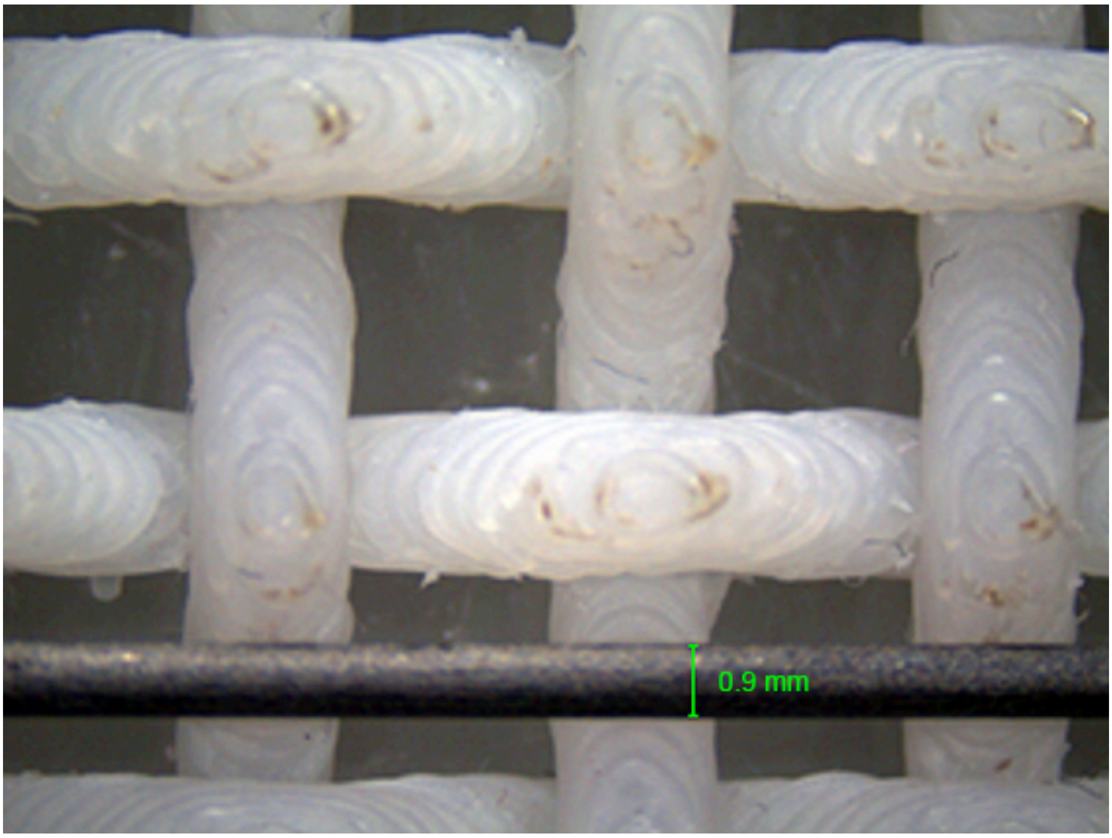


Image 6.47
FDM printed plain weave
Stereomicroscope (transmitted light)

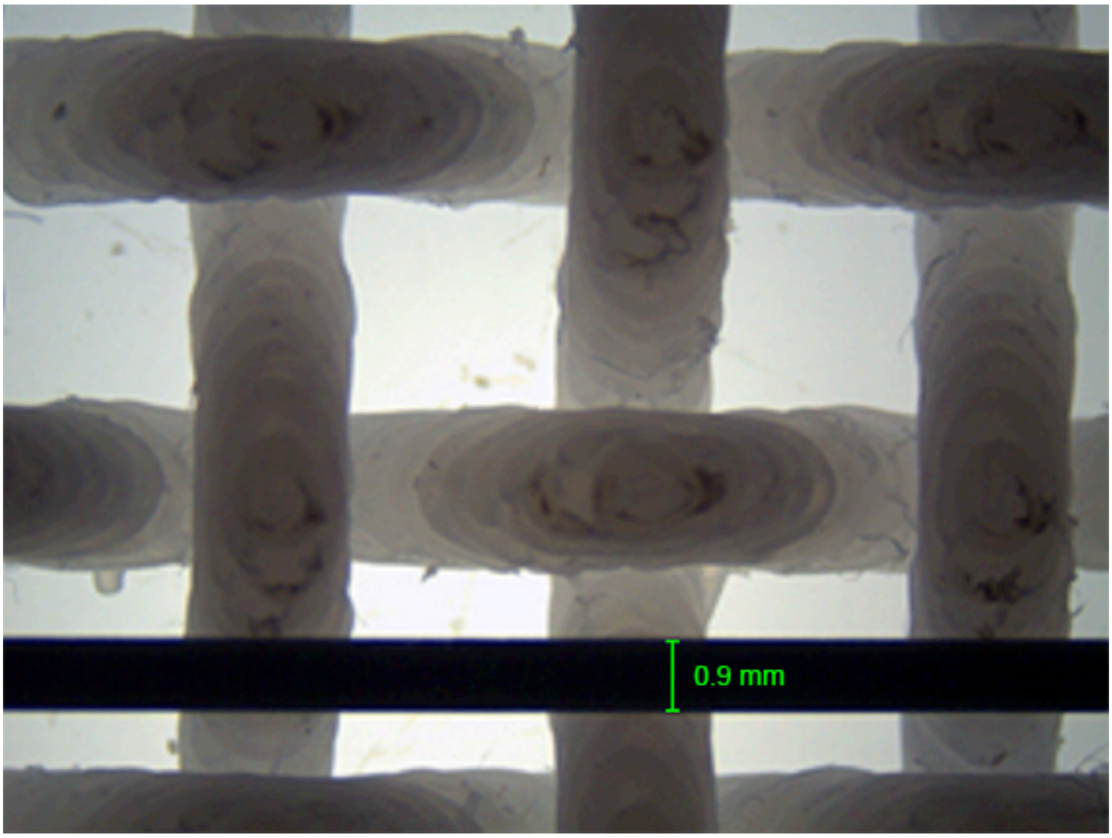


Image 6.48
FDM printed plain weave
Stereomicroscope (reflective light)
Lynn Tandler (2015)

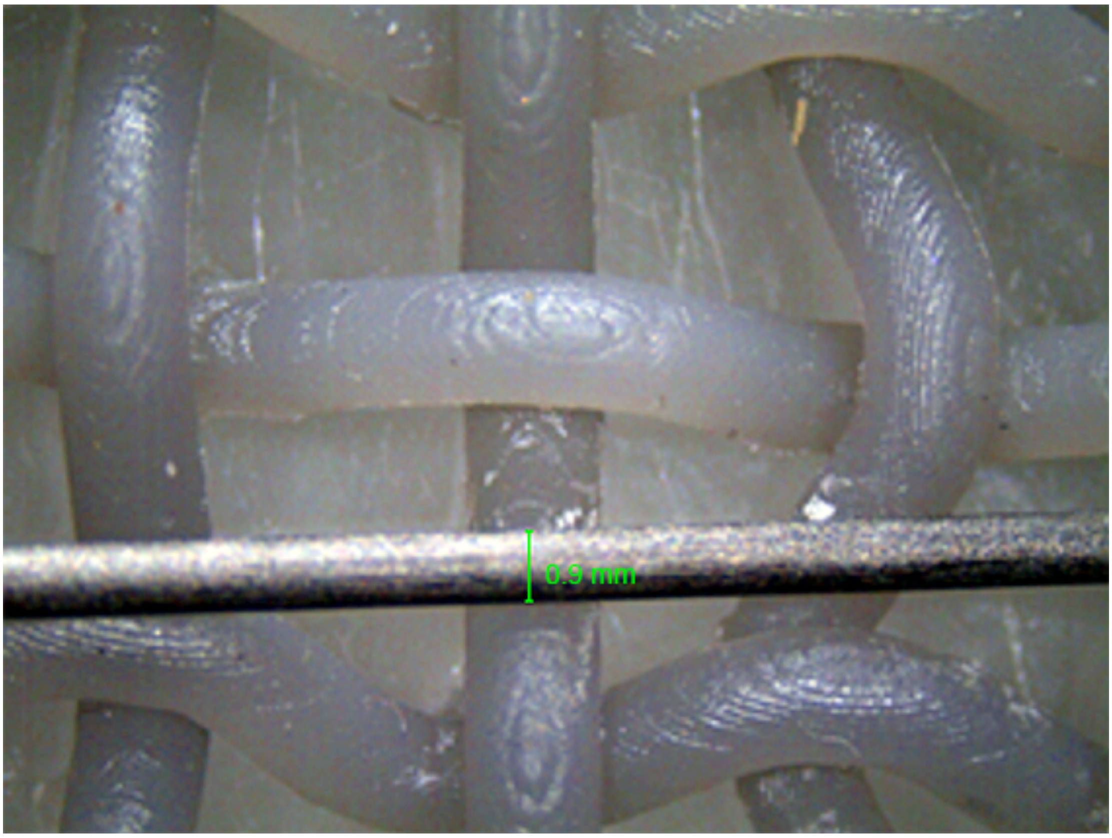


Image 6.49
SLA printed plain weave
Stereomicroscope (transmitted light)

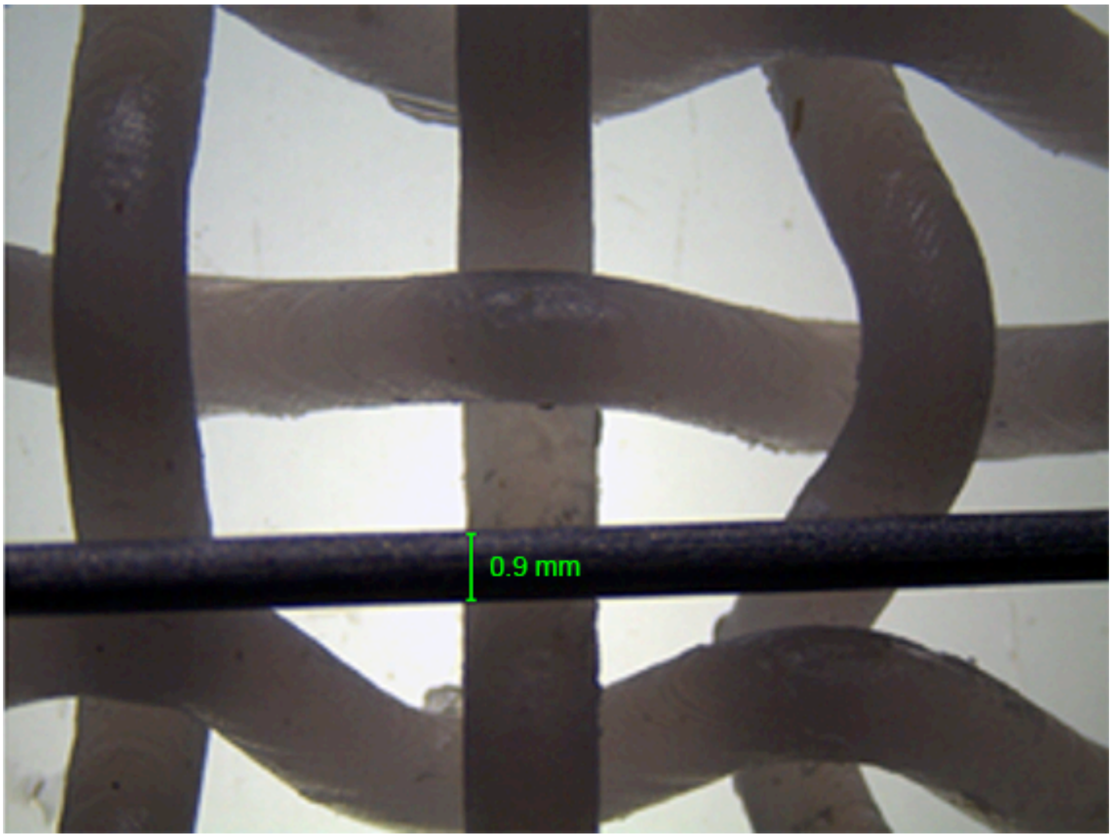


Image 6.50
SLA printed plain weave
Stereomicroscope (reflective light)
Lynn Tandler (2015)

6.3.5 Case study 3 – Discussion of the results

The properties of 3D printed monofilaments are determined by three main factors: the wavelength (WL), amplitude (A) and diameter (D) of the strand. In total, ten samples were 3D printed: five samples were printed out with a FDM technology on a *dimension st1200* machine, and five more were printed out with a SLA technology on a *FormLabs 1+* machine. The dimensions of the printed samples were altered and so was the ratio between wavelength, amplitude and filament diameter. The most movement was found in sample no. 10 with ratio of 9mm x 1.5mm x 1.25mm to wavelength, amplitude and filament diameter respectively.

Chapter 4 of this research had demonstrated how the physical and mechanical properties of conventional textile components are determined by the properties of their constituents and the methods used to bind them into a unified form: for example, the properties of yarns are determined by the properties of the fibres that they bind and the technologies used for spinning the yarns. In 3D printed woven materials however, the properties of 3D printed monofilaments are governed by digital specifications of the designed form. Not only do the dimensions of the monofilament, its travel movement and its relation to other filament need to be determined in advance - those would not change in ration to their neighboring components within the architecture. In other words, the physical and mechanical laws that dominate conventional textile components such as stretch, stress and strain and the dependent relativity of all component on each other within textiles systems do not have the same impact on 3D printed textile components: in a 3D printed woven architecture, the printed objects remain independent. In other words, they do not form a system.

