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The Circular Techno-Aesthetics of Woven Textile-forms: A Material and Process-driven Design Exploration

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Keywords: Sustainable fashion and textiles; 3D weaving; Material-driven design; Multimorphic textile-form; Circular techno-aesthetics.

Abstract: Material-Driven Design (MDD) proposes that we value the behaviours, performance properties, and aesthetics that emerge from a material's inherent properties – an approach that provides a much-needed perspective for the textile and fashion industry as it develops new sustainable and circular systems. This research expands this material-led approach to include design-production processes framed within holistic notions of sustainability. In contrast to a conventional top-down design research process, material-processual-driven design approaches may enable us to break from the trap of developing and evaluating the outcomes of new design systems through the lens of our existing (usually unsustainable) approaches. This paper reflects on the tensions experienced by the authors in navigating concerns of technological feasibility, aesthetic outcomes, and the sustainable goals framing two sets of woven textile-form design experiments. Textile-forms are design-production processes that emerge from the simultaneous production of textile and form via the interlacement of matter/fibre/yarn and are designed to facilitate localised, on-demand production of textile-based objects. We will present the experiments, which were developed over six months, reflecting on the technical and evaluation processes that contributed to their development and the challenges that arose. This paper provides grounded examples of design researchers navigating this challenging space and the outcomes that emerge and aims to contribute to a greater understanding of circular techno-aesthetics that may support the industry as it develops the new systems it needs.

Introduction

The majority of garments look the way they do because of a complex interaction of social, cultural, economic, and technological factors. Everything from spinning technology, loom design, the technical requirements of fabric cutting equipment, the division of labour to facilitate mass production, and the expectation that we can extract and waste vast quantities of raw materials and exploit people in repetitive and/or dangerous working conditions, all contribute to the aesthetics of the garments we wear every day. Now, both ordinary citizens and the industry's understanding of evaluation criteria for textile and garment performance and aesthetics are based on technological development focused on uniformity, ease and speed and low-cost production. Decades of building and then operating within this deeply problematic paradigm have created a landscape and regime (Geels, 2011) with a set of processes and expectations - for both industry and users - that seems difficult to deviate from.

This paper presents two woven textile-form (WTf) design cases that take a user or material-centred research through design (RtD) (Stappers & Giaccardi, 2017) approach while attempting to holistically address identified sustainability issues in the textile and garment industry. We argue that for the textile and fashion industry to transform in the manner and scale required, our technical, design, aesthetic processes, evaluation metrics and expectations need to be fundamentally redesigned. By reflecting on our experiences as designers attempting to navigate this complex space, we hope to provide insights that support a broader understanding of the transformation that is needed within the design discipline.

Sustainability in Fashion and Textiles.

In the textile and fashion industry, efforts aimed at sustainability have emphasised increasing efficiency (e.g., Rissanen & McQuillan, 2016; Runnel, Raihan, Castle, Oja, & Bhuiya, 2017), the replacement of problematic materials (de

