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Woven Textile-Form Design: A Method to Design Woven 3D Form

Milou Voorwinden and Holly McQuillan

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Holly McQuillan explores the design and development of complex interconnected fibre-yarn-textile-form systems as a means for transforming how we design, manufacture, use, and recover textile-based forms. Oriented through a holistic lens, her research advocates for a new understanding of the relationship between designer and system, material, and form to prototype alternative futures.

ABSTRACT In recent years, there has been a growing interest in the use of conformal manufacturing approaches for consumer textile products such as WholeGarment knitting, 3D Weaving and Woven Textile-form (WTf) design. By emphasizing zero-waste, local and on-demand manufacturing, these approaches have the potential to significantly impact the production of textile-based objects and contribute to the larger sustainability movement. Despite significant efforts in textile design and engineering, there is still a lack of research on WTf design methodologies for industrially producing textile-based products. This is a crucial step required to ensure wider adoption of these approaches. This article proposes a method for designing industrial jacquard woven textile-forms. We will first introduce the theoretical basis of our method, and then present the method, illustrated by the four-year-long development of a WTf trouser. Additionally, this paper identifies gaps in knowledge, technology, and infrastructure within the textile industry, which can guide future research directions.

KEYWORDS: Textile-forms, method, weaving, industrial design, research through design (RtD)

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Introduction

The negative impact of the textile industry is well documented and profound – contributing as much as 10% of GHG (Niinimäki et al. 2020). Simple drop-in solutions are often desired by industry; however, garments and other everyday textile-based products are complex personal, social and technical constructions. The aesthetic and performance expectations that we have of textile products, particularly the ones designed to be worn or carried on our bodies every day, are personal and intimate, and also a consequence of long-standing and problematic industry norms.

Appropriate material selection has been a key lever in efforts to reduce the impacts of textile products. Eco design guidelines (such as ESPR) and certification (Higgs Index, GOTS) advocate for the substitution of undesirable materials and the use of recycled and recyclable content. Such drop-in solutions have resulted in a per unit reduction in a garment's impact, alongside an overall increase in the industry's impact (Textiles 2030, WRAP, 2023), because materials do not exist in isolation. The complex interactions between fabrication processes, material, shape and function (see Figure 1) are well understood in material science and engineering. Most seminal works guiding designers have focused on selecting appropriate materials based on desired performance and shape, as well as limitations or requirements from manufacturing processes (Ashby 1999; Olson 1997). Additionally, the material's role in shaping our experience with products is now widely researched (Giaccardi and Karana 2015), and design methods such as Material Driven Design (Karana et al. 2015), provide designers with tools to navigate technical and performance elements, while also integrating material and user experience.

A common perspective in material science, product and fashion design, is to view textiles as a raw material or substrate. Even in fields where textiles are commonly used, many designers are unaware of the potential to tune the properties of textiles through yarn and weave structure interactions. This lack of awareness, together with the emphasis on speed and quantity in industrial production, has limited the development of complex structures (Hagan 2020), and therefore our understanding of the potential of textiles to create the textile and form simultaneously.

While textiles are commonly used in the context of form design (garment, upholstery, footwear, etc), textile and form designers often have limited knowledge or experience of each other's fields; this is particularly the case in woven textiles (compared to printing/embroidery or knitting). This separation reflects educational and industry contexts where woven textile designers develop and realize 2D planar fabrics, which garment or product designers then utilize to generate 3D form. This separation results in 15–25% production waste (Niinimäki et al. 2020; Runnel et al. 2017) and 30% garment overproduction (WRAP, 2023), and is a process essentially unchanged since the introduction of industrial weaving looms. Additive manufacturing

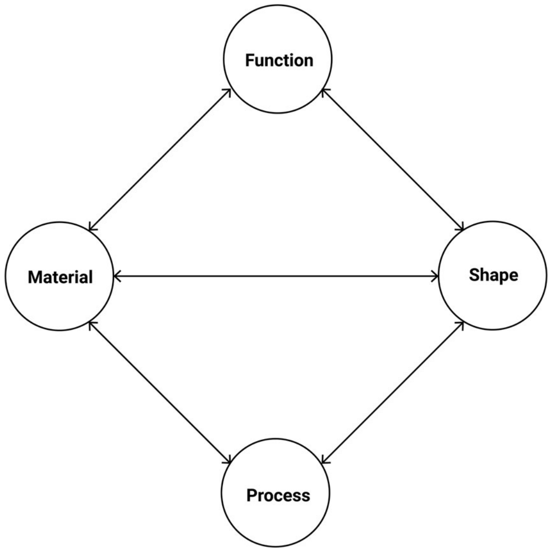

Figure 1.
Ashby's model visualizes the interactions between material, function, shape and process in mechanical engineering.

design methods for textile-based objects would address the waste generated by current methods, but industry-scale methods are primarily for 3D knitting (Shima Seiki 2025), which limits application domains, material experiences, and wider adoption. There has been significant scholarship in the domain of 3D weaving, as revealed in detailed reviews of the development of 3D weaving (Perera et al. 2021), outlined textile technologies for 3D textile preforms (Ishmael et al. 2017). Researchers have also defined the differences between types of 3D weaving (Khokar 1996) and provided overviews of current development (Gries et al. 2022). To create 3D form, researchers have developed (near) net-shape fabrics for composites (Klapper et al. 2021; Schindler et al. 2019; Vo, Hoffmann, and Cherif 2018), 3D woven preforms (Fazeli et al. 2016; Klapper et al. 2021; Zheng et al. 2013), shell woven textiles (Buesgen and Ehrmann 2015; Xiaogang Chen and Ebru Tayyar 2003), circular woven textiles (Bilisik et al. 2014) and 3D freeform weaving (Chen et al. 2024). These examples are situated within technical and engineering contexts, and often utilise specialized 3D looms developed specifically for the work presented. While examples of garment applications with specialized machine setups are limited, there are examples such as a 3D woven bra (Shi et al. 2022, 2024), a 3D woven shoe (Harvey et al. 2019), and the development of circular weaving processes to fabricate parts of garments (Unspun 2024).

