UNFOLDING CIRCULAR TECHNO-AESTHETICS

An exploration of shape-change through woollen Woven Textile-form

Integrated Product Design
MSc thesis by Bente Arts

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ABSTRACT

Textiles are unimaginable out of our lives - from the moment a human is born until existence stops - textiles are touched by wearing, seeing and feeling them. Where it once was fundamental for survival, today, the textile industry has grown towards a system that prioritises speed, efficiency and uniformity (Goldsworthy & Politowicz, 2018) while largely neglecting the impact of waste, mass production and material extraction. The industry designed a system that prioritises the desires of form, function, aesthetics and cost above the environment.

A design process with a systemic lens acknowledges waste as an essential element in the system, enabling an execution providing for a circular economy.

The exploration consists of technological, experiential and aesthetical research of woollen Woven Textile-form in which the shape-changing properties of wool fibres make them morphic Textile-forms. The potential for a circular economy, using biodegradable, recyclable, mono-material widens the scope towards multimorphic Textile-form (McQuillan & Karana, 2022).

This research aimed to unfold techno-aesthetics emerging from material expressions through woollen woven Textile-form exploration in a circular economy. Experiential Characterisation (Camere & Karana, 2018) unfolds the material experiences of the created samples, identifying a new aesthetic formed by materiality.

Techno-aesthetics (Dalmasso, 2019) questions the origin and nature of aesthetical values concerning technology, demonstrating the necessary value change of perception and expectations of the typical textiles and textile-based products and potentially beyond when a sustainable design outcome is a goal.

All together, this should make us seriously question the appropriate perception and expectations of typical textiles and textile-based products and potentially beyond when a sustainable design outcome is a goal. Woollen Woven Textile-form and Morphic Textile-Form methods, together, may create a new understanding of materiality to move towards Multimorphic Textile-form. This research suggests embracing material traces induced by exploring methods such as Woollen Woven Textile-form methods to unfold 'new circular techno–aesthetics' to create an understanding of materiality and move towards a circular economy.

Embracing 'circular techno-aesthetics' through materiality may bring about the needed global fundamental change of value and move towards a circular economy.

ACKNOWLEDGEMENTS

With this graduation project, my seven years of studying at the TU Delft are coming to an end. In 2015, Industrial Design Engineering seemed like the right fit for me, a place to explore and embrace the analytical and creative side of me as a person. Now, I can finally tell you - it definitely was!

These years in education and work as a designer helped me find the reason why I want to be a designer and to define what kind of projects fill my heart with passion, rush, grit and desire as a designer but also as a person. With this research undertaken for my graduation, I can finally mark the last 'to-learn: sustainable textile development', of my education (for now at least ..)

I would like to bring my appreciation to words for a few that contributed to this experience.

First, my chair in this project, Holly, thank you for introducing me in the world of textiles and helping me to position myself in it as Industrial Design Engineer. I appreciate your critical comments and questions to make me go beyond the familiar. But maybe most of all, guarding over my health with my (time-)enthusiastic responses and your reassurance of my skills and experience gained throughout this project as well as and offering help in unforeseen events.

Next, Caroline, thank you for mentoring me during this project which was, to some extent, a new design field for us both. Your enthusiasm and critical perspective made me question why I was performing particular steps to emphasise the importance and improve steps in the process. Thank you for offering your help and time and being a soundboard throughout the project, exactly at the right time, as if you knew I needed it.

Together you created an experience in which I was comfortable expressing myself and asking for help which is not in my nature. I very much enjoyed and was inspired by the collaborative nature of our meetings, and every discussion uplifted my project to a whole different level. Thank you for this experience!

Thank you, Milou Voorwinden, for your time and support with programming, and for introducing me to 3D weaving.

To all my fellow students and friends in 'het hok' in the faculty, thank you for the collaborative and fun workspace. And to my friends, I appreciate your time, laughs, and support and especially for bringing me back to my senses when I made it far bigger and more complex than it had to be.

And most of all, my family, Papa, Mama and Dante, thank you for all the opportunities you gave me throughout my life and what you offered me in this project: 'The sky is the limit'.

Enjoy reading!

Bente

CONTENTS

CONTENTS

INTRODUCTION

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Textiles are unimaginable out of our lives - from the moment a human is born until existence stops - textiles are touched by wearing, seeing and feeling them. Where it once was fundamental for survival, today, the textile industry has grown towards a system that prioritises speed, efficiency and uniformity (Goldsworthy & Politowicz, 2018) while largely neglecting the impact of waste, mass production and material extraction. The industry designed a system that prioritises the desires of form, function, aesthetics and cost above the environment.

The timeframe of thinking about 'what Textile-forms should be' became shorter overtime due to trend-sensitive business models, where fast fashion became the norm and now even ultra-fast fashion (Oxford Analytica, 2021), both tremendously increasing the time frame of innovation, unfortunately with economic growth as the driver to create as much, as fast as possible, resulting in inevitable amounts of waste and pollution which are harming our planet.

Waste is inevitable in most Textile-form-creating practices due to waste not being part of the design. The industry designed a system that prioritises the desires of form, function, aesthetics and cost above the environment. A design process with a systemic lens acknowledges waste as an essential element in the system, enabling an execution providing for CE.

This research starts from a material perspective, where the material guides the process rather than forcing materials towards a particular desired aesthetics for form and function. The exploration consists of technological, experiential and aesthetical research of wool's inherent shape-changing property in Woven Textile-form (McQuillan, 2020).

This research aimed to unfold techno-aesthetics emerging from material expressions through woollen woven Textile-form exploration in a circular economy.

Techno-aesthetics (Dalmasso, 2019) questions the origin and nature of aesthetical values concerning technology, demonstrating the necessary value change of perception and expectations of the typical textiles and textile-based products and potentially beyond when a sustainable design outcome is a goal.

Demonstrating that it is necessary to look at textile products with a systemic lens and include their interaction with the whole system, where designers question conventional methods and start optimising for sustainability rather than for economic growth, with speed and efficiency.

Exploring the possibilities for woollen woven Textile-form constructions identified a coherent new material experiences using experiential characterisation (Camere & Karana, 2018) to understand how humans interpret them.

All together, this should make us seriously question the appropriate perception and expectations of typical textiles and textile-based products and potentially beyond when a sustainable design outcome is a goal. Woollen Woven Textile-form and Morphic Textile-Form methods, together, may create a new understanding of materiality to move towards Multimorphic Textile-form. This research suggests embracing material traces induced by exploring methods such as Woollen Woven Textile-form methods to unfold 'new circular techno–aesthetics' to create an understanding of materiality and move towards a circular economy.

Embracing 'circular techno-aesthetics' through materiality may bring about the needed global fundamental change of and move us towards a circular economy.

BACKGROUND

BACKGROUND

This chapter outlines the necessary information to motivate the research approach, starting with an exploration of the unsustainability of the current textile system. The research on novel textile production methods explores potential improvements for sustainability through textile design. This section also provides the necessary theoretical information for designers to experiment with such techniques in the context of a circular economy, as this research will in the next chapter.

Why do textiles have to change?

Textiles used to be a way of protection to meet fundamental needs (Y. Boomsma, 2020) and have been crucial in the existence of humans. However, today's industry has grown towards a system that prioritises speed, efficiency and uniformity (Goldsworthy & Politowicz, 2018). While largely neglecting the impact of waste, mass production and material extraction. Within the linear economy (Figure 5), extraction, production, consumption and waste resources follow one direction, resulting in the depletion of resources, and wasteful and toxic production methods, leading to excessive amounts of waste, contamination and pollution of the Earth.

In the textile industry, this lead towards an industry where quantitative practices overrule qualitative products (Taitler, 2020). This phenomenon describes as fast fashion (Taplin, 1999), through the decrease in lifecycle through the rise of trend-sensitive design (Lujan-Ornelas et al., 2020), and now even ultra-fast fashion (Oxford Analytica, 2021), creating a cycle of low-quality mass production and a shorter initial life span of products via a direct-to-consumer business model (Pereira, 2018). Driven by consumerism (Boström et al., 2019), this causes a critical amount of 30% of 'deadstock' where textiles go into landfills without being seen by a customer (McKinsey & Company & Global Fashion Agenda, 2020). Others are bought and owned by consumers but later discarded, resulting in 83% of all textiles ending up in landfills or incinerated (Textile Exchange, 2020).

A tragical situation in which humanity lives today, where all energy used, all the materials and creative ideas to make them in the first place lost their value, both environmentally and economically, faster than ever. This textile system can be described in a linear process (Figure 5) which is driven by overconsumption, underutilising of products and exploitation of resources, contributing significantly to global warming, resource depletion and pollution of air, water and soil (Ninnimaki et al., 2020), working towards a desperate future for humanity.

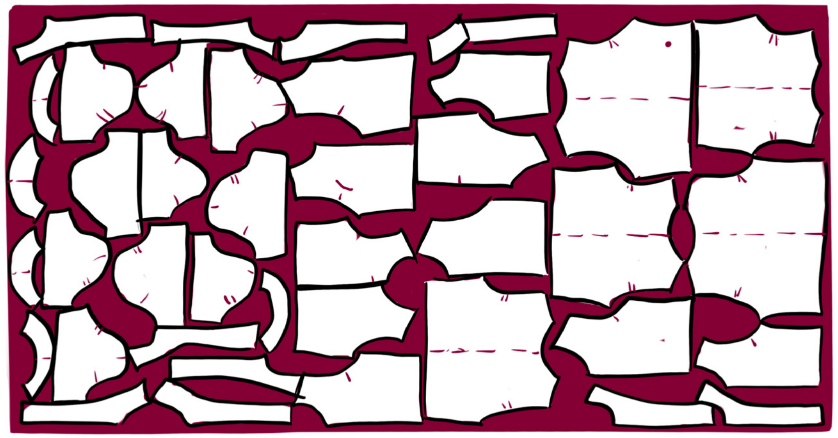
The environmental improvements caused by recycling textiles are a common misconception since only 13% of our discarded textiles go into the recycling process, of which only 1% return in the loop as high-quality products (Ellen MacArthur Foundation, 2017). Textiles made from a mixture of synthetic and natural fibres make recycling without reduction of fibre quality challenging and automation in recycling almost impossible, resulting in many downcycling practices and only temporarily extending the lifecycle, which eventually will be incinerated or dumped in landfills.

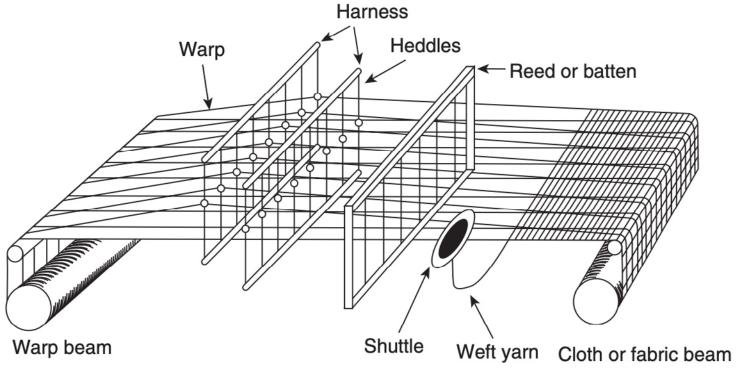
The discussed aspects make the industry partly responsible for biodiversity loss through water pollution by chemicals and microplastics (Ellen MacArthur Foundation, 2017, Komyakova et al., 2020), soil degradation and the depletion of natural ecosystems by extracting raw materials from the planet. From the social-cultural perspective, the textile industry is guilty of forms of modern slavery, child labour (Fashion revolution CIC, 2020), unsafe working environments and contamination of local communities' water sources (Ellen MacArthur Foundation, 2017).

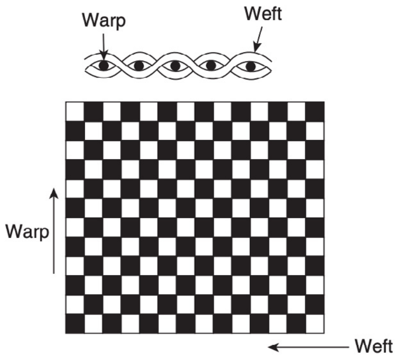
Cut and assembly methods to create textile objects

Cut and Assembly (C&A) is a distinguished method in textile form-creation practices, carrying out high consumer demand. Large rectangular pieces are cut into pieces which are then joined together by sewing. However, it is a time-consuming, resource-depleting and complex practice. Waste is inevitable (Figure 1), with nearly 20% (Rissanen, 2013; Runnel et al., 2017), partly caused by textiles' siloed processes when the pattern cutter is often not the Textile-form designer (Rissanen, 2013).

Cut & Assembly methods
Textile + Cutting + Sewing = Textile object **+ waste**







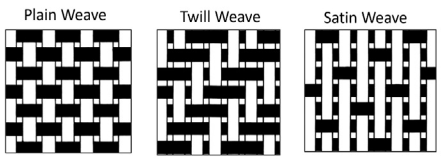


Figure 1 (top): Cut & Assembly method. The red colour resembles the inevitable waste produced during this method
Figure 2 (top): Illustration of a loom (Adolph, 2009)
Figure 3 (bottom left): Diagrams explaining a plain weave method
Figure 4 (bottom right): Diagrams of plain, twill and satin weave

Weaving

These rectangular textiles are woven, non-woven or knitted before being transformed into textile objects. Thus far, the primary focus in research has been on knitting, which leaves opportunities for weaving.

Weaving is performed on looms (Broudy, 2021), making the heddles in the loom move up and down (Figure 2), driven by the card information consisting of 0 and 1's, allowing the warp to divide and enable the weft yarn to be placed across, creating an interlaced structure, being the weave binding (Figure 3). There are three types of weave bindings, (Figure 4) plain or tabby, twill and satin, and the other bindings are typically variations on these bindings.

To conclude, textiles design and production are depleting and intoxicating the Earth, driven by an unsustainable linear process. Contributions such as reselling or recycling textiles are not enough when the industry produces more products than ever, explaining the need for fundamental global system change in the textile industry.

Introducing a circular economy for textiles

The current linear system is unsustainable and increasingly polluting in a world with high consumer demand for garments (European Environment Agency, 2022) and a population that will continue to grow (United Nations, n.d.). Therefore introduces the Ellen MacArthur Foundation (2017) the global move towards a circular economy including all silos in the production chain. About 80% of the total environmental impact of textiles occurs in the production phase (ECOS, 2021; Östlund et al., 2020); hence efforts should be concentrated here to have the most impact.

Eliminating waste and pollution out of the linear system and integrating these components into a circular system (Ellen MacArthur, 2020) in the textile industry introduces the 'new textile economy', where garments, fabric, and fibres are reintegrated by keeping them at their highest physical and economic value, considering waste a valuable resource. This observation concludes that a circular economy eliminates petroleum-based, synthetic fibres that release microfibre and concerning substances. Shifting towards a circular economy attributing longevity, durability (European Environment Agency, 2022), recovery and efficiency (Kapsali, 2022) addresses consumer behaviour and design production constraints.

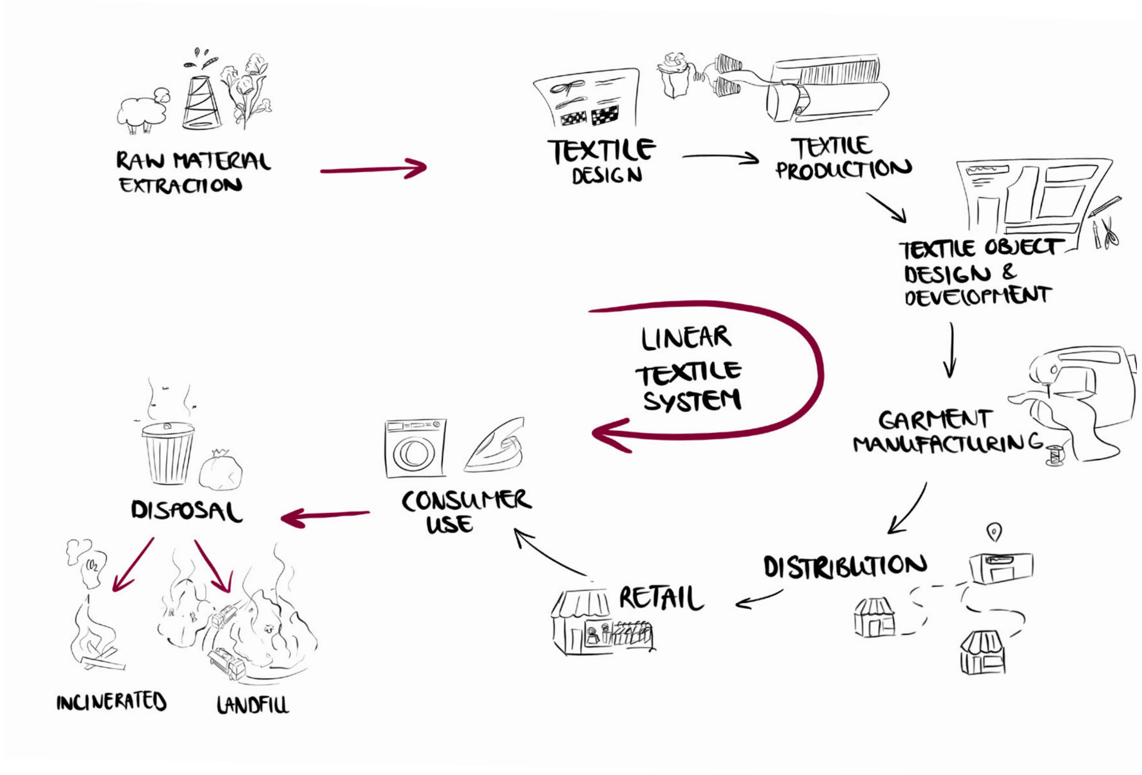


Figure 5: Illustration of the current linear textile system

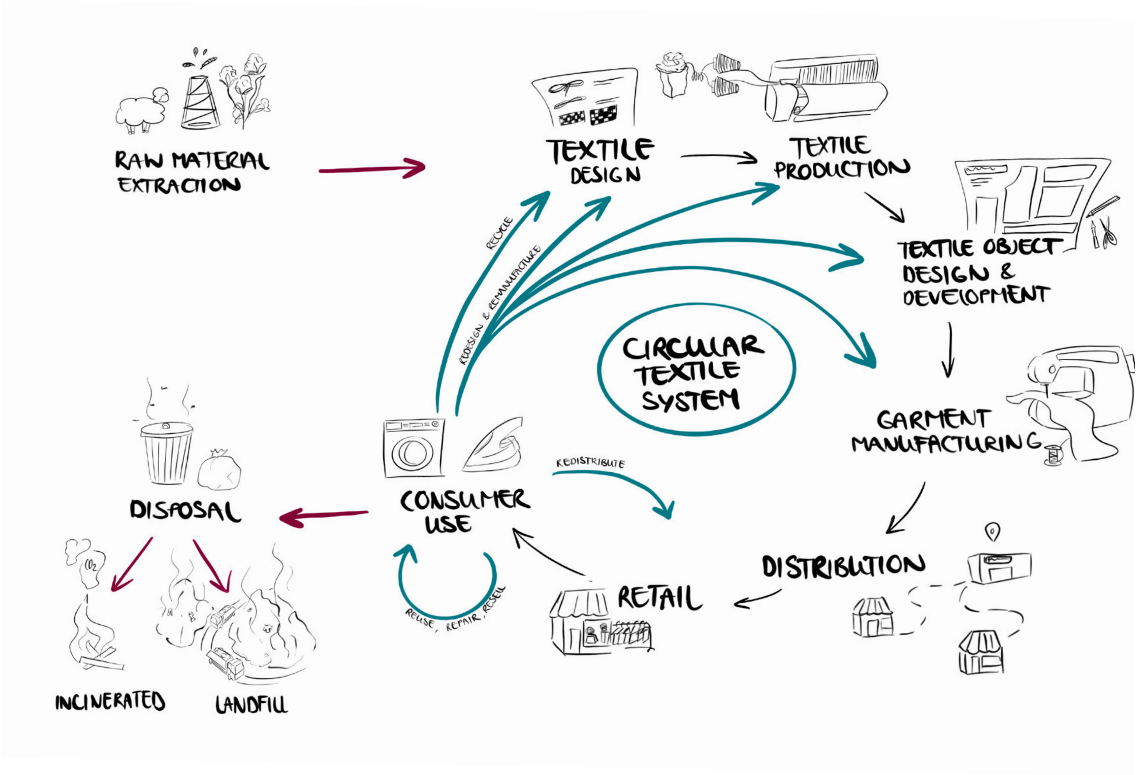


Figure 6: Illustration of the needed circular textile system, where raw material extraction and disposal are elimindated from the system.

Textile methods for a circular economy

Over the past years, some contributors in the industry have been making efforts to reduce GHG emissions, the use of resources, water use and the use of recycled material to be more conscious. Binswanger (2001) expresses the risk of such contributions as the 'rebound effect', where actions that increase resource- and energy-efficiency result in increased production and consumption by decreased overtime and ability to grow its production, which in turn can lead to energy increase. The risk of intentionally embellished branding of such contributions, known as 'greenwashing' (Delmas & Burbano, 2011), potentially leads to increased consumption.