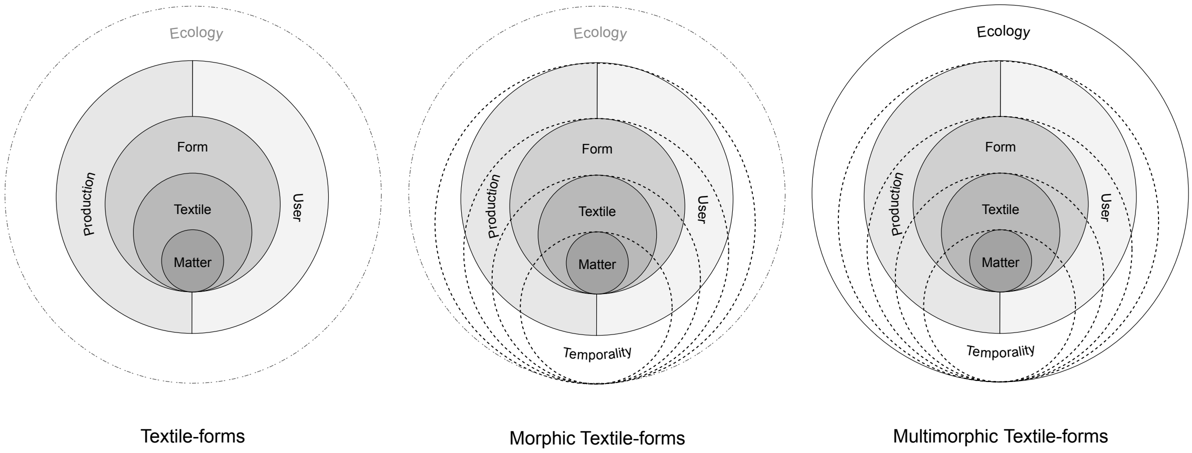

Figure 1. Model for Textile-form, Morphic Textile-form and Multimorphic Textile-form showing the relationship between all common elements (Textile-forms: Matter, Textile, Form, Production and User), and the differences when temporality (Morphic Textile-forms) and ecology (Multimorphic Textile-forms) are emphasised. Adapted from McQuillan & Karana (2023).

Oliveira Neto, Correia, Silva, de Oliveira Sanches, & Lucato, 2019), an emphasis on consumer responsibility (Shen, Wang, Lo, & Shum, 2012) and circularity (Rathinamoorthy, 2019). Increasingly we see policy levers imposed on the textile and fashion industry (e.g., "Dutch Policy Programme: Circular Textiles 2020-2025," 2020; Juanga-Labayen, Labayen, & Yuan, 2022). Systemic over-production of fibre, yarn, textiles, and garments is a major contributing factor to the industry's climate impact (Niinimäki et al., 2020; Sandin, Roos, Spak, Zamani, & Peters, 2019).

Textile-Form Design and Production.

The most used textile methods, weaving and knitting, usually make 2D fabrics for cut and sewing into 3D form. This multi-step process divides textile and form production across multiple locations, contributing to exploitation, overproduction and carbon emissions (Sandin et al., 2019). In contrast, textile-forms emerge directly from the interaction of molecules, fibres, yarns, textile structures and finishing processes, into 3D form such as garments (Peterson, 2020), products (Albaugh, Hudson, & Yao, 2019), or even architecture (Popescu et al., 2021). They move closer to or achieve, additive and automated manufacturing processes, eliminating much of the manual labour in garment production, enabling localised, affordable garment on-demand production, therefore reducing overproduction. The most well-known example of a textile-form method is 3D knitting, or WholeGarment™ knitting, where a knitted object emerges directly from the knitting machine, with little waste or post-knitting processing required. Other less-known methods are 3D printing ("Kinematics Dress 6," 2016), moulding (Hoitink, 2016), weaving (Walters, 2021), and growing textile-form in the context of bio-design (Zhou, Barati, Wu, Scherer, & Karana, 2021).

The focus of this research is Woven Textile-forms (WTf) which makes 3D form by interlacing warp and weft yarn on a loom. Outside of hand-woven shaped woven garments (e.g, Piper, 2019; Wagner et al., 2022), industrially woven examples include: those woven on digital jacquard looms (Buso, McQuillan, Jansen, & Karana, 2022; Lucchi, 2018; Miyake & Fujiwara, 1999); 3D looms (Harvey et al., 2019; Shi, Taylor, Cheung, & Sayem, 2022); and the use of novel looms developed specifically for this purpose (Zorthian, 2021). Compared with knitting, there is significantly less research and development for weaving form. Loom development has focused on the production of 2D fabric for the cut-and-sew garment industry, and there has been limited development of infrastructure or digital design tools for WTf (an exception is Wu et al., 2020). The existing technological system, and related industry and societal expectations, have profound impacts on the acceptance and potential uptake of WTf. However, WTfs relative newness provides an opportunity to forefront sustainability in its development. In this paper we focus on this complex intersection.