Because specialized 3D or circular weaving setups are not widely accessible to textile and fashion designers, this paper focuses on the use of Jacquard harness rapier looms equipped with one warp beam, which are often employed in standard textile design practices. Woven Textile-form Design (WTfD) is a design method to navigate scales of textile, form and material simultaneously for the purpose of designing woven textile-based objects for industrial production. This work does not propose a technical (or machine) innovation. Instead it contributes to design research by adapting existing textile and fashion techniques such as multilayer weaving (Salolainen, Fagerlund, and Leppisaari 2023) and zero-waste design (Rissanen and McQuillan 2015), to provide approaches for zero-waste, on-demand, and locally fabricated garments that reduce post-weaving fabrication steps. We enhance the reproducibility of woven textile-forms by providing a transparent, flexible set of techniques with annotated examples. As such, we aim to broaden the practical applicability of Woven Textile-forms, bringing together textile and form knowledge and allowing designers to prototype within the constraints of commonly available tools.

In the following section, we first explain the theoretical foundation of the WTfD method. We ground our discussion in both design and engineering sources and argue why such a method is needed. We then outline the suggested steps of WTfD using iterations of a woven textile-form trouser (Figure 2) as a primary case and examples from other WTf projects in support. Finally, we identify gaps in knowledge, technology, and infrastructure within the textile industry, setting the stage for future research directions.

Theoretical Foundation

The WTfD method is centered around key foundations that guide our approach to designing and manufacturing WTf's. As the intended audience for this method are designers with diverse backgrounds, we will clarify the key theoretical foundations of our approach in detail, aiming to provide a strong basis for understanding the nuances and implications of the WTfD method within textiles' complex socio-technical system.

- While woven textiles may be commonly understood as materials, within WTfD, a woven textile should be considered a system of materials and processes in interaction. While the components that construct woven textiles and textile-forms can be regarded as hierarchical in scale (Guo et al. 2016; Tandler 2016), they are not in behavior (Scott 2016).
- In Textile-forms, form and textile are equal partners and designed simultaneously (McQuillan 2020; Townsend 2003). Thus, designing woven textile-forms requires a thorough understanding of both textile structure and form design.
- Textile-forms (like all materialized designed products) exist in a socio-technical context beyond design and use-time, and extend to ecological time (McQuillan and Karana 2023)

Figure 2.
Woven textile-form trouser iterations.

- A non-hierarchical and simultaneous approach characterizes the design of Woven textile forms, however, a set of distinct steps can be followed to achieve the desired outcomes. The order in which the design method is followed may vary depending on factors such as the designer's experience, the design scenario involved, and accessibility to necessary machines and software. Therefore, each designer can follow their own non-linear path through the design method.

Textiles as a System

Textile things, according to Hallnäs (Hallnäs 2019), are any things made of textiles – towels, garments, sofa upholstery, fabric, shoes and more. When designing textile things, fashion and soft-goods designers typically understand textiles as a material; flat sheets of fabrics that can be formed into a garment or product. However, most textile designers understand textiles as material systems - composed of yarns with behavior, arranged in weave structures, with a particular expression. Textile thinking expands this understanding by recognizing the intertwined relationship between the cognitive processes involved in designing and the physical act of crafting textiles (Igoe 2021). This perspective views textiles not only as a material to be used in products, but also as embodiments of thought, creativity, and cultural expression (Dormor 2020; Sauer et al. 2023). The embodied cultural component of textile things is perhaps most evident in garments' role in communicating cultural and self-identity (Crane 2000).

In the context of materialized textile design practices, the nuances of textile thinking are often limited by machine constraints and design conventions, and therefore, outcomes commonly manifest as textiles as 'canvases'. There have been efforts to expand these outcomes to and explore material-specific properties (textileness) for animated textiles (Buso 2022; Gowrishankar, Bredies, and Ylirisku 2017), bio-inspired approaches centered on "structure and information" (Kapsali and Hall 2022)] emergent behavior (Walters 2022) and metamaterials (Singal et al. 2024). When these parameters are well understood, designers can utilise these for multilayer weaving (Devendorf et al. 2016; Hemström 2020; Pouta, Mikkonen, and Salovaara 2024), create surface three-dimensional[1] texture (Andersen, Voorwinden, and Goveia Da Rocha 2024; Berthonneau 2017; Graca 2018; Walters 2021), shaped textiles (Huang et al. 2021; S. Wu and Devendorf 2020), enable origami folding (Boon 2016) or create interfaces textiles (Sun et al. 2020; Van Dongen et al. 2022; T. Wu et al. 2020). These examples demonstrate that while textile systems are hierarchical in scale (Tandler 2016), to manipulate change in a textile, careful control of the parameters of yarn, fabric and form is required (Scott 2013).

Form Thinking and Textiles

While 'form' in the context of garment design usually is held to mean its shape, with particular manifestation or configuration of parts that is usually constructed after the textile (as a material) is designed and produced, in textile-thinking, form can be defined as the formula (structure of the knit or weave made of material) without a fixed idea of shape (Hallnäs 2018). Simultaneous design (Townsend 2003) attempts to bridge the gap between textiles and form by framing a practice for garment design that occurs at the intersection of body, textile and form, while textile-led fashion design (Salolainen, Fagerlund, and Leppisaari 2023) approaches frame textile design as part of a fashion design method by integrating textile thinking in fashion studies (Piper 2019).