Nevertheless, these actions are necessary, but more is needed; the fashion industry needs a global systemic change into a circular economy. Both McQuillan (2020) and an article by Parisa et al. (2018) share a systemic approach as a solution for environmentally responsible practices and advocating to include all silos of the supply chain rather than focusing on one part of the chain when taking these actions.

Zero-Waste Cut and Sew

An example of eliminating waste is zero-waste pattern making, a design challenge forcing the designer to work on the aesthetics and function of the garment simultaneously (Figure 7). A paper by Carrico and Kim (2014) discusses different techniques for Zero-Waste, demonstrating the advantages of practices from a zero-waste perspective. Perhaps the most serious disadvantage of this method is due to the impact of the 'rebound effect' could be using all the material for the reason not to waste it where they could potentially be used to make more products.

Zero waste pattern cutting
Textile + Zero-waste PatternCutting + Sewing = Textile object (+ **minimised waste**)

(Rissanen, 2013)

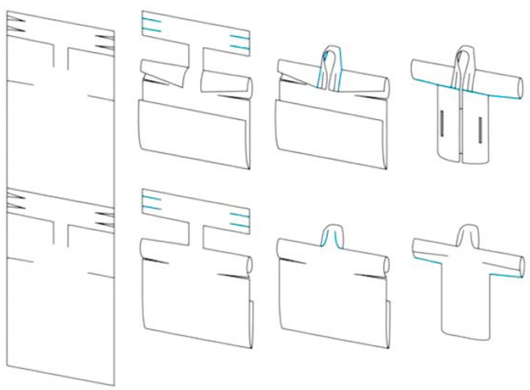


Figure 7: Zero waste pattern cutting by Rissanen (2013)

Whole textile object production

In whole textile object productions, the conventional human-made steps (C&A) in the supply chain are replaced with one mechanical process to create a 3D form, described as simultaneous design and production of textile and form (Piper & Townsend, 2015). This method is described by McQuillan (2020) as the creation of a 'Texile-form', which describes 'form made at the same time as the textile is constructed'.

Creating a Textile-form through flat-bed knitting demonstrates that such methods do not necessarily create a sculpted 3D form fit to the anatomy of a human body through the three-dimensional form.

Textile-form production
Material + Form-creating method = Textile-form

(McQuillan, 2020)

Woven Textile-form

Weaving creates two-dimensional textiles, which through C&A methods, become three-dimensional forms. Woven Textile-forms (McQuillan, 2020) address the relationship between textile and form, described by Piper and Townsend (2015) as simultaneous design. Woven Textile-forms include altering properties of the textile, which create form through multi-layer woven textile construction (McQuillan, 2020). It allows a woven 2D structure to exist as a woven 3D form while eliminating waste. Weaving (un)connected multi-layered structures through specific divisions of the warp creates a Textile-form by releasing and unfolding these layers (Figure 8).

Woven Textile-form
Yarns + Weaving = Woven Textile-form

(McQuillan, 2020)

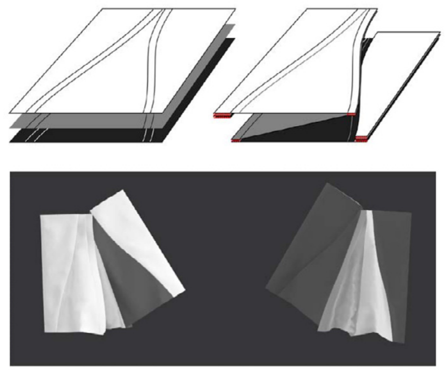


Figure 8: Woven Textile-form constructions of layers by McQuillan (2020)

Weaving for woven Textile-form

For woven Textile-form, the loom heddles divide the warp to create unconnected layers in the weave structure. Figure 10 shows that the first and second weft yarns are not interlaced; the third and fourth weft yarns are neither. Therefore, the interlacement happens between the first and third weft yarn and the second and fourth weft yarn. This method is explained in more detail in appendix E. Through variation of the interlacements between weft yarns in the layer set-up and warp yarns, building the form-creating structure (Figure 8).

Workflow for woven Textile-form

The workflow (Figure 9) for woven Textile-form development supports different types of jacquard looms containing different design constraints and variables; see appendix G for an example of such a loom set-up process. A variety of supporting tools is available:

- Idea sketching
- Paper models
- Textile models
- Map of Bindings (MoB)
- Sampling of weave structures
- Illustrator or PhotoShop: Visualising the MoB
- Digital 3D models: Clo3D
- Weave cards creation: AdaCad, ScottWeave, NedGraphics

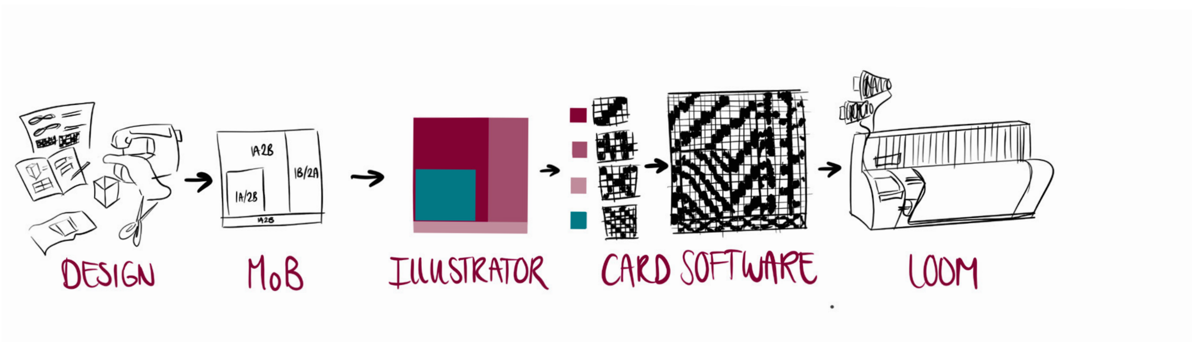


Figure 9: Woven Textile-form Workflow

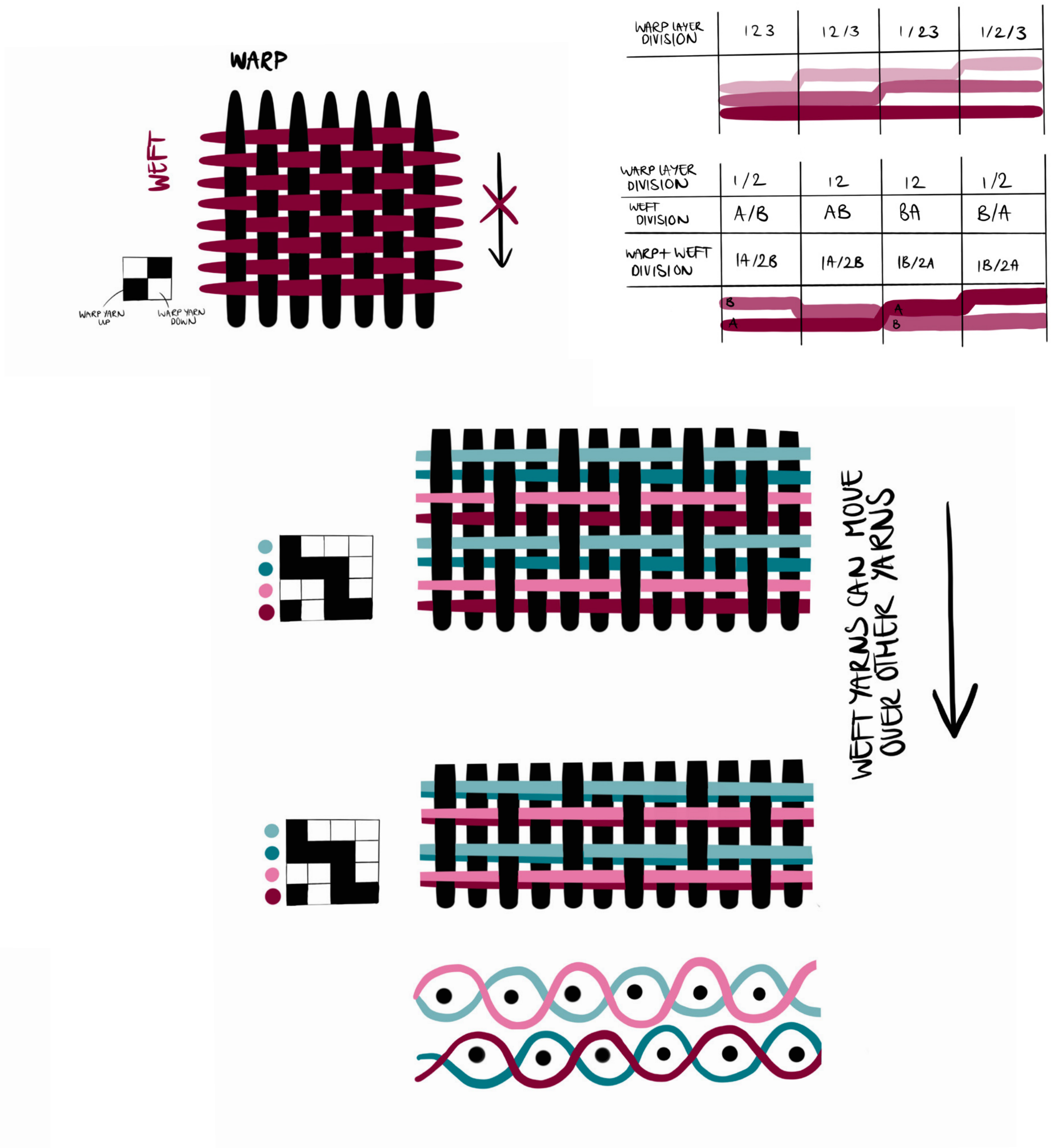


Figure 10: Illustration explaining multi-layered weavings

Tools for woven Textile-form

The following section elaborates on these supporting tools, explaining the undertaken process for woven Textile-form in the following experiments, which appendix D explains in detail.

Designing

In the design process of woven Textile-form sketches, layered paper models and layered textile models (C&A) to imitate the layer construction potential are tools to visualise and develop a form for woven Textile-form (Figure 11).

Map of bindings (MoB)

The potential form-construction for woven Textile-form translates to the Map of Bindings (McQuillan, 2020); the 2D plan, existing of the flattened 3D form, includes the specific weave bindings in the multi-layered construction. Programs such as Photoshop and Illustrator support the creation of MoB files.

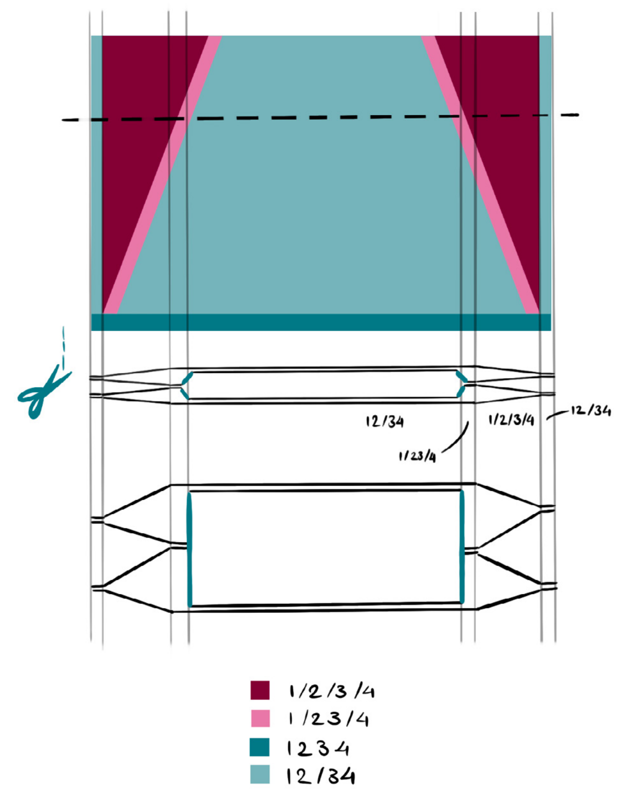
The MoB consists of a visual representation of the form-creating structure, including annotation for the weft and warp divisions (Figures 12). Each colour represents a different layer construction, including the specific weave bindings of each layer.

Digital 3D model

The process can benefit from integrating digital modelling programs, such as 'Clo3D' or 'Weavecraft' (Rundong et al., 2020), where a designer can import the MoB file and visualise the three-dimensional model (Figure 13). Especially, 'Weavecraft' has to support designers in understanding multi-layered weave constructions.
However, these digital tools have their limitations, limiting the explicability of the relationships between different stages in woven Textile-form development. Bio-Inspired Textiles (Bio-Inspired Textiles | Circular and Sustainable Design Research, n.d.) seeks to enforce the movement towards a comprehensive knowledge base, respectively providing communication terms and enabling programming and visualisation of woven-textile forms.

Cards software

Next, designers must communicate which heddles the loom has to move to create the woven Textile-form. Implementing the MoB in digital software, such as ScotWeave, AdaCad or NedGraphics, supports the transition of the MoB into the weaving card containing programmed information (Figure 14). The MoB consists of colours representing specific weave bindings which these programs translate to the programmed bindings, consisting of the multi-layer weave constructions(Figure 12).



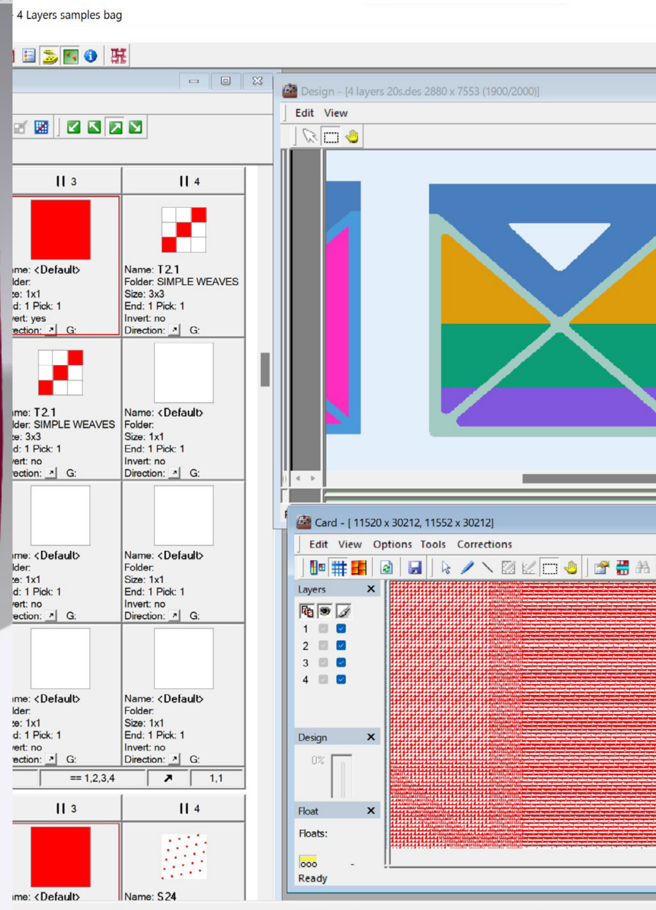


Figure 11: Design process of woven textile-form
Figure 12: Map of Bindings set up with annotations for layer constructions
Figure 13: Digital model in Clo3D
Figure 14: Overview of NedGraphics, left: creating the different bindings, right: MoB made in Illustrator, bottom: created weave card consisting of red and white annotations for communication with the loom

Morphic Textile-form

A development workflow supports the potential of woven Textile-form for persuasive sustainable design outcomes. In the next section, temporality is introduced to woven Textile-forms as potential in a circular economy.

Morphic Textile-form (McQuillan, 2022) enables change through activation in the production and use phase, stimulated by temperature, electricity or water. This method creates another dimension of form-creation through the shape-changing properties of materials, resulting in opportunities for textile-based form production in a circular economy through diversity and personalisation.

Morphic Textile-form
Yarns + Weaving = Woven Textile-form + external stimuli = Morphic Textile-form

(McQuillan & Karana, 2022)

Shape-changing materials

Shape-changing materials experience changes in form or structure through external stimuli (Coelho & Zigelbaum, 2011). This research means the external stimuli also include interaction in the production phase rather than the user phase. Shape change in material occurs through structural fibre change, which results in a shape change of the material's structure, challenging the designers' knowledge in material science and design (Addington & Schodek, 2012).

Shape-change in textiles

Materials with shape-change properties, identified by Papadopoulou et al. (2017), consist of three general design parameters: material composition, activation energy and transformation mechanics used to explain the changeability of a textile. The changeability of textiles is categorised as reversible or irreversible (Worbin, 2010). Irreversible changes can indefinitely influence a textile's visual expression, structure and tactility (Talman, 2021). Morphic textile-form methods can utilise shape-change in textiles through the addition of temporality in the design and production phase or create the shape-change conductors in such a way it can be done by consumers.

Multimorphic Textile-form

The previous section discussed shape change in woven Textile-form and defined the potential of temporality in design. Taking into account environmental factors, using mono-material, biodegradable and recyclable materials broadens the scope towards multimorphic Textile-forms (McQuillan, 2020; McQuillan & Karana 2022). As well as the previously discussed methods, this method encompasses on-demand local production, extended life cycles and zero waste (McQuillan, 2020)

Multimorphic Textile-form
Morphic Textile-form → Integrating CE → Multimorphic Textile-form

(McQuillan & Karana, 2022)

Introducing wool as shape-changing material

The wool fibre has a heterogenous composition, responsible for resilience, flexibility, and elasticity, creating wrinkle recovery and dirt- and fire-repellant properties. The ability of wool fibres to felt, causing shrinking, gives the material shape-changing properties and has the potential for shape-change in woven Textile-form in the context of a circular economy, as discussed in the previous section.

The research on wool felt-resistant treatments (Wan & Yu, 2012; Hassan & Carr, 2019; Hassan, 2020) demonstrates the industry's aim for wool to perform similarly to other textile fibres. These deliberate practices reveal a disregard for the existing natural properties and the potential of wool fibres.

(Un)Sustainability wool

As discussed in the previous section, using a biodegradable, recyclable mono-material widens the scope towards integrating environmental factors; therefore, using a natural material, such as wool, has potential.

Wool is a complex biological fibre retrieved from a sheep's fleece, a yearly renewable resource that can store CO2 (Woolmark, n.d.). Considering woollen products are biodegradable, compostable, and 100% recyclable demonstrates the potential in a circular economy.

However, when sheep have a dual purpose for meat and wool (Woolmark, n.d.), the wool industry is partly responsible for animal slaughtering. The impact of unsustainable and animal-unfriendly wool-retrieving practices cannot be neglected, such as land clearing for sheep grazing causes deforestation and biodiversity loss. These matters in the wool industry demonstrate the hidden cruelty and potential environmental destruction.

The industry's lack of purpose for wool, caused by the perception of wool's lower quality compared to the exceptional quality of Merino sheep wool fibres, results in underutilising this wool and eventually incineration. Holland Wol Collectief questions this misconception and explores the quality of 'Dutch' wool by creating half-products and consumer products (J. Hoop, personal communication, June 22, 2022)(Appendix I).

These findings demonstrate the complexity of defining a material as sustainable when it is highly dependent on the whole system in which it performs. Exploring the whole system requires moving away from the industry's anthropocentric perspective and including the ecological system. Al together, the potential of wool in a circular economy and its felting abilities define the introduction of wool as shape-changing material, which the following section further explores.

Shape-change through felting

As mentioned in the previous section, this research explores the potential of the felting properties of wool. The surface of wool fibres causes the felting ability; the overlapping cuticles hook into each other through external stimuli (Hassan & Carr, 2019), causing the wool to become thicker and more fibrous (Figure 17). Research by Dobozy (1958) and Van Der Vegt (1955) (Figure 18) found felting causes the singular fibres to loose their parallel position within a yarn, being responsible for the change in the irregularity of the surface of the yarn. The experiments throughout this research indicate the same findings regarding wool felting.

Wool is a keratin-protein-based fibre consisting of Cystine molecules (Babu, 2019; Zhang et al., 2018). Disuphilde bridges form between these molecules, causing sensitivity to heat and alkaline pH environments. This explains the enhancement of felting abilities by using detergent in a warm washing environment (appendix B).

Wool needs external stimuli to felt, which is the friction caused by the washing process through mechanical action and time (Van Der Vegt, 1955). Irreversible changes in wool occur gradually over a short period of time, influenced by external factors such as heat, fluid dynamics and mechanics. The scale, duration, intensity and repetitions of these external factors define the expression of felted wool.

A series of experiments (appendix C) explores the felting ability of a woollen weave binding, demonstrating the positive correlation between the amount of felting and the density of the weave binding (Figure 15), making the samples shrink in size. The type of weave binding and the specific float lengths define the density of the weave binding. Additionally, the increase in layer count of woven Textile-form decreases the density.