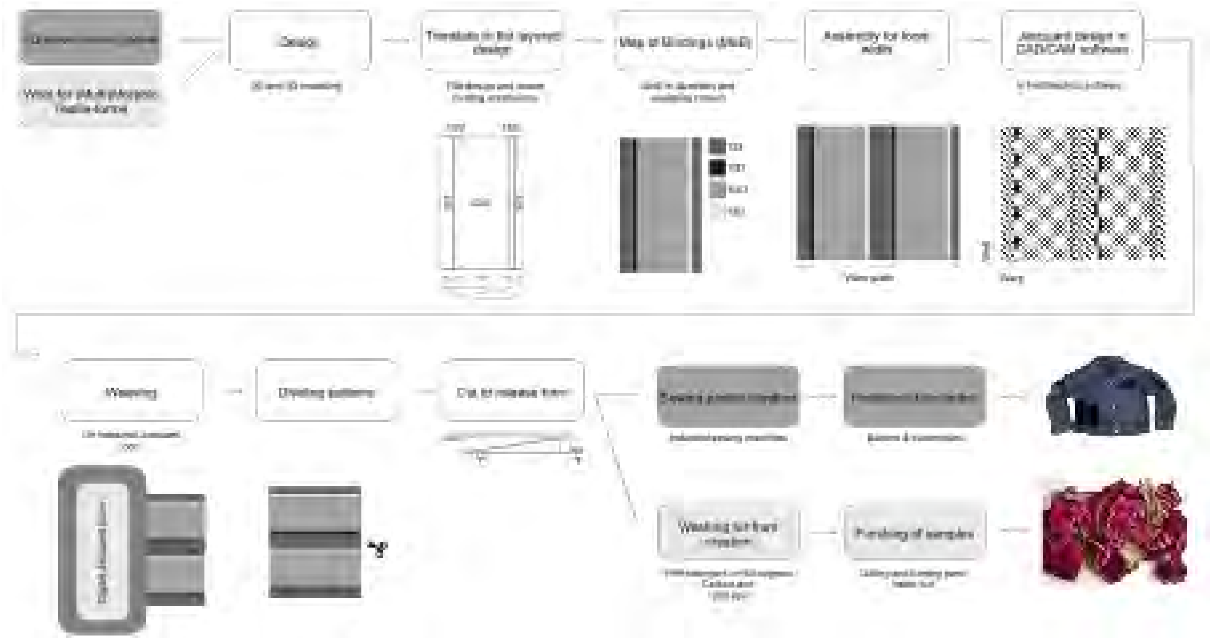

Figure 2. Overview of the application of Woven Textile-form production in the conventional textile industry production chain specified for both 3DWDJ and W4MTF, addressing design, programming, production, and finishing.

Our Approach

When a holistic view of sustainability is applied to the development of WTf then design and production consider change over time across material, use and ecological scales - Multimorphic Textile-forms (Fig. 1) (McQuillan, 2020; McQuillan & Karana, 2023). This approach goes beyond the reimagining of the processes which make textile-based form, and into new material relations and aesthetics. This research uses RtD develop outcomes that help build on Material-Driven Design (MDD) (Karana, Barati, Rognoli, & Zeeuw van der Laan, 2015) to include process-driven design approaches (designing and weaving textile-forms) and aims to contribute to sustainable transitions for the fashion and textile industry (Buchel, Hebinck, Lavanga, & Loorbach, 2022).

We build on emerging discourse for MMTF by providing two contrasting cases that deepen our understanding of the application of this method (Fig. 2) in the industry and the ways in which users may respond. The 3D Woven Denim Jacket (3DWDJ) was developed with a user-centred lens, aiming to maintain as much of the look and feel of existing denim jackets to support user acceptance. A small user study was conducted to understand how users responded to the aesthetics and material experience that result from the novel production process. Wool for (Multi)morphic Textile-forms (W4MTF) used MDD to develop textile-forms using wool as a shape-changing material. The aim was to discover novel material expressions from a mono-material, and used the materials experience framework (Camera & Karana, 2018; Giaccardi & Karana, 2015) to understand the unique material experiences provided by wool's inherent properties in the context of WTf.

To unpack this complex and interconnected negotiation between the existing regime within fashion and textiles, and the emerging design and technological niche practices of MMTF, next we present two design cases, discussing the challenges and evaluation processes that contributed to their development.