Textile-Form Thinking

Textile-form (Tf) design is an approach that fabricates products with form at a macro scale (e.g. garments, furniture or buildings), by utilizing fibers and yarns in a textile formula to generate complex micro and macro topologies. When designing Textile-forms, 3D-thinking of a different scale to what textile design usually considers is required to deal concurrently with a macro and micro understanding of form, simultaneously 2D and 3D (McQuillan, Walters, and Peterson 2021; Walters 2021). Various techniques such as knitting (Albaugh, Hudson, and Yao 2019; Liu et al. 2021), weaving (McQuillan 2020), non-woven moulding (Peterson 2022), 3D printing, and growing (Zhou et al. 2021) have been explored in creating textile-forms. Beyond their potential for sustainable manufacturing, Tf's can also achieve unique material functions and expressions, creating opportunities in fields such as HCI (Buso et al. 2024; Huang et al. 2021; Meiklejohn, Devendorf, and Posch 2024; Zhu et al. 2023), product design (Lefferts 2016b), and medical applications (Li et al. 2013) and some, are already in use in industry (Uniqlo 2022; Unspun 2024).

In weaving, Anni Albers already recognized the potential of multi-layered (Albers 1959) and shaped (Albers 2017) textiles, but believed that the possibility of form on the loom was lost with their industrial mechanization. This perspective seems confirmed by the tendency of many contemporary examples of macro woven form to be hand-crafted (Deshpande, Takahashi, and Kim 2021; Jongerius 2021; Sekimachi 1996). Woven Textile-forms (WTf) as an alternative for cut and sew have been explored using unmodified hand looms (Minami 2022; Piper 2019), hand looms with modifications or additional components (Cnaani and Sterman 2023; Drews, McQuillan, and Mosse 2023; Steinmetz n.d.), or developed on specialized looms such as 3D looms (Shi et al. 2022), or novel loom technology (e.g. Unspun).[2]

The potential for WTf to simplify supply chains, and reduce over-production, waste, and reliance on manual labor within cut and sew (McQuillan 2020; Shi et al. 2024) means that the use of existing, available industrial jacquard looms has been an important area of research. The earliest known industrial jacquard WTf for the garment industry was produced for Issey Miyaki in the 1980s (Miyake 2024). Recently, research in this field has explored the use of digital jacquard looms and elastic yarns to generate surface patterning and shaping (Lefferts 2016a). Many examples focus on the creative potential of such approaches (Konings 2024), some explore the use of active or engineered (Buso et al. 2024; McQuillan 2020; Voorwinden et al. 2025; Walters, Devendorf, and Landahl 2024) yarns for WTf's, while others are speculative provocations of the future (McQuillan, Walters, and Peterson 2021). In the fashion industry, examples of jacquard WTf are rare, Issey Miyake has re-explored weaving whole garments with reactive yarns (Miyake 2024), fashion brand Liquid Editions and Weffan (*WEFFAN* 2023)[3] developed woven trousers to explore the relocalization of UK fashion industry.

Multimorphic Textile-forms (McQuillan 2020; McQuillan and Karana 2023) expands textile-form design to consider the qualities and behavior of material and form to enable change in design, production, and use-time through multiplicity and extended life cycles. The Multimorphic Textile Systems model (McQuillan 2023) grounds abstract and theoretical concepts of holism in anthroposystems and ecosystems with descriptions of concrete design prototypes. Multimorphic textiles have been explored regarding their multisituated performativity for users (Buso et al. 2024), and the sustainability, user experience and industrial implications that arise in the design-production of jacquard WTf have been explored (McQuillan et al. 2023).

Despite all of these efforts, there still remains a lack of published research articulating in detail the design methods for WTf's produced on standard jacquard design machinery and software - a crucial step required if these approaches are to be adopted more widely.

Woven Textile-Form Design (WTfD) Method

Having worked in textile, fashion and design domains for a considerable time, we have gained experience across a large number of WTfD projects, including developing zero-waste fashion design methods for WTf's (McQuillan 2019), designing an industrially WTf denim jacket (Vroom 2022) and denim jeans (Groskamp 2024), designing morphic WTf using heat reactive yarns (Buso et al. 2023b), wool (Arts 2022), the hygromorphic properties of linen (van Looveren 2023), SMA yarn (Chrysikou 2023), designing performativity in WTf interfaces (Buso et al. 2023a, 2023b), and designing for industrial WTf (Milou Voorwinden's ongoing PhD research). Learning from these projects, reviewing the advantages and disadvantages of steps in the design process (including in educational contexts e.g. (Drews, McQuillan, and Mosse 2023)), and drawing upon theoretical foundations introduced in this paper, we developed the Woven Textile-form Design (WTfD) method to facilitate design processes in which textile and form are designed to be woven simultaneously on industrially available jacquard looms. To aid designers, we envisage four scenarios where designers can apply the WTfD Method.

1. Outcome-driven: The idea of a specific product, behavior, function, or outcome drives the process. For example: the trousers we use as the key example in this paper, or Zero Waste Weavers (McQuillan, Walters, and Peterson 2021).
2. Form-driven: Where a designer begins with an abstract notion of a form to flat transformation - for example: an unfolding three-layer pleat in paper for possible interactive experiences (Buso et al. 2023a).
3. Material-driven: Where a designer has a specific material or textile structure they wish to explore (for example: a specific structure like the expandable binding (Buso et al. 2023b) or a particular yarn property such as heat reactive (Buso 2022)).
4. Process-driven: Where a designer has access to a particular loom or tool and wants to explore how it could facilitate novel outcomes. (for example: (Voorwinden et al. n.d.))