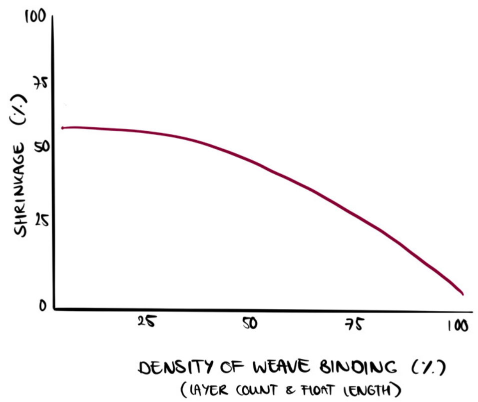
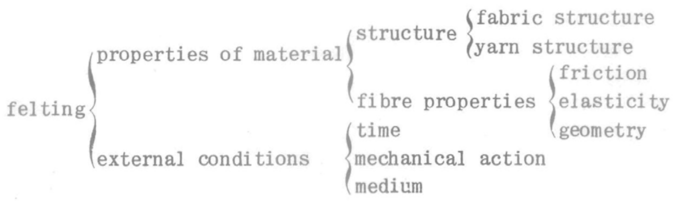


Figure 15: Correlation between felting and binding density

Felting process theoretical research

Van der Vegt (1955)



Hassan & Carr (2019)

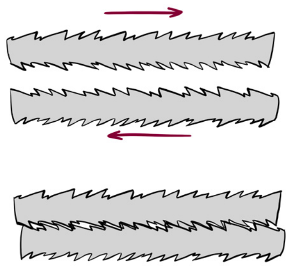
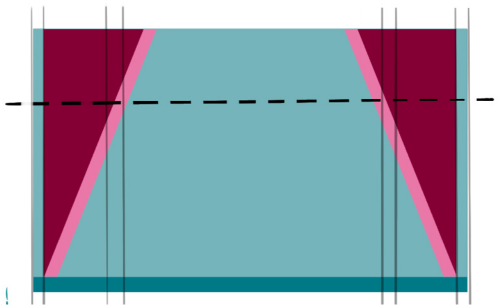


Figure 16 (left): Overview of Van der Vegt (1955) on wool felting
Figure 17 (right): Felting of wool fibres, the cuticles hook into each other, by Hassan & Carr (2019)
Figure 18 (bottom): Overview of wool fibres, yarns and weave binding before and after the felting process



			1	2	3
13	1A/2B3C		S4	S32	S32
14	1A2B/3C		S32	S32	S4
15	1A/2B/3C		S32	S16	S4

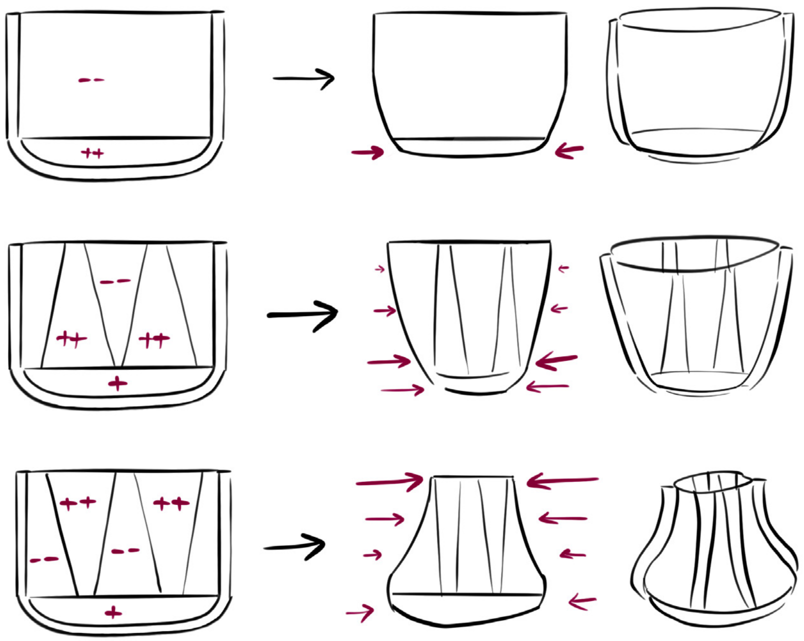


Figure 19: MoB for morphic Textile-form is similar to woven Textile-form with additionaly the shape-changing binding or material in the annotation. In this case the number behind the wool binding indicates the float length which induces the felting process. S32: +++ felting ability S4: - felting ability.

Weaving for multimorphic Textile-forms

For multimorphic Textile-forms, the previously explained MoB is added with the information on the specific weave binding for shape-changing properties (Figure 19). The higher the number behind the weave binding (f.e. S32), the longer the float length, increasing the felting ability. Appendix E elaborates on the weave bindings set up in detail .

Summary of Opportunities

The capitalistic anthropocentric perspective (McQuillan, 2020) causes the unsustainability of the current textile industry, which defines the call for a global systemic change towards a circular economy. The new textile economy (Ellen MacArthur, 2017) calls for a transformation of the way textile and textile-based products are designed and produced, which requires simultaneously approaching design through different lenses (McQuillan, 2020; Piper and Townsend, 2015; Townsend, 2003), defined as a holistic approach.

When designing form and material simultaneously while integrating environmental factors, the material is addressed as a system, which explains the complexity of defining materials as sustainable. The potential of this perspective on design is defined in the following sections.

Comparing the explained methods demonstrates similar outcomes, Textile-forms. However, the significant difference is the integration of internal and external variables in the design process, demonstrating distinct aesthetics and environmental impact.

The potential of wool as shape-changing material introduced in woven Textile-form and using a biodegradable mono-material broadens the scope towards multimorphic Textile-form (McQuillan, 2020), moving towards a circular economy.

The next chapter discusses related explorations positioning the potential of this research in the context of a new textile economy (Ellen MacArthur, 2017)

RELATED WORK

RELATED WORK

As mentioned in the previous chapter, the conventional methods in the industry can be questioned on their appropriate contribution to the environment, and the need for systemic change in the textile industry is clarified. This chapter aims to understand relevant research and contributions by exploring the principles and opportunities of such methods, forming the focus for further research by positioning this research in the context of textile object productions moving towards a circular economy.

Form-creation

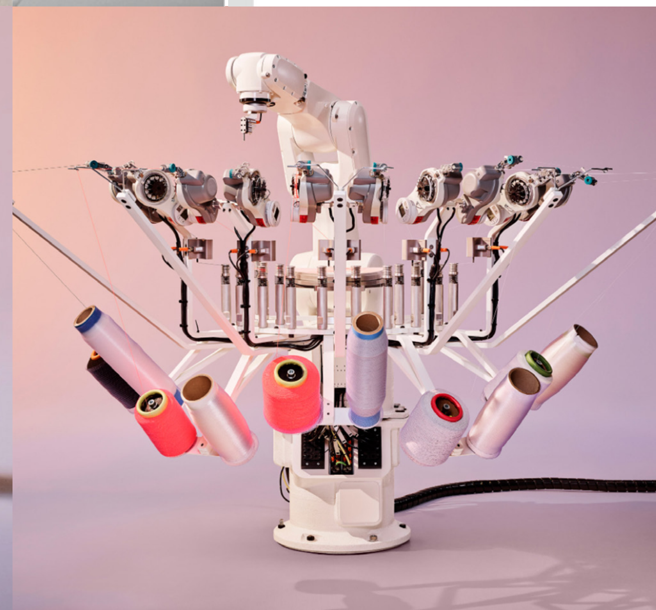
Form-creation in design often uses 3D printing as a rapid prototyping tool and for manufacturing finished products, such as the 3D-printed robot woven shoe by Adidas. This research combines weaving and 3D printing techniques to explore complex geometries, which integrate customisability in the woven shoe part and the soles' ability to change shape and properties over time to increase the athlete's performance, described as '4D', which is related to nature-inspired design practices. The ability of response in construction to increase product qualities provides opportunities for further exploration in morphic Textile-form, which is discussed later.

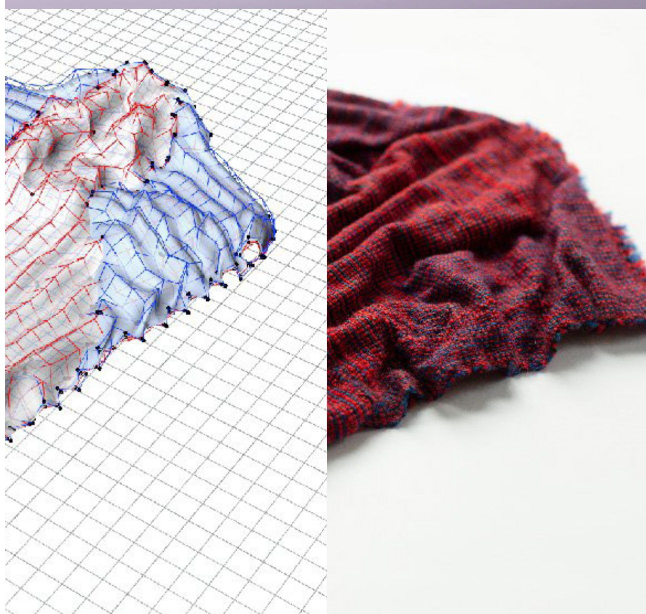
Form-creation in textiles

Textile-form practices design textiles and forms simultaneously, requiring designers to have a holistic view of the process. The following section discusses related explorations in Textile-form creation by their opportunities and limitations compared to this research.

Woven Textile-forms

Woven Textile-forms use woven multi-layer construction to create a 2D structure that requires altering to transform into a 3D form. This method is referred to as 3D weaving, performed on a digital jacquard loom, but differs from 3D weaving performed on 3D looms with multi-axis weaving having the ability to create a finished form(Perera et al., 2021;Vassiliadis, 2011). Virtual Textiles Research Group explores these methods creating a material library and rapid sketching tool for 3D weaving (Figure 23) as well as the exploration of Weffan (Figure 20) and, Holly McQuillan and Milou Voorwinden constructing a conventionally-fitting zero-waste pair of trousers using woven Textile-form (McQuillan, 2020)(Figure 21). These woven Textile-forms are created for specific aesthetical and functional design goals, aiming to come as close to the conventional aesthetics can induce embracing new techniques and explores the limitations of the method.





Top to bottom, left to right:
Figure 20: Weffan take on conventional denim trousers in 3D weaving
Figure 21: Exploration of conventional-fitting zero waste pair of trousers byHolly McQuillan and Milou Voorwinden
Figure 22: Adidas 3D print woven sneaker, described as 4D by reactive materials
Figure 23: Rapid Textile Sketching Tool by Virtual Textile Research Group
Figure 24: Needle felting wool by Yvonnes Workshop

Moulded Textile-forms

Moulding a 3D form with textiles is a standard production method in the wool industry; a 3D form is created by felting and shaping wool fibres. These methods use either felted wool rectangular cloth or needle felting techniques which combine painting and sculpting methods (Figure 24) to create a finished 3D form. By felting wool, the material maintains its fibrous properties but can increase in firmness and therefore create a product with structural properties, which is interesting for exploration in this research.

These examples provide traditional and innovative methods for Textile-form creation, emphasising the holistic designer perspective thinking simultaneously about form and material. The following section discusses temporality in Textile-forms through shape change.

From-creation through shape-change

The ability of a form to change its shape can accommodate sustainable and zero-waste outcomes through the ability of on-demand production by integrating finishing methods and extended life cycles through personalisation by the user. This section discusses examples of shape-changing Textile-forms by adding temporality as a design variable to woven Textile-form textiles.

Shape-changing forms

Addressing shape-change in forms as the interaction between the material and the structure, which follow changes in shape, shows examples in the textile industry and other fields. This section widens towards other fields exploring shape-changing properties in form-creation. Rasmussen et al. (2012) (figure 25) overview for user interface design enables designers to explore shape-changing methods, often used in animated materials.

Researchers from MIT experimented in 2019 where a 3D printed flat mesh structure exposed to specific temperature changes to the shape of a human face, see figure 21. They developed a design method to determine the pattern of the flat mesh structure to make the structure transform into the intended shape with the given material's properties. This technique could produce structures that automatically deploy or change when exposed to certain temperatures or other environmental factors, which is discussed later

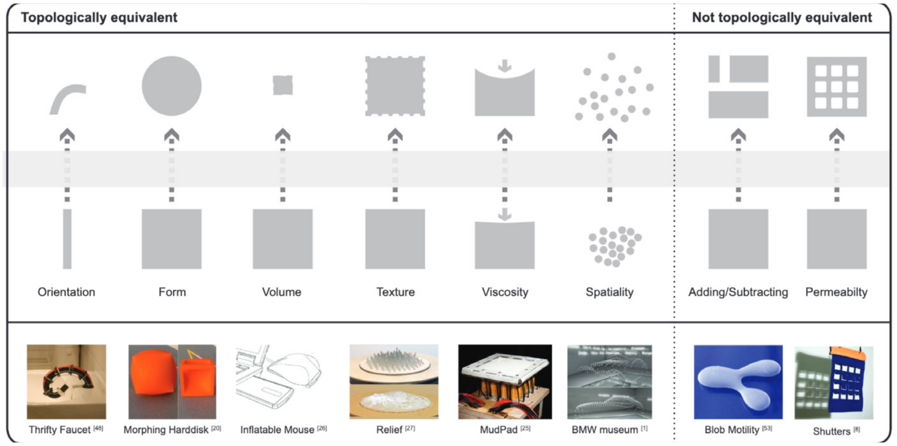


Figure 25: Shape-change in forms for interaction design (Rasmussen et al., 2012)

Shape-change in Textile-forms

This section discusses related explorations in constructing Textile-forms through shape-changing properties of the material or shape. In these explorations, the temporality added through shape-change is addressed as design variable, which describes as morphic Textile-forms (McQuillan, 2022)

Morphic Textile-forms

Morphic Textile-forms (McQuillan & Karana, 2022) differ from woven Textile-form, enabling change through activation during the production or using phase. The work of Riika Talman(2022) (figure 28) explores the changeability in textiles, where change is a design variable in textile design. In her experiments, the textiles respond to stimuli such as water and heat, changing through dissolving, shrinking, stretching, and variations in thickness. Riika's research demonstrates that the changeability depends on the proportions, placement and materials within the textile structure, also recognised in the other discussed projects, should be considered in this research.
In 'Woven Forms', Leonie Burkhardt (Figure 29) proposes a systemic approach using woven Textile-form techniques for form creation through activation using shape-changing materials. Both explorations are an inspiration, though the use of multiple materials for shape-changing creates concerns about recycling such textiles in a circular economy.

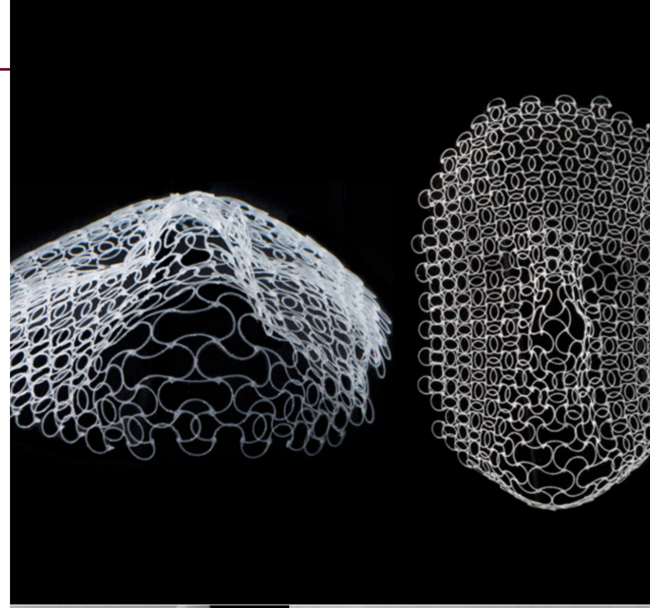
This concern could be addressed using a mono-material, such as the 'Touch the forest' collection by Zuzanna Wojcik (figure 27), which explores textures found in the forest, using woven Textile-form for aesthetical and sensorial performance. In contrast to Zuzanna's explorations, an interesting approach regarding sustainability is following the design process and let the aesthetics be the result of rather than the reason for creating an object.

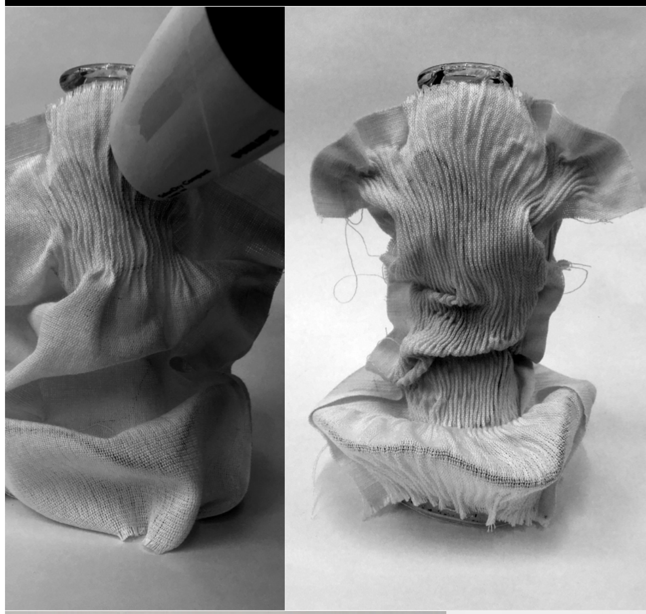
Shape change in moulded Textile-form

A collaboration of Karin Peterson; Riikka Talman; Holly McQuillan; Kathryn Walters explores woven Textile-form through a moulded tunic design (Figure 30). The 3D form transforms into a 2D layered textile design through 'flattening' and then expands into a 3D form. The Textile-form consisting of heat-reactive synthetic yarns is placed around the mould, allowing the form to be manipulated by varying the applied heat or shrinking uniformly without mould with a washing dryer. While being an inspiration for this research, using wool yarn excludes the manipulation through manually varying the intensity and placement of the external stimuli, though acknowledging the potential of variation in shape-changing abilities.

Multimorphic textile-forms

Multimorphic textile-forms (McQuillan & Karana, 2022) are textile-based objects designed through a lens of sustainability via on-demand local production, extended life cycles and zero waste perspective. The use of biodegradable, mono-material and materials that are responsive to their surroundings, such as the 3D printed mesh discussed before, has the potential for sustainable design outcomes. In costume design for the movie 'Planet City' (Figure 31), McQuillan et al. (2021) explore morphic textile-forms, creating zero-waste garments with recyclable polyester, acknowledging the environmental context, however creating some concerns on sustainability, nevertheless it demonstrates the potential in material-driven approaches for sustainable design outcomes.






Top to bottom, left to right:
Figure 26: MIT 3D printed face mesh reacting to the environmental factors
Figure 27: 'Touch the forest' by Zuzanna Wojcik, shape-change through wool felting
Figure 28: Explorations by Riika Talman on changeability of textiles (2022)
Figure 29: 'Woven Forms' by Leonie Burkhardt, shape-change through heat reactive yarn combined with linnen
Figure 30: 'Moulded tunic design' by Karin Peterson, Riika Talman, Holly McQuillan and Kathryn Walters, shape-change through heat-reative yarns shaped with the use of a mould

Conclusion

The discussed explorations have a simultaneous design approach, where designers have to think of form and textile at the same time. In morphic Textile-forms (McQuillan & Karana, 2022), the holistic perspective is extended by shapeshifting during the production or use phase, creating the potential for these forms in a circular economy. Explorations of Textile-forms are discussed on their potential to be explained as multimorphic Textile-forms (McQuillan & Karana, 2020), which integrates the interaction with the environment. The ability of on-demand, localised manufacturing of whole-form production methods forms the potential for sustainable design outcomes. Most of these approaches intend to produce a specific outcome, enforcing a material to have a desired form and function, risking the neglect of sustainability in the design process. This causality demonstrates the potential of a material-driven approach, which discovers material expression by exploring the opportunities of a material by which the form and function

Figure 31: Costume design for 'Planet City' (McQuillan et al., 2021)

RESEARCH AIM

RESEARCH AIM

Informed by the research in the previous sections, which explores the context as well as other related explorations, this research aims to:

Unfold the new techno-aesthetics emerging from material expressions through textile form-creation in a circular economy

These expressions demonstrate the necessary value change of perception and expectations of the Textile-form aesthetics and potentially beyond when a sustainable design outcome is a goal.

The outline on the right side (Figure 32) shows the topics covered in this thesis report, together with the actions that provided the knowledge, experiences and conclusions to facilitate the achievement of this aim.