Woven Textile-forms - Design Cases

3D Woven Denim Jacket

The 3D Woven Denim Jacket (3DWDJ) project sought to redesign the construction of a conventional denim jacket (Fig. 3, top) by using WTf design methods to reduce waste and production steps during the construction of a denim jacket while retaining the existing emotional and physical durability users expect. An analysis of denim jackets' cultural meaning with existing wearers and existing construction methods, led to design requirements (see Table

1) that aimed to maintain the features that are commonly associated with denim jackets.

Figure 3. Top: Levi's Type 3 Trucker Jacket is a classic example of a conventionally constructed denim jacket. Bottom: V.1 of the 3DWDJ for comparison.

Using these design guidelines, three versions were developed from a single WTf concept to explore different design variables (Table 1). All were woven on a digital jacquard loom in a vertically integrated factory in Pakistan (Fig. 4). V.1 (Fig. 3, bottom) focuses on minimising finishing processes, and so has only 5 sewing steps (compared to the usual 29) by leaving all edges raw. V.2 explores a higher level of finish by using conventional finishing processes in combination with 3D weaving to finish all of the edges. V.3 is a zero-waste version of V.1, achieved by overlapping the pattern pieces. See Table 1 for a summary of all three.

V.1 was presented to the initial denim jacket user group that contributed to the design guidelines, and additionally to three denim jacket users without prior knowledge of the project. All described V.1 as being in the category of a denim jacket, while also recognizing some differences (which were all material expressions of the process used, see Table 1) from a denim jacket as they know it.

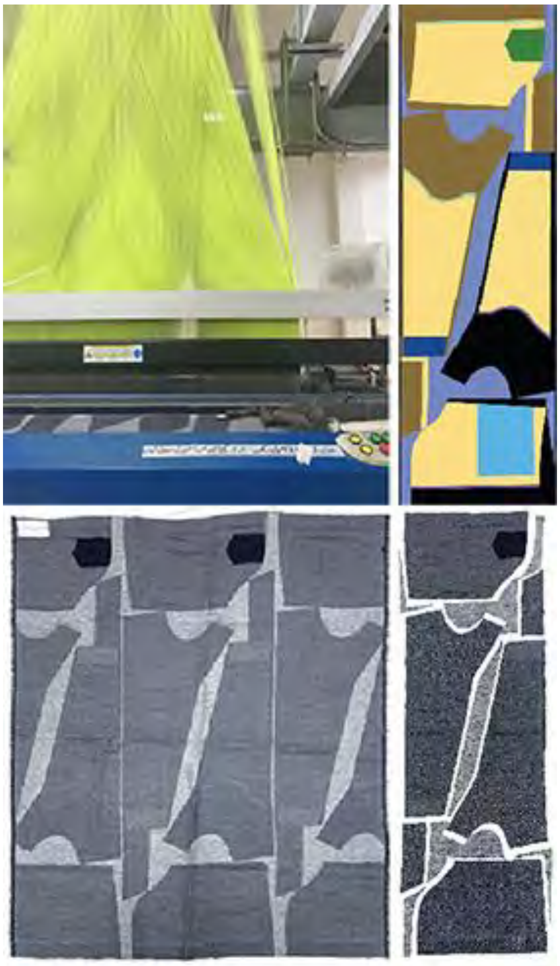

Figure 4. Top left to right: Digital jacquard loom used to weave all the 3DWDJ samples, The MoB for V.1 which is programmed with 3D weave structures. Bottom left to right: Loom state of V.1, and a single jacket panel after cutting – the light areas of textiles are waste.