In this paper, we will describe the development of the WTf design method (Figure 3) using iterations of WTf trousers (Outcome-driven) as an illustrative case (Figure 2). For the sake of clarity and ease of understanding, the following sections present the method as a linear process (Figure 4), beginning with the desired outcome and concluding with the construction of the garment. Nonetheless, it is crucial to recognize that the actual method is inherently non-linear and frequently necessitates the simultaneous consideration of various stages. To facilitate a thorough understanding, we have segmented the design process into four distinct parts, based on our

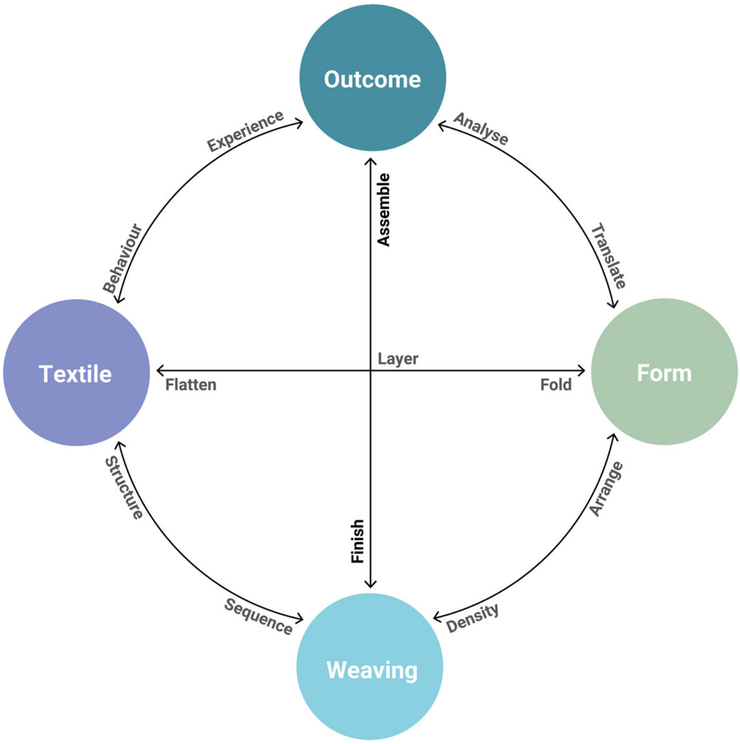

Figure 3.
The WTfD method.

interpretation of Ashby's model, each serving as a foundational building block for the subsequent phase. Through detailed descriptions of each segment, we aim to clarify the interconnections and relationships among the different sections, thereby offering a comprehensive overview of the entire process.

Outcome

Determining a set of prioritized design requirements for the intended outcome can be an initial step in WTfD. For outcome-driven jacquard WTfD outcomes, designers first have to establish the desired non-developable surface (3D form), analyze how this can be translated into a stack of developable surfaces (folded) so that it can be woven flat on a loom[4], and unfolded into a version of the original 3D form. In tandem, designers must consider the material experience and textile behavior desired and identify the goals relating to sustainability and form fidelity within the limitations of available technology (Figure 5).

Identification of Design Requirements: Analysis and Translation

In WTfD, the relationship between form and textile *via* flattening is complex and non-linear. For example, the flattening process that

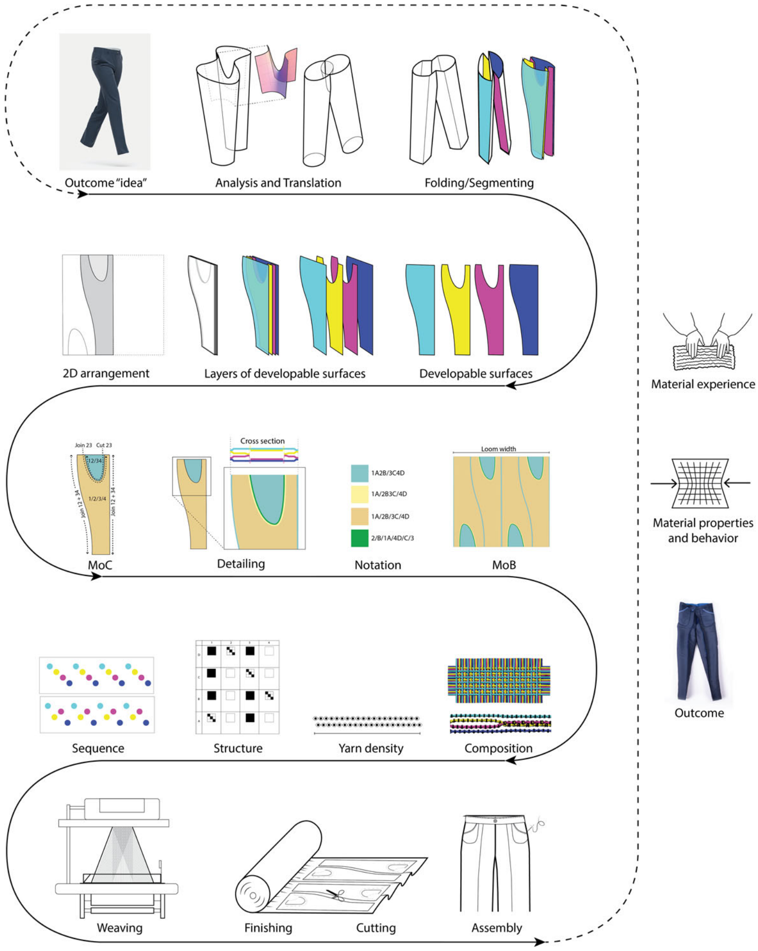

Figure 4.
Visualization of the process steps taken in the development of WTf trousers.