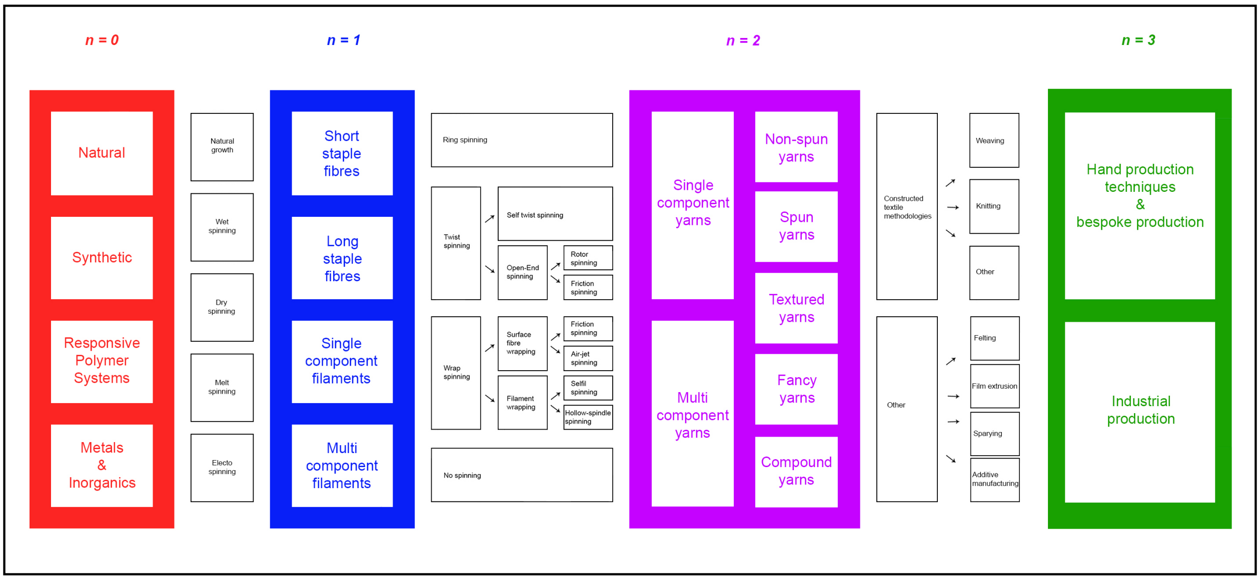
On the basis of all that has been discussed in previous chapters, this means that in fact there is currently no such thing as 3D printed textiles nor there is likely to ever be, woven or not. For what distinguishes textiles form other groups of materials is the fact that they are materials systems where every one of its components is dependent upon another. This is the key for textiles' strong structural complexity. This travels back to the principles of structural hierarchy upon which textiles are built and formed. Putting it simply, there is no such thing as 3D printed textiles and nor can there ever be only potentially, 3D printed materials.

Additive manufacturing in its current form offers production on a small scale allowing a breadth of design explorations with regard to 3D form and overall shape. However, the properties of 3D printed products themselves cannot be altered much. Which is another restricting element that makes their potential competition with conventional textiles problematic. The products made from AM technologies today are still largely governed directly by the properties of the polymers and resin solutions used, and the technologies that administrate the production. And these are still limited in their mechanical abilities. Just as it would be mistaken to assume that the creation of a bird's skeleton through methods of 3D printing would be enough for the manufacture of a 'smart' synthetic bird, it would also be mistaken to assume that the 3D printing of a textile skeleton would be enough for transforming it into smart; just as the bones of the birds are governed by principles of structural hierarchy, so do the so-called bones of textiles.

But more importantly, through this case study it was demonstrated that above all, the structural complexity that governs constructed textiles is missing in 3D printed textiles, which in turn principally make 3D printed textiles inferior to traditional textile products. 'Textile anatomy' mapping (figure 5.12, p. 92) is brought here as an example that demonstrates this fundamental difference in structural integrity: Figure 6.33 illustrates the structural complexity of textile systems in comparison to an inherent inferior structural complexity of additive manufacturing textile products.

Due to its complex structural hierarchy woven textiles are able to occupy a wide reaching application scope – currently more than any other textile construction methodology. And it is that exact structural hierarchy that 3D printed textiles lack, due to which irrespective to materials properties - they remain inferior within their structural properties to conventional woven textile products.

Structural hierarchy of textile products (accroding to TA mapping)



Structural hierarchy of additive-manufacturing products (according to TA mapping)

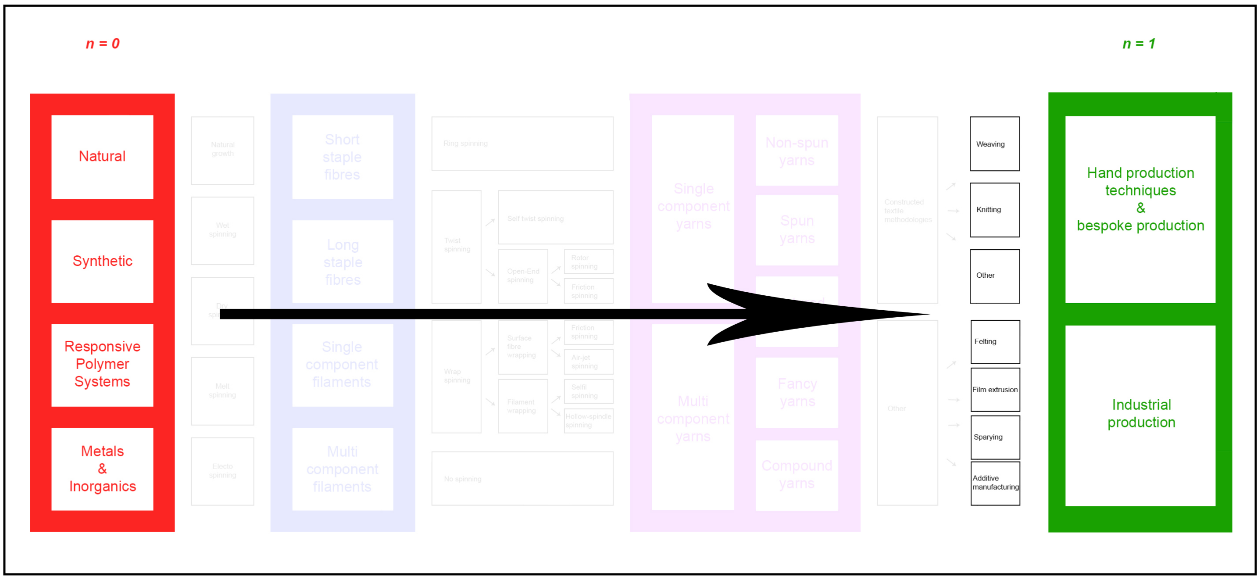


Figure 6.37
Illustration of the structural complexity of textile systems (above)
and additive-manufacturing products (below)
Lynn Tandler (2015)

The experimental work of case study 3 had shown that current attempts to use AM technologies for the creation of textile, will keep on generating inferior so-called textile materials. The fundamental difference between the two construction methodologies that of conventional textile manufacturing and that of newly explored 3D printed textile manufacture (figure 6.37, p. 171), proves that 3D printed textiles could not compete with conventional textile construction methodologies. Due to their relatively simple structural complexity, 3D textiles would be able to lend themselves to a limited application scope. More over, and as a result, the prospect of making the current textile industry redundant for the sake of developing a new industry based on AM for the production of textiles should be rejected.

6.3.6 Case study 3 - Further investigation and tool making

Case study 3 has shown the extent to which AM technologies are incompatible with the production of construction textiles. The discussion of the results also strongly suggests that inherently, current AM lattices/interlaced materials are likely to continue to be inferior to conventional constructed textiles. Nonetheless, the fascination with AM technologies and with 3D printing is unlikely to fade away, and although it was deemed incompatible and unsuitable for the creation of textiles, it still has a valid and important role in product making today.

AM technologies rely on CAD files, and there is a great advantage in the ability to share the same file in different machines and throughout various AM process making. The design of CAD files for weaving is by no extent a simple task mainly because the movement of the filament needs to be predicted and drawn out throughout the cloth. Unlike continuous filaments that in a way curve and bend into place once woven, digitally designed continuous filaments need to be drawn out precisely since they are unable to bend into shape within the printed woven architecture. Crucially, the ratio between the filament diameter, it's amplitude and wavelength needs to be determined in advance. Similarly, in the digital design and patterning of various weave structure on Solidworks it is worth noting that it is impossible to so-call flip the pattern, for example, from an S twill to a Z twill, as in conventional weaving softwares.

For each weave structure, for each interlacement and for each architecture within the weave, a new design needs to be drawn out. Although some evidence can be found for 3D digital plain weaving, no account could yet be found across the literature or the internet, that extend the exploration of woven architectures beyond the plain form of weaving.

As a result, it was decided to start a digital library of various weave structures: one that can be applied onto various AM technologies and machines. James E. Thomas – a senior computer technician and code developer - has developed a unique code that outlines eighteen different variations of weave structures – as well as a basic plain weave digital architecture that could be applied and manipulated to suit. On the current code there are: 1/3 Z twill, 1/3 S twill, 2/6 Z twill, 2/6 S twill, 1/7 Z twill, 1/7 S twill, 4/4 Z twill, 4/4 S twill, 2/2 Z twill, 2/2 S twill, hopsack, herringbone, 8-end satin, mock leno, honeycomb, basket weave, 4-pick warp rib, and 4-end weft rib. The code for creating these weaves can be found in Appendix B.

6.3.7 Discussion of experimental studies

Chapter 6 sought to examine weaving through practice-led research, as a potential fabrication methodology for smart structures, i.e. structures that mechanically can change and adapt to changes in their environments, or to changes that affect their constituents. Case study 1 dissected leno twists and leno weaving and examined its suitability for the creation of reversible weave structures. As a result, a new headle and a new reed were developed but their effectiveness could not be validated. Case study 2 explored the way in which more conventional weave construction methodologies such as double cloth could be further manipulated into creating a woven geometry that is adaptable and reversible. Focusing on the principles of auxetic movement in macro structures, case study 2 saw the development of a novel reversible weave structure that expanded in both axes simultaneously upon stretch, but the movement that was generated from the auxetic weave was limited and very much dependent on the properties of the yarns from which it was built. Case study 3 explored some additive manufacturing fabrication technologies for the creation of textile structure, with the aim to validate, or disprove, a new assumption amongst designers that textiles could be 3D printed. Through the process of making and a collaborative experimental coding – kindly drafted by James E. Thomas – an original library of digital weave structures was created. Although a number of printed 'weaves' were made on different machines, the results were very poor, and although demonstrating a plain weave construction, the samples lacked the mechanical, physical and thermal properties that plain weave fabrics often have. At this point 'textile anatomy' mapping was applied revealing the inferior inherent structural properties that 3D printed products have in comparison to constructed textiles.

Aside from the rejection of current additive manufacturing technologies as a potential textile construction methodology, chapter 6 highlighted the elements within weaving that stand in the way of converting woven architectures into smart.

Chapter 7

Discussion: The Role of Weaving in Smart Textile Systems

This research deals with current and future developments of woven textiles; their meaning, formation and potential methods of production. In particular, it seeks to demystify the idea of smart textiles through an explanation of the way constructed textile systems work.

The critical review of the literature in chapter 3 was used to illustrate current misconceptions regarding the meaning of smart textiles. Although smart textiles are often discussed across academia – as well as within the public domain – the definitions that seek to explain their benefits and value are often contradictory, lacking in coherence or just misleading. The majority of accounts describe smartness in textiles as a synonym for responsive behaviour – something that is susceptible to changes in the environment such as moisture, temperature, light, electrical current and/or chemical stimulations. This poses a complex philosophical question as to whether responsive behavior, in and of itself, can be properly described as smart. At the base, there is an epistemological question here about the nature of intelligence that is beyond the remit of this research. My challenge to 'smart textiles' has been more modest and this was summarised in the provisional discussion of the literature in chapter 3. Instead of referring to the quality of individual components as the agent for smartness, smart materials systems (or smart textiles) are actually about the relationship between multiple individual components that together give a material system beneficial value as a smart system.

There is much intellectual stimulation amongst STEM practitioners who seek to understand the merits of genuinely smart materials. The issue at hand therefore is not the lack of understanding of the term 'smart' across STEM, but rather the lack of this understanding among designers, who are key participants in the introduction of new textile materials into the marketplace. Currently, in most existing examples of 'smart textiles' the reference of the creators is to the technology that is often fitted onto or into the textile. In such examples, the technology is separate to the textile and as a result the material system itself is ignored. In other words, only technologically infused individual components – upon implementation onto or into a textile – are misunderstood to attribute textile 'smart' properties.

By taking the engineering perspective of Culshaw (1996) and of Lakes (1993) and applying their logic to textile construction, I propose that any meaningful definition of smart textiles has to locate the smartness within the material system itself; that is, in the relationship between the various components that make up the system, and form it into a piece of textile. Here, textiles remain textiles; they are not made smart because of some foreign element or additional technology.

Similarly, I believe that a relationship between textiles and some sort of an artificial intelligence is unsubstantial and remote**:** a piece of textiles doesn't need to have a so-called 'brain' (Gandhi and Thompson, 1992; Wang and Kang, 1998) in order to qualify as smart. I go along with general views that smart is, to an extent, a form of responsivity. However, since all textile materials are in some ways responsive, I distinguish between what I call *superficial* responsivity – simple responsiveness to external stimuli – and *deep* responsivity (i.e. smart) in which it is the structure of the material system that considers the unique individual properties of its elements across its structural hierarchy. Meaning that each of the components within the system is linked to the others by reaction into creating a material system. In such case, when one component changes, so do the rest of the components accordingly. The (smart) system is therefore inherently cross-linked and this makes it *deeply responsive* to *external and internal stimuli*.

The evidence gathered from the theoretical exploration and practical experimental studies undertaken through chapters 4, 5 and 6, allows the argument that textiles are better understood not as materials but as material systems, governed by principles of structural hierarchy. The particular structural hierarchy that governs textile systems has been expressed through the development of a unique mapping tool - 'textile anatomy' (figure 5.12, p. 92) - which traces the hierarchical structure of its individual components from the molecular scale (n=0), through the micro scale (n=1), meso scale (n=2) and the macro scale (n=3). This mapping tool describes the actuation of a hybrid research methodology, outlined throughout chapter 2 as Design: S-T-E integration. It emphasizes the particular structural complexity that ties together n's 0 to 3 into attributing cloths with a wide range of properties and suitability for large range of product applications.

'Textile anatomy' mapping (figure 5.12, p. 92) reveals that the behaviors and properties of individual material components are currently used as sole instigators for responsive behaviour in textile system: polymers (levels n = 0), fibres (level n = 1) and yarns (level n = 2) are used to enhance textile performance. Thus far the textile industry has relied on the properties of its components – the polymers, fibres and yarns - to enhance the performance of the cloths it produces.