		Overall	V.1	V.2	V.3
Design requirements /aim		The design should maintain the 'essence' of a classic denim jacket and fulfil a similar role in the user's wardrobe. The fabric structure, colour and material experience should be consistent with what is expected of denim fabric. The form should have a boxy fit with a well-fitting sleeve-to-body relation, and a front waistline that is longer than the back, with a collar and strong front placket for hardware.	 Minimise post-weaving sewing steps to support automati-on.	 V1 but with a finish more consistent with existing denim jackets.	 V1 adapted for zero waste layout
Technical/ Production	Loom	Digital jacquard loom, air jet weft insertion. 144.3 cm wide, 40.3 ends/cm, One full centre repeat (59.5 cm) in the centre and two partial repeats on either side (42.4 cm).	Most areas are 1 or 2 layers. 3 layer areas (such as pockets) are woven using 1/4 of warp and weft to maintain the structural integrity of the overall form. The unusual (uneven) repeat arrangement significantly impacted the form design/layout and the resulting waste as a proportion of fabric width.		
	Material	*Warp yarn:* (Ne20) Indigo dyed cotton *Weft yarn:* 50 picks/cm Ne8 60% Hemp, 40% cotton. 2 indigo, 2 white	To maintain an overall denim look with an indigo surface and a white back of the fabric, two blue and two white weft yarns were used.		
	Textile	*Structure:* Warp-faced twill variations, 3D woven, mostly limited to 2 layers. *Finishing:* Uncut cloth was singed, resized and sanforized	*Structure:* Structures were locally programmed to ensure even overall density and consistent indigo surface appea-rance.		
	Form	*Construction:* Minimise sewing steps and complexity. *Seams and edges:* Seam strength is compara-ble to, or stronger than cut and sewn denim seams. Weave structures and pattern pieces are designed to reduce fraying as much as possible. Woven seams areon the outside of the jacket, while sewn seams were internally constructed. *Cutting:* All cut lines should be on the outside to facilitate CNC cutting processes at a later date. Separate pattern pieces can be cut in multi-ply lays, but any multilayer, overlapping structures have internal cut lines that must be cut in single lays.	*Pattern:* 6 pattern pieces: *Cutting:* 6 pieces can be cut in multi-ply lays. 5 internal cut lines. *Edges:* Cut edges were left raw. *Construction:* 5 sewing steps	*Pattern:* 5 pattern pieces modified to utilise 3D weaving methods for finishing edges. *Cutting:* 5 pieces can be cut in multi-ply lays. 10 internal cut lines. *Edges:* All edges are finished. *Construction:* 9 sewing steps.	*Pattern:* 6 pattern pieces overlapped to eliminate waste. *Cutting:* 1 cut line can be multi-ply lay. All remaining cuts are internal. *Edges:* Cut edges were left raw. *Construction:* 5 sewing steps
Sustainability		*Supply chain:* Textile and form are simultane-ously produced. Automation supports perso-nalised, local and/or on-demand production. *Supply chain challenge:* single-ply cuts limit mass production potential. *Waste:* Aim for reduction. Calculations for waste were based on the weight of panels rather than the surface area of the fabric or the width of the repeat. *Manual labour:* Automation leads to a reducti-on in manual labour.	*Supply chain:* Single-ply cuts limit mass production potential. *Total material weight:* 514g *Waste:* 14% *Manual labour:* Most automated	*Supply chain:* Single-ply cuts limit mass production potential. *Total material weight:* 490g *Waste:* 15,5% *Manual labour:* Least automated.	*Supply chain:* Single-ply cuts significantly limit mass production potential. *Total material weight:* 340g *Waste:* 1,16 %. *Manual labour:* Cutting may require more manual labour than V1.
User study		Users reported its lighter weight, variable surface structures, external woven seams and fraying edges, as differences from a standard denim jacket. The participants did not report the differences as 'bad', but rather as something 'cool' and raw, like a denim jacket as they know it.			

Table 1. An overview of 3D Woven Denim Jacket design requirements, technical, production, sustainability, and user findings.

Wool for (Multi)morphic Textile-forms: Exploring Novel Material Experiences.

Wool for (Multi)morphic Textile-forms explored novel material expressions merging from the inherent properties of wool (that it can shrink and felt - a behaviour that the textile industry often seeks to suppress) when manipulated in WTf to challenge conventional expectations and processes for textile objects. MDD facilitates the emergence of material expressions from the inherent properties of the hybrid material-process and supports holistic perspectives when designing for sustainable transitions.

W4MTF integrated temporality as a design variable with WTfs to enable shape-change in the production or use phase using wool. An understanding of the shape-change process was established by tuning the felting process via the density and layer arrangement of wool yarns in multi-layered weave binding constructions, as well as the use of washing-moulds to manipulate the final shrunken form. The various methods used (Table 2) sought changes in scale, form, texture, and firmness, creating atypical aesthetics and expressions (Fig. 5, bottom). Framed as an exploration of circular design focused on biological nutrients, ideally, both the warp and weft would be wool to make the outcomes a monomaterial, but limited loom availability meant that a loom with a polyester warp was used for sampling.