generates developable surfaces usually requires some generalization of the non-developable surfaces. Therefore, decisions made regarding how the form is segmented or what axis is used for flattening will likely result in a change in the original form. If the resulting textile is isotropic, then maintaining high-fidelity with the original form (non-developable surface) will be difficult or impossible without segmentation. The fidelity of the flattened design to the original form is a decision that should be based on design requirements. Additionally, it may be desirable to weave a design inside-out so that after weaving, seams can be turned to the interior of the product to achieve a more conventional aesthetic. This requires consideration of form for this assembly approach, attention to weave structures (particularly those with aesthetic differences on each face, such as warp-faced twills) and its impact on the number of post-weaving production steps.

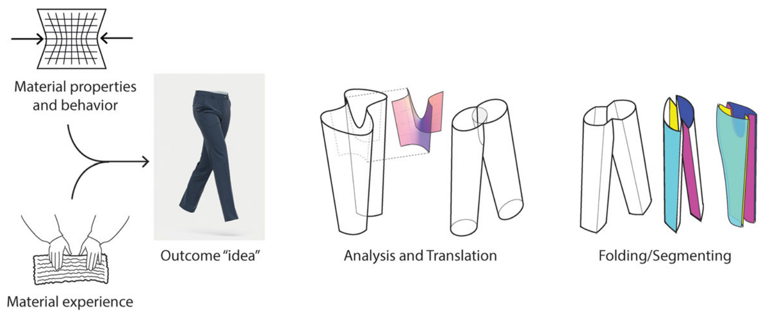

Figure 5.
To determine design requirements for the intended outcome designers must consider the material experience and textile behavior, and identify the goals relating to sustainability and form fidelity within the limitations of available technology.

Textile material properties and behavior should also be a part of establishing the design requirements. For example, the material properties should align with user expectations and needs if a garment is worn on the body, such as a trouser. These requirements can impact other elements of the WTfD method, such as what loom or yarn is used, or the number of layers the form is flattened into. The integration of wider needs regarding sustainability should be incorporated here, as this will have impact on choices such as yarn selection, arrangement of elements on the loom for zero waste, or the reduction of segmentation to enable greater automation.

This step results in the development of a set of design guidelines or goals (e.g. product type, material experience, sustainability, automation, cost) whose priority is determined by the motivations for the project.

Form

The design requirements will determine the approach taken to translate the form. All WTf require the designer to translate non-developable surfaces into developable surfaces - commonly called flattening (Yuan, Cao, and Shi 2023). While not referred to in this way, this translation is also part of routine processes with established norms within garment pattern cutting[5]. In conventional cut-and-sewn garments made from isotropic 2D textiles, the pattern-cutting process of segmenting and unwrapping is necessary to make complex forms. In WTfD, however, not all tubes need to be segmented or unwrapped because they can be woven as a (folded) tube. While not all complex forms require segmentation, in general, the more complex the geometry of the non-developable surface is and the more fidelity to the original form the design requires, the more segmentation is required. The outcomes from form analysis and inputs from design requirements will determine the approach for segmentation and the axis used for folding (Figure 6).

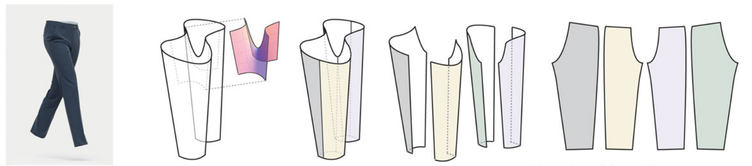

Figure 6.
Segmenting and unwrapping a trouser for cut and sew. Basic trouser form has one main area of form complexity - where the two legs (tubes) intersect at an angle, forming a hyperbolic paraboloid. This which is where conventionally constructed trousers are segmented. The resulting tubes (legs) are segmented down their length (from waist to hem) usually at either the sides of the body or inseam, or both, so they can be "unwrapped" into flattened developable surfaces used to make garment patterns.

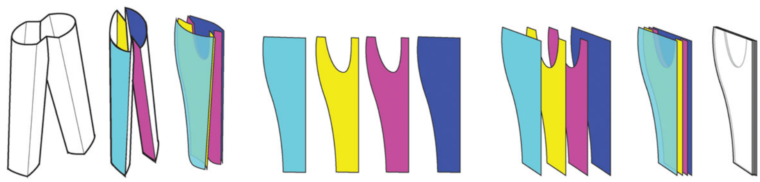

Figure 7.
Caption: Folding, segmenting, unwrapping to developable surfaces and stacking for Trouser Woven Textile-form.

Flattening

Next, a WTf designer must flatten the form into a 2D format (Map of Bindings) so that it can be used as input for the textile design process. To achieve this, designers must take into account overall design requirements in combination with elements such as loom specifications and the materials utilized in the warp and weft (Figure 7).

Flattening for jacquard WTfD requires an understanding of how to translate the non-developable form into developable surfaces that are (in some areas) stacked in layers. As the total number of warp yarns per cm on a loom is divided across the number of layers in a stack (known as fractional density—Figure 8), the maximum number of stacked layers is constrained by the desired fabric behavior and material properties that results.