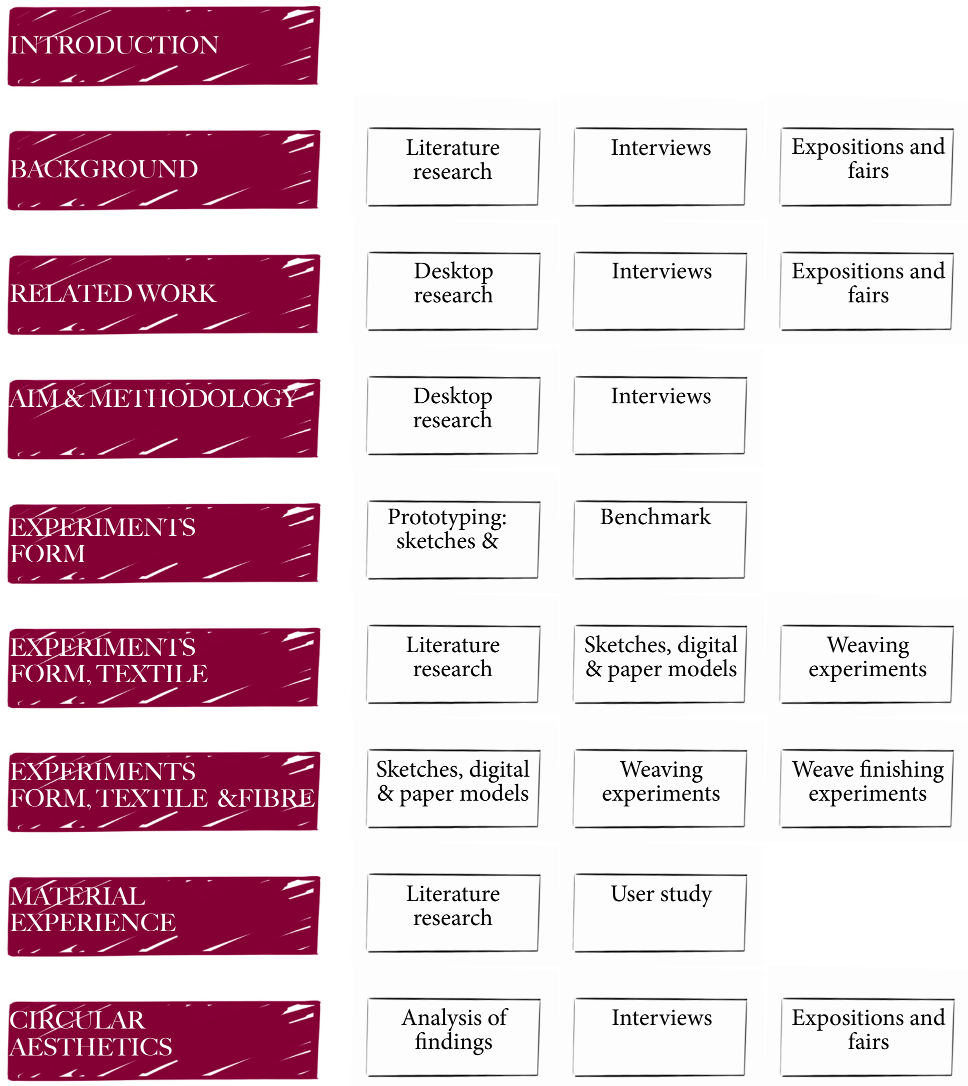


Figure 32: Research actions overview

METHODOLOGY

METHODOLOGY

This chapter discusses the methodological approaches to frame this research, demonstrating the entanglement of the method (materials + methods) and the aesthetics in the context of sustainability. The framework in figure 33 shows areas of compromising when not addressing the research with a holistic perspective, including all three areas.

This research approaches textile design, starting from the raw state of materials in the context of circularity, including the drivers of the 'new textile economy' (Ellen McArthur, 2017), as discussed in the previous chapters.

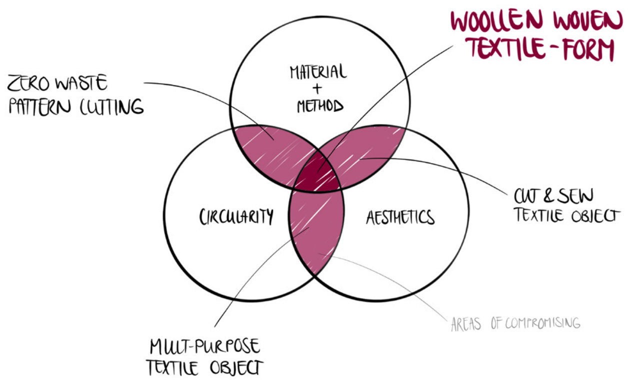


Figure 33: Balance over Circularity, Aesthetics and Material-Method.

Material-led Design

The Material Driven Design (Karana et al., 2015) addresses a material to understand and characterise it technically and experientially, enabling implementation in design (Figure 34). This method allows the material to guide the process rather than the desired design outcome, which is an unfamiliar approach in the Delft Design Methods. The inversion of the conventional design process of function→form→structure→material, towards a material system following a 'material→structure→form→function' approach embraces the materiality (Oxman, 2010; Ainamo, 2014). However, unlike most material-led practices, MDD distinguishes the importance from an experience perspective next to materials' technological and performative characteristics. The aesthetics, coming from such material experiences, can be expressed as techno-aesthetics (Dalmasso, 2019), described as the relationship between aesthetical dimensions and technical performance by questioning the origin of aesthetic values and experiences concerning technology and its position in the broader ecological system.
In contrast to the human-made parts and assembly methods, nature-made products consist of one heterogeneous material while varying material properties for specific performances (Oxman, 2010), including interacting with the environment, production and user. Nature-inspired design demonstrates that materials have processes to exist and therefore perform in a material system, making textiles products consisting of fibres, yarns and structure manufacturing processes to enable form-creation. In industrial design engineering practices, textiles are often addressed as materials, missing the holistic lens and leading to unsustainable design outcomes.

Additionally, Ribul et al. (2021) introduce Material Driven Textile Design (MDTD) which acknowledges that materials have processes and applications and starts with the raw state of such materials, which then are explored, translated and activated on the material science and design level. The process establishes new material design processes, followed by a repetition of the MDTD process in the circular economy context, showing the shift of focus in this material process-oriented approach and the lack of a continuous holistic lens.

These methods start with a material-first perspective in a sustainability or circular economy context and acknowledge that materials interact with a specific system, in this research referred to as materials being 'material systems', demonstrating the simultaneously existing perspectives in such systems.

Research-through-design

Research-through-design (Stappers, 2017) describes the experimental nature of MD approaches by producing new knowledge through design actions. Throughout the design process and later by analysing and reflecting on the created objects, new knowledge is captured and limits or opens new space for exploration. The design process relies on trial-and-error practices when designing with known or new materials in a new technological context. The performed experiments throughout this design research are undertaken by creating various samples; to understand the material, methods and actions to find patterns to control the shape-change in woollen woven Textile-forms.

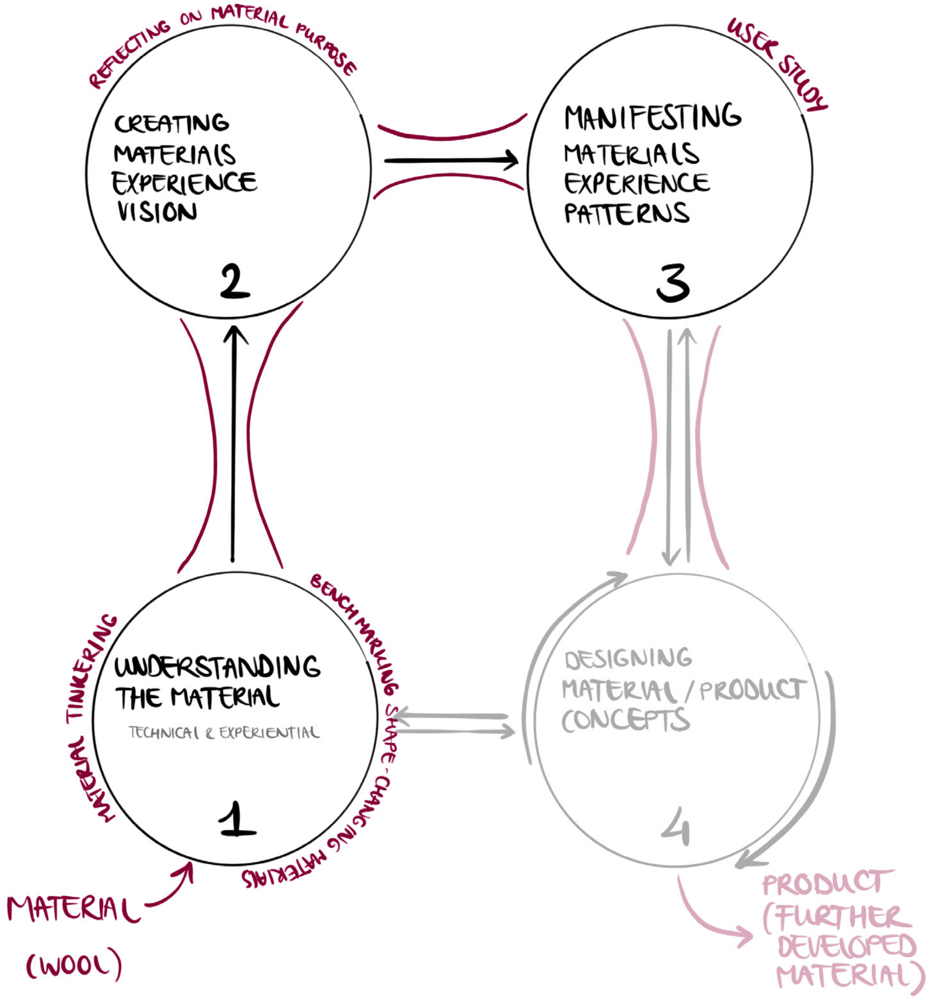


Figure 34: Material Driven Design (Karana et al, 2015) including the undertaken steps of this research

Artefacts

The samples created in various experiments to explore Textile-form and construct new material expressions are unfinished and open for experimentation. Design is the process of becoming, making a Textile-form an artefact, a thought at first, then constructed or produced. These thoughts are often sketches and notes to understand what they could mean in the context. Next, these could be constructed in paper or textile models, both 2D and 3D, to facilitate an object for presentation and conversation. Also, constructing woven Textile-form and shape-changing materials explore a deeper understanding of technical, manufacturing and material expressions. This research avoids the creation of objects as perfectly finished or produced, emphasising the explorative nature and ensuring the intended understanding of such objects.

Decisive constraints

Integrated into the research-through-design concept is the acknowledgement of the "designerly way of knowing" (Schon, 1983) that advocates using the RtD method in contrast to standard research methods. Including 'reflective practice' by Schön (1983), learning and designing through 'reflection-on-action', where creating and experiencing interlace in which prototyping forces to confront theory and stimulate discussion.

Practising this principle acknowledges that new knowledge consists of valuable insights for generating design iterations, creating opportunities, research gaps and constraints for following design actions. These constraints, stated by Biskjaer and Halskov (2014) as decisive constraints, being creative resources and opportunities instead of limiting boundaries; embracing these constraints fuels the design process by making creative iterations more accessible.

As explained in the previous chapter, the main drivers of this research are circularity, using biodegradable mono-material and eliminating waste, as well as the limitations of the weaving technique, shape-changing methods and prototyping, which frame the space in which this research acts. These elements mark the creation and exploration of the decisive constraints occurring throughout this research.

Multimorphic-thinking

Donella Meadows (2008) describes the system-thinking lens to understand relationships between elements, their impact on system outcomes, and how this system fits in the broader context. This concept is addresed by McQuillan (2020) as multimorphic thinking, an design element for Zero Waste System Thinking (ibid) as 'the lens needed when designing Textile-forms, considering multiple scales, time-frames, perspectives and contexts at the same time to develop holistic outcomes.
The multimorphic approach requires the designer to behave as a multi-disciplinary designer compared to conventional practices. This holistic approach requires the designer to be the material scientist and the product designer at the same time, which is partly addressed in MDTD. Townsend (2003) addresses the simultaneous design approach in textiles by considering both the textile and the textile form as design outcomes. Rissanen and McQuillan (2016), in 'A hybrid zero waste design practice', explore this simultaneity as the hybrid approach that combines two fields of design practices.

These approaches incorporate a holistic system in their design practices for sustainable design outcomes, showing the potential and the necessity of a holistic approach in simultaneous design (Piper & Townsend, 2015) activities supported by multimorphic or system thinking.

In this process often a feeling of chaos occurs, the feeling of designing multiple elements simultaneously in multimorphic thinking. Only some elements can be addressed simultaneously with the same efforts; hence the actions in this research to grip the abstraction by starting with one element while actively mapping the impact and interaction with the other elements in the system (Figure 35).

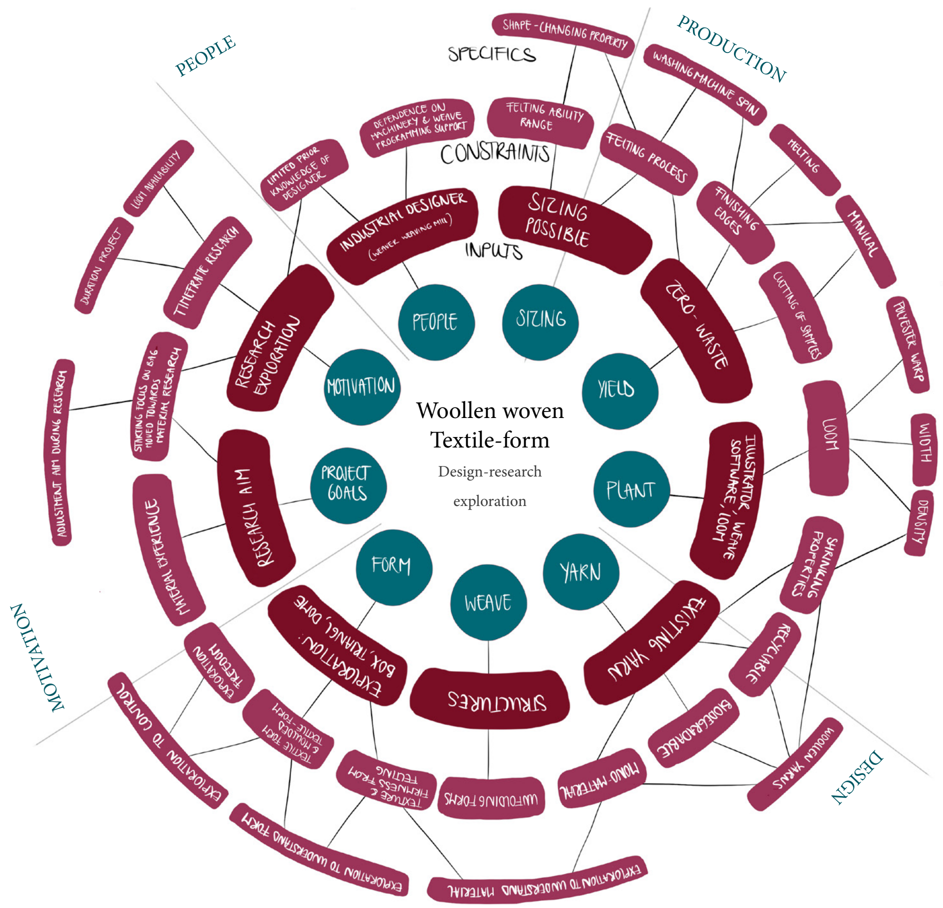


Figure 35: Zero Waste System Thinking map for: woollen woven Textile-form exploration (McQuillan, 2020)

Conclusion

This thesis challenges the conventional industry's perspective to shift towards designing from a material-first perspective which demands shifting from a 'form-first' or 'structure-first' approach to 'material-first', marking the starting point in this research as the wool fibre rather than the woollen yarn or woollen textile cloth. In this research, MDD, supported by the material science perspective of MDTD, explores wool fibres on scientific, technological and expressive material performances. The material-led approach in this research leads to new material expressions through the exploration of woollen woven Textile-forms. These experiments create artefacts, which are communicators of abstract theories, enable exploration to find paradigms, and are carriers for (interdisciplinary) discussions.

Approaching this research from the broad perspective of the ecosystem in which it acts, approaching wool as a material system ensures the integration of the impact on the social and environmental context without neglecting the economic impacts. This interdisciplinary way of designing and researching is explained as multimorphic thinking in McQuillan's research (2020) which includes all silos in the production of Textile-forms simultaneously rather than separately, causing the complexity and abstraction in sustainable design processes and outcomes.

This research process is captured in figure 36, addressing the methodological and theoretical practices in design to demonstrate the holistic process undertaken for establishing the experiments discussed in the following chapter.

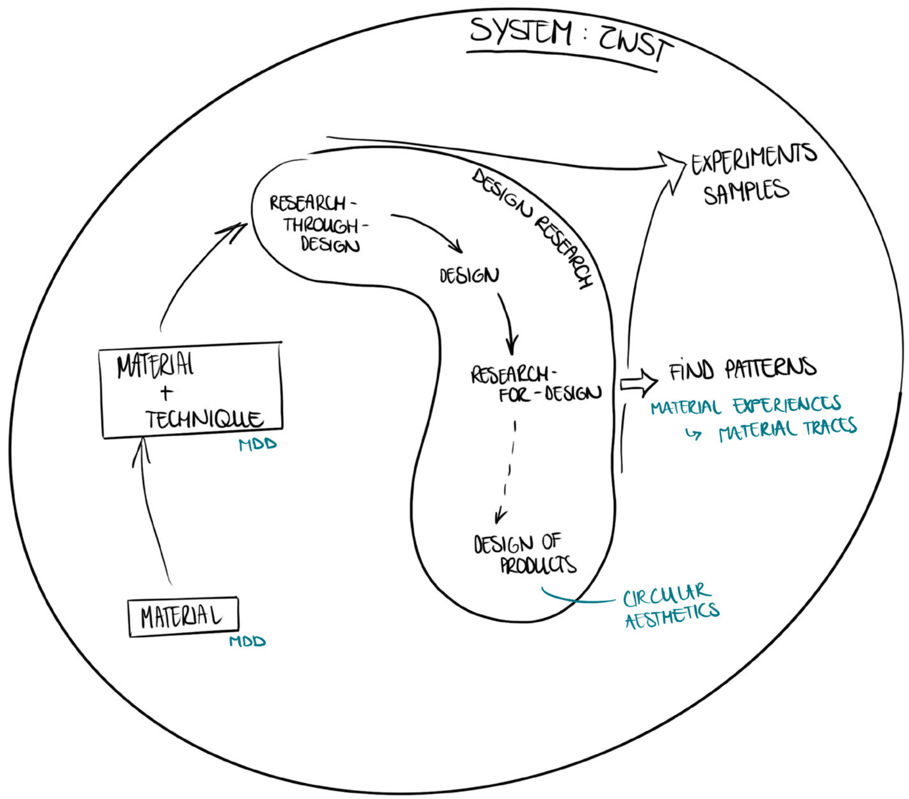


Figure 36: Overview of undertaken research steps and including methodological and theoretical practices

EXPERIMENTS

EXPERIMENTS

The experiments in this chapter explore form-creation through expandable structures where a flat object (2D) can exist as a 3D object. The flow of the iterative process derives from the 'reflection-on-action' (Schön, 1983) to assess the performed steps' novelty and define the following experiments or potential product design explorations.