The production and manufacture of manmade fibres and yarns has created a pathway out of the restrictions of traditional textile production and the addition of such manmade materials into the textile industry in the turn of the 20^{th} century proved transformative. Since then manmade fibre production has been at the forefront of innovation and as a result fibre production has been on a constant increase, with several fibre materials emerging in the market to suit specific textile applications. However, no one fibre has all the properties to accommodate the requirements for all applications, and with a growing need for innovation or commercial advantage, no one material is likely to fulfill that ambition.

At the same time the introduction of new fibre materials into the industry has proven expensive. And as a consequence, it has become the widespread belief that new fibres can only be introduced if they have significant advantages in performance or cost. The same applies for new polymer materials and yarn structures. However, with that in mind, the common impression is that smart textiles rely solely on the so-called smart properties of their components. And although this is true when it comes to the creation of technical and electronic textiles - it is not the case when it comes to the development of smart textiles.

Contrary to common belief, the use of any component material – however responsive - does not convert a piece of textile into a smart material system. Away from the textile community the view is that no one single material could ever be smart, only systems can. The smartness in smart material systems would manifest itself in the ability to sense the environment and through some processes of data reduction make a judgment to adapt and optimize its function, structure or shape in a predetermined and sustainable manner. Thus far no such system yet exists.

New materials such as shape memory polymers and phase change materials are often taken to be smart but in fact such materials have been shown to be no more responsive than cellulose, keratin or even copper for that matter. Their molecular architecture is different and this allows them to be able to manifest different properties and sets of behaviour. But shape memory polymers or phase change materials don't respond to any external stimuli at a level that exceeds their programing. In other words, such polymer systems may response to external stimuli – but so would cotton and wool fibres if exposed to a different set of external stimuli. Which makes them responsive polymers but not necessarily smart. However, the way in which individual components such as polymers, fibres and yarns in the case of smart textiles - whether responsive or not - come together to form a system, can potentially make it smart. In other words, it is not the individual properties of selected component materials that turn textiles into something smart but rather, the structure that brings them together to form a system and facilitate their combined behaviors accordingly.

In textiles, the most common construction methodology is that of weaving. It dates back thousands of years - preceding the invention of the wheel. The heydays of the weaving industry are often linked with the Industrial Revolution - when power looms were developed and a new textile industry was formed. An investigation into the evolution of weaving – presented in chapter 5 – reveals the dependent progression of weaving on the evolution of yarns. For weaving would not have evolved without yarns the evolution of weaving machines comes as a response to the widening innovations of yarn-spinning techniques. Yarn-spinning machines emerged across Britain throughout the 18th and 19th centuries - infusing a momentum of creativity and invention, and forming the foundation upon which the Industrial Revolution was built. Much yarn was produced due to innovations in yarn-spinning technologies, and this had led to a need to speed up the weaving process itself and further enhancing the productivity of the industry. By the mid 19th century all weave structures previously crafted by hand were achieved mechanically and in an industrial fashion.

The fundamental driver of the Industrial Revolution was the creation of an automatic manufacture line that saved the costs of labour, increased the rates of production and eliminated much human error. So effective was the production that today we rely still on the same principles of manufacturing established during Victorian Britain some 250 years ago. But the Industrial Revolution and that which relates to textile manufacture in particular was not the revolution of the weavers as craftsmen but rather of the entrepreneurs, the businessmen and the technically savvy. These were the people that shaped the era and reaped its rewards. What is significant is that the geometry of weave structures did not change during the Industrial Revolution. Indeed this geometry has changed only a little during its thousands of years life span, since the first discoveries from around about 8000 BC. But the machines upon which weavers weave have changed enormously. Which is to say that much of the change in textile production has been effected by mechanical engineers but also and even more prominently, by the businessmen who sought an opportunity and translated new inventions into a thriving industry.

The efficiency of process of manufacture that the Industrial Revolution created in Britain following the 18th and 19th centuries had formed a reality by which the production of textiles was informed by the specifications, limitations and engineering ability of the weaving machines. In other words, it was the specifications of the machine that determined which cloths could be woven and which could not - not necessarily of the weavers. Their job now was simply to supervise the industrial manufacturing process.

The new weaving machines that came out of the Industrial Revolution reveal an essential link between apparatus and textile products; connecting the specifications and hence, limitations of machines to the product which they produce. This still applies in present day with hand weaving forming only a small niche within the textile industry, and production mechanisms still relying on the capabilities of individual mills. Special weaving looms that have been designed for the production of unique weave structure reaffirm the strong link between machine specifications and the geometries that they produce or, in other words, the woven textiles that they are able to generate.

Weaving has changed very little during the thousand of years of its practice mainly because, by and large, the principles of weaving have remained the same. Even with the introduction of specialty looms such as velvet and leno, the principles of the weave structure itself remained the same. They are outlined below:

(First) All woven fabrics are made of two sets of threads: the warp and the weft. The warp always runs vertically, and the weft – horizontally.

(Second) In all weaving looms a shuttle or another transfer mechanism transports the weft from one side to another inside the opening shed.

(Third) The warp is always transferring from one beam to another on the opposite side of the loom - meaning that the warp yarns must be of a continuous length. Consequently, no staple fibres could be woven on a loom.

(Four) The warp threads must always be under tension, however this may vary depending on yarn type and structure.

(Five) All warp ends are threaded through headles, which are attached to shafts or to other lifting mechanisms, such as those found in Jacquards.

The limitations of weaving have been tested through a series of case studies outlined in chapter 6 in an attempt to break from them and create new woven architectures. But just as special weaving looms and techniques that have been designed for the production of unique weave structure reaffirm the strong link between machine specifications and the geometries that they produce, so do the woven textiles that they are able to generate.

With the integration of S-T-E into textile manufacture the role of the textile designer increasingly comes into question. The rise of alternative computerized manufacturing technologies such as additive manufacturing and 3D printing techniques have begun to lend themselves to an alternative method for textile construction in an attempt to replace or compete with conventional textile productions. But the investigation into the creation of so-called 3D printed 'weaves' – as presented through case study 3 in chapter 6 - revealed two main concerns thus far overlooked.

Firstly, it has become evident that practitioners with no textile awareness cannot differentiate between the various textile construction methodologies and their respective merits. The problem here chiefly lays in the probability of repeating mistakes and disadvantages of construction, which textile practitioners have taken long to learn and establish: weaving, knitting and braiding are unique assembly techniques used to attribute materials with softness, malleability, stretchability and drape. Different machines create different textiles and the various techniques used for the assembly of yarns into cloths is one of the key elements that make textiles different from other materials.

Secondly, the inferior properties of 3D printed 'weaves' in comparison to current conventional textiles have been demonstrated. 'Textile anatomy' mapping was used to present the structural complexity of conventional constructed textiles and that of 3D printed textiles. In doing so it showed that current additive manufacturing technologies cannot yet compete with current textile production methodologies for the creation of better textiles. This is primarily due to the structural hierarchy that governs all textiles, which 3D printed 'weaves' lack. 'Textile anatomy' demonstrated that textiles have at least four predominant levels of structural hierarchy, namely polymers, fibres, yarns and fabric architecture. In comparison, 3D printed weave structures have only two: polymers and a 3D product shape.

Just as woven textiles are affected by the specifications of weaving looms, so are 3D printed structures affected by the specifications of the Additive Manufacturing (AM) technologies used for their build. Currently the specifications of such machines cannot produce an alternative to conventional production methodologies for woven textiles. In addition, with technologies currently available, there is only a limiting amount of materials that can undergo the processes of 3D printing. This means that the selected polymers, resins and powders currently at use are those that control the properties of the end products. Nonetheless, even if (a) AM machine specifications become more sophisticated over time, allowing finer and more accurate control over the depositions of suitable materials, and (b) the materials used would also prove more applicable and feasible in properties and cost respectively, this thesis has revealed that the structural complexity of such potential 3D printed textile materials will forever be inferior to that of conventional constructed textiles due to the structural complexity of both. In principle, potentially, this also means that textiles have the ability of becoming much smarter than any other 3D printed fabric, and since structure is the essence of smartness in textiles, as far as the morphology of smart textile systems go, they are unlikely to be the products of an AM manufacturing process.

Smart textiles do not yet exist - partly because our widespread understandings of smartness with regard to textiles have been distorted but also because we use new materials with outdated techniques. This gap between cutting edge technology, advanced material science and ancient construction methodologies is bound to prove idle. The experimental case studies presented in chapter 6, demonstrate the restrictions and constraints that traditional weaving methodologies offer to the construction of textiles. And so, since AM, in its current form, is a less fruitful way forward, a revision of the way in which we bring material together into new systems is required.

The investigations of this research points towards a realization that the principal geometries of woven textile structures, as we know them currently to be, in fact stop textiles from ever becoming smart. In other words, in their current form woven textiles cannot be smart.

A simple proposal may therefore be to invent new looms, ones that will still maintain the superior mechanical constructions of woven methodologies, but also that will be allowed to step away from the restrictions of current weaving methodologies. But how can we know what to change and what shape or mechanism should such looms have?

Today, ideas of conventional engineering are making way to those of nanotechnology - meaning that traditional techniques for materials fabrication, which exist on the macro scale, are beginning to give way to new techniques of manipulation of materials at the micro and nano levels. STEM has so far governed the recent shift of discussion down to the micro and nano scales: the micro and nano materials worlds have not yet become a designers' territory. For the purpose of material system fabrications on the micro and nano scales, scientists and engineers have been looking to the textile industry for inspiration. And so, textile methodologies such as yarn spinning and weaving have been mimicked and miniaturized in various forms for the construction of micro and nano materials. But methods that are relevant for the production of macro scale material systems, such as yarns and fabric assembly, could work differently on the micro and nano scales, away from the restrictions posed on them by the macro material world. There is, therefore, an opportunity here to overcome some of the restrictions that govern weaving methodologies - on the macro scale today.

Just as looms have developed to accommodate various yarns, new textile fabrication machines for the production of smart textile systems cannot be invented without materials to manipulate - meaning that the fibrous units used for the creation of textiles on the micro or nano scales should be known before a machine is imagined. Since structure is paramount to the creation of smart material systems it can therefore be understood that smart textiles could never exist on the macro scale, as we know them now at least, if conventional weaving methodologies are continued to apply. This is mainly true because current weaving methodologies are designed to create static architectures aimed at maintaining a stable geometric form. This means that the limitations of current woven geometries restrict the potential movements and behaviour of individual components within the system. Away from the macro material world weaving may have a role to play in micro and nano scale textile systems, once the limitations that dominate the macro materials world are overcome. With different set of mechanical and physical laws dominating the micro and nano fabrication realms, the limitations, which have identified weaving for thousands of years, could be revoked. A new so-called 'nano loom' would not need to obey mechanical and physical laws that govern the physical and mechanical world of macro scale fabrications. On the nano scale the construction of weaves would not be limited to only *two* sets of threads; the interlacement of wefts would not be restricted only to horizontal positioning; the warps would not necessarily be of a continuous length; and constant tension would be made avoidable. Additionally, warp end would not be led through heddles as a necessity.

If materials therefore inform the development of machines, and machine specifications inform the creation of potential structures, then it means that new fabrication tools should be considered as an integral part of the design process - especially now, at the dawn of a so-called new industrial revolution, which seeks to examine and further advance the fields of nanotechnology and synthetic biology. Accordingly, the properties of new materials should be examined and their mechanical, physical, chemical and thermal properties assessed, in order to inform the workings of future textile systems.

The convergence between Design and S-T-E (Science, Technology and Engineering) for the creation of new textiles on the macro scale had created a reality by which in order to generate a novel piece of textile, the works of chemical and mechanical engineers is required: the former to develop new textile components such as polymers, fibres or filaments, and the latter to build machines for yarn spinning and/or fabric constructions. This separation between Design and S-T-E however has also allowed the creation of new technical and electronic textile prototype that together enrich our consumerism habits, fashion choices and lifestyle. Such methodologies, however, can no longer be relied upon as a tool for the creation of smart textiles, because unlike technical textiles, smart textiles are not textiles that have one sole function. Smart textiles are deeply responsive material systems.

The Design: S-T-E integration methodology that governed my research has dramatically changed my weaving and my design practices. As a result of the research undertaken in the past three years I no longer perceive weaving as the assembly of different foreign fibrous objects but rather as a new holistic approach for the construction of material systems with various properties in tuned to diverse changes and conditions.

It has therefore become clear from the work undertaken throughout in this research that to claim a material as smart is to over claim and presume that the relationship between the inherent properties of materials and the technology on which material systems are produced are in sync. Today, they are not and this could be one of the reasons why, after decades of research and development, we still mostly use conventional textiles. But using textiles construction methodologies as an inspiration for the creation of new material fabrications on the nano scale is advisable. Because the history of textiles and materials in general confirms that textiles have lasted thousands of years, and in the process have evolved only a little - purely because there was no need for them to progress further: here, the structural complexity of textile material systems was enough to offer diversity applications with wide rage of properties. Perhaps now we will find that smart textiles will not be textiles at all, as they are currently known to be, but micro or nano material systems created by textile methodologies.

From a design perspective, materials have physical, mechanical and thermal properties. But they also have aesthetic properties. For materials themselves in their raw state have got their own sense of aesthetics: wood *looks* different to glass, and glass *looks* different to metal, or stone. Plastics, which had only been invented in the turn of the 20^{th} century – no more than one hundred years ago – have a vastly different aesthetics to natural or organic materials too, for they offer the aesthetic world a somewhat unnatural colour palette – one that can only be synthetically and/or chemically manufactured. It is therefore not a surprise that the world in 2015 *looks* differently to that in 1915 when wooden carts and indigo cotton dresses adorned the streets. The emergence of genuinely new materials into our reality therefore has wide reaching repercussions: not only do our perception regarding materials changes as we gain a deeper understanding about their architecture and operating mechanisms, but also the way in which we view their aesthetics changes too. It is interesting to see how science, technology, engineering and mathematics have been informing Design – mainly throughout the 20th and 21st centuries. Slowly, as our perception and understanding of materials become more specific and in tune with micro and nano scale configuration so our design methods adapt to suit the possibilities of new material systems. In other words, STEM in general – and science in particular - informs and inspires new Design. Today, at the dawn of the age of nanotechnology and synthetic biology it will be interesting to further explore what other possibilities are there for woven material systems – from material synthesis and fabrication to a new aesthetic that we are yet to have imagined or explored.