Once the maximum number of layers is known (see also section on warp and weft systems), designers fold and/or segment the non-developable surface so as to flatten it into developable surfaces. Folds are two or more layers of developable surfaces with matching and aligned perimeter geometry. These expand out to the form without post-weave construction. In jacquard WTf (that is woven on a rapier loom), any fold needs to be translated into a woven 'seam' which takes space in adjacent areas.[6] Multiple axis can be used for

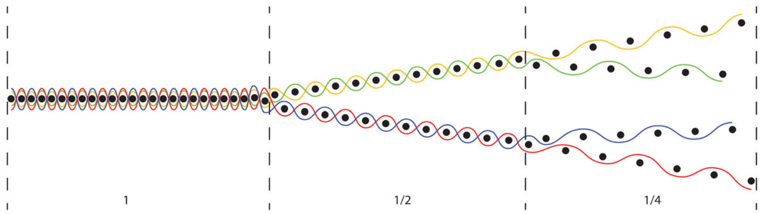

Figure 8.
With the separation of each layer, the warp and weft yarns divide over the layers, thus resulting in a fractional density.

flattening, particularly if the non-developable surface is segmented, and each subassembly can then be flattened along its own axis (such as the sleeves and body of denim jacket (McQuillan et al. 2023)). If seeking increased automation, the appropriate axis for flattening is the one that requires the least segmentation as this minimizes post-weaving construction. Segments have edges with non-matching/non-aligned perimeters, their 2D arrangement relative to other segments is non-defined and (usually) require post-weaving construction. Segmenting should only then be done if it is required, as segmented subassemblies will require sewing to reconstruct them.

2D Arrangement

The exact shape and arrangement of the flattened forms is determined in the Map of Construction[7] (MoC) - like a kind of "garment pattern" for woven textile-form. In WTfD, the width of the jacquard repeat informs the shape, size and arrangement of the perimeter geometry of the flattened form. Segmentation can also ensure the shape of the resulting subassemblies nest efficiently into the fabric width. Here, segmentation is informed not only by the 3D geometry but also, as shown in Figures 9 and 10, by how the 2D geometry of the resulting developable surfaces will fit within the width of the jacquard repeat without making cutting waste.[8] WTfD provides flexibility to ZWFD (Rissanen and McQuillan 2015), as this arrangement can occur both in relation to the surface of the textile (*x* and *y* axis) and its cross-section (*z* axis). Designers of WTf need to consider the shape of each zone's perimeter, the number of layers in each zone, and the differences and relationships between adjacent zones.

In the MoC,[9] a simple layer notation coding can be used to indicate layers (in pairs of warp and weft) when communicating. For example, in a 4 layer system, a notation of 1/2/3/4 represents 4 separate layers, while 1/23/4 indicates three layers where systems 2 and 3 are interwoven to make a single layer. This notation system can also communicate layer order change, for example 23/1/4.

The outcome of this step is a Map of Construction comprised of interlocking 2D shapes (zones) with technical colors and layer notation codes that indicate the number of layers in these zones

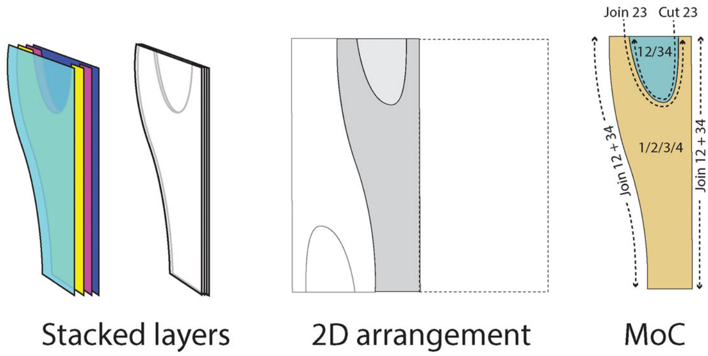

Figure 9.
The layers of developable surfaces are stacked, and a layer notation coding can be used to indicate layers.

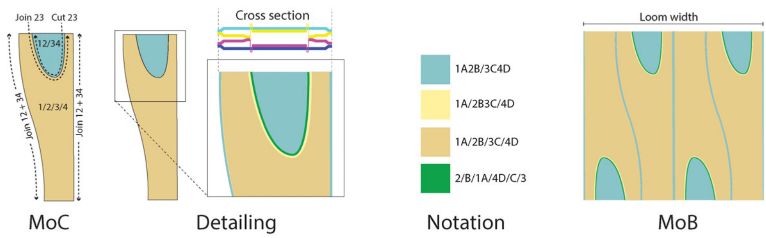

Figure 10.
Translation of the MoC to the MoB.

(Figure 10), and fold/edge indication, which is then used to develop the Map of Bindings for jacquard WTfD.

Map of Bindings

Next, the MoC is translated into a Map of Bindings.[10] Here the number of layers, perimeter geometry and fold/edge information contained in the MoC, along with loom and material specifications is used to determine location and width of any woven seams or cutting areas, and to encode with warp and weft notation required for developing specific weave structures and composition for programming the jacquard WTf. The weave structure zones are determined by the 2D shape and number of layers generated in the flattening process, and are therefore a 2D representation of the stacks of developable surfaces which enable the desired 3D form to be encoded in the 2D format of a MoB. Often a MoB (in its entirety or a subassembly) can be repeated across the width of the jacquard loom a number of times (Figure 11), depending on the width and repeat size of the loom. In the case of the trouser, this was achieved in a variety of fit and style variations all without negative space or waste between each Trouser. The cutting waste generated from this approach for this trouser design is approximately 0%, in contrast to the industry-reported