Form primitives

Form primitives guide the form-creation process in woven Textile-form, selecting three form primitives for their variety of shapes and possible combinations for textile-product applications; Box shape, Triangular shape and dome shape (Figure 37). The idea of a product is introduced to guide the form-creation of hybrid design possibilities, additional features, other materials or aesthetical purposes, enabling creativity by decisive constraints of creating a bag

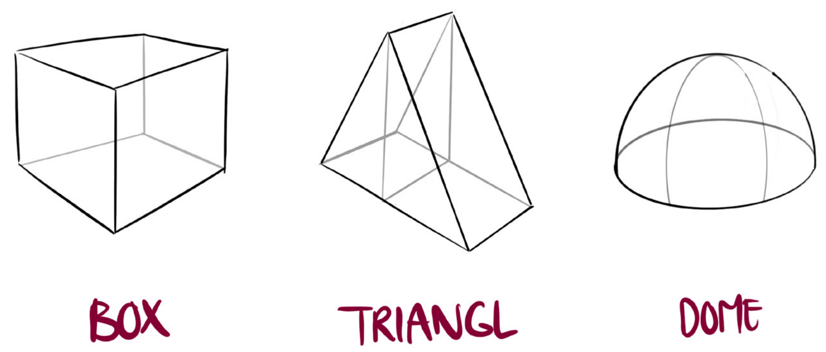
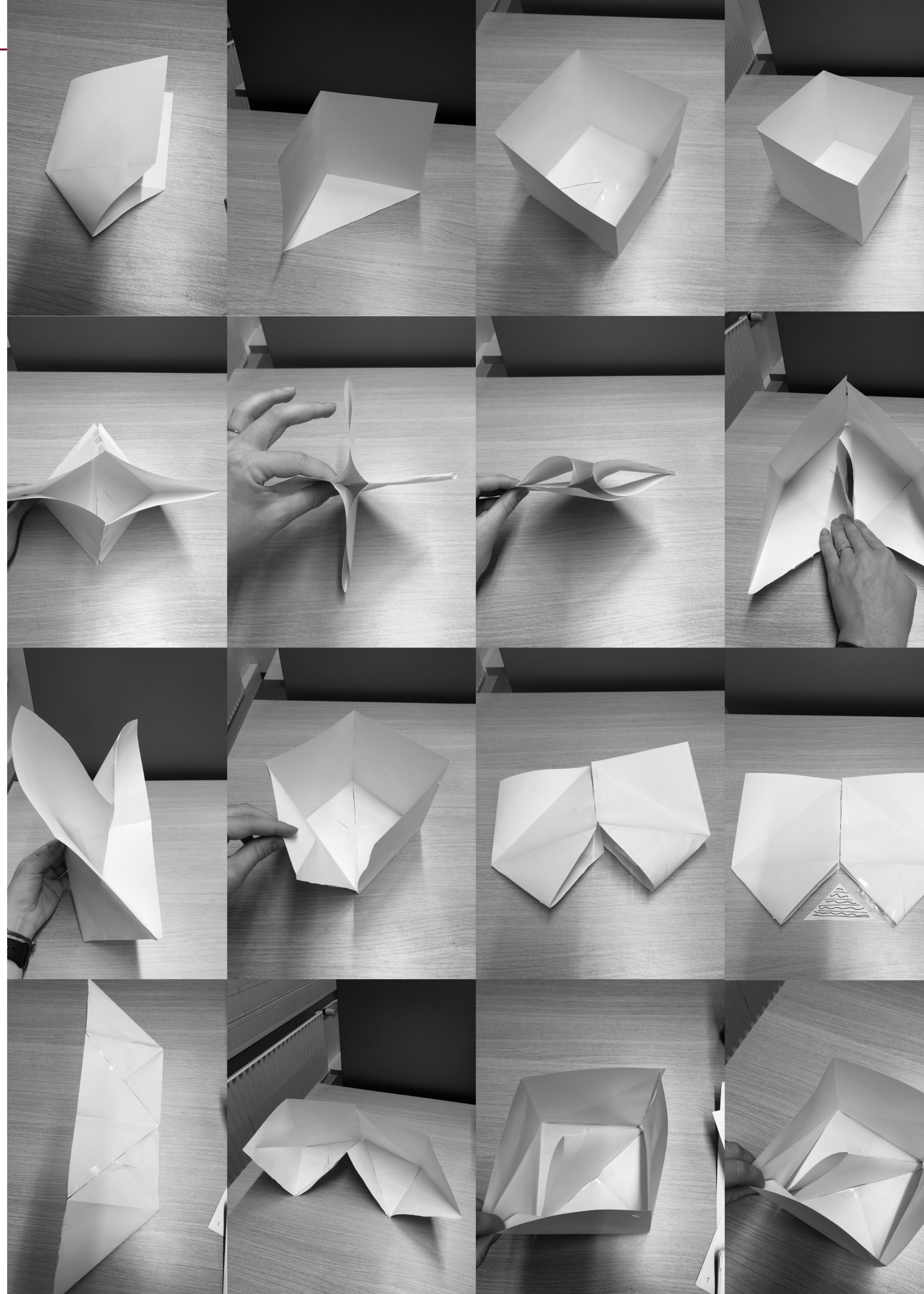


Figure 37: Form primitives

Designing of form-creation

Various methods for visualisation or prototyping support the discussed workflow for woven Textile-form. As previously explained, all experiments aim to create a three-dimensional form from a multi-layered flat surface. Using sketches and paper models is valuable for understanding how flat-layered textile constructions can evolve to form. The following section introduces one experiment to understand the form-creation process of the performed experiments (Appendix D).

Figure 38: Form-creation exploration with paper models



FORM

Experiment A - Change in scale & initial shape

Aim

Exploring a rectangular to a triangular expansion of form through the specific layer construction in the MoB that forms the ability of the three-dimensional form to expand in scale and shape.

Method

- Sketching the idea
- Sketching the map of bindings, including annotation of multi-layer bindings
- Create the paper model:
- Draw the MoB and cut all layers
- Attach the cut pieces with tape at the intended connecting layers
- Analyse the created paper model's shape on scale, shape, and expression before (2D), during and after (3D) the transformation

Key insights

This experiment demonstrates the ability of a sketched MoB to expand into a three-dimensional form and change shape by using flat multi-layered paper models. Analysis of the experiment outcome demonstrates the potential of this idea for woven Textile-forms, such as applications for creating sleeves, pockets, and aesthetical or shape-enhancing features.

Findings on form

Transferring the idea of a 3D form to an MoB requires some experimenting and often challenges on the visualisation part when exploring woven Textile-forms. Sketches and paper models utilise the visualisation and the possibility of testing an idea (Figure 39).

When more familiar with the process, iterations on a tested form potentially leave out some steps, though the development process explained in this chapter is the basis for all samples. The following chapter elaborates on Textile-form creation as a supporting tool for further developing woven Textile-form.

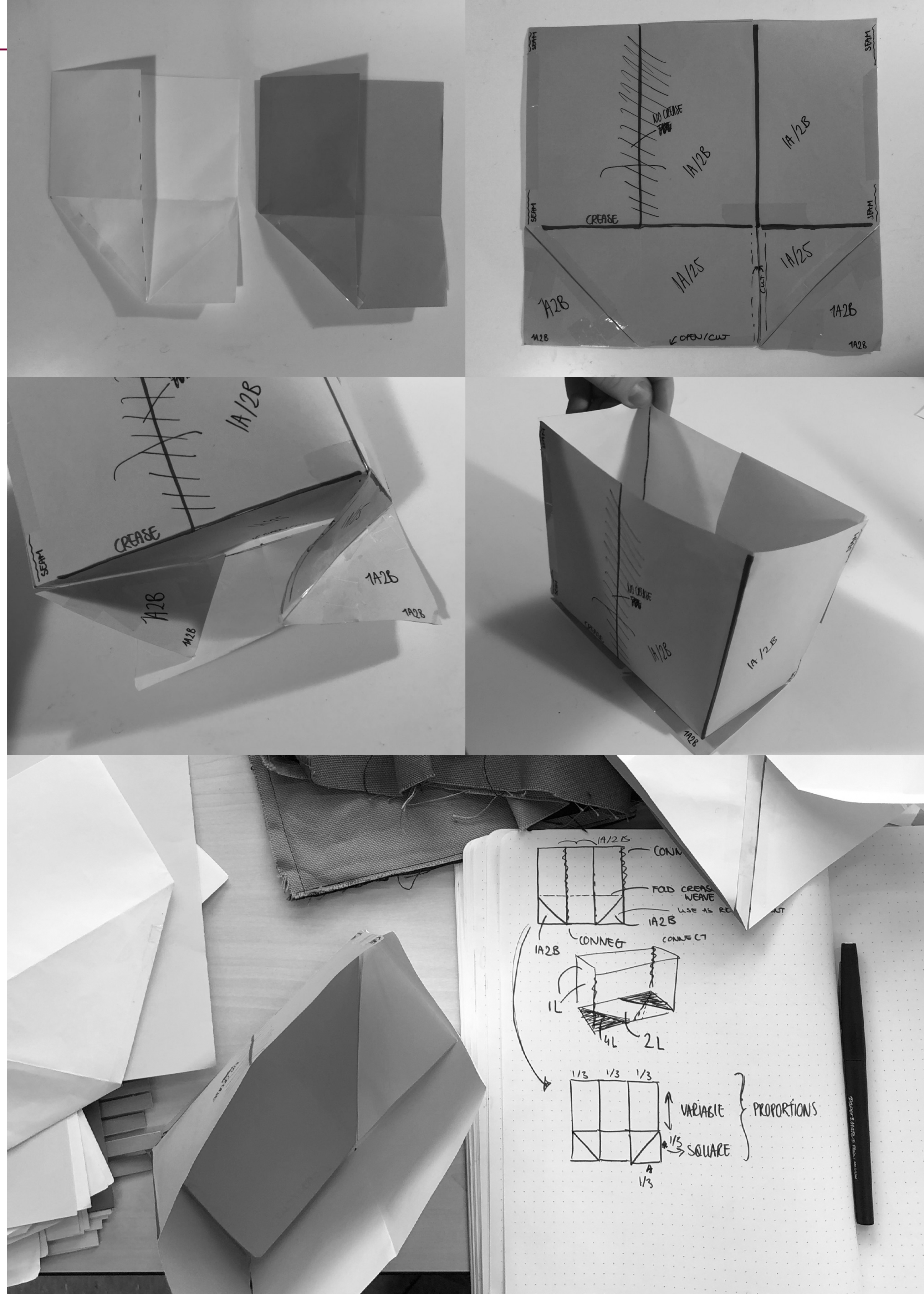


Figure 39: Exploring form-creation through sketches and paper imitating the multi-layered construction

FORM & TEXTILE

The previous chapter explored form-creation through paper models which this chapter builds further on by exploring form-creation with textiles imitating the layer construction to move towards understanding woven Textile-form development.

As explored in the previous chapter, the visualisation of form-creation in paper models facilitates the experimental development of woven Textile-forms. Translating the created paper models to textile form new design constraints due to the softness of textiles. (Figure 40)

The following section presents one of these experiments to demonstrate the exploration process of multi-layered Textile-forms.

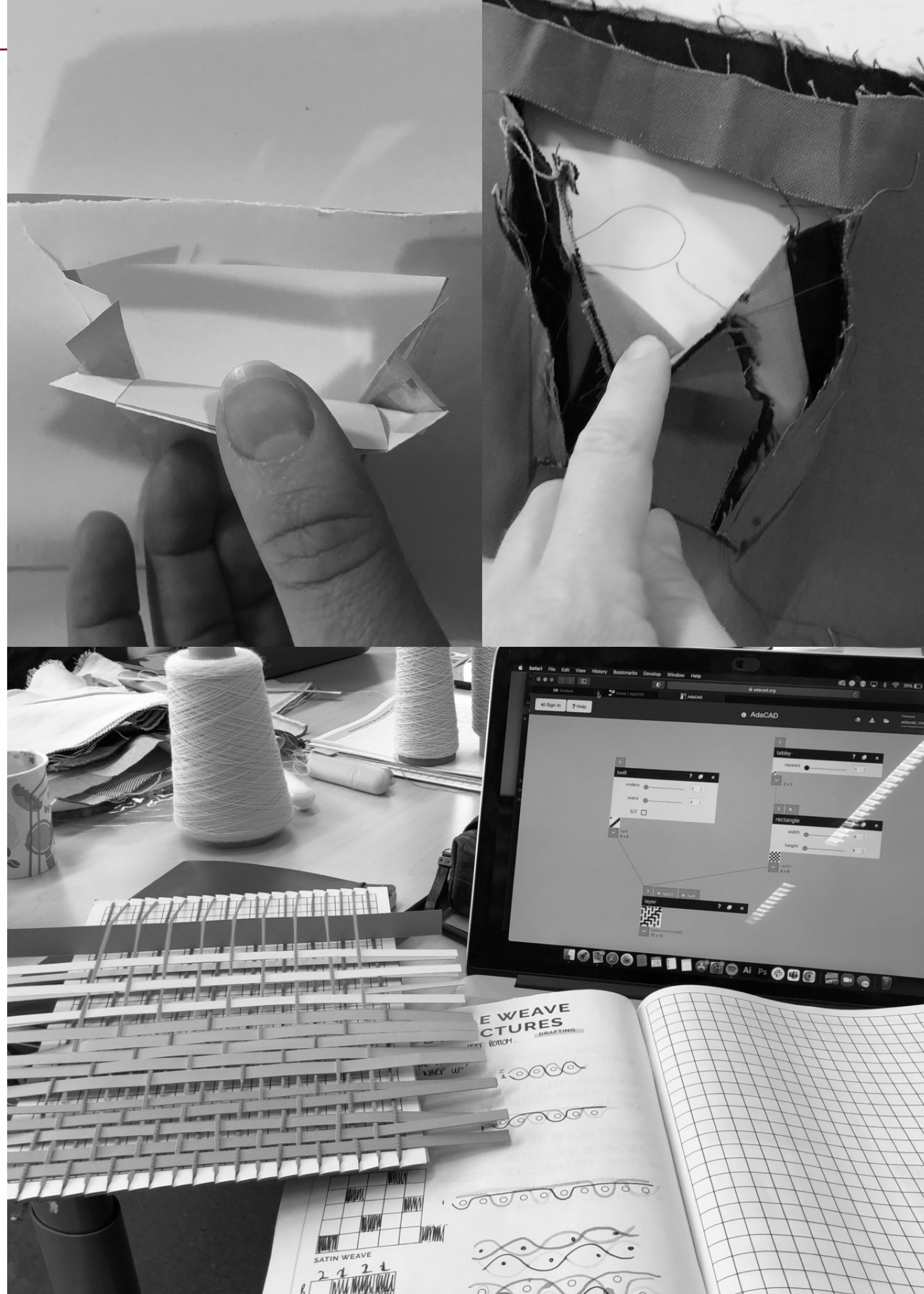


Figure 40: Exploring form-creation paper to textile

Experiment B - Paper to textile

Aim

To understand the influence of textiles on the developed form-structure and analyse the softness and firmness.

Method

Create the Textile-form model:

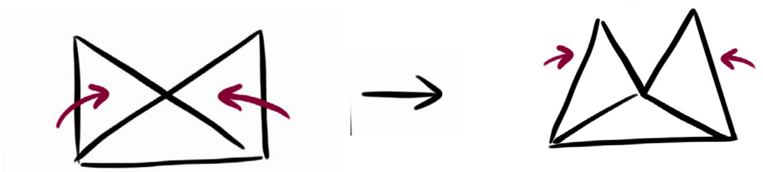
- Adjust the MoB if necessary for textiles, taking into account the seams
- Draw the MoB and cut all layers
- Attach the cut pieces by sewing at the intended connecting layers

- Analyse the textile model's shape on scale, shape, firmness, softness and expression before (2D), during and after (3D) the transformation

This experiment demonstrates the considerable influence of textiles on a three-dimensional form created through multi-layer textile construction. The defined sharp edges established in paper models do not similarly translate to textiles, identifying research potential for the creation of 'sharpness' in woven Textile-forms. The loss of firmness influences the expression of the shape and should be considered in Textile-form and woven Textile-form design.

The paper and textile models allow examination of the potential for woven Textile-form without needing a loom, stretching the opportunities for designers to explore such methods. The following section builds further on these models in woven Textile-form development.

The following experiments explore the integration of product features; hybrid design allows woven Textile-form to integrate the interaction with the ecological system by using a material system that varies in properties to enable multi-purposed performances.



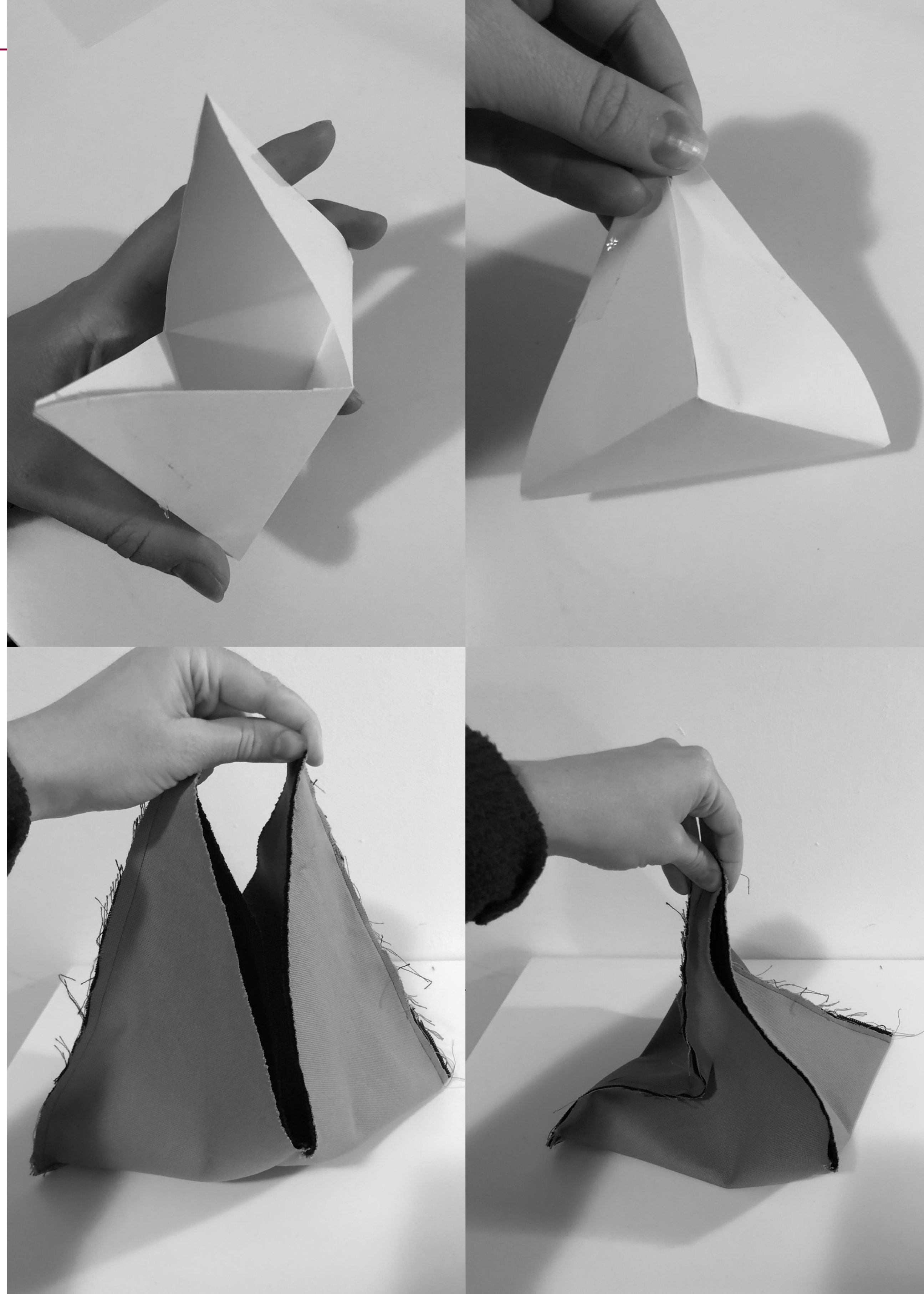


Figure 41: Intended change in shape
Figure 42: Difference paper and textile

Experiment C - Woven hybrid design

Aim

To explore hybrid design (Figure 43) in woven Textile-form to understand woven textile forms' technical potential, exploring shape and applications.

Method

- Create the MoB in illustrator, taking into account the loom's dimensions
- Assign colours to the different surfaces (Fig X)
- Create the weave card (NedGraphics)
- Program the bindings, consisting of layer and weave binding information (Fig X)
- Assign these bindings to the MoB colours (Fig X)
- The weave card consists of all information for the loom (Fig X)
- Weaving the sample on the loom.
- Analyse the woven model's shape on scale, shape, firmness, softness and expression before (2D), during and after (3D) the transformation

Key insights

The systemic approach in this experiment, combining multiple silos of textile production processes, defines the potential for woven Textile-form by on-demand, local, minimising waste productions. However, executing such feature integration methods requires specific exploration for the desired performances.

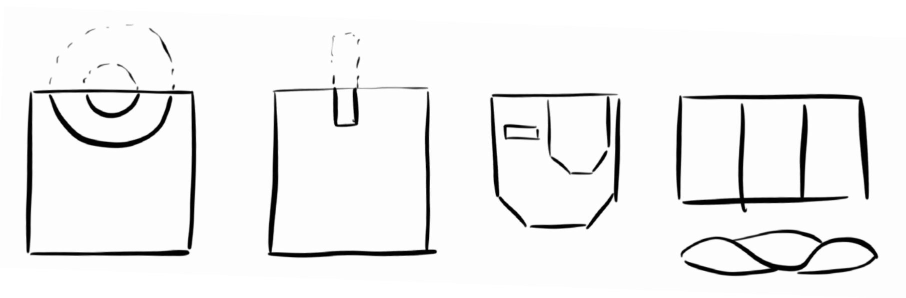


Figure 43: Hybrid design exploration in sketches
Figure 44 (opposite page): Woven exploration of a hybrid design, integrating performative features in the design using layered constructions.

Findings on designing for woven Textile-form

The experiments in previous sections demonstrate the complexity of the experimental approach in woven Textile-form development, formed by the transition from paper to textile to woven multi-layer form construction. This section discusses essential technological and environmental constraints in woven Textile-form development.

Loom properties

The width of the warp, for placement of the weave sample and possible repeat, is a vital design variable considering the aim of this research, zero waste production. Also, the direction (x/y) of placement could influence the extent and efficiency of the finishing process when cutting apart the samples of the woven cloth.
Digital models
Digital 3D modelling programs such as Clo3D are not designed to create woven Textile-forms. However, with some altering, these programs can imitate the layered constructions and visualise the interaction with the loom constraints, supporting the visualisation of transitions in woven Textile-form.