Chapter 8

Conclusions

From the work carried out throughout this PhD research the following conclusions are presented in the context of their original contribution to knowledge:

i. A bespoke hybrid research methodology was developed for the purpose of conducting this practice-led research, one that sought to bridge over and narrow the gap between textile designers and textile engineers. Such new methodology - governed by the creative tools of Design and some investigative methods derived from the fields of Engineering (chapter 2) - has proven to be a fruitful tool for the generation of new insights and new knowledge into the development of smart textiles.

ii. 'Textile anatomy' lay out and illustrates, in a straightforward way – as a map - the structural complexity that governs all constructed textile systems. Examples from the end of chapter 4 demonstrate the usefulness of TA mapping in illuminating this complexity.

iii. 'Textile anatomy' mapping had clarified that currently responsive behaviour in textiles only occurs in hierarchical levels 0-2 (through polymers, fibres and yarns characteristics) and not in level 3 through the adaptation of the structure of the system itself, i.e. in weave structures. This revelation was the foundation for the experimental studies carried out throughout chapter 6. Consequently, what the findings have shown was that in its current state, weaving cannot generate responsive behaviour in constructed textiles. But clues towards the future of textile construction could be manifested away from current constraints.

iv. Textiles are *material systems* governed by principles of structural hierarchy. The fact that textiles are systems - and not individual materials in their own right – means that as long as we ignore the structuring methodologies of textiles as an active catalyst for allowing responsive behaviour to any degree to occur, textiles could not become smart.

v. The misconception of the term ‘smart textiles’ often regards it as a synonym for responsive behaviour. But, all textile materials demonstrate responsive behaviour to some extent and so the conundrum with regard to smartness still persists.

vi. The structure of the material system as well as the properties of each of its components across lengthscale was found to be crucial in determining potential smartness. As a result, a grammatical investigation into smart textiles was set to demystify current perceptions of the term and has resulted in an original differentiation between *superficial* and *deep* responsivity in textiles. This form of inherent or *deep* responsivity is the key for the creation of smart textile systems.

vii. In an attempt to step away from current constraints of weaving methodologies, additive-manufacturing technologies were examined. Results from the research revealed a fundamental advantage of textile construction methodologies over those of 3D printing. Based on the principles of structural hierarchy, and a ‘textile anatomy’ mapping tool, the superior structural integrity of textile systems overcomes those of 3D printed products.

viii. Weaving has been shown to be relevant for the creation of smart textile systems because, as indicated through chapter 4, 5 and 6, it has enough degrees of freedom to potentially allow the properties of its components to emerge.

ix. Weaving incorporates micro and meso scale components. Although much explored as a macroscopic materials assembly technique, on the meso, micro and nano scales weaving itself has not been comprehensibly investigated. With more research and attention drawn to micro and nano scale materials assemblies, the limitations of weaving could now be overcome and new smart textile systems could be made possible.

x. As the principles of textile construction, as a fabrication tool, are beginning to have traction with the micro and nano worlds, smart textile systems will predominantly exist in that realm and not on the macro scale - replacing existing textiles, as we know them today. Such new smart textile systems are expected to have very different properties and functions compared to the textile systems that currently occupy the macro world of natural and synthetic materials. Most prominent would be our perception of textures since nano smart textile systems will be inherently smooth to the touch.

Chapter 9

Suggestions for future work

The integration of Design with STEM, as approached throughout this research, holds a key for better understanding the problems that textile developments face today. The grammatical investigation of the term smart textiles (chapter 3) has equipped the reader with a new and profound understating to the meaning of smart textiles. The novel development of 'textile anatomy' mapping tool (chapter 4 and 5) stemmed from that understating with the need to better comprehend the complexity that governs current textile systems – in a simple and straightforward way. The development of 'textile anatomy' mapping had led to a series of unique investigations – all of which are rooted in the art of woven textile constructions (chapter 6). Both the practical and theoretical work presented throughout this research forms a solid foundation for further investigations, and this is briefly outlined below.

9.1 'Textile anatomy' mapping as an interactive digital predictive tool for future smart material systems

Designers increasingly rely on the properties of individual materials to inform the applications of new products, and the necessary task of requiring such knowledge and understanding is becoming progressively more difficult (Miodownik, 2015). In textiles the case is even more complex since textiles deal with the composition of many components across lengthscale into the one material system. A need therefore for an interactive digital tool that uses the structural, mechanical, physical and thermal properties of individual textile components has emerged to operate as a digital hybrid modelling system.

9.2 Smart textiles development

The design of smart textile systems should be anchored in human centered design, meaning that the needs of textile consumers should be taken into account over the technological advancement of individual components – designed and developed away from the textiles. One way of interpreting human centered design in smart textile systems is to aspire for optimal and sustainable solutions for long standing problems that are persistently attached to textiles at present day. Through the utilization and adaptations of structuring methodologies across lengthscale anti-crease textile systems can be created - where the structure of individual textile components within the systems, as well as the structure of all the components together, is used counterintuitively under changing conditions of stress and strain. By doing so the structure of the system as a whole can be used to prevent the textile from ever retaining any creases. This example of development is considered here to be smart not only because the material systems is designed as *deeply responsive* (chapters 3 and 7) but also because the benefits of such fabrics will be all inclusive for they will not only profit the consumer but they will also reduce energy consumptions significantly and in doing so will become sustainable for the textile industry as a whole.

9.3 'Quantum weaving': investigating weaving on the nano scale

Textile methodologies have long been implemented by scientists and engineers as materials assembly methods. However, as this research revealed, the limitations of weaving – as they currently manifest themselves on the macro scale – should not be taken as face value when attempting to apply them onto the micro and nano scales. Instead, current principles of weaving should be accordingly altered to create flexible and durable nano material architectures. The development of a 'quantum weaving' technique could give way for this, by weaving individual single walled carbon nanotubes into so-called nano fabrics. CNT's have enhanced physical, mechanical and electronic properties that together with modified weaving techniques could be applied to create invisible sensory material systems and/or artificial skins. Weaving at the lower end of the nano scale is called here ‘quantum weaving’ – for the textiles that it will create will be invisible and as a by-product, the weaving will be too.

Appendix A

Polymers, fibres, yarns, weave-structures and their properties

This part of the thesis is brought fore to further explain how 'textile anatomy' mapping (chapters 4 and 5) has come about. It is intended for the informed reader, covering common perceptions of individual textile components as explained through STEM practitioners.

STEM (Science, Technology, Engineering and Mathematics) is an integral part of any piece of textile. Through the development of 'textile anatomy' mapping tool (chapter 4 and 5) my research revealed how STEM applies for the creation of all textile systems. This manifests itself in the way in which the various aspects of STEM (Science, Technology, Engineering and Mathematics) apply to the various level of structural hierarchy that governs all constructed textiles [Figure A.1, p. 194]. This sees the development and synthesis of polymers (marked in TA mapping in red) governed by Science; their formation into fibres (in blue) and those into yarns (in purple) by Technology; the assembly of yarns into cloth (in green) by Engineering; and the modeling methods used to predict textile properties and behaviors controlled by the algorithms of Mathematics (marked inside a black frame).

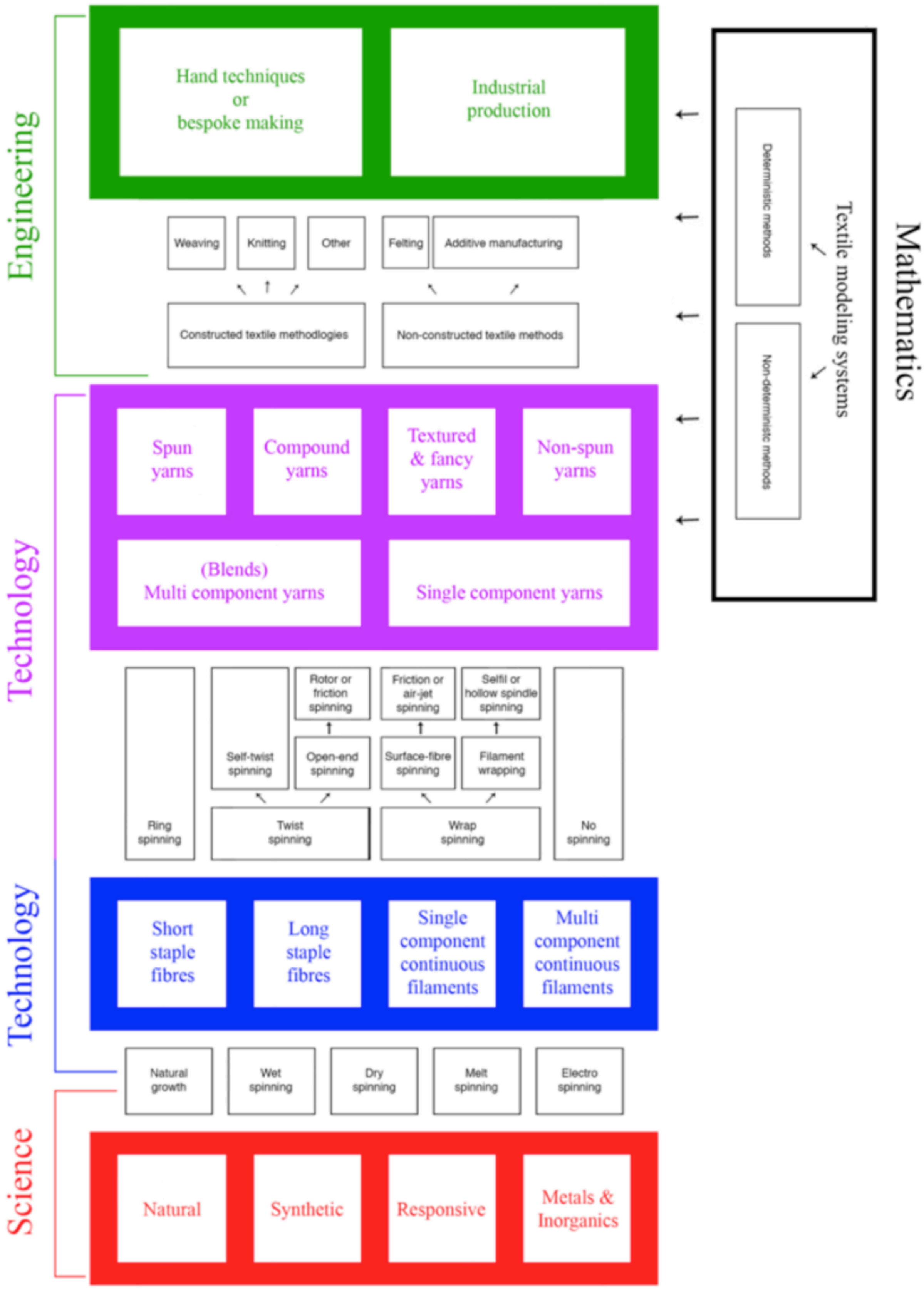


Figure A.1
STEM (Science, Technology, Engineering and Mathematics) and their relevance
to textile components, construction and analysis – visualized through TA mapping
Lynn Tandler (2016)

A.1 Science in 'textile anatomy' mapping

The study of chemistry enables vital understanding of polymer properties (Alfrey & Gurnee, 1967; Hearle, 1982; Shirtcliffe, McHale and Newton, 2011): In the words of Nielsen (1963), the researcher "is interested in knowing why one polymer is tough while another is brittle, or why one polymer is rigid while another one is rubber. The synthetic polymer chemist wants to know how mechanical behaviour is related to chemical structure in order that can tailor-make materials with any desired properties" (Nielsen, 1963, p. 1-2).

In the process of polymerization, monomer molecules – which are the building blocks of polymers – respond to a chemical reaction and in doing so they form linear chains or three-dimensional networks of polymer chains (Young, 1981). These arrangements of molecules within the polymer have great affect on the properties and behaviour of the polymer thereafter. In *Introduction to Polymers*, Young (1981) divides polymers into three main groups of thermoplastics, rubbers and thermosets – each group according to the unique set of properties it demonstrates:

- Thermoplastics refer to a group of polymers that are able to completely melt in high temperatures. This allows them to be manipulated into various forms. Upon cooling, thermoplastic polymers re-shape themselves either into a crystalline or an amorphous state - a distinction that affects their elasticity and as a result may compromise their applications. The vast majority of polymers covered in the following 'textile anatomy' report belong to the thermoplastic polymers group.
- Rubbers, due to their unique polymeric structure, can stretch easily to great extent and restore their original shape when stress is released.
- Thermosets are rigid polymeric materials and are difficult to manipulate. Both rubbers and thermosets degrade rather then melt in high temperatures (Young, 1981), which their manipulation difficult.

The chemical units – monomers - that make up a polymer can be identical to one another or not (Hearle, 1982). When linked up into a chain, identical monomers turn into homopolymers, which describe homogeneous polymeric materials. Mixed units with more than one type of monomer are called copolymers. There are five types of copolymers – each demonstrating a different arrangement of the monomers – which in turn affect the properties and the behaviour of the polymer: (a) Alternating copolymers, (b) Random copolymers, (c) Block copolymers, (d) Graft copolymers, and (e) Mixture of homopolymers (Hearle, 1982).

The chemical bonds that are used to tie individual and groups of atoms together also play an important part in determining the polymer's properties (Hearle, 1982) – not only the nature and order of each monomer within the chain. The molecular chains inside the polymer are seeded with covalent and electrovalent salt linkages, and these operate according to van der Waals' forces and hydrogen bonds that rule the mechanics of the overall polymeric structure (Hearle, 1982).

Additionally, the length of a polymer chain and the way in which it is branched - reaching out to other chains, whether in straight lines or in the shape of a lattice as described before – are important features in determining the properties of polymers and their behaviour (Hearle, 1982): Simple polymeric lattices, also referred to as crystal lattices (Hearle, 1982), display arrangements in which all polymeric chains all lined up parallel to one another. Amorphous lattices on the other hand, display arrangements of polymeric chains that are intertwined with one another.

The majority of the polymers discussed throughout the 'textile anatomy' exhibit both segments of crystalline regions and segments of amorphous regions. In other words, the chains inside the polymers are neither completely aligned nor completely tangled or intertwined. The key feature, which probably plays the greatest role in determining the behaviour of the polymer therefore is the degree of crystallinity (Hearle, 1982) - which effectively indicates how flexible, elastic and durable a polymer is and how suitable to undergo different processing methods for a variety of applications.