Participants interacted with the outcomes of the experiments in an experiential characterization (Camera & Karana, 2018) user study (Fig. 5, middle right, and Table 2), and validated the apparent coherent aesthetic expression - which are the material traces (Robbins, Giaccardi, & Karana, 2016; Rosner, Ikemiya, Kim, & Koch, 2013) of the processes used - which differs significantly from the textile aesthetics of existing industrial processes.

Figure 5. Top Left to Right: Weaving samples on industrial jacquard loom. Samples of the loom separated by cutting. Middle left to right: Samples after the felting process, displaying changes. Participants conducting the experiential characterization user study. Bottom: Detail of Ex. 1 sample.

	Overall	Ex.1	Ex.2	Ex.3	Ex.4
Aim	Explore the shape-change potential of wool yarn in woven textile-forms	Change in texture and firmness to construct a rigid structure of a firm mono-material	Change in texture, firmness and scale to create rigid 3D spaced materials and to compensate the density loss of multiple layered bindings	Change in firmness and form to control the shape-changing with a mould during form creation	Change in scale and form to create mono-material structures
Technical/process variations	Loom: Digital jacquard Fabric width: 150 cm Warp density: 76 ends per cm Warp material: 78 Dtex Polyester Weft material: 714 Dtex Wool in two colours Woven cloth is cut into separate samples and they are washed separately in washing bags at 60 degrees Celsius, with detergent on 1200 spin and air dried afterwards.	Structure: 4 layers. Bindings: Variation of bindings with the lowest density - highest felting ability (S48) on the two inside layers and moderate (S24) to low (S6) felting ability on the top and bottom layers The two thin parts over the width of the sample with the lowest density - highest felting ability (S48) create the ruffle effect and increase the firmness of the sample together with the felting of the inside layers.	Structure: 3 layers Bindings: Variation of bindings with the lowest density - highest felting (S64) ability and highest density - creating the lowest felting ability (S8) The connections between layers 1-2 and layers 2-3 enable the shape to form 3D space in between the shrunk outside layers.	Structure: 4 layers Bindings: Progressing from inside to outside of the oval shape, bindings with a higher density - lower felting ability (S12) to lower density - high felting ability (S48). Taking into account during the design, that the most felting occurs over the width of the warp. Using four layers instead of 2 to maximise the shape forming around the sphere shaped mould. Finishing: Washed on 3d printed mould	Structure: 3 layers Bindings: Variation small parts with floats over the full width of the part to maximise the felting ability and using a lower density to minimise the felting (S8) on the overall shape. The full width float parts maximise the felting creating the shape to form pleats and build structure which can be used in textile-object constructions.
Loom state (before washing)					
Post processing (after washing)					
Experiencial Characterisation User study focused on the interpretive level while including elements from the other research levels. "What do you associate with the material?" "How would you describe it?" Answering such questions to validate the assumptions on the sample's coherent aesthetic expressions.		Natural, organic and strange *"Repetition and texture give an idea of being organically grown from a natural material"*	Frivolous, strange and hand-crafted *"The sample appears hand-crafted due to the raw edges and irregularities on the outside"*	Natural, nostalgic and hand-crafted *"The rigidness, texture and imperfections give the sample a nostalgic appearance"*	Strange, organic and aggressive *"Clearly created from one material but expresses a whole organic object with potential for multiple purposes"*

Table 2. Overview of Wool for (Multi)Morphic Textile-form experiments. The technical or process variables, aims of the experiment, how the experiment sample changed, and the resulting experiential characterization outcomes demonstrate novel material experiences possible with this material-driven design approach to morphic textile-forms.