Experimental nature

The development process of woven Textile-form requires multiple cycles of experimentation to achieve specific outcomes. The experiments conducted in Appendix G demonstrate this experimental approach. As previously explained, it is essential to focus on opportunities rather than forcing materials into the desired shape by neglecting the material as a system. These methods require textile-based product designers to shift their design perspective and approach.

Findings on form

This chapter demonstrated the development of woven Textile-form, supported by the tools in the workflow, such as sketches, paper and Textile-form, to facilitate visualisation and understanding of transitions between the different design stages.

As discussed in the background, adding temporality as a design variable to woven Textile-form enables change through activation in the production and use phase using shape-changing materials. Additionally, using biodegradable, recyclable, mono-materials integrates a broader perspective on the ecosystem, with potential in a circular economy. The following chapter explores these additions, described as morphic and multimorphic Textile-form (McQuillan & Karana, 2022).

FORM & TEXTILE & FIBRE

In this chapter, another level of form creation is added to woven Textile-form, explained as the interaction between shape-changing materials and woven Textile-form enabling form-creation. Temporality in the Textile-form defines by having a before, during and after state, causing a change over time (McQuillan & Karana, 2022).

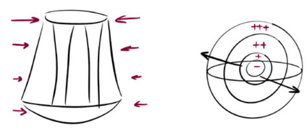
The experiments conducted in this context are morphic Textile-forms and potentially move towards multimorphic Textile-forms by exploring wool's potential as a mono-material system. However, due to the limited loom access, the samples consist of a woollen weft and polyester warp. Nevertheless, the inability of polyester to shrink in scale supports the understanding of wool's behaviour.

The density of a weave binding resulting from the layer count and the float length of the specific weave binding within the structural form causes the felting ability. Appendix C elaborates on a specification of the felting ability of woven wool yarn, which depends on various factors, such as micron, twist, treatment, and density.

Designing of woollen woven Textile-form

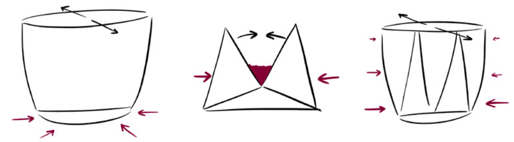
For the experiments in the research space, similar form primitives guide the form-creation process, the shape of a box, triangle and dome. The conducted experiments explore the interaction between woven Textile-form and shape-changing materials. Appendix G contains the complete exploration, which follows the principles and prototyping methods explained previously.
In the following section, a selection of experiments, explaining their aim, methods and key insights, demonstrates the potential performance of woollen woven Textile-forms categorised by changeability perspectives. It is important to note that some experiments explore methods from multiple categories and are grouped by the change occurring.

The experimental nature of this research allows for defining a range of specific bindings for the felting abilities to explore the shape-changing properties of wool. The range from non-felting to most-felting, annotated by -, +,++, and +++, explains the intended change in shape, supported with illustrations in the following experiments.



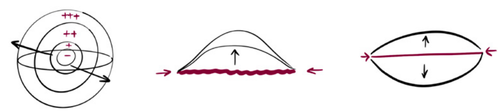
Changes in scale

Explores the ability of a Textile-form to shrink in size through felting.



Changes in form

Explores the ability of Textile-form to change its initial shape into another form primitive shape.



Changes in firmness

Explores the change in firmness caused by the felting process and the construction.

Changes in textures

Explores the change in texture caused by the felting process.

Experiment D - Changes in scale

This experiment (see Appendix F & G for the complete exploration) explores the ability of a woven Textile-form to shrink in scale through felting.

Aim

To explore the controllability in form-creation with woollen woven Textile-forms inspired by moulded Textile-form techniques.

Methods

- The experiment explores the following aspects of a four-layered construction::
- The ability to form shapes through layer construction (Figure 45).
- The ability to enhance form through the felting process by shrinking (binding variation of + to +++)(Figure 45).
- The ability to control the felting process through the use of a mould (Figure 46).
- The ability to maximise felting by lowering the density by increasing the layer count (four instead of 2)

In this experiment, the mould is placed inside the woven Textile-form and explores the felting process by activating the shape-changing properties through the friction caused by the washing machine.
The mould requires light, soft and flexible properties, preventing damage to the washing machine and enabling removal afterwards; see appendix F for an example of creating such a mould.
The sample can be closed after insertion of the mould to dispose of the chances of the mould moving out of the sample in the process.

Key insights

The flexible mould and the multimorphic Textile-form interact with each other, where the mould enforces the shape to form around the mould (Figure 47 & 48).
This experiment demonstrates the opportunity of this method to create specific shapes for a desired aesthetic. Integration of such methods can regulate the outcome, creating potential for consumer-products production. Designers could also explore this method for diversification by using irregular, intentionally smaller, or multiple moulds inside a morphic Textile-form, causing an increased friction irregularity.
This experiment demonstrates that using four-layered constructions, even though only two layers are necessary to create this shape structurally, causes an increased shape forming through shrinking.

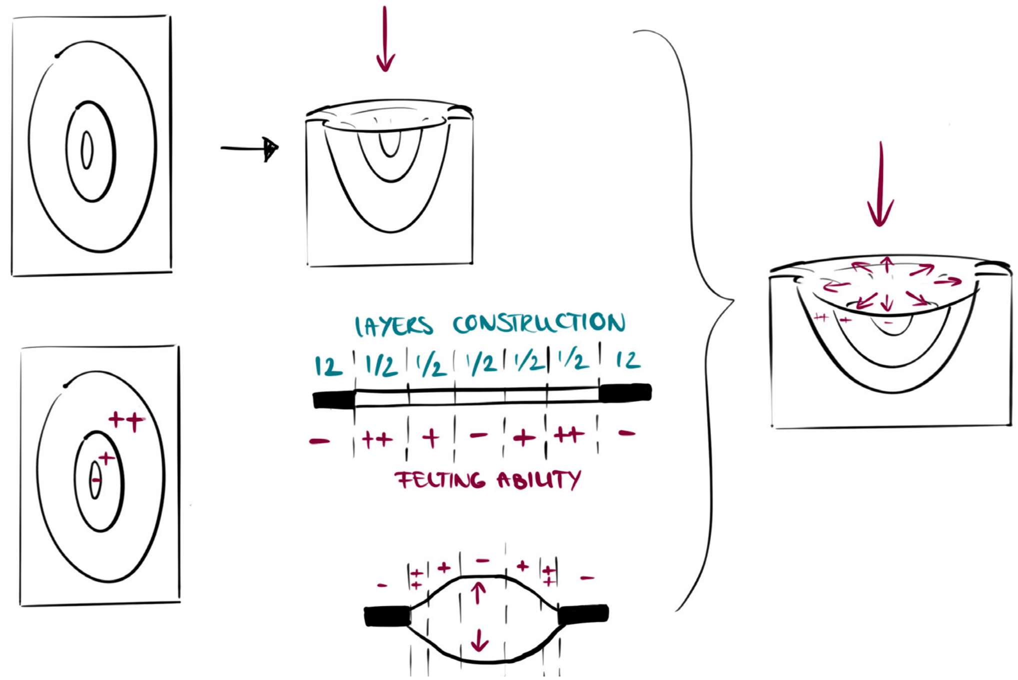


Figure 45: Illustration of intended shape-forming through moulded felting
Figure 46 (left): Flexible 3D printed mould
Figure 47 (right): Sample after felting, shrunk to size of the mould
Figure 48 (next pages): Samples after felting with mould, demonstrating the created firmness


Experiment E - Changes in form

This experiment (see Appendix F & G for the complete exploration) explores the ability of a woollen woven Textile-form to change its initial shape into another defined form primitive shape through the shrinking effect of felting.

Aim

To explore how the use of floats causes a flat shape to transform into a triangular three-dimensional shape. In these experiments, some woollen weft yarns do not interlace with the warp yarns over the width of a particle of the surface (Figure 49).

Method

This experiment explores the following methods in a three-layered construction:

- Longer floats to explore the extremity of felting (maximised +)(Figure 50).
- Shrinking of parts to enhance the shape forming for imitating folding or corners (++) (Figure 51).

This construction allows exploring the extremity of the felting ability of wool when the warp does not interfere with the felting process. The shrinking of these floats over the width of the top layer with connections to the middle and bottom layers, pulling the shape into triangular tubular shapes. Adding some felting ability on the parts that have to imitate folding enhances the shape forming.

Key insights

These experiments explore long floats without interlacement as in bindings and show similar effects (Figures 50 & 51). Experimenting with this technique could pull a shape in the right direction to guide the finishing process or enhance the shape. By turning the Textile-forms inside-out, an increased shape enhancement can be established. Next to a structural implementation, these methods could be used for aesthetic reasons or create forms for external attachment. The addition of felting parts on both sides of the samples demonstrates form enhancement capabilities.

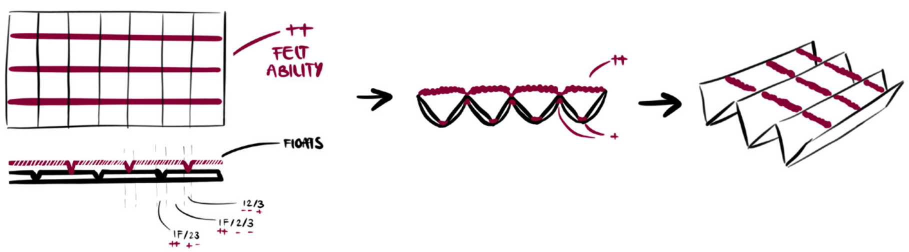
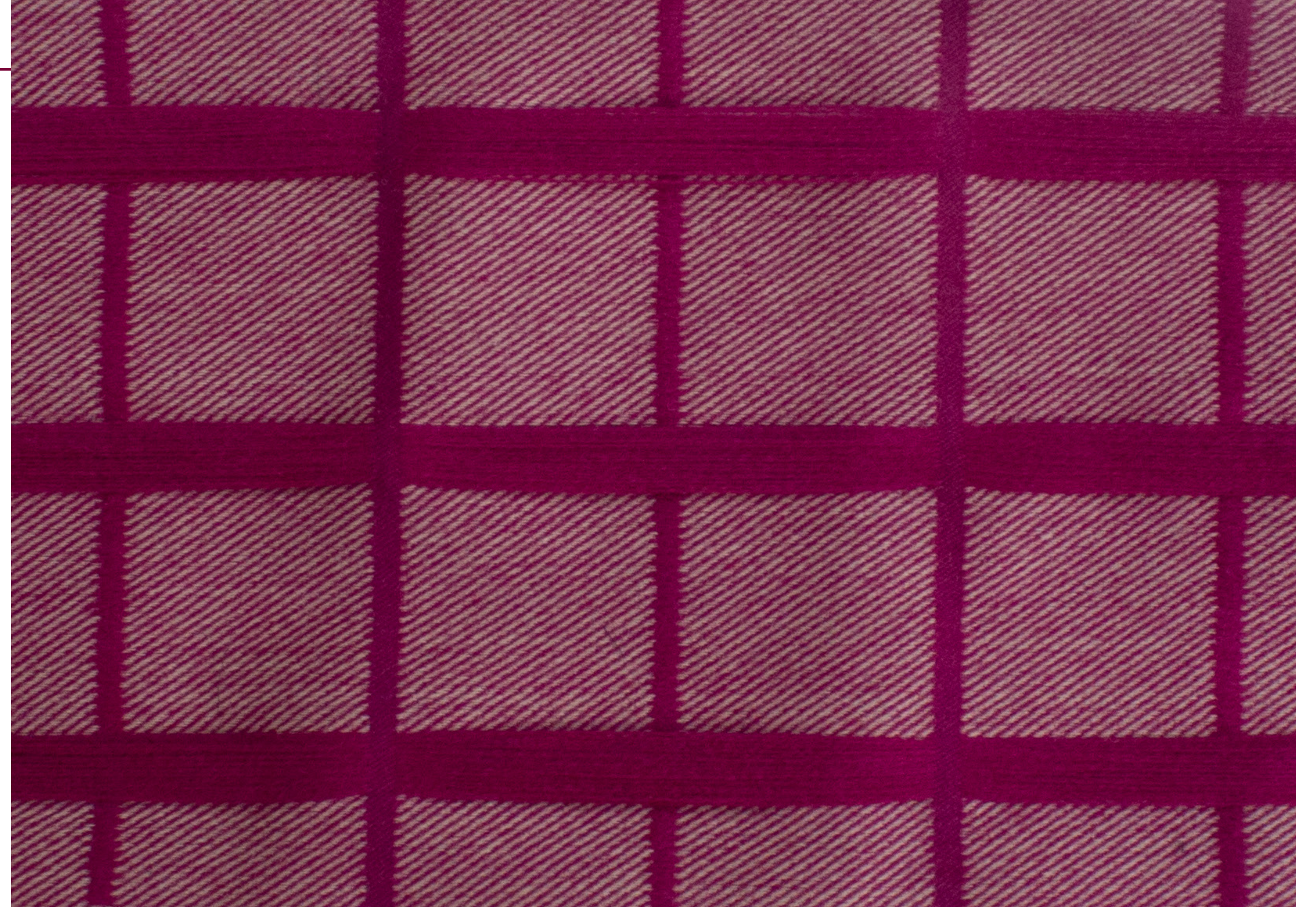


Figure 49: Illustration of intented shape forming
Figure 50 (opposite page, top): Picture of sample before felting
Figure 51(opposite page, bottom): Picture of sample after felting
Figure 52 (next page): Sample after felting



Experiment F - Changes in firmness

This experiment (see Appendix F & G for the complete exploration) explores the change in firmness caused by the felting process, causing the wool fibre to increase in thickness and fibrousness.

Aim

To explore the increase in thickness and firmness caused by the fibrous change in texture during the felting process. Also, exploring spacer fabrics (Qin, 2016) by felting the outside layers creates space formed by the middle layer.

Method

This experiment explores the following properties in a three-layered construction:

- Expansion in thickness of the outside layers through high felting ability (+++) (Figure 53,54,55,56 & 57).
- The shape forming caused by the difference in felting ability (- and +++)

The outside layers shrink in scale over the weft direction, while the inside layer does not shrink, creating space between the outside layers caused by the attachments to the inside layer.

Key insights

This experiment explored the change in firmness by maximising the difference between the felting ability of particles, demonstrating the significant change in thickness, shape and rigid feeling. The construction creates the idea of a filled shape or part, giving the sample the imitation of embodiment by the increased rigidness.
Further exploration of spacer methods potentially increases the maximum layer count without form firmness loss, resulting in more design freedom to create a structural shape. Adding a stiffer yarn, such as linen or paper, can increase the rigidness of the middle layer, though the recyclability when creating a compound product should be considered.

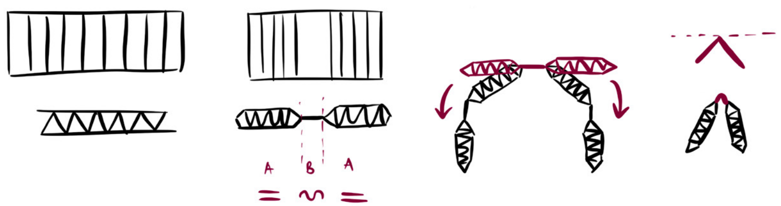


Figure 53: Illustration of intended shape forming and future application to create sharp corners in Textile-form
Figure 54 (opposite page, top): Sample creates firmness by including the lining in the design and pushing it inside the sample.
Figure 55 (opposite page, middle): Creating firmness by high felting ability which creates a thick fibrous texture
Figure 56 (opposite page, bottom): Pattern felted on the connection points of the two layers creating a firmer structure
Figure 57 (next page): Illustrated spacer as samples after felting, outside layers shrink and middle layer moves outwards creating space between the layers

Experiment G - Changes in textures

These experiments (see Appendix F & G for the complete exploration) explore two samples with a change in texture caused by the felting process in the washing machine. It is important to note that all samples undergoing a felting process changed in textural expression, and this experiment discusses the significant changes.
The exploration consists of intended change results and unexpected results, demonstrating the unpredictability of experimenting with woven Textile-form in combination with wool because of the unknown context in this research.

Aim

To explore the changeability in textural expression caused by the wool felting process and the sample's structure. It explores textural expression for aesthetical or application opportunities.

Method

This experiment explores the following aspects in two, three and four-layered constructions:

- The variation of the felting ability of sections in the shape
- The interactions between these sections
- The changeability of textures and expressions.

Key insights

The variations of textures result in a broad range of extremeness caused by the methods used (Figure 58 & 59. Combining binding, structure, felting ability and felting process define the textural expression of the materials. Such methods can explore the textural expression and aesthetics of compound textures (made of multiple materials) to be made of mono-materials potentially.
The amount of friction applied to the samples influences the textural expression, as discussed by van der Vegt (1955), demonstrated by the significant difference between felting in or without a washing bag. This insight demonstrates the substantial design variable of applied friction. These experiments also show the influence of the whole structure on the felting ability of a part in the structure.

Figure 58: Illustration explaining how textures are created through felting
Figure 59 (opposite page): Images of different textures caused by the felting process

On designing for woollen woven Textile-form

The experiments, using woollen woven Textile-form, seek to find the limitations and opportunities of these methods while aiming to find patterns in the shape-changing properties of wool, defining design variables that support designers in such methods' applications. The temporality allows shape change in woollen woven Textile-form next to the layer construction and weave bindings. This approach establishes a functional product made of one material, including structural and behavioural performances, creating a multi-purpose material system.

Predictability

This research explored multiple shapes, textures, combinations and material expressions, which demonstrates the complexity of predicting what happens during the felting process. As mentioned before, the simulation of digital models in Clo3D supports the visualisation process suggesting the intended shape change by changing the shrink percentage of the yarns in weft and warp direction. However, such programs do not apply the change happening in the fibres' position in the yarns and structure during the felting process.
Designers can manually adjust these properties to some extent. However, they cannot predict the exact change in shape because of the many factors influencing the felting process. This demonstrates that some level of inventiveness is necessary to visualise the contribution of change over time in form creation.

Felting ability

Thus far, the research found that wool's felting ability correlates to the binding density caused by the type of binding, float length and layer count. However, this research did not establish specific design tolerances due to the uncontrollability of external stimuli—the spin cycle, fluid dynamics, and the interfering samples in the washing machine influence the ability of the samples to undergo identical friction. Therefore predicting that several identical samples undergoing the same felting process result in distinct shapes and textures.

Conclusion

These experiments explored the development of morphic Textile-form, adding temporality as a design variable to woven Textile-form enables change through activation in the production and use phase using shape-changing materials. It explored various methods to seek change in structure, texture, aesthetics and expression, creating new material experiences.
Additionally, suggestions for using biodegradable, recyclable, mono-materials to integrate a broader perspective on the ecosystem are made to move these methods towards multimorphic Textile-form (McQuillan & Karana, 2022).

FINDINGS

WOOLLEN WOVEN TEXTILE-FORM

This chapter elaborates on the findings discussed in the previous chapters and includes the complete research, see Appendix F. The experiments in this research shown on the next page only address a small part of the full potential of this method, creating opportunities for further creative exploration for designers.

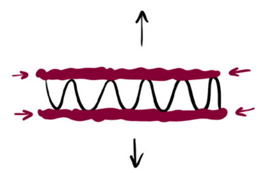
Primarily, this research found that the construction of the overall shape substantially influences the felting ability of a particle in this construction. F.e., the rigidness or non-felting construction withholds a particle in this construction in a felting process. Therefore, suggesting the addition of the surrounding material to the discussed scheme by van der Vegt (1955) (Figure 64) in the context of 3D weaving. These findings demonstrate the complexity of felting as the shape-changing conductor in (multi)morphic Textile-forms.

Next, this research demonstrates that experimenting is required to understand form-creation in woven Textile-form through multi-layer constructions supported by tools such as paper, textile and digital models. In morphic Textile-form, understanding the emergent material inducing the change in shape is necessary.
The temporality in morphic Textile-form gives the form a before, during, and after state induced by shape-changing materials. This means the input shape can be very different from the output shape enhanced by the designers' creative approaches, such as integrating other materials, spinning yarns for elasticity, varying the felting ability or using moulds. The latter could increase the controllability of the felting process or be used to increase the irregularity. Qualitative reserach is neccesary to understand the felting process, designers can perform a series of identical samples to form design tolerances for industrial purposes.

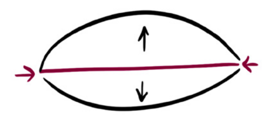
Moreover, mono-materials can move morphic Textile-form integration towards multimorphic Textile-form. However, using a material made of natural fibres that designed itself to perform efficiently in their specific environment results in microscopic differences in the fibres, which can influence the yarn properties, resulting in slight differences over the length of the yarn in turn influences the final form. Designers should question the needed range of design tolerances to facilitate optimisation for sustainability.