The thermal properties of polymers refer to two main properties: the glass transition temperature (identified as *Tg*) and the melting point of the polymer – also referred to as the melting point of a polymer and is identified as *Tm* (Nielsen, 1963). Glass transition temperature (*Tg*) is the temperature by which polymers undergo change in their chain structure – or, a change in their crystalline structure – and as a result change from solid state to a rubbery, malleable state (Nielsen, 1963). The melting temperature (*Tm)* of polymers indicates, quite literally, the temperature by which specific polymer melt.

A.1.1 Natural polymers and fibres

Biopolymers can be derived from polysaccharides, polypeptides or polynucleotides – these are the sugar molecules, the protein molecules or the information molecules within a plant respectively. For the production of fibrous textile elements only polysaccharides and polypeptides are currently used. Polynucleotides, which are DNA and RNA molecules might only play a part in the future – perhaps as a living textile form. But this is still entirely speculative.

In plants, cellulose is the most abundant biopolymer (Ciechanska*,* Wesolowska and Wawro, 2009). It can be found in various parts of plants: it is generated in seeds, bast, leafs, and fruits. According to the place where the cellulose is formed within the plant, different fibres are created through process of natural growth. This way for example, the fibres of cotton, which are formed in the casing where the seeds of the plant resides, are different from the fibres that are found in stokes, which are longer and stronger.

In animals, polypeptides are polymers that exhibit various arrangements of amino acids - and they are the proteins. Keratin for example, is the polymer that forms wools and hairs in animals, and Fibroin is the polymer that forms silk threads. Natural fibres - originating in plants or animals - come in a staple form, which means that they are not continuous and have a relatively short length. Silk filaments are the only exception to this rule, since the silk worm spins its filaments continuously, at times for tens of meters long.

Plant fibres vary in structure and in their mechanical properties according to the parts in the plants from which they are formed. Based on that understanding, Ansell and Mwaikambo (2009) divides plant fibres into two main groups: ultimate fibers that originating in seeds, and fibre bundles originating with in the bast (or stem), leaf, or fruit of plants (Ansell and Mwaikambo, 2009). Cotton, kapok, and akund are examples for ultimate fibers, which grows in the seeds of plants: these are single celled fibres with a relative short length – not exceeding 65 mm (Ansell and Mwaikambo, 2009). Depending on the species, natural fibres may display different structural properties. Petkar, Oka and Sundaram (1983) documented variations in the cross sectional shape of cotton fibres from four different species of plants. Their research verified that different structural properties – such as cross sectional shape – result in distinctive fabrics properties: this also explain variations in fabric properties between plain cotton fibres, Pima cotton and Egyptian cotton fibres.

Fibre bundles, on the other hand, are multicellular, which makes them stronger and much longer than their ultimate fibre counterparts (Ansell and Mwaikambo, 2009). Commonly found examples for bast fibres include hemp, jute, kenaf, ramie and flax (more commonly known as linen). Bundle fibres found in leaves include sisal, henequen and pineapple. And fibres found in the fruits of plans include coir and palm (Ansell and Mwaikambo, 2009).

Animal fibres are also called protein fibres and their structure is much complex – mainly since they are formed according to the DNA code of some animals. The literature classifies them in terms of increasing complexity of their formation. The most common animal fibres in use today are wool, hair and silk - naturally however they differ greatly from one another, due to the fact that they originate in different animals. Wool, hair and silk all have many levels of structural hierarchy, which contributes to the properties of the fibres (Eichhorn, Hearle, Jaffe and Kikutani, 2009).

Wools and Hairs are made of a protein called keratin. They vary however in their chemical structure, which affects their mechanical, thermal and physical properties: Wool fibres grow into much shorter lengths than other mammalian hairs, which grows into long staple fibres. Silk, on the other hand, is made from the polymer fibroin, which is a block copolymer formed within gland cells of worms or spiders and is extruded as long continuous filaments through cell walls, which act as spinnerets (Ciechanska, Wesolowska and Wawro, 2009). The silk filaments have homogenized matrix macrostructure on the surface topography, which contribute to its high strength and high elastic extension (Porter and Vollrath, 2009).

Natural regenerated fibres are made from naturally regenerated polymers, which often originate in cellulose I. They can undergo wet or dry fibre spinning methodologies. Synthetic fibres, however, are always spun through process of melt spinning. Depending on the chemical structure and physical bonds, Cook (1984) divides synthetic fibres into five groups, naming them: Polyamides, Polyesters, Polyvinyl derivatives, Polyolefin and Polyurethane – or synthetic rubber.

A.1.2 Manmade polymers

Manmade polymers are chemically formed by synthesis under controlled conditions in labs. The unique processes of synthesis allow creating polymers with specific properties and characteristics - ones that are tailored made for certain textile application (Baird and Collias, 1995; Robinson, 1980). The field of manmade polymers and their formation into textile materials is only about a hundred years old – which in textile terms is relatively new. According to Goodman (1968), the major innovations with regard to the development of synthetic polymers and fibres were during the years of 1928-1939 (Goodman 1968). To affirm this Cook (1984) also wrote, “until the 1930s, synthetic fibres existed only as a few experimental filaments that showed little sign of serving any useful purpose in the textile trade. Who would have dreamed that in twenty years or so the production of synthetic fibres would have become one of the world’s great industries?” (Cook, 1984, p. 192).

Manmade polymers are polymers that are created in laboratories through processes of synthesis. They can be further divided into two main groups – conditional to the origin of their base molecules: (1) natural regenerated polymers that are derived from biopolymers, and (2) synthetic polymers that are derived from chemical source - in most case petroleum. Both groups are discussed in more details next.

A.1.2.1 Natural regenerated polymers

Polysaccharides, are sugar macromolecules found in plant – and they can often be used as polymeric source for the creation of natural regenerated fibres. Di-saccharides are smaller molecules (‘Di’ reefer for the numer 2) and they can be found in the forms of lactose and sucrose: respectively, they are used to make poly-lactic acid (PLA), poly-l-lactic acid (PLLA), and poly-glycolic acid (PGA). The formation of lactose and sucrose into a copolymer produces poly-lactic-co-glycolic acid (PLGA).

Cellulose is a polysaccharide. In its natural occurrence –as the raw material found in plant – chemical engineers know it as Cellulose I. Once dissolved in caustic soda solvent however, the parallel arrangement of the molecules is lost and a new form of cellulose is formed - known as Cellulose II. Cellulose II can be used for making viscose, modal, cupro, lyocell, cellulose acetate (CA) and cellulose tri-acetate (CTA). Proteins such as soybean, milk, corn and groundnut, can be used for making protein based manmade fibres but these are not as common in production today – mostly due to their inferior mechanical properties in comparison to natural protein fibre made form natural protein polymers (Eichhorn, Hearle, Jaffe and Kikutani, 2009).

A.1.2.2 Synthetic polymers

Synthetic polymers are created from petroleum. Hearle and Peters (1963) have divided synthetic polymers according to their chemical structure into two groups: condensation polymers and addition polymers (Hearle and Peters, 1963). This division had informed them of what each group of synthetic polymers could potentially do and what methodologies should be used to synthesis them into textile fibrous materials. Cook (1984) divided all synthetic polymers into five groups according to the type of bonds that held the molecules inside the polymer chain together:

- *Polyamides* - polymers with recurring amide groups, such as Polyamide 6 (PA6) and Polyamide 6.6 (PA6.6).

- *Polyesters* - polymers with recurring esther groups, such as Polyethylene Naphthalate (also know as PEN), Polyethylene Terephthalate (PET), Polybutylene Terephthalate (PBT), Poly Trimethylene Terephthalate (PTT) and Polyethylene Glycol (PEG).
- *Polyvinyl* derivatives – polymers made from vinyl monomers where the double bonds turn into single bond and link together to form long molecular chains, such as Polyacrylonitrile (PAN), Polyvinylchloride (PVC), Polyvinylidene chloride (PVDC), Polyvinyl alcohol (PVAL), Polyvinylidene fluoride (PVDF), Polytetra Flouroethylene (PTFE), P-phenylene terephthalamide (PPTA), Poly-metaphylene isophthalamide (MPIA), and Polystyrene (PS).
- *Polyolefins* – polymers made of olefin hydrocarbons, such as Polyethylene (PE) and Polypropylene (PP).
- *Polyurethanes* – polymers with recurring urethane groups, such Polyurethane (PU).

A.1.3 Phase Change Materials

Phase Change Materials - also known as PCMs - are affected by temperature and as a result they often have been used to control temperature fluctuations (Mattila, 2006). PCMs have the ability to absorb energy during heating process, change their actual molecular structure in response, and release energy back to the environment during cooling, once reverting back to their original molecular structure (Mondal, 2008): PCMs can also store energy when they change from solid to liquid, and dissipate it accordingly once restored back to their original state (Mattila, 2006; Sarier and Onder, 2012). PCMs are difficult to control and are often worked only under controlled laboratory conditions vivo. According to Langenhove (2011), PCMs are used for the production of medical textiles, such as heating and cooling patches, warming blankets and surgical protective garments, which are designed to maintain a comfortable microclimate temperature for extended periods of time (Langenhove, 2011).

A.1.4 Actively Moving Polymers

Actively Moving Polymers – also known as AMPs - are elastic polymer networks that are made out of switches and netpoints, which allow them to change their shape in a predetermined way once exposed to an external environmental stimuli, such as temperature, pH, chemicals and light. In other words, AMPs can convert stimuli-responsive effects on the molecular level into a macroscopic movement (Behl and Lendlein, 2007) – one that we can see with our naked eyes. According to the nature of their movements, AMPs can be further classified into two sub-groups: shape memory polymers, and shape changing polymers (Behl and Lendlein, 2007). Shape Memory Polymers – also known as SMPs - and Shape Changing Polymers – also known as SCPs - can both adopt different macroscopic shapes and as a result they each exhibit distinctive qualities of shape change (Hu and Chen, 2010). The main differences between SMPs and SCPs are the conditions upon which they undergo shape change, as well as the duration with which they are able to retain the change.

SMPs can be fixed into a temporary shape and later retrieved back to their original shape by singular yet not continuous exposure to an external stimulus (Chen, 2006; Chen and Hearle, 2009). In other words, the shape change in SMPs is triggered by an external stimulus but do not need the exposure to the stimulus to be on-going to remain in their temporary shape: In order to reverse the shape change and return to their original shape, SMPs would require an additional and separate exposure to a different external stimulus. SMPs has acquired good reputation in recent decades, both in academia and in the industry for their low cost, good processing ability, large recoverability, light weight properties and superior moulding proprieties (Hu, 2007; Hu, 2008; Ni, Zhang, Fu, Dai and Kimura, 2007). The most common SMPs currently in use are the trans-polyisoprene (TPI), poly(styrene-co-butadiene), polynorbornene and the segmented polyurethane (Hu, 2007). Such SMPs have already been documented to been used in novel medical devices (Wischke, Neffe, Steuer and Lendlein, 2009; Nagahama, Ueda, Ouchi and Ohya, 2009; Behl and Lendlein, 2007), self-peeling reversible adhesive (Xie and Xiao, 2008), self-healing materials (Voyiadjis, Shojaei and Li, 2011), and so-called smart textiles (Meng and Hu, 2009).

SCPs on the other hand, can change their shapes only and as long as they are exposed to the stimulus (Chen, Hu, Zhuo and Zhu, 2008; Kunzelman, Chung, Mather and Weder, 2008). The shape change that occurs in SCPs is therefore subjected to the length of time that the SCP is exposed to the external stimulus. On the whole, SCPs exhibit great advantage on SMPs because of their ability to change not only under heating conditions but also under cooling for example. However the high cost and low quantity of SCPs prevent them from practical applications, and their present investigations are limited to explorations and laboratory experimentation (Hu and Chen, 2010).

Polymers	Tensile Strength (MPa)	Compressive Strength (MPa)	Tensile Modulus (GPa)	Poisson's Ratio	Density (g/cm^{-3})
Air					1.293 at 0ºC 0.946 at 100ºC
Water					1
Synthetic Polymers					
PET (Polyethylene Terephthalate)	80	-	2.0-4.0	0.37-0.44 (oriented)	1.3-1.4
PBT (Polybutylene Terephthalate)	50	-	2		1.31
PA6 (Polyamide 6)	78	-	2.6-3.0	0.39	1.13
PA6.6 (Polyamide 6.6)	82	-	3.3	0.41	1.14
PA11 (Polyamide 11)	44	-	0.4-1.5	-	1.04
PA12 (Polyamide 12)	50-55	-	0.00950-64.1	-	1.02
HDPE (Polyethylene High Density)				0.46	0.95
LDPE (Polyethylene Low Density)				-	0.92
PEN (Polyethylene Naphthalate)	200 (biax film)	-	5-5.5 - biax film	-	1.36
PP (Polypropylene)		-	2.2-4.2 (biax film)	-	0.9
PS (Polystyrene)	30-100	-	2.3-4.1	0.35	1.05
PTFE (Polytetra Fluoroethylene)	10.0-40.0	-	0.3-0.8	0.46	2.2
PMMA (Poly-methyl methacrylate)	80	-	2.4-3.3	0.35-0.4	1.19
PVC (Polyvinylchloride)			1.38 - 55.0 (Mpa)		
PU (Polyurethene)	-	69	-		
PC (Polycarbonate)	55-75	>80	2.3-2.4	0.37	1.2
PVF (Polyvinylfluoride)				0.4	1.37-1.39
PVDF (Polyvinylidenefluoride)				0.34	1.76
ABS (Polyacrylonitrile-butadiene-styrene)	41-45	-	2.1-2.4	0.35	1.5
PEG (Polyethylene glycol)					
PAN (Poly-acrylonitrile)					
PEEK (Poly-ether-ether-ketone)					
PES (Poly-ether-sulfone)					

Polymers	Tg: Glass Transition (ºC)	Tm: Melting Point (ºC)	Coefficient Thermal Expansion (x10^{-6} K^{-1})	Thermal Conductivity (W m^{-1} K^{-1})	Elongation at Break (%)
Air					
Water		0ºC			-
Synthetic Polymers					
PET (Polyethylene Terephthalate)	76	250	20-80	0.15-0.4 @23ºC	-
PBT (Polybutylene Terephthalate)	66	227	-	-	250
PA6 (Polyamide 6)	47	220	95	0.24-0.28 @23ºC	-
PA6.6 (Polyamide 6.6)	50	255	90	0.25 @23ºC	-
PA11 (Polyamide 11)	42	175-185	125	0.3 @23ºC	320
PA12 (Polyamide 12)	-	167-176	100-120	-	290-300
HDPE (Polyethylene High Density)			100-200	0.45-0.52 @23ºC	
LDPE (Polyethylene Low Density)			100-200	0.33 @23ºC	400
PEN (Polyethylene Naphthalate)	120	270	20-21 (biax film)	-	-
PP (Polypropylene)	-10	173	100-180	0.1-0.22 @23ºC	150-300
PS (Polystyrene)	100		30-210		1.6
PTFE (Polytetra Fluoroethylene)			100-160	0.25 @23ºC	400
PMMA (Poly-methyl methacrylate)	114		70-77	0.17-0.19 @23ºC	2.5-4
PVC (Polyvinylchloride)	85	240			
PU (Polyurethene)					
PC (Polycarbonate)	145	225	66-70	0.19-0.22 @23ºC	100-150
PVF (Polyvinylfluoride)	314		50-97	-	90-250
PVDF (Polyvinylidenefluoride)	-38	160	80-140	0.1-0.25 @23ºC	50
ABS (Polyacrylonitrile-butadiene-styrene)			80	0.17 @23ºC	45
PEG (Polyethylene glycol)					
PAN (Poly-acrylonitrile)	85	317			
PEEK (Poly-ether-ether-ketone)	143	334			
PES (Poly-ether-sulfone)	220				

Figure A.2
Polymers properties
Lynn Tandler (2013)

A.2 Technology in 'textile anatomy' mapping

Unlike the creation and synthesis of polymers into fibrous materials - which is fruit of the efforts of material scientist and chemical physicists - the creation of fibres is more dependent on the machines that are use for the extrusion of some molten substances. The basic forms of fibre extrusion are descried in chapter 4 of this research. Below however, are few more example that show the relevance of technological interventions for the creation of different fibres.