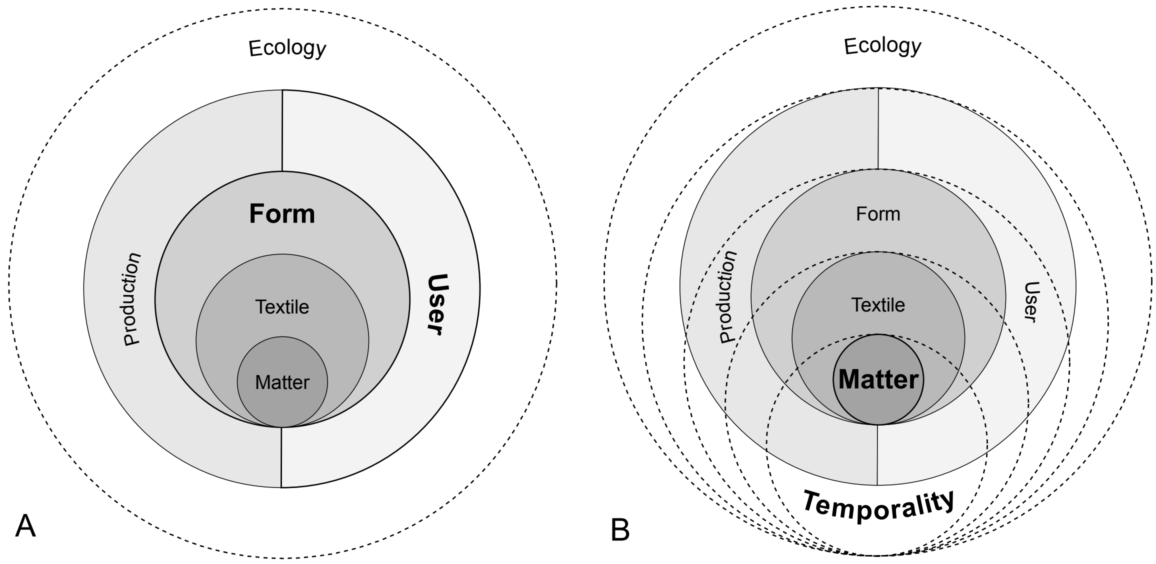

Figure 6: For both cases, matter, textile, form, production, user, and ecology all need to be holistically attended to. However, the lens for the development of 3DWDJ (A) was in the form outcome (a denim jacket) for users (and their expectations). W4MTF (B), focuses on material, and temporality across all scales. Figure developed from McQuillan and Karana (2023).

Discussion

The cases both use a material-process driven design approach to explore the development of novel WTf's, however, their differences provide opportunities for reflection in the context of sustainable transitions. Where 3DWDJ (Fig. 6 A) aims to rethink the existing production opportunities, W4MWTF (Fig. 6 B) rethinks how we design and evaluate the outcomes of new material-driven design-production systems. Both design cases reveal the opportunities that such niche practices present designers, users, and industry, while simultaneously unveiling the power the existing paradigm has over designers, industry, and users - and the challenges that arise from this.

The Opportunities and Challenges of Woven Textile-forms.

The textile industry can transition to a more sustainable process by utilizing technology, such as industrial weaving looms, and developing new models of design and production that reduce water and material waste, localise, and decarbonise production. WTf's, for example, can increase durability via the integrated woven seams (as was found during strength testing for the 3DWDJ), or locally tune weave structures to reinforce areas that experience increased wear. Furthermore, W4MTF demonstrates that designers can locally tune material properties such as density, cushioning, size or shape, and this can be activated during design or use-time – further enriching material/product experiences. These properties can be generated using mono-materials, reducing the need to use textile composites which are difficult to recycle. Furthermore, 3D weaving facilitates zero-waste production by enabling the overlapping of pattern pieces, while also utilizing fewer materials for the same garment unit (see Table 1, V.3).

The unique design-production process leaves material traces on the textile-form and create novel Circular Techno-Aesthetics (CTA) (developed from Simondon, 2012). The user responses from both design cases suggest that when an outcome communicates its origin and performance and gives meaning to humans, users may embrace new design aesthetics which emerge from circular design-production approaches. Their CTA could become a unique selling point for consumers.