Finally, the methods in this research demonstrate similar aesthetic expressions showing their materiality, origin and material system and creating diverse material experiences. Compared to the aesthetics of the conventional textile industry, these observations question the appropriate perception of the aesthetics of textiles. How important is uniformity? What does materiality suggest for consumers? Does the way consumers approach a product depend on the purpose of the product? Should we regulate the process of producing multi-morphic Textile-forms?

The following chapter explores these assumptions, focusing on the material experiences of these samples compared to the conventional textile industry outcomes.



Scale
Shape
Firmness
Texture



Scale
Shape
Firmness
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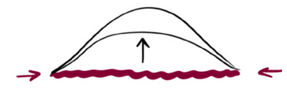
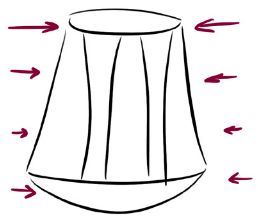
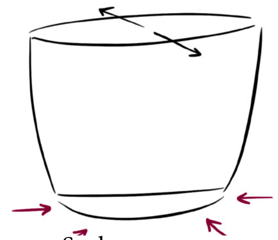


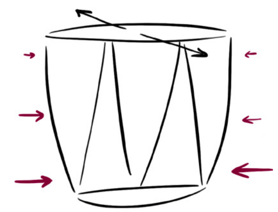
Scale
Shape
Firmness
Texture



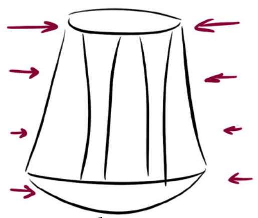
Scale
Shape
Firmness
Texture



Scale
Shape
Firmness



Scale
Shape
Firmness
Texture



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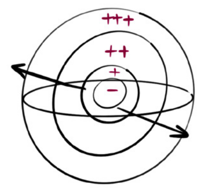
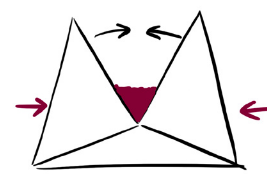
Firmness



Scale
Shape
Firmness



Scale
Shape

MATERIAL EXPERIENCE

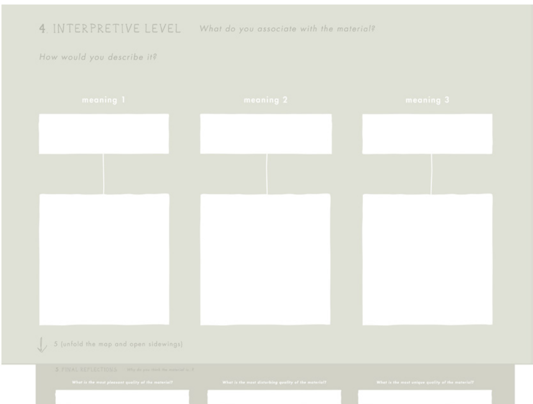
MATERIAL EXPERIENCE

This chapter explores the assumptions made on the material experiences (Karana et al., 2013) of this research's samples. As a result, it questions the appropriate perception of the conventional industry on textile aesthetics.

All the samples have similar aesthetic expressions caused by the material system, including the processes resulting in the technological aspect of the aesthetic, described as techno-aesthetics. Noticing that all samples have different material experiences because they exist in different material systems, allowing various applications.
Therefore, this research explores how people perceive such new material experiences to understand what these materials evoke to enable implementation in a proper context, where function follows material. It assumes that explicitly using material traces to explain the materiality of a product demands consumers to embrace a new aesthetic which follows from a sustainable perspective on design.

Experiential Characterisation

The toolkit 'Experiential Characterisation' by Camere & Karana (2018) explores such material experiences. The 'interpretive' level addresses the meaning materials evoke, which this user study explored (see Appendix H)



The user study (Figure 60) examines a selection of four materials (Figure 61) to understand the overall interpretation of these materials. As a result, the analysis defines an understanding of the aesthetics of the samples.

Figure 60: Interpretive level of Experiential Characterisation and reflective questions
Figure 61 (opposite page): Samples in user study, top to bottom: number 1, 2, 3 & 4

Conclusion

The conducted user study in Appendix X explored the material experiences of these samples to understand what they evoke. The next section will elaborate on these studies. The analysis of these user studies formed the following understandings and conclusions.

Primarily, the alive-like experience formed by the organic shape creates associations with natural living organism environments, which Karana et al. (2020) describes as material quality; livingness. Most participants chose 'natural' while explaining organic would be more descriptive, to include the livingness and speculative expression. Participant supported this with words, such as imperfections, roughness, irregularity and origin traces. Traces of origin are explained as material traces (Robbins et al., 2015; Rosner et al., 2013; Robbins & Karana, 2016, 2014), describing the interaction and communication of materials by material qualities such as imperfections and ageing.

Next, two participants describe the experience of one sample as stubborn. They addressed this explanation as 'aggressive', which seems too extreme and forcing when they would describe it as determination caused by the rigid structures.

Furthermore, the participants explained the experience of two materials as playful and speculative, which needs to be captured in the vocabulary. The participants used words such as 'toylike' and 'strange' to describe these meanings, though these do not capture the newness, surprising and speculative meanings. Therefore, one participant suggested funky describing such experiences.

Finally, in the reflection, the participants explored more samples of this research and compared them to the analysed samples in the study. They all mentioned a strong coherence throughout the pieces, defined by the colours, textures, shapes and structures establishing the organic expressions. The samples are unlike what they have seen before, characterised by the material's ability to communicate its origin, unlike conventional textile materials. The participants mentioned imperfections, organic, textured, speculative and unfamiliar, which interprets as the authenticity and newness of the samples' aesthetic.

Altogether, these observations define the understanding that these materials differ from those in the conventional textile industry.

Figure 62 (opposite page): Participants exploring the sensorial level with the samples

DISCUSSION

DISCUSSION

This research aimed to unfold the new techno-aesthetics emerging from material expressions through woollen woven textile-form exploration in a circular economy.

Throughout this research, including various morphic textile-form explorations with wool as a shape-change conductor, new aesthetical expressions are recognised, which differ from the typical textile-based products aesthetics. The techno-aesthetics question the origin and nature of aesthetical values concerning technology, demonstrating the necessary value change of perception and expectations of the typical textiles and textile-based products and potentially beyond when a sustainable design outcome is a goal. These observations suggest embracing material traces to move towards 'circular techno–aesthetics' to induce a circular economy.

The analysis of the experiments and the user study identifies several findings explained in the previous chapters, covering the methodology of this research, the technological aspect of woven textile-form, the inherent properties of wool and material experience. The following section elaborates on these findings supported by evaluating how these findings relate and contribute to previous studies, literature in the textile industry and material-driven approaches, as covered in the background and related work section of this thesis.

Change with Woollen Woven Textile-form

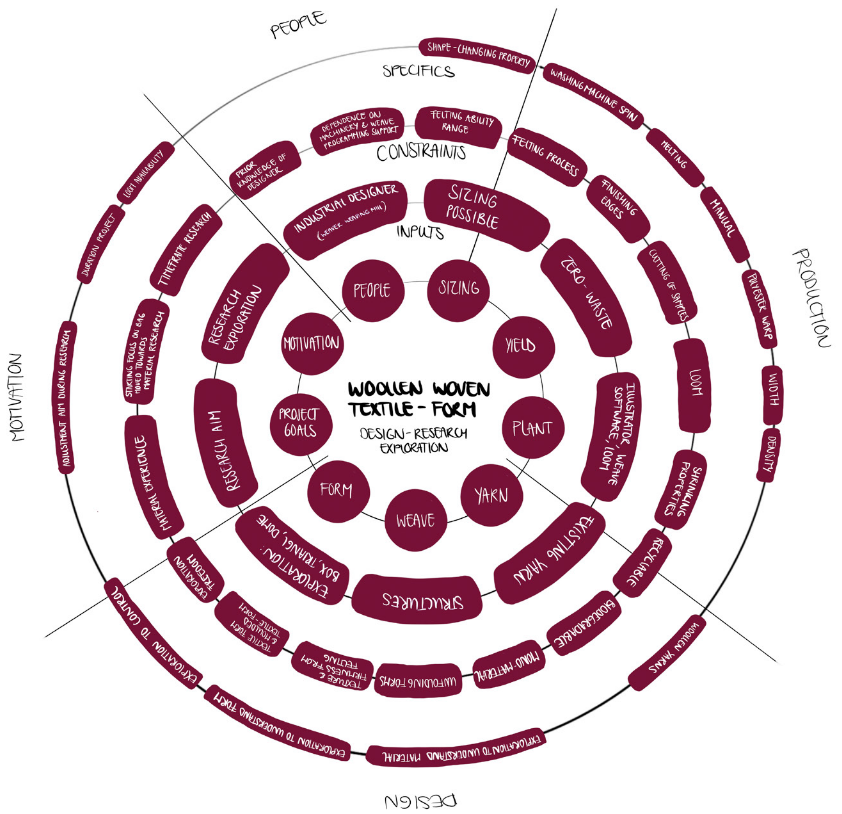
Throughout this research, form-creation evolved from flat paper form constructions to an exploration of woollen woven Textile-form, aiming to understand the interaction between the material and Textile-form creation.

The transition towards a circular economy and moving away from siloed improvement for sustainability requires a global change in the textile industry. Integrating perspectives such as 'Fibreshed' (Burgess, 2019), a movement of local (textile) economies, addressing the disconnection between consumers' knowledge and the environmental impact of their textile products through on-demand and zero-waste practices. Woven Textile-form contributes to these sustainable improvements, simultaneously integrating textile- and form-production and finishing processes, making consumer-ready products on singular machinery. Additionally, can shape-changing behaviour of the material in textile-form diversifies the applications and bring about the ability for consumers to adjust and personalise.

The key motivation in this research is the industry's action to suppress the inherent properties of wool fibres with felt-resistant treatments to accommodate the conventional expectations and processes of textile objects. This observation allowed this research to go beyond aiming to improve and move towards changing (woollen) textile objects. An understanding of the shape-change process was established by seeking control over the felting process. Using wool in Woven Textile-form, a biodegradable and recyclable mono-material pursues the move towards multimorphic Textile-form (McQuillan & Karana, 2022). Addressing form-creation as a mono-material system explores emergent multi-purposed Textile-forms, increasing the potential for sustainable outcomes created through its form, structures, textures and context of use. This also demonstrates the high dependence on the whole system, identified as material system, including production and finishing methods, making it impossible to state a material as being sustainable. Therefore using 'sustainable materials' likely influences consumers' buying behaviour, described as greenwashing (Delmas & Burbano, 2011).

In this material system, several factors influence the shape-changing behaviour of wool fibres, as the overview by van der Vegt (1955) demonstrates, categorised as external stimuli and material properties. Additionally, this research identified the significant influence of the construction of the overall shape on the felting ability of a particle in this construction in 3D weaving practices and constructed a modified overview for woollen woven Textile-form (Figure 64).

The woollen Woven Textile-form methods and other shape-change explorations are inspirations for acknowledging the inherent properties and complexity of wool fibres to open space for further explorations on the potential of wool fibres for sustainable design outcomes.



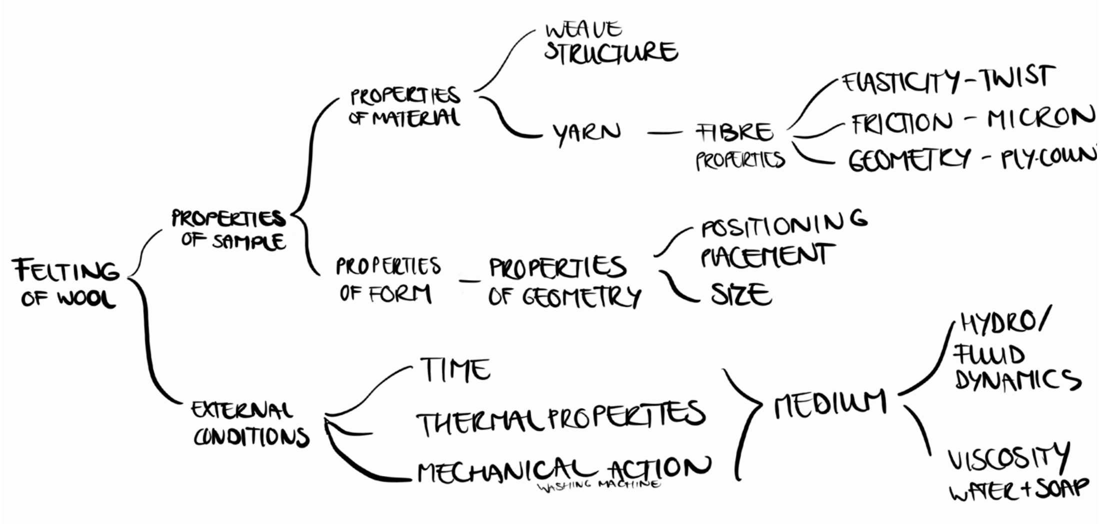


Figure 63 (top): Woollen Woven Textile-Form in Zero Waste System Thinking (McQuillan, 2020)
Figure 64 (bottom): Addition of Form in Van Der Vegt's (1955) Wool Felting overview

On design knowledge and methodology

Material-driven approaches explore the unique properties of known and developing materials to discover unforeseen potential performances in which material guides the structure and, in turn, the form and function (Oxman, 2010). These approaches are often connected to sustainable design (Bak-Anderson, 2018), which Material Driven Design addresses as the positive improvements a material can make (Karana et al., 2015). These practices seek to address the missing entanglement with design sustainability, in which the interaction of a material with its surrounding factors, a material system, is crucial. This holistic approach requires multimorphic thinking (McQuillan, 2020) or system thinking (Meadows, 2009) and for the designer to find tools to deal with the abstraction of simultaneously designing (Piper & Townsend, 2015; McQuillan, 2020) multiple things in this system; which this research attempted by mapping progress and keeping track of uncovered research using the Zero Waste System Thinking overview (Figure 63).

The reflections directed the design-research process, as a reflective practitioner (Schön, 1983), on material behaviour, form construction, application potential and the impact on the ecosystem. Decisive constraint (Biskjaer & Halskov, 2014) guided this process regarding these developments and their interaction with their environment. The experimental process resulted in unexpected diversity the author did not aim for, imposed by the limitation of prior knowledge. The experiments' unexpected outcomes created opportunities or provided decisive information through their failed intended form-creations. Finding out why something did not happen contains valuable information to gain control over the shape-change process.

The methods for woollen Woven Textile-form can potentially be a starting point for designers applying this knowledge to initiate moving towards multimorphic Textile-form (McQuillan & Karana, 2022). Starting the design process with material science-related research to create an understanding of the materials' behaviour opens the research and development of alternative ways to address form-creation in textile production.

Designing textiles and textile objects using MDD raise some complications in the methodology, as the fibre, yarn and textile cloth in textile production are accompanied by specific processes to exist as materials. This emerged from the perception that textiles are materials, only becoming form in Cut & Assembly processes, while the textile itself is a product. When using MDD for textiles, designers may consider the 'material tinkering' limitation when considering textiles as material or widening the framework beyond textiles by addressing the fibre as material, and the complexity of Textile-form creation, working on textile-based material and form simultaneously.

Experiencing materials

The conducted user study explored, using Experiential Characterisation (Camere & Karana, 2018), the interpretations of the created material experiences. This study explored the material experiences of the samples on the assumed coherent aesthetic expressions by aiming to understand how humans interpret them, defining design variables for further development of adequate applications.

The results describe different emotional, sensorial and interpretive experiences through the materials expressing unique, natural and organic qualities. The participants described these qualities as alive-like experiences, described as material livingness by Karana et al. (2020). "Creating alive-like expressions emulating structures and behaviours of living organisms. Livingness can be prolonged to the use time of artefacts so that the design outcomes go beyond being a mere sustainable material alternative or a unique material expression." Unlike this research, mainly integrating electronic components and actuators, such as Shylight by Studio Drift, achieved such experiences. This suggests the textileness and tactile qualities (texture, shape and structure) of Textile-forms can suggest alive-like expressions creating sustainable design outcomes.

The analysis of the user study identified limitations on the proposed interpretive vocabulary, suggesting further research to widen the vocabulary to include similar material experiences as the ones established in this research. Effectively, this focus could move towards the inclusion of the whole spectrum regarding biomimetic experiences, identified by the difference between natural and organic experiences, including livingness as material quality (Karana et al., 2020).

In woollen woven Textile-form as well as morphic Textile-form (McQuillan & Karana, 2022), the temporality forms besides other material qualities, the material experience via entangled material traces, demonstrating the method, production and using processes. An inversion of the conventional design process towards one with form and function following material formed this materiality. The conducted user study identified the unfamiliarity and newness of the studied material aesthetic.

New Aesthetics

The user study identified a coherent aesthetic which differs from typical textile objects induced by the production method, defined by the use of the machinery and a technology perspective on design. The methods applied in this research demonstrate that the way design is approached on the same machinery influences the aesthetical features of the outcome, resulting in a new materiality.

Typical textile form production starts the design process with the function and purpose of the outcome; it may force a material to behave in a specific set of boundaries together with the aesthetic coming from the technological, automation and quality control processes and causing almost total elimination of errors and imperfections in consumer products.

The growing ambition of optimisation for speed over the years has led to the desire for uniformity in textile production, forming the current aesthetic as well as its consumers' perceptions and expectations. The uncontrollability of wool fibres as shape-change conductors is addressed in this thesis, questioning the importance of uniformity. This naturally identifies the distinct aesthetics of woollen woven-textile form.
Moving away from optimisation for speed to optimisation for sustainability (Goldsworthy et al., 2018) requires some deep fundamental questioning of our manufacturing and aesthetic practices.

The specific material traces forming the aesthetic identify the different design approaches leading towards 'circular' aesthetic expressions. The aesthetics following from such methods can be expressed as techno-aesthetics (Dalmasso, 2019), describing the relationship between aesthetical dimensions and technical performance by questioning the origin of aesthetic values and experiences concerning technology and its position in the broader ecological system. Therefore the term techno-aesthetics is introduced to describe this research' concluding coherent aesthetic expression.

Understanding imperfections as material traces and how people interpret these expressions may support embracing this new design aesthetic (Rognoli &Karana, 2014). As well as, Troy Nachtigall suggests addressing 'materiality as a tool to delineate how an object is designed and to communicate this, the object needs an aesthetic that represents the material process and materiality. In a framework of materiality, designers should learn how to use data as material in order to understand or to come to a material understanding' (personal communication, October 25, 2022)(Appendix I). Salvia et al. (2010) and Zafarmand et al. (2003) argue that we have to reassess the aesthetics of conventional production techniques and change our value perception of 'imperfection' when looking with a sustainable future-focused lens. The Japanese philosophy of Wabi-Sabi emphasises authenticity and reality by acknowledging;

"nothing lasts, nothing is finished, and nothing is perfect" (Tsaknaki & Fernaeus, 2016), which is seen as full embracement and valuing imperfections in design

These perspectives interpret these imperfections of the created materials as essential in the material system, suggesting that when an object communicates its origin and performance and gives meaning to humans, it may support embracing a new design aesthetic.

All together, this should make us seriously question the appropriate perception and expectations of typical textiles and textile-based products and potentially beyond when a sustainable design outcome is a goal. Embracing 'circular techno-aesthetics' through the materiality of woollen woven Textile-form may bring about the needed global fundamental change of the value and move towards a circular economy.

LIMITATIONS

This research covers a broad exploration of woven textile-form with wool as shape-changing material through a holistic circular by design approach. Other biodegradable materials with shape-changing materials where not explored throughout the experiments while these could be valuable in circular design approaches addressing woven textile-forms.

The MDD approach was only addressed further in the context exploration the research did not start with MDD from the beginning due to change of the research direction, therefore an in-depth execution of these methods has not been performed. Therefore. the material experience context-research and user study was undertaken far near the end of this research.

Methods outside of woven textile-forms are not explored and the experiments are only explored in the context textiles with most focus on fashion and material expressions while further exploration on other textile-based forms would be valuable.

The availability of looms with specific warps caused these samples consist of a combination of a woollen weft with a fine polyester warp. In future implementations of these methods with wool as shape-change conductor, the selection of a material for the warp can improve the environmental responsiblity.

The nature of this research is experimental, therefore industrial implementation of the explored methods is not possible without further experimentation. F.e. in this research a conventional washing machine is used for felting therefore the outcome will differ from industrialised washing set ups.

This research is marked by the researcher's limited prior knowledge in the textile field. Therefore the first 30% of this research were primarily focused on getting familiar with textiles and, in turn, woven textile-form. As well as, the set timeframe of this research.

The enthousiasm of exploring a lot of samples created a broad knowledge on the felting of wool in various woven textile-form constructions. For which the research is limited on in-depth knowledge of specific changing methods of wool. This was stated by the aim for controllability, which was only explored in a range of felting abilities. Nevertheless, the external stimuli and structure have significant influence on the felting ability which in further research may unfold in controllability through design variables for woollen woven textile-form.