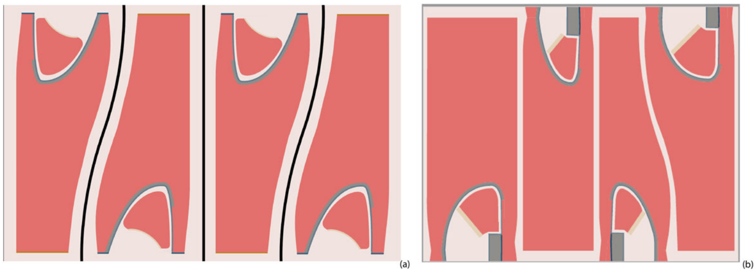

Figure 11.
Left: 4 identical trousers are repeated across the width. Right: Two style variations are woven in two different sizes to demonstrate the flexibility of the method when a full repeat jacquard loom is used.

average for cut and sewn garments of 15–25% (Niinimäki et al. 2020; Runnel et al. 2017).

Each color of the MoB has a corresponding layer notation that indicates where in the cross-section warp/weft should be placed to make layers and if it is interlaced.[11] The relationship between adjacent colors in the MoB determines the transition from one layer notation to another,[12] which, in combination with its fold geometry and edge cutting information, determines the resulting unfolded form.

The basic layer coding system in the MoC is extended in the MoB to encode the movement of individual warp or weft systems within a layer order. The warp is numbered (1, 2, 3, 4), while the weft is lettered (A, B, C, D), resulting, for example, in layer notation that may read 1 A/2B3C/4D for a 3 layer structure constructed from four warp and four weft systems.[13] The layer notation system can also indicate if layers are reordered, for example changing 1 A/2B3C/4D to 2B3C/1A/4D. Additionally, if certain warp (or weft) systems are interlaced or not, for example the notation 23/1AB/4CD, communicated that warps 2 and 3 are not interlaced with any wefts, and so are floating.[14]

The outcome of this step is a MoB which includes the arrangement of zones relative to each other within the width of the loom repeat, seam and cutting information, and warp and weft layer notation.

Textile Composition

The MoB's outcome and associated notations are the input for the textile design process. This phase of WTfD dives deeper into the textile hierarchy, focusing on yarn-level interactions. In this phase the designer translates the MoB, where the colored zones are technical indications of warp and weft systems and layer relationships, into all aspects of the textile composition, determining not only where the warp and weft yarns are distributed and ordered (arrangement) but also how this is done (structure). As in all phases of the WTfD method, the process needs to be understood in relation to the other aspects of the design process and the technology used.[15] For example, the material choice, both in weight and fibre type impacts sustainability and material experience goals, but is dependent on the warp density and amount of layers. Thus, knowledge of the design requirements, weaving process, and post-processing are needed. Furthermore, the process of determining the textile arrangement and structure is iterative because the choice of yarn, density, and order influences the yarn systems, sequence, and interlacements, and vice versa.

Textile Arrangement

The textile arrangement is all the elements that determine what and how yarns are placed on a loom. It is defined through the yarn choice, density, and order in both warp and weft directions. Certain aspects, such as the weft selection, may be readily adjusted during weaving, while others, such as the arrangement of the warp, require significant investments of time and resources. For this reason, designers often use the existing warp arrangements available on (industrial) looms. While there are many opportunities to utilize material properties and special loom configurations,[16] we will focus on utilizing common (jacquard) loom configurations for WTf in the following sections.

Yarn Density and Yarn Choice

The material and density of the warp can be selected by considering what is possible on the available loom, the necessary number of layers, and the preferred material qualities. Unlike specialized 3D weaving looms where the warp yarns are arranged grid-like (Khokar 2001), a ‘standard’ industrial loom arranges the warp as a single layer with yarns side by side (Figure 12a). How these yarns are distributed determines the warp density (ends per CM). In WTf the warp yarns are divided across layers, resulting in fractional density (Figure 8). Selecting the warp material and density is therefore often focused on compensating for the fractional density.[17] Differences in density and yarn choices impact the structural and aesthetic quality of the fabric (Figure 12). WTf’s fabric instability caused by fractional density can be addressed by increasing the warp coverage (Figure 12e-f).

Weft yarn density[18] is determined differently in multi-layered fabrics compared with single-layered fabrics. This is because achieving adequate material density across multiple layers can be challenging, especially when warp materials and density cannot be altered to compensate. Through determining the desired density of each individual layer and then adjusting the overall density accordingly, the negative impacts of fractional density (poor fabric handle for example) is reduced. Although this approach makes single-layered sections denser, adjustments in weave structures can mitigate any density

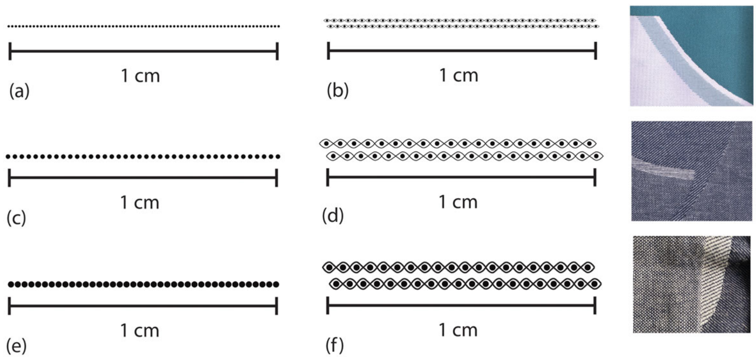

Figure 12.
Differences in warp coverage the warp arrangements outlined in fig.a b and c all present a different warp coverage (a) Polyester 78 Dtex warp, 76 EPC, warp cover factor 0.61 (b) Warp a woven in two layers, showing fractional density (c) Cotton 20 Ne warp, 40EPC, warp cover factor 0.64 (d) Warp c woven in two layers, showing fractional density(e)Cotton 10 Ne warp, 40 EPC warp cover factor 0.88 (f) Warp e woven in two layers, showing fractional density.