A.2.1 High performance fibres

High performance fibres – also known as HM-HT fibres - are "developed with high strength and high stiffness in mind" (Gabara, 1994, p. 241). According to Hearle, Hollick and Wilson (2001), HM-HT fibres fall into three main groups: aramids and polyethylene fibres, carbon fibres, and inorganic fibres made from ceramics or from glass (Hearle, Hollick and Wilson, 2001). The uniqueness of these fibres lays in their polymeric refined chemical structure, where rigid polymer chains linked together by strong hydrogen bonds, creating strong and long molecular chains with low molecular weight characterize the molecules.
But high performance fibres can also be descried as fibres that are spun out of high-performance polymers either through processes of wet spinning, melt spinning or electro spinning. Such can appear as single component shape memory fibres (known as SMFs) or as composite fibres (Viry *et al.,* 2010). Shape memory fibres are lightweight and strong: they are able to withstand large strains and possess a wide range of temperatures - and with their low manufacturing costs they are easily accessible to process (Hu and Chen, 2010).

One of the most commonly found shape memory fibre is a segmented polyurethane fibre - also referred to as shape memory polyurethane (SMPU) (Hu, 2007). Because shape memory fibres are made from shape memory polymers - their physical properties vary above and below the point in which shape change occurs, according to the glass transition temperature (*Tg*) of the polymer (Tobushi, Hara, Yamada and Hayashi, 1996). Additionally, the properties of SMPU for example, have been shown to be determined by the spinning methodology and thermal treatment they undergone (Hu, 2007; Hu, Zhu, Lu, Yeung and Yeung, 2007).

Bi-component shape memory fibres are designed to operate between two permanent shapes: one formed at higher temperatures and one formed at lower temperatures. Such examples include a bi-component SMF form of Polystyrene (PS) and Low Density Polyethylene (LDPE). Similarly, SMFs such as Coolmax© and Thermax© - produced by DuPont, have been designed to take advantage of the cross-sectional shapes of fibres in order to enhance comfort at high and low temperatures.

Other forms appear as Shape Memory Alloys (SMAs) for example - metal compounds that memorize a predetermined shape: once bent and mechanically deformed, SMAs can return to their original shape under certain temperature conditions (Mattila, 2010). Gandhi and Thompson (1992) explained: "Shape-memory alloys are unique in the sense that when deformed at low temperatures they revert back to their original shape upon heating. However, some permanent deformation may remain in the alloy" (Gandhi and Thompson, 1992, p. 199).

The mechanical properties of SMAs are principally determined by the properties of the metals that they are consisted from (Mattila, 2010). Some SMAs may enable a two-way shape memory effect, which is known as an all-round shape memory effect (Otsuka and Ren, 2005). Their ability to morph easily under predetermined conditions allows an all-round shape memory effect to be used as actuators (Hu, 2007).

Nickel-Titanium alloys (NiTi), and copper-base alloys such as CuZnAl and CuAlNi (Mattila, 2006; Langenhove, 2011) are SMAs in popular use. SMAs such as Nitonol are in use for biomedical applications such as cardiovascular stents, guide wires and orthodontic wires (Hedayat, Rechtien and Mukherjee, 1992; Shu, Lagoudas, Hughes and Wen, 1997; Langenhove, 2011) due to their unique set of properties (Otsuka and Ren, 2005). Other applications for SMA's were documented in the military sector, as eyeglass frames and underwire women's brassieres (Wu and Schetky, 2000), and as sensors, actuators and antennas for mobile phones, as reported by Otsuka and Kakeshita (2002). But in spite of the fact that shape memory alloys are able to recover most of their deformation, their ability to revert perfectly to their original state is inferior to that of shape memory polymers and that of shape memory polymeric filaments (Mattila, 2006; Hu 2007).

Within that group of shape memory alloy wires, less popular still are magnetic shape memory materials (MSMs). These metal alloys belong to a novel group of shape memory materials that can change their shape in different ways to stretch, bend or twist - in less than a millisecond - when exposed to a magnetic field (Mattila, 2010). And this expands their application scope ever further, with examples of Ni-Mn-Ga used as an actuator to produce motion and force (Tellinen, Suorsa, Jaaskelainen, Aaltio and Ullakko, 2002).

A.2.2 Inorganic and metal components

Ceramic elements are made from a combination of some metal elements with non-metal ones. But in spite of them, technically, being partly made out of some metals, they are considered to be non-metallic materials (Carter and Norton, 2007). According to Schneider (1969), the melting point of ceramics is not different to that of other materials and it is described as "the temperature at which solid and liquid of the same chemical composition are in equilibrium for a giving confining pressure" (Schneider, 1969, p. 19). The low thermal conductivity of ceramics materials makes them into good insulators. They are strong and brittle materials – both characteristics are informed by their crystalline inner structure. The prime inorganic element within this group is Silicate (SiO2), which is used for making glass, and for making glass fibres respectively.

Silicate (SiO2) behaves similarly to other organic polymers in the way in which it adapts to heat and restructure its molecules depending on its glass transition state (*Tg*) - particularly upon cooling. Jones and Huff (2009) explained, "Because of the rapid change in viscosity of glass-forming liquids with temperature, the structure which is frozen in is dependent upon the cooling rate" (Jones and Huff, 2009, p. 310). In other words, the *Tg* of Silicate profoundly affects the behaviour of the glass -and it is that which makes it so brittle. Accordingly it also affects the properties of the fibres and filaments, which it forms.

Carbon is the most versatile of all metal components: it exists in three physical forms - as amorphous carbon, as graphite and as diamond. Within different structures it can form into one of the softest materials existing, where under different construction it can shape into one of the hardest materials known: but although graphite and diamonds and essentially made of Carbon, their chemical structure is far more complex and as a result they are not classified as metals - but in fact as ceramics (Carter and Norton, 2007).

According to Cook (1984) "the production of glass filaments suitable for textile use requires that they should be flexible enough to stand up to normal wear and tear. This is achieved", he continues, "not by changing the composition of the glass itself, but by making the filaments so fine that they can bend without breaking" (Cook, 1984, p. 642). This further informs the importance that lay within the mechanical behaviour and product formation of polymers, in order to make them suitable for the creation of fibres and filaments. As a result, Cook informs, glass filaments are produced with diameters of twelve micron or less (Cook, 1984).

Silver (Ag) and gold (Au) have been used for fabric decoration for thousands of years due to their high lustrous appeal, properties of strength and resistance to corrode. Throughout history, fine silver and gold wires were embroidered onto fabrics as a symbol of richness, class and prestige. However since the synthetic fibre and yarn sector have been offering softer, user-friendlier alternatives in the form of Lurex and SPMV, silver has been used primarily for biomedical applications, due to its anti bacterial properties. Gold has similar properties to Silver but is far more expensive, which is the prime reason for its relatively minimal use.

Nickel (28Ni), copper (Cu), titanium (Ti) and aluminum (Al) are used in textile application due to their aesthetic values, strength and conductive properties – either in the form of fine wires or in that of alloys, as well as in coatings for non-conductive filaments. Different metallic elements vary in their ability to conduct electricity and their unique properties are used to tailor them to specific product applications. At large, metal elements can be used for textile applications either as single-component elements or as multi-component elements.

Fibre	Tenacity (dry) g/den	Tensile Strength Standard kg/cm2	Elongation (dry) Regular %	Initial Modulus g/den	Average Stiffness g/den	Average Toughness g/den
Cellulose:						
Acetate (Cellulose)	1.1-1.3	1260-1540	23-30	-	-	-
Triacetate (Cellulose)	1.2-1.4	-	25-30	44	-	-
Cellulose (recycled paper)						
Cotton fibre - Staple						
Cotton (mercerised)	2.0-5.0		7.0-3.0			
Flax fibre bundle						
Jute						
Hemp fibre bundle						
Coir fibre bundle						
Ramie						
Kenaf fibre bundle						
Viscose - Standard	1.5-2.4		30.0-15.0			
Viscose - High-tenacity	2.4-2.6		20.0-9.0			
Cupro Rayon						
PLA						
Protein:						
Regenerated Protein Fibres - Casein	1.1-0.9	-	60-70	-	-	-
Soy-bean fibres (Protein)	0.8		50			
Ground-nut (Protein in plants)	0.7-0.9	11000-14000	40-60			
Rabbit - Common						
Rabbit - Angora						
Regenerated Protein Fibre - Merinova						
Silk - B, Mori, Raw - Tussah	2.2-4.6		25.0-10.0			
Sheep's wool						
Wool fibre / fibre bundle						
Wool - non medullated	1.0-1.7					
Acrylic:						
Orlon - tyoe 81	4.7-5.2		17-15			
Orlon - type 41	2.0-2.5		45-20			
Courtelle						
Zefran						
Acrilan, Creslan						
Modacryloc:						
Dynel						
Teklan						
Verel						
Glass:						
E-glass						
C-glass						
A-glass						
S-glass						
Mineral Silicate fibres						
Silica (Quartz) fibres						
Teflon						
Synthetic:						
Nylon 6.6 - Standard	4.6-5.8	4550-5950	26-32	40-60	18	1.08
Nylon 6.6 - High-tenacity	9	6300-9100	19-24	-	32	0.77
Nylon 6.6 - Staple	4.1-4.5	4200-4620	37-40	-	11	-
Nylon 6 - Standard	4.5-5.8	5110-5880	23-42.5	35-50	23	0.67
Nylon 6 - High-tenacity	7.5-8.3	7700-8400	16-19	-	44	0.68
Nylon 6 - Staple	3.8-5.5	-	23-50	-	-	-
Nylon 11 - Standard	5.0-7.5	7.5	25-30	50		
Polyester:						
Dacron - fibre 5600	4.4-5.0		22-18			
Dacron - fibre 5400	3.0-3.9		40-25			
Kodel						
Terylene, Vytcron						
PET filament - High tenacity	56.5-70.6 (cN/Tex)	7350-8750	8 - 11	110-130		
PET filament - Med. tenacity	35.3-44.1 (cN/Tex)	4900-5950	15-30	100-115		
PET staple - High tenacity	48.6-57.4 (cN/Tex)	5250-7350	20-30	80		
PET staple - Med. tenacity	35.3-44.1 (cN/Tex)	4900-5950	30-50	30-60		
PET staple - Low tenacity	22.1-30.9 (cN/Tex)					
Chlorofibre:						
PVC	2.7-3	32-36	12 - 20			
Polyvinyl Alcohol fibres (PVA) - Staple	33.5-54.7	-	13-26	25-70	17-52	0.41-0.52
Polyvinyl Alcohol fibres (PVA) - filament High-Tenacity	53-75.1	-	9 - 22	70-180	-	-
Polyvinyl Alcohol fibres (PVA) - filament Water-Soluble	26.5-35.3	-	13-20	50-90	-	-
Elastane (PU)			500			
Polystyrene fibres - 'Darvan'	2	2100 (g/cm2)	30-50	20-25	6	0.3
Aramid:						
Nomex						
Technora						
Para-aramid:						
Kevlar						
Twaron						
Polyolefin:						
Polypropylene - Ulstron	4.5-6.0					
LDPE	1-1.5					
HDPE	8					
Carbon						
Alumina						
Alumina/Silioca						
Alumina/Zirconia						
Steel						

Figure A.3
Fibres properties
Lynn Tandler (2013)

A.3 Yarns

Yarns can be measured and categorised according to weight, size, count, diameters, and fibre constituents, as well as by their spinning techniques, twist variation or other special properties if stated. There is no one database that classifies yarns into groups. Depending on the yarn spinning machines owned by manufacturers, companies have freedom to create a variety of yarn types and counts.

Primarily, yarns can be referred to according to the hierarchical complexity of their structure:

Single yarns refer to a bundle of fibres or filaments, which are twisted together to form one singular strand. Twists can be inserted in either of two directions. Left twists referred to as S-twists, and right twists referred to as Z-twists: the diagonal line in the S and Z describe the direction of the twist. The level of twisting is defined as the number of twists per unit length of yarns – usually measured by the inch or by centimetres - and while it is important to maintain this level high so the yarn does not fray under tension it is fundamental to keep the angle at which the fibres lie to the axis of the yarn constant (Taylor, 2007). The amount of twist per one centimetre or inch length determines the strength of a yarn: the more twists per unit length the stronger a yarn becomes. However with the increase of twists, the stress that is put onto the yarn gets greater and above a certain amount of twists the action of twisting is counter productive.