The created shape change methods are limited by wools' properties. As wool induces shape-change through felting this requires an intense uncontrollable process. In such projects using heat reactive yarns provides more control and therefore more understanding can be created. As wel as, the provided wool in the weaving mill was appropriate for industrial looms. Using a variety of wool yarns on a digital hand loom creates more design freedom, f.e. raw, thicker or fibrous yarns potentially result in a wider variety of shape-changing experiences.

This research, al together, is focused on a future perspective for the aesthetics formed by novel developments regarding sustainability. Integration in an industrialised context has not been explored, nor possible right now.

CONCLUSION

CONCLUSION

This research aimed to unfold the new techno-aesthetics emerging from material expressions through woollen woven Textile-form exploration in a circular economy. This thesis consists of technological, experiential and aesthetical research of woollen woven- Textile-form in which the shape-changing properties of wool fibres make them morphic Textile-forms. The potential for a circular economy, using biodegradable, recyclable, mono-material widens the scope towards multimorphic Textile-form. The binding density, yarn, and external stimuli, as well as indicated in this research, the structure of the Textile-form, influence the felting ability of wool.

The experimental nature of this research requires the intuitiveness and visualisation skills of the designer to achieve control over the complexity of these methods. Using material-driven design (Karana et al., 2015) and research-through-design (Stappers, 2017) approach addresses the needed holistic perspective for a circular economy.
The outcomes of the experiments demonstrate a coherent aesthetical expression confirmed through the material experience user study, which differs from the conventional industry's textile aesthetics.

Evaluation of the aesthetical expressions through material experience studies questions the appropriate perception of the aesthetics of typical textile-based products in the industry. Techno-aesthetics questions the origin and nature of aesthetical values concerning technology, demonstrating the necessary value change of perception and expectations of the typical textiles and textile-based products and potentially beyond when a sustainable design outcome is a goal.

Woollen Woven Textile-form and Morphic Textile-Form methods, together may create a new understanding of materiality to move towards Multimorphic Textile-form.

To conclude, this research suggests embracing material traces induced by Woollen Woven Textile-form methods exploration to further unfold 'new circular techno–aesthetics' and move towards a circular economy.

RECOMMENDATIONS

While this research explores with a broad perspective the shape-changing properties of wool fibres, woven Textile-forms and new material experiences induced by their aesthetics and performance, it remains open for further research.

Potentially, designers may use the woollen woven textile-form methods explored in this research to explore for sustainable design outcomes. In this case, it is recommended to start from any experiment outcome and work back to the behaviour of the fibre in that specific structure. This provides all the necessary knowledge to understand and implement these methods in the designer's interested context.

Areas for future research

- Further experimental research on shape-changing properties of materials to find paradigms creating design tolerances for shapeshifting using woven textile forms.
- Combining the researched methods with biomimetics to create specific material properties of the design outcome, for example, to influence the hydro-dynamic, movement or water-repellent properties of textiles.
- Exploring the relationship between specific yarn properties, such as the spinning of the yarn and woven- and multimorphic Textile-form (McQuillan, 2020). Including bio fabricated yarn's ability by f.e. 3D printing to control specific (shape-change) properties by specific placement of properties over the length of the yarn and, in turn, the width of the warp.
- Digitalising with 3D models of multi morphic Textile-forms to facilitate visualisation, supporting the understanding of these methods and being tools for communications in interdisciplinary teams.
- Application of the explored methods in other fields, such as interiors, cars, garments and accessories or for innovation in contexts such as using spacers for ergonomic or architectural purposes.
- Development of digital CAD programs to visualise the transition flat to form constructions based on the created MoB.
- Researching the environmental impact of wool as shape-changing material through its felting abilities. Focusing on felting wool in industrial settings (washing machine vs factory washing street) to produce with less energy and water usage. Furthermore, comparing it to other circular and biodegradable materials with shape-changing properties in the context of woven Textile-forms.
- Further exploration of Woollen Woven Textile-form and other Morphic Textile-form (McQuillan & Karana, 2022) methods to create an understanding of the materiality of circular techno-aesthetics (Dalmasso, 2019) to move towards multimorphic Textile-Form (McQuillan & Karana, 2022)

REFERENCES

REFERENCES

Addington, D. M. & Schodek, D. (2005). Smart materials and new technologies : for the architecture and design professions. Architectural Press. https://ci.nii.ac.jp/ncid/BA74186113

Adolph, S.J.K (2009) The use of knitted, woven and nonwoven fabrics in interior textiles. Interior Textiles, Woodhead Publishing, Pages 47-90, ISBN 9781845693510. https://doi.org/10.1533/9781845696870.1.47.

Ainamo, Antti. (2014). Rethinking textile fashion: New Materiality, Smart Products, and Upcycling. Swedish Design Research Journal. 12. Pages 53-60. 10.3384/svid.2000-964X.14253.

Babu, S. (2019). Chemical composition of wool fibre, chemical formula of wool, physical structure of wool. https://www.textileadvisor.com/2019/07/chemical-composition-of-wool-fibre.html

Bak-Andersen, Mette. (2018). When matter leads to form: Material driven design for sustainability. Temes de Disseny. 10.46467/TdD34.2018.10-33.

Bebbington, J. (2007). Sustainability Accounting and Accountability. Routledge.

Binswanger, Technological progress and sustainable development: what about the rebound effect?, Ecological Economics,Volume 36, Issue 1,2001,Pages 119-132,ISSN 0921-8009,https://doi.org/10.1016/S0921-8009(00)00214-7.

Biskjaer & Halskov (2014) Decisive constraints as a creative

Boomsma, Y. (2020). The Fabricated Self - The role of clothing in identity development. https://essay.utwente.nl/85053/1/Boomsma_MA_PSTS.pdf

Boström, M., Micheletti, M. & Oosterveer, P. (2019). The Oxford Handbook of Political Consumerism. Oxford University Press. Pages 307-308

Broudy, E. (2021). The Book of Looms: A History of the Handloom from Ancient Times to the Present (New edition). Brandeis University Press.

Burgess, R. (2019). Fibreshed: Growing a Movement of Farmers, Fashion Activists, and Makers for a New Textile Economy. Chelsea Green Publishing.

Camere, S. and Karana, E. (2018), “Experiential characterization of materials: Toward a toolkit”, DOI: 10.21606/dma.2017.508

Carrico, Melanie & Kim, Victoria. (2014). Expanding zero-waste design practices: A discussion paper. International Journal of Fashion Design. 7. 10.1080/17543266.2013.837967.

Coelho, M., Zigelbaum, J. Shape-changing interfaces. Pers Ubiquit Comput 15, 161–173 (2011). https://doi-org.tudelft.idm.oclc.org/10.1007/s00779-010-0311-y

Dalmasso, A. C. (2019). Techno-aesthetic Thinking. Technicity and Symbolism in the Body. Aisthesis: Pratiche, linguaggi e saperi dell’estetico, 12(1), 69+. https://link.gale.com/apps/doc/A593676873/AONE?u=anon~59b9a842&sid=googleScholar&xid=28b069ec

Delmas, M. A., & Burbano, V. C. (2011). The Drivers of Greenwashing. California Management Review, 54(1), 64–87. https://doi.org/10.1525/cmr.2011.54.1.64

Dobozy, O. K. (1958). Cause of Wool Felting. Textile Research Journal, 28(8), 717-719.

ECOS, 2021, Durable, repairable and mainstream — how ecodesign can make our textiles circular, ECOS, accessed DATE

Ellen MacArthur Foundation, A new textiles economy: Redesigning fashion’s future, (2017) http://www.ellenmacarthurfoundation.org/publications).

Ellen MacArthur Foundation. (2020). What is the circular economy?

European Environment Agency. (2022). Textiles and the environment: the role of design in Europe’s circular economy. https://doi.org/10.2800/578806

Fashion revolution CIC, Why we still need a fashion revolution (2020) pp 29-31

Goldsworthy, K., Earley, R., & Politowicz, K. (2018b). Circular Speeds: A Review of Fast & Slow Sustainable Design Approaches for Fashion & Textile Applications. Journal of Textile Design Research and Practice, 6(1), 42–65. https://doi.org/10.1080/20511787.2018.1467197

Hassan, Mohammad & Carr, Chris. (2019). A review of the sustainable methods in imparting shrink resistance to wool fabrics. Journal of Advanced Research. 18. 10.1016/j.jare.2019.01.014.

Hassan, Mohammad. (2020). Enhanced thermal stability, hydrophobicity, UV radiation resistance, and antibacterial properties of wool fabric treated with p -aminobenzenesulphonic acid. RSC Advances. 10. 17515-17523. 10.1039/D0RA02267E.

Kapsali, Veronika. (2022). All things bio : A conceptual domain-based approach to mapping practice within the landscape of biologically informed disciplines. The Design Journal. 25. 1-21. 10.1080/14606925.2022.2058449.

Karana, Elvin & Barati, Bahar & Rognoli, Valentina & Zeeuw van der Laan, Anouk. (2015). Material Driven Design (MDD): A Method to Design for Material Experiences. International Journal of Design. in press.

Karana, E. (Ed.), Pedgley, O. (Ed.), & Rognoli, V. (2013). Materials experience: Fundamentals of materials and design. Butterworth Heinemann.

Komyakova, Valeriya & Vince, Joanna & Haward, Marcus. (2020). Primary microplastics in the marine environment: scale of the issue, sources, pathways and current policy. Report to the National Environmental Science Program, Marine Biodiversity Hub. IMAS, University of Tasmania.

Lujan-Ornelas, C., et al., 2020, 'A life cycle thinking approach to analyse sustainability in the textile industry: a literature review', Sustainability 12(23), p. 10193.

McKinsey & Company & Global Fashion Agenda. (2020). Fashion on climate: How the fashion industry can urgently act to reduce its greenhouse gas emissions. https://www.mckinsey.com/~/media/mckinsey/industries/retail/our%20insights/fashion%20on%20climate/fashion-on-climate-full-report.pdf

McQuillan, H. (2019). Waste, so What? : A reflection on waste and the role of designers in a circular economy. Nordic Design Research Journal., 8. Retrieved from http://urn.kb.se/resolve?urn=urn:nbn:se:hb:diva-21028

McQuillan, H. (2020). Zero Waste Systems Thinking : Multimorphic Textile-forms (PhD dissertation, Högskolan i Borås). Retrieved from http://urn.kb.se/resolve?urn=urn:nbn:se:hb:diva-23961

McQuillan, H., Walters, K., & Peterson, K. (2021). Critical Textile Topologies X Planet City: the intersection of design practice and research . Research in Arts and Education, 2021(1), 241–268. https://doi.org/10.54916/rae.119326

McQuillan, H., & Karana, E. (2022). Conformal, Seamless, Sustainable: Multimorphic Textile Forms as a Material-Driven Design Approach for HCI. [Unpublished manuscript]. Department of Industrial Design Engineering, TU Delft

Meadows, Donella H. (2009). Thinking in systems : a primer. London ; Sterling, VA :Earthscan

Niinimäki K., G. Peters, H. Dahlbo, P. Perry, T. Rissanen, and A. Gwilt, 2020. "The environmental price of fast fashion," Nature Reviews Earth & Environment, vol. 1, no. 4, pp. 189-200,

Östlund, A., et al., 2020, Investor brief: sustainability in textiles and fashion, Mistra Dialogue, Stockholm.

Oxford Analytica (2021), "Ultra-fast fashion risks eroding sustainability gains", Expert Briefings.
https://doi.org/10.1108/OXAN-DB265931

Oxman, N. (2010). Structuring Materiality: Design Fabrication of Heterogeneous Materials. Architectural Design, 80(4), 78–85. https://doi.org/10.1002/ad.1110

Papadopoulou, A., Laucks, J. and Tibbits, S. (2017). General principles for programming material. In: Active matter. (Ed. S. Tibbits). Cambridge: The MIT Press.

Parisa Rafiaani, Tom Kuppens, Miet Van Dael, Hossein Azadi, Philippe Lebailly, Steven Van Passel,Social sustainability assessments in the biobased economy: Towards a systemic approach,Renewable and Sustainable Energy Reviews,Volume 82, Part 2, 2018, Pages 1839-1853, ISSN 1364-0321,
https://doi.org/10.1016/j.rser.2017.06.118.

Pereira, S. C. F. (2018). Paving the way to ultra-fast fashion: an exploratory research | col:8295 | com:2197. https://bibliotecadigital.fgv.br/dspace/handle/10438/25784

Perera, Y.S., Muwanwella, R.M.H.W., Fernando, P.R. et al. Evolution of 3D weaving and 3D woven fabric structures. Fash Text 8, 11 (2021). https://doi.org/10.1186/s40691-020-00240-7

Piper, A. and Townsend, K. (2015) 'Crafting the Composite Garment: The role of hand weaving in digital creation', Journal of Textile Design Research and Practice. Routledge. doi: 10.1080/20511787.2015.1127037.

Qin, Y. (2016) Applications of advanced technologies in the development of functional medical textile materials, In Woodhead Publishing Series in Textiles,Medical Textile

Materials,Woodhead Publishing,2016,Pages 55-70,ISBN 9780081006184,https://doi.org/10.1016/B978-0-08-100618-4.00005-4.

Rasmussen, M. K., Pedersen, E. W., Petersen, M. G., & Hornbæk, K. (2012). Shape-changing interfaces: A review of the design space and open research questions. In Conference on Human Factors in Computing Systems - Proceedings (pp. 735–744). New York, New York, USA: ACM Press. https://doi.org/10.1145/2207676.2207781

Rissanen, T. (2013) Zero Waste Fashion Design: A Study at the Intersection of Cloth, Fashion Design and Pattern Cutting. Sydney: University of Technology Sydney.

Rissanen, T. and McQuillan, H. (2016) Zero Waste Fashion Design. Bloomsbury Academic, London.

Ribul, M. (2021). Material-Driven Textile Design (MDTD): A Methodology for Designing Circular Material-Driven Fabrication and Finishing Processes in the Materials Science Laboratory. MDPI. https://www.mdpi.com/2071-1050/13/3/1268

Robbins, Holly & Giaccardi, Elisa & Karana, Elvin & D'Olivo, Patrizia. (2015). Understanding and Designing with (and for) Material Traces. Studies in Material Thinking. In Press.

Robbins, E. Giaccardi, and E. Karana, 2016. "Traces as an Approach to Design for Focal Things and Practices," in Proceedings of the 9th Nordic Conference

Rognoli and E. Karana, 2014. "Toward a new materials aesthetic based on imperfection and graceful aging," in Materials experience: Elsevier, pp. 145-154.

Rosner,Daniela K. Miwa Ikemiya, Diana Kim, and Kristin Koch. 2013. Designing with traces. In Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI '13). Association for Computing Machinery, New York, NY, USA, 1649–1658. https://doi.org/10.1145/2470654.2466218

Rundong Wu, Joy Xiaoji Zhang, Jonathan Leaf, Xinru Hua, Ante Qu, Claire Harvey, Emily Holtzman, Joy Ko, Brooks Hagan, Doug James, François Guimbretière, and Steve Marschner. 2020. Weavecraft: an interactive design and simulation tool for 3D weaving. ACM Trans. Graph. 39, 6, Article 210 (December 2020), 16 pages. https://doi.org/10.1145/3414685.3417865

Runnel, A. et al. (2017) The Undiscovered Business Potential of Production Leftovers within Global Fashion Supply Chains: Creating a Digitally Enhanced Circular Economy Insight from research among fabric and garment factories of China and Bangladesh. Tallin.

Rudofsky, B. (1947). Are Clothes Modern? An Essay on Contemporary Apparel. (1st ed.). Paul Theobald.

Runnel, A., Raihan, K., Castle, N., Oja, D., and Bhuiya, H. (2017). The Undiscovered Business Potential of Production Leftovers within Global Fashion Supply Chains: Creating a Digitally Enhanced Circular Economy Insight from research among fabric and garment factories of China and Bangladesh, Reverse Resources, http://www.reverseresources.net/about/white-paper

Salvia G., Ostuzzi F., Rognoli V., Levi M. (2010). The value of imperfection in sustainable design. The emotional tie with perfectible artefacts for longer lifespan.

Schon, D. A. (1983) The reflective practitioner: how professionals think and act. Nueva York: Basic Books.

Stappers, PJ, & Giaccardi, E (2017) Research through Design. Chapter in: the Encyclopedia of Human-Computer Interaction, 2nd edition.

Stappers, PJ, Sleeswijk Visser, F, & Keller, AI (2014) The role of prototypes and frameworks for structuring explorations by research through design. In:

Taitler, R. (2020). Mass Production in the Fashion Industry: How quantity outweighs quality and leads to waste and financial loss. 3D Insider | Optitex Blog. https://3dinsider.optitex.com/fashion-quantity-outweighs-quality/

Talman, R. (2022). Designing for changeability in textiles. (Doctoral dissertation). Borås: Högskolan i Borås

Taplin, I. M. (1999). Continuity and change in the US apparel industry: A statistical profile. Journal of Fashion Marketing and Management, 3(4), 360–368.

Textile Exchange, Materials change insights report 2019 (2020), p. 29

The Woolmark Company. (2021). Why work with wool? https://www.woolmark.com/industry/use-wool/
tion/overview/

Townsend, K. (2003) "Transforming Shape : A simultaneous approach to the body , cloth and print for textile and garment design (synthesising CAD with manu- al methods)". PhD Theis. Nottingham Trent University.

Tsaknaki, V., & Fernaeus, Y. (2016, May). Expanding on Wabi-Sabi as a design resource in HCI. In Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems (pp. 5970-5983).

United Nations. (n.d.). Population.
Van der Vegt, A. K. (1955). A Study on the Mechanism of Wool Felting. Excelsior.

Vassiliadis, S. , (Ed.). (2011). Advances in Modern Woven Fabrics Technology. IntechOpen. https://doi.org/10.5772/678

Wan, Ailan & Yu, Weidong. (2012). Effect of wool fiber modified by ecologically acceptable ozone-assisted treatment on the pilling of knit fabrics. Textile Research Journal. 82. 27-36. 10.1177/0040517511414973.

Worbin, L. (2010). Designing dynamic textile patterns. PhD diss., University of Borås. Borås: University of Borås Studies in Artistic Research 1.

Zafarmand, S.J. Sugiyama K., Watanabe M. (2003). Aesthetic and Sustainability: The Aesthetic Attributes Promoting Product Sustainability. In: The Journal of Sustainable Product Design, Vol.3, No 3-4, pp.173-186

Zhang, N. Wang, Q. Yuan, J. Cui, L. Wang, P. Yu, Y. Fan, X. (2018). Highly efficient and eco-friendly wool degradation by L-cysteine-assisted esperase, Journal of Cleaner Production, Volume 192, 2018, Pages 433-442, ISSN 0959-6526, https://doi.org/10.1016/j.jclepro.2018.05.008.

IMAGES

Adidas (2020). Strung uppers adidas robotically woven trainers. [photograph] Dezeen. https://www.dezeen.com/2020/10/08/strung-uppers-adidas-robotically-woven-trainers/

Weffan (2022) 3D woven trousers. [photograph] instagram. https://www.instagram.com/wef.fan/

Virtual Textile Research Group (2020) Rapid Sketching of Woven Textile Behavior [photograph] virtualtextileresearchgroup. http://www.virtualtextilesresearchgroup.com/library-3d-woven/selzmu0b0zmi839cdvebnp62ilbe1o

Yvonnesworkshop (2022) Needle felting wildlife [photograph] Boredpanda. https://www.boredpanda.com/needle-felting-wildlife-yvonnesworkshop-part-2/?utm_source=google&utm_medium=organic&utm_campaign=organic

Rasmussen et al. (2012) Shape changing interfaces overview [photograph] researchgate. https://www.researchgate.net/publication/239761305_Shape-changing_interfaces_A_review_of_the_design_space_and_open_research_questions

Risannen, T. & David Telfer (2010) (2012) Zero-waste garments. [photgraph] http://www.textiletoolbox.com/research-writing/design-minimise-waste/

MIT (2019) Mesh structure shape temperature changes [photograph] MIT news. MIT mesh: https://news.mit.edu/2019/mesh-structure-shape-temperature-changes-0930

Wojcik, Z. (2021) Touch the forest [photograph] zuzannawojcik. https://www.zuzannawojcik.com/touchtheforest
Permission to use images

Burkhardt, L. (2022) Woven Forms [photograph] leonieburkhardt. https://www.leonieburkhardt.com/woven-form-from-flat
Permission to use images

McQuillan, H. (2020) Diagram showing the relationship between three layered Woven Textile-form in a proposed sample.[photograph] Zero Waste Systems Thinking: Multimorphic Textile-Forms. hollymcquillan.com. http://hb.diva-portal.org/smash/record.jsf?pid=diva2%3A1478307&dswid=2382

McQuillan, H., Walters, K., & Peterson, K. (2021). Planet City custome. [photograph] Critical Textile Topologies https://doi.org/10.54916/rae.119326

REFLECTION