Many of the challenges facing this niche practice stem from the industry's ongoing focus on rapid, uniform, and low-cost production of 2D fabric - for the cut and sew industry. While these WTf's can be produced on any digital jacquard loom, a high warp density with no repeat in the jacquard is preferred to allow for more design flexibility. However, only a few companies have looms suitable for this type of production, and they must be willing to provide their production facilities for research. Therefore, when using non-ideal looms, designers must make technical, material, aesthetic, and/or sustainability compromises. 3DWDJ for example encountered limitations caused by the unusual repeat size of the available loom - which impacted the form design and waste produced. While the lack of available jacquard looms with a wool warp meant it wasn't possible to create mono-material outcomes in W4MTF. Additionally, the production of WTf's requires a fundamentally different approach which imposes limits to the scale of production, particularly regarding the cutting of garments pieces in multi-ply lays (see Table 1). The appeal of scalable technology is powerful under the current industrial paradigm, but researchers and emerging brands must develop and prototype alternative models that resist growth, and reduce material use and emissions, while extending product lifetimes. These are perspectives which are fundamentally disruptive to the industry, and so likely to be resisted.

Another challenge facing the adoption of these approaches in the industry is the lack of educational resources and technological support. While the composition of our research team covered a wide range of experience with WTf, user and material-centred design methods, and programming for industrial jacquard looms - many of the insights from the design process were gained due to these differences in knowledge and background. Fashion and textile designers often have little knowledge of the technical details of each other's fields; therefore, new skill sets and shared vocabularies are needed. While such knowledge gaps can be supported by digital tools, there are few available for WTf. Furthermore, the complexity of the process and competing requirements require both knowledge and compromise. The comparative evaluation of outcomes can be challenging. While efficiency in woven materials is typically measured as a function of surface area, measuring efficiency in 3D knitting is more aligned - measuring the weight of the yarn - such an approach will be necessary when conducting a comparative LCA. From a designer's perspective, the novelty of the approach, and a desire to mimic existing processes/aesthetics (e.g., faithfully recreating a denim jacket) pulls focus toward the limitations of the processes. For example, W4MTF the material consistency/uniformity standardised in industry isn't possible or desirable but was still a challenge for the designer to accept – we anticipate that challenging such expectations for many designers, industry stakeholders and users will be difficult.

There is a clear need for research to develop alternative evaluation methods that align with sustainable transition goals. Furthermore, a common vocabulary will enable communication between researchers, brands, technicians, and designers. Also, design and pedagogical tools need to be developed to support designers and students working in these novel and complex spaces, and infrastructure must be developed through the lens of sustainable transitions to support these ways of making.

The Circular Techno-aesthetics of (Multimorphic) Woven Textile-forms

To realise the potential opportunities of WTf, open questions relating to infrastructure, technology, education, design, evaluation, and user expectations need to be addressed in future research. The gap between theory and practice in sustainability is often critiqued (e.g., de Wit, Verstraeten-Jochemsen, Hoogzaad, & Kubbinga, 2019; Remy, Gegenbauer, & Huang, 2015). In the textile industry sustainability is commonly framed within transparency, material replacement, or evaluation processes for existing product domains. Multimorphic Textile-forms bridge theory and practice by embedding holistic sustainability as part of a design process that generates unique Circular Techno-Aesthetics that result from the material-process driven design approach. While presented as an opportunity, CTA also presents significant challenges for designers, the industry, and users.

For designers, CTA suggests the need to question current design evaluation methods for textile-based products (such as developing an outcome of a novel design-production process by embracing the CTA that may emerge, rather than using the lens of existing and familiar product expectations). While material and process-driven design approaches may enable us to break from the trap of developing and evaluating the outcomes of new design systems through the lens of our existing (usually unsustainable) approaches, most designers are familiar with top-down design research processes that address product or user needs. For users, when it comes to textile products, consumers have clear existing expectations. Denim, for instance, is expected to be durable, have a unique aesthetic, and fit and feel a certain way. However, changing the production process of these garments to a material-process driven approach, could change how consumers experience these garments. However, this should not be assumed to be a negative outcome and may support changing perceptions and expectations of textiles and textile-based products, within sustainable transitions.

Material-driven design surfaces the inherent properties of materials to support designers to move beyond a top-down, problem-centric approach to the development of technological or anthropocentric solutions. In combination with holistic design-processes, such as WTf, it forms a material-process driven design approach combing sustainable production with an enriched user experience of materials, and in doing so, may extend product lifetimes.

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