Two single yarns can then be twisted to form a folded yarn - or ply yarns – always twisted in the opposite direction to the twist that binds each single yarn. Similarly, two folded yarns can be twisted into a cabled yarn – also called a corded yarn. Cabled or corded yarns are twisted in the opposite direction to that of the folded yarns.
Three main yarn-spinning methods have come to dominate the yarn production industry - these are: ring spinning, twist spinning and wrap spinning. Out of which the most prominent are ring spinning for yarns spun out of staple fibres, and wrap spinning, which contains a core fibre bundle that is wrapped with fibres and/or filaments.

A.3.1 Ring spinning

Ring spinning is the most ancient of the three, dating back to 1832. Originally designed as an optimization of the Crompton's mule, it had since remained the most used method for yarn production across the world. Ring spinning offers high production speed of a wide range of fibre types in a verity of counts: The ring spinning method lead the fibres through the yarn path, follows by a spindle rotation - and in doing so each completed circle of rotation binds the fibres in one turn of twist (Lawrence, 2010). This mechanical principle of operation attributes ring spinning much versatility. Much so that until this days ring spinning methods still produce yarns with superior structure to those attained by alternative spinning methods (Lawrence, 2010).

A.3.2 Twist spinning / Rotor spinning

Twist spinning methods is different to ring spinning systems. There are two methods that demonstrate twist spinning: self-twist spinning, and open-end spinning.

The self-twist spinning method was developed in order to attribute yarns greater strength and better evenness (Lawrence, 2010): Two strands can be twisted or plied during the same process, which results in a two-fold yarn with equal balanced weight. In open-end spinning however, individual fibres are drafted and only then collected into a twist in a continuous process.

Currently two techniques employ the open-end method: rotor spinning and friction spinning. Rotor spinning method operates as a fibre selective method, where slivers rather than rovings are fed into the machine and a large pinwheel separates individual fibres from the main supply. Those fibres that do not twist into the yarn form are scattered and removed from the opening roller by air suction (Lawrence, 2010). But in friction spinning, individual fibres are collected in a groove formed by two rotating drums. The motion of the drums and their frictional contact with the yarn tail - hence the method's name - insert twist into the yarn (Lawrence, 2010).

A.3.3 Wrap spinning

Wrap spinning methods refers to the spinning methods used to wrap or bind any protruding surface fibres from the continuous twist around the yarn in order to make it stronger. This method is found through surface fibre wrapping or filament wrapping (Lawrence, 2010). According to Lawrence (2010), surface fibre wrapping can be done through friction spinning and air-jet spinning: In friction spinning, the binding and the twist of the fibre bundle is fed between two counter rotating drums; where in air-jet spinning, two air-jet streams - with different velocities - run along a central tubular channel in order to spin the fibres together into yarns.

Filament wrapping methods refer to the actions of wrapping a filament around a bundle of fibres. This is done through selfil spinning, or by hollow-spindle spinning: In selfil spinning, many continuous filaments wrap around a ribbon of fibres (Lawrence, 2010). In hollow-spindle spinning, the fibres and the filaments are fed through a 'hollow-spindle' mechanism (Lawrence, 2010, p. 38) and threaded at the bottom – wrapping the filament around the fibre ribbon to form a wrap-spun yarn.

A.3.4. The properties of various yarns

Spun yarns can either appear in regular or irregular forms. Regular yarns are yarns in which the fibres have been organised before spinning, whereas drawing out bundle of fibres together into a twist produces irregular yarns.

Most yarns used in the industry are found to either be 'carded' or 'combed' (Taylor, 2007, p. 61): carding is the process used to disentangle the fibres in the machine - laying them fairly straight before twisting into a yarn. Combing, on the other hand, involves an additional process that lays the fibres parallel to each other discarding all short fibres in order to create a homogenized fibre bundle. This results in better quality and often very fine yarns. Due to the added process, combed yarns are more costly to produce than they carded counterparts but at the same time they are also stronger, more regular in thickness and have increased lustre.

In order to produce a continuance spun yarn, several hundreds of staple fibres need to be packed together and settle into a homogenous form through the insertion of a twist. The way in which fibres sit next to one another in this packed arrangement, is referred to as fibre migration (Lawrence, 2010) – and it varies according to the structural properties of the twisted fibres; such as size, diameter, length, surface textures, and cross-sectional shape. The properties of yarns, therefore are mainly determined by the mechanism from which they were spun and of course the individual properties of the fibres and filaments that they have incorporated in their structure. They are therefore identified by their unique structure as ring spun yarns.

The properties of ring spun yarns are measured therefore through the evaluation of the fibers' tensile properties, mass irregularity and imperfections (Lawrence, 2010). The level of twisting controls the strength of the yarn, and yarns with *optimum twists* – representing the "twist at which yarn strength s highest" (Lawrence, 2010, p. 123) – are often desired for their optimal strength.

Rotor spun yarns exhibit three-part structure: the core of fibres, the outer zone of fibres, and fibres wrapped around the exterior façade of the yarn (Lawrence, 2010). The properties of the yarns therefore are greatly affected by the properties of the fibres spun (Barella, Manich, Marino and Garofalo, 1983). Fibre parameters such as fibre tenacity, fineness and length, the quality of the fibre bundle itself and the variables upon which the machine is set – such as speed, rotor diameter and rotor angle – can all affect the properties of the yarns.

In comparison to ring spun yarns, rotor spun yarns are more uniform in both their appearance and linear density (Lawrence, 2010): they are more extensible, have fuller body with an increased bulk volume, and they are smoother, less hairy and soft to touch (Lawrence, 2010). At the same time, rotor spun yarns are less strong than ring spun yarns and their maximum tenacity is lower (Lawrence, 2010).

A.3.5 Structural properties of various yarns

The spinning methodology applied to bind fibres and/or filaments into yarns greatly affect some properties of the produced yarns. Examples to the extent to which such methodology influence the structural properties of spun yarns are briefly outlined below.

A.3.5.1 Structural properties of air-jet spun yarns

Air-jet spun yarns are yarns that have a central core wrapped around and bound together with wrapper fibres. Air-jet spun yarns can be classified according to their structure: those that are wrapped with a regular twist fibre bundle but with no wrapping fibres, those bound with regular wrapper fibres, and those wrapped with irregular fibres (Lawrence, 2010). Consequently, the properties of air-jet spun yarns depend primarily on the fibre content. Fibre properties such as fibre diameter, fibre length, friction and strength all play a role in determining the strength, stretch and handle of air-jet spun yarns (Lawrence, 2010).

A.3.5.2 Structural properties of friction spun yarns

The structure of friction spun yarns informs the properties of such yarns. The properties of friction spun yarns however cannot be generalized since they highly dependent on the characteristics of the fibres and / or filaments from which they are spun, variations in friction spinning machines and the spinning conditions used for producing such yarns (Lawrence, 2010). Friction spun yarns consist of two-part structures: a densely packed core of straight, and twisted fibres randomly distributed (Lawrence, 2010). As well as fibre and filament properties, fibre migration also plays a role in structuring the yarns.

A.3.5.3 Structural properties of wrap spun yarns

The predominant feature of wrap spun yarns is the fact that they spun off filament, rather than staples. This gives wrap spun yarns several advantages in higher manufacturing productivity, higher yarn tenacity and uniformity, as well as smoother surface roughness due to less hairiness (Lawrence, 2010). In the case of wrap spun yarns, it is mostly the wrapper filaments, which affect the properties and uniformity of the wrap spun yarn the most: the strength of wrap spun yarns are subject to the wrapper filament modulus and wrap density (Lawrence, 2010).

A.4 Engineering in 'textile anatomy' mapping

Gandhi and Thompson (1992) explain: "As the structural complexity of materials increases, the coupling between design, analysis, and manufacturing processes becomes more and more inextricably intertwined" (p. 42). Constructed textile systems are complex and they mostly cover construction methodologies such as weaving and knitting – both of which have been discussed throughout chapter 5. The following text will outline briefly some of the textile properties generated through processes of weaving. The effects of various weaving structures on the physical and mechanical properties of textiles are outlined as follows:

A.4.1 Physical properties of woven fabrics

The physical properties of woven fabrics represent the sum of properties and processes undertaken for the making of a cloth. These include fabric cover, fabric mass, specific volume and thickness based on yarn count, thread spacing and yarn crimp (Gandhi, 2012). The consequent effects that weave structures themselves have on the properties of textiles have long been known to be of great significance (Schiefer, Cleveland, Porter and Miller, 1933).

Fabric cover informs the handle, feel, permeability and density of the fabric. It is the value that is derived from the number of yarns per unit length – both warp or weft yarns. Fabric mass, which is measure in grams per square meter, indicates the weight of the fabric, and in doing so it informs the suitability of the textile for specific use or application scope. Fabric thickness is indicated by the ratio given due to the measurements of weft and warp yarn cross sectional shape and diameter: minimum fabric thickness produces fabric with smooth surface and as a result it ensures uniform abrasion in wear (Hari, 2012). Specific volume of fabrics is measured by the ratio between the thickness of the cloth and fabric mass (Behera and Hari, 2010). Such physical properties of fabrics help manufacturers and consumers alike to fit different fabrics for a specific use.

A.4.2 Mechanical properties of woven fabrics

The mechanical properties of woven textiles are often expressed in a series of mathematical calculations measuring the deformation performance of a woven textile under an applied force, such as fabric strength, fabric elongation, surface durability, breaking strength, and drape (Hari, 2012). Fibre and yarn properties such as creasing and wrinkling, shear, compression and abrasion indicate the use and application of woven fabrics (Hari, 2012). The thermal properties of the fibres and yarns that make into a woven structure are the thermal conductivity, thermal absorption and thermal resistance - all indicating the thermal comfort properties of the cloth (Karaca, Kahraman, Omeroglu and Becerir, 2012). Different weave structures also tend to produce fabrics with different mechanical properties: varying from plain weave, which is considered to produce very architecturally stable structures to long float structures such as satin which impair the structural stability of the cloth – exposing the fibre and the yarn they inhabit to more wear (Thomas, 2009; Wilson, 2011b).

A.4.3 The affects of woven geometries on textiles properties

Regardless of the type of loom employed for weaving, various weave architectures attribute cloths with different structural and mechanical properties. The most basic form of cloth construction is plain weave. Fabrics made from plain weave are firm and stable. They do not drape well usually, they fray less and are less absorbent usually than textiles with other weaves (Thomas, 2009).

Hopsack and basket weave fabrics fray much more easily. Such fabrics however are flexible and prone for less creasing: they have good tear resistance, which means that the construction of hopsack and basket weaves contribute to fabric strength. They are more open and therefore have been known to enhance properties of breathability (Thomas, 2009). Fabrics made with twill construction demonstrate a distinctive diagonal line running along the fabric's length. These are strong fabrics, stable and durable, with good resistance to abrasion; they are less prone to creasing and are flexible - and therefore display good drape qualities (Thomas, 2009; Wilson, 2011b). Satin and sateen constructions help with water repellence but at the same time they also tend to fray more easily. Satin weave-construction gives cloths a smooth and lustrous appearance and a good drape (Wilson, 2011b). The 3D honeycomb construction enables a fabric to trap air in its dimples and as a result honeycomb fabrics have been known to be good thermal insulators (Thomas, 2009). They have poor abrasion, but at the same time due to their unique weave structure, they are very absorbent (Thomas, 2009). Lastly, the double cloth construction results in heavy weight and durable fabrics - the high thread count allow them to be stable and firm (Thomas, 2009).

A.5 Mathematics in 'textile anatomy' mapping

Modeling systems are widely used by STEM practitioner for predicting the behaviour of fibres, yarns and overall fabric structures. These are divided broadly into two prime methods: the deterministic and the non-deterministic.

The deterministic approach derives from applied physics. Deterministic models are used to explain the relationships between structure and property, and can be used to create textile constructions that meet specific applications. Such models are problem specific and, as a result, when applied elsewhere, can often produce large prediction errors. They require deep expertise, which, at times, can prove hard to access (Behera and Hari, 2010). Types of deterministic modeling techniques include computer simulation models and Finite Element Modeling – also known as FEM.

Empirical modeling refers to prediction through experimental investigation. It is conducted under controlled conditions where statistical techniques are used. Such techniques are used to predict the behaviour of textiles when data does not exist, and a hypothesis is not required. Through the use of empirical models it is possible to process only a narrow range of materials and the scope of the experiments are generally limited to specific operating conditions. This is also the reason that empirical modeling techniques are ineffective for complex nonlinear processes such as woven fabric manufacturing (Behera and Hari, 2010). Computer simulation models, as proposed by Meredith and Hearle (1959) for example, can give an approximation of textile behaviour, however such simulation is still unable to predict the behaviour of actual materials. Finite Element Modeling, also known as FEM, is used extensively to give numerical solutions for engineering problems. They allow the calculation of the behaviour of the material; enabling an in-depth understanding of physical processes and the scope technically to change important physical parameters quickly in order to test the performance of new products. (Lin, Ramgulan, Arshad, Clifford, Potluri and Long, 2012; Romelt and Cunningham, 2012; Davies, Hitchings, Matthews and Soutis, 2000).

Non-determinist modeling systems – unlike those discussed above - are known to be more tolerant of imprecision, uncertainty, partial truths and approximations. Those include techniques known as fuzzy logic (FL), artificial neural networks (ANN), genetic algorithms (GA), and hybrid modeling.

The application of fuzzy logic can be achieved through objective or subjective modelling techniques. As part of the FL objective modelling, no prior knowledge about the system exists, and/or expert knowledge is not accessible. As a result, raw input and output data sets are used to generate knowledge about the system (Behera and Hari, 2010). On the other hand, FL subjective modelling assumes a priori knowledge about the system is available and that this knowledge can be directly acquired from expert users.

Artificial neural networks, abbreviated as ANN, provide a relatively simple way to acquire information about a system through processes of learning: such modeling techniques are able to capture and represent various kinds of input-output relationships. ANNs are composed of processing elements. The connections between these elements contain the knowledge of the system or the network (Maleki and Tehran, 2011; Behera and Hari, 2010; Chen, Zhao and Collier, 2001). In other words, the system gathers its knowledge from the input-output connections between its elements through unsupervised or supervised learning: In unsupervised learning the outputs are unknown and the network is simply presented with inputs. In supervised learning however, the network is presented with pair of inputs and outputs and as a result for each set of input values there is a matched set of output data.