Figure 13.
In this example, the density was altered below the red stripe on the garment, resulting in a darker appearance and more material in that portion of the fabric. First trouser iteration shows tests in two different weft densities, divided by a red line drawn on the fabric (a) The first trouser iteration in flat fabric state (b) the cut and unfolded garment (c) Detail of the pocket.

problems during the weaving (see structure and interlacement in the next section) (Figure 13).

Yarn Order and Yarn Choice

The next consideration in the design process is the yarn order, which is the placement of selected yarns in the x-axis for the warp and the y-axis for the weft direction.[19] Warp order is typically difficult to change as it requires installing a new warp on a loom, however, controlling the order of weft yarns is a common textile design strategy. The weft yarns can have different properties (e.g. material type, diameters or color), and the order of weft material can be assigned to have a regular pattern, or by assigning yarns irregularly to make horizontal bands of weft material in the MoB. In the majority of WTf trousers we have developed, the order of weft and warp yarns is uniform/consistent across the whole design.[20]

Textile Structure

The textile structure consists of all the elements determining how the textile arrangement is controlled. It can be determined by selecting warp and weft systems, sequencing the yarns in these systems, and using a particular type of interlacement (weave structure). In most industry software, the systems, sequence, and interlacement can all be controlled per zone of the MoB, but it is also important to consider how the yarns are arranged in transitions between zones.

Warp and Weft Systems When selecting warp and weft systems, it is important to consider the MoB, textile arrangement, and the layers in the design. Most industry software represents the warp and weft systems through a table, and this table will allow the designer to choose structures for each warp and weft intersection (Figure 14). While in most cases the warp and weft systems are equal to the notation in the MoB, this is not always the case. The systems are not direct representations of warp and weft yarns, but represent the rows and columns used for designing weave interlacements. The number of warp and weft systems used can vary between zones, but over the MoB as a whole designers should consider how the yarns transition between each zone to ensure the desired form unfolds as intended. The overall number of systems is a factor of the maximum number of layers and the most used/important number of layers in a design.

Yarn sequence The sequence determines how warp and weft yarns are grouped within a weave structure or zone of the MoB. In the textile arrangement, the overall yarn allocation is determined on a fabric level, but the sequence dives even deeper into the textile hierarchy allowing for further refinement of the yarn placement within a zone.

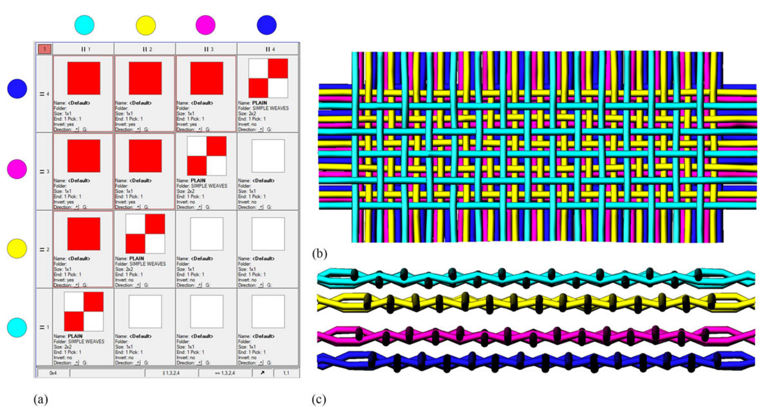

Figure 14.
Table weave and resulting interlacements (a) the table (b) Cross-section of the structure shown in the table (c) top view of the fabric.

Allocating warp or weft yarns in a specific sequence can stabilize the fabric structure and enhance its appearance. There are several methods to distribute warp yarns across layers. In the trouser design, seams are created by placing two-layered zones (1A2B/3C4D) adjacent to a four-layered zone (1 A/2B/3C/4D) for the trouser legs. However, various approaches exist to divide the warp yarns over these layers. Figure 15g depicts a linear order of the four-layered structure (1/2/3/4). However, this sequencing results in uneven yarn distribution when it transitions to a two-layered zone (12/34) (see Figure 15b). Alternatively, another arrangement could involve altering the warp sequence to 1/3/2/4 (see Figure 15h and c), facilitating a more even distribution of warp yarns within the two-layered zone[21] (13/24).

In some cases, an uneven distribution of warp yarns through changing the yarn sequence can also support the structural qualities of the WTf. For example, when weaving a pocket, one side of the fabric can be constructed thinner to serve as the pocket lining, which typically requires a more lightweight material. Figure 15d shows an example of a distribution of yarns for two layers. Weft 1,2 and 3 are used in the top layer to weave the outside of the pocket, while weft yarns 4 weaves the lining.

Yarn Interlacement How yarns are interlaced in a woven textile significantly impacts the fabric's stability and its overall aesthetic properties.[22] In certain weaves, like the satin weave, there are fewer interlacement points, enabling the yarns to compress. Weave structures like the tabby weave contain a high number of interlacement points, and thus do not compress. To create a well-balanced fabric with stability across multiple layers and zones, it's essential to leverage these characteristics of weave structures.

Multiple strategies are available to utilize compressing weaves (e.g. compound, interlacing or non-interlacing double cloth (Walters