Lastly, textile engineers may use hybrid-modeling systems, which just as their name suggest, combine two or more modeling systems in an attempt to benefit from their advantages and minimize their drawbacks (Shahrabi, Hadavandi and Esfandarani, 2013; Yu, Hui, Choi and Au, 2010; Wong, Li and Yeung, 2004).

Appendix B

Program coding for 3D printed ‘weaves’

```
/**
 * James Thomas Dec 2015
 * Generates 3D models of weave patterns
 */


import unlekker.mb2.geo.*;
import unlekker.mb2.util.*;
import ec.util.*;

int n=12;
int m=4;
int r=10;
int h=50;
float curve = 1;

int patternWidth = 8;
int patternHeight = 8;
boolean[] pattern = new boolean[patternWidth * patternHeight];
boolean[] vertChangePattern = new boolean[patternWidth *
patternHeight];
boolean[] horiChangePattern = new boolean[patternWidth *
patternHeight];

UGeo weave;
UGeo weaveCurve;
UGeo weaveStraight;
UNav3D nav;


float offsetEquation(float i)
{
  float result = cos(PI*i);

  //float sinX = cos(PI*i);
  //float aSinX = abs(sinX);
  //float result = pow(aSinX,0.6) * aSinX / sinX;

  return result;
}

void initWeaveCurve()
```

```
{
  UVertexList vlBase  = new UVertexList();
  UVertexList[] vl = new UVertexList[m];

  // add vertices representing a circular base to vl. note
  // that the map() function does not actually close the list
  // since the last vertex does end up at 360 degrees.

  vlBase=new UVertexList();

  for(int i=0; i<n; i++) {
    float deg=map(i, 0,n, 0,TWO_PI);
    vlBase.add(new UVertex(r, 0, 0).rotY(-deg));
  }

  weaveCurve=new UGeo();

  // create vl2 as a copy of vl, translated to the desired height
  for(int i=0; i<m; i++) {
    float j = ((float)i)/(m-1);
    float xOff = r*offsetEquation(j);
    float yOff = 0;
    if(i==0) yOff = 0;
    else if(i==(m-1)) yOff= h;
    else yOff=h*(1-curve)/2+(curve*j*h);
    vl[i]=vlBase.copy().translate(xOff,yOff,0);
    if(i>0)
    {
      UGeo tempGeo=new UGeo().quadstrip(vl[i].close(),vl[i-
1].close());
      weaveCurve.add(tempGeo);
    }
  }
}

void initWeaveStraight()
{
  UVertexList vlBase  = new UVertexList();
  UVertexList vl2 = new UVertexList();

  for(int i=0; i<n; i++) {
    float deg=map(i, 0,n, 0,TWO_PI);
    vlBase.add(new UVertex(r, 0, 0).rotY(-deg));
  }

  weaveStraight=new UGeo();

  vl2=vlBase.copy().translate(0,h,0);
  weaveStraight=new UGeo().quadstrip(vlBase.close(),vl2.close());
}

void setup() {
  size(600,600,OPENGL);

  // initialize ModelbuilderMk2 and add navigation
  UMB.setPApplet(this);
  nav=new UNav3D();

  initWeaveCurve();
  initWeaveStraight();

  setupPattern();
```

```
}

int patternNo;
String patternName = "";
void setupPattern()
{
  pattern = new boolean[patternWidth * patternHeight];
  switch(patternNo)
  {
    case 0:
    patternName = "1/3 Z twill";
    for(int i=0;i<patternHeight;i++)
    {
      set(patternHeight-i-1,i,true);
      set(patternHeight-i-1,(i+4)%8,true);
    }
    break;
  case 1:
    patternName = "1/7 Z twill";
    for(int i=0;i<patternHeight;i++)
    {
      set(patternHeight-i-1,i,true);
    }
    break;
  case 2:
    patternName = "2/6 Z twill";
    for(int i=0;i<patternHeight;i++)
    {
      set(patternHeight-i-1,i,true);
      set(patternHeight-i-1,(i+1)%8,true);
    }
    break;
  case 3:
    patternName = "4/4 Z twill";
    for(int i=0;i<patternHeight;i++)
    {
      set(patternHeight-i-1,i,true);
      set(patternHeight-i-1,(i+1)%8,true);
      set(patternHeight-i-1,(i+2)%8,true);
      set(patternHeight-i-1,(i+3)%8,true);
    }
    break;
  case 4:
    patternName = "1/3 S twill";
    for(int i=0;i<patternHeight;i++)
    {
      set(i,i,true);
      set(i,(i+4)%8,true);
    }
    break;
  case 5:
    patternName = "1/7 S twill";
    for(int i=0;i<patternHeight;i++)
    {
      set(i,i,true);
    }
    break;
  case 6:
    patternName = "2/6 S twill";
    for(int i=0;i<patternHeight;i++)
    {
      set(i,i,true);
```

```
    set(i,(i+1)%8,true);
  }
  break;
case 7:
  patternName = "4/4 S twill";
  for(int i=0;i<patternHeight;i++)
  {
    set(i,i,true);
    set(i,(i+1)%8,true);
    set(i,(i+2)%8,true);
    set(i,(i+3)%8,true);
  }
  break;
case 8:
  patternName = "plain weave";
  for(int x=0;x<patternWidth;x++)
  {
    for(int y=0;y<patternHeight;y++)
    {
      set(x,y,((x+y)%2)==0);
    }
  }
  break;
case 9:
  patternName = "2/2 Z twill";
  for(int x=0;x<patternWidth;x++)
  {
    for(int y=0;y<patternHeight;y++)
    {
      set(x,y,((x+y)%4)<2);
    }
  }
  break;
case 10:
  patternName = "hopsack";
  for(int x=0;x<patternWidth;x++)
  {
    for(int y=0;y<patternHeight;y++)
    {
      set(x,y,((1+x+y+(y%2==0?1:0))%4)<2);
    }
  }
  break;
case 11:
  patternName = "2/2 S twill";
  for(int x=0;x<patternWidth;x++)
  {
    for(int y=0;y<patternHeight;y++)
    {
      set(x,y,((y-x+400)%4)<2);
    }
  }
  break;
case 12:
  patternName = "herringbone";
  for(int x=0;x<patternWidth;x++)
  {
    if(x<patternWidth/2)
    {
      for(int y=0;y<patternHeight;y++)
      {
        set(x,y,((x+y-2+12)%4)<2);
      }
```

```
    }
    else
    {
      for(int y=0;y<patternHeight;y++)
      {
        set(x,y,((y-x+400-1)%4)<2);
      }
    }
  }
  break;
case 13:
  patternName = "satin 8 end";
  setSatin(new int[]{1,4,7,2,5,8,3,6});
  break;
case 14:
  patternName = "mock leno";
  for(int x=0;x<patternWidth;x++)
  {
    for(int y=0;y<patternHeight;y++)
    {
      set(x,y,(((x%4==0||x%4==3)&&(y%4==0||y%4==3))^(x<4))^(y<4));
    }
  }
  break;

case 15:
  patternName = "honeycomb";
  setFrom1(1, new int[]{4,6});
  setFrom1(2, new int[]{3,5,7});
  setFrom1(3, new int[]{2,4,5,6,8});
  setFrom1(4, new int[]{1,3,4,5,6,7});
  setFrom1(5, new int[]{2,4,5,6,8});
  setFrom1(6, new int[]{3,5,7});
  setFrom1(7, new int[]{4,6});
  setFrom1(8, new int[]{5});
  break;
case 16:
  patternName = "basketweave";
  setFrom1(1, new int[]{1,2,3,4});
  setFrom1(2, new int[]{1,5,6,7});
  setFrom1(3, new int[]{1,4,3,7});
  setFrom1(4, new int[]{1,3,5,7});
  setFrom1(5, new int[]{2,4,6,8});
  setFrom1(6, new int[]{2,5,6,8});
  setFrom1(7, new int[]{2,3,4,8});
  setFrom1(8, new int[]{5,6,7,8});
  break;
case 17:
  patternName = "4 pick warp rib";
  setFrom1(1, new int[]{1,3,5,7});
  setFrom1(2, new int[]{1,3,5,7});
  setFrom1(3, new int[]{1,3,5,7});
  setFrom1(4, new int[]{1,3,5,7});
  setFrom1(5, new int[]{2,4,6,8});
  setFrom1(6, new int[]{2,4,6,8});
  setFrom1(7, new int[]{2,4,6,8});
  setFrom1(8, new int[]{2,4,6,8});
  break;
case 18:
  patternName = "4 end weft rib";
  setFrom1(1, new int[]{1,2,3,4});
  setFrom1(2, new int[]{5,6,7,8});
  setFrom1(3, new int[]{1,2,3,4});
```

```
    setFrom1(4, new int[]{5,6,7,8});
    setFrom1(5, new int[]{1,2,3,4});
    setFrom1(6, new int[]{5,6,7,8});
    setFrom1(7, new int[]{1,2,3,4});
    setFrom1(8, new int[]{5,6,7,8});
    break;
  }

  for(int x=0;x<patternWidth;x++)
  {
    for(int y=0;y<patternHeight;y++)
    {
      int yA = (y)%patternHeight;
      int yB = (y+1)%patternHeight;
      if(yB<0) yB=patternHeight-1;
      vertChangePattern[x + y*patternWidth] = !(pattern[(x) +
(yA)*patternWidth] == pattern[x + yB*patternWidth]);
    }
  }

  for(int x=0;x<patternWidth;x++)
  {
    for(int y=0;y<patternHeight;y++)
    {
      int xA = (x)%patternHeight;
      int xB = (x+1)%patternWidth;
      if(xB<0) xB=patternWidth-1;
      horiChangePattern[x + y*patternWidth] = !(pattern[xA +
y*patternWidth] == pattern[xB + y*patternWidth]);
    }
  }

  println(patternName);
}

void setSatin(int[] vals)
{
  for(int y=0;y<vals.length;y++)
  {
    set(vals[y]-1,patternHeight-y-1,true);
  }
}

void setFrom1(int row,int[] vals)
{
  for(int y=0;y<vals.length;y++)
  {
    set(vals[y]-1,patternHeight-row,true);
  }
}

void set(int x, int y, boolean state)
{
  pattern[(x) + (y)*patternWidth] = state;
}

void setFrom1(int x, int y, boolean state)
{
  pattern[(y-1) + (patternWidth-x)*patternWidth] = state;
}

void keyTyped() {
  patternNo++;
```

```
  if(patternNo>16) patternNo=0;
  setupPattern();
}

void draw() {
  background(50);
  drawCredit(patternName);

  translate(width/2,height/2);
  nav.doTransforms();
  lights();

  // UMB has chainable shorthand versions of PApplet functions
  UMB.pnoStroke();
  UMB.pfill(color(255,128,128));

  int repeat = 1;

  weaveCurve.translate(0,-patternHeight*repeat*h/2,-
patternHeight*repeat*h/2);
  weaveStraight.translate(0,-patternHeight*repeat*h/2,-
patternHeight*repeat*h/2);

  for(int i=0;i<repeat*patternHeight;i++)
  {
    for(int j=0;j<repeat*patternWidth;j++)
    {
      int offset = (i%patternHeight) + (j%patternWidth)*patternWidth;
      if(horiChangePattern[offset])
      {
        if(pattern[offset]) weaveCurve.scale(-1,1,1);
        weaveCurve.draw();
        if(pattern[offset]) weaveCurve.scale(-1,1,1);
      }
      else
      {
        weaveStraight.translate(pattern[offset]?-r:r,0,0);
        weaveStraight.draw();
        weaveStraight.translate(pattern[offset]?r:-r,0,0);
      }
       weaveCurve.translate(0,0,h);
      weaveStraight.translate(0,0,h);
    }
    weaveCurve.translate(0,h,-patternWidth*repeat*h);
    weaveStraight.translate(0,h,-patternWidth*repeat*h);
  }
  weaveCurve.translate(0,-patternHeight*repeat*h,0);
  weaveStraight.translate(0,-patternHeight*repeat*h,0);

  UMB.pnoStroke();
  UMB.pfill(color(128,128,255));


weaveCurve.translate(0,patternHeight*repeat*h/2,patternHeight*repeat*
h/2);

weaveStraight.translate(0,patternHeight*repeat*h/2,patternHeight*repe
at*h/2);

  weaveCurve.rotX(PI/2);
  //weaveCurve.translate(0,h,-h);
  weaveStraight.rotX(PI/2);
  //weaveStraight.translate(0,h,-h);
```

```
  weaveCurve.translate(0,-patternHeight*repeat*h/2,-
patternHeight*repeat*h/2);
  weaveStraight.translate(0,-patternHeight*repeat*h/2,-
patternHeight*repeat*h/2);

  for(int i=0;i<repeat*patternHeight;i++)
  {
    for(int j=0;j<repeat*patternWidth;j++)
    {
      int offset = (i%patternHeight) + (j%patternWidth)*patternWidth;
      if(vertChangePattern[offset])
      {
        if(!(pattern[offset])) weaveCurve.scale(-1,1,1);
        weaveCurve.draw();
        if(!(pattern[offset])) weaveCurve.scale(-1,1,1);
      }
      else
      {
        weaveStraight.translate(pattern[offset]?r:-r,0,0);
        weaveStraight.draw();
        weaveStraight.translate(pattern[offset]?-r:r,0,0);
      }
       weaveCurve.translate(0,0,h);
      weaveStraight.translate(0,0,h);
    }
    weaveCurve.translate(0,h,-patternWidth*repeat*h);
    weaveStraight.translate(0,h,-patternWidth*repeat*h);
  }
  weaveCurve.translate(0,-patternHeight*repeat*h,0);
  weaveStraight.translate(0,-patternHeight*repeat*h,0);


weaveCurve.translate(0,patternHeight*repeat*h/2,patternHeight*repeat*
h/2);

weaveStraight.translate(0,patternHeight*repeat*h/2,patternHeight*repe
at*h/2);

  //weaveCurve.translate(0,-h,h);
  weaveCurve.rotX(-PI/2);
  //weaveStraight.translate(0,-h,h);
  weaveStraight.rotX(-PI/2);



  stroke(255,0,0);
  // get the ArrayList<UFace> stored in geoto draw the face normals
  // The parameter 10 is the desired length of the drawn normals
  //for(UFace f:weave.getF()) f.drawNormal(2);
}
```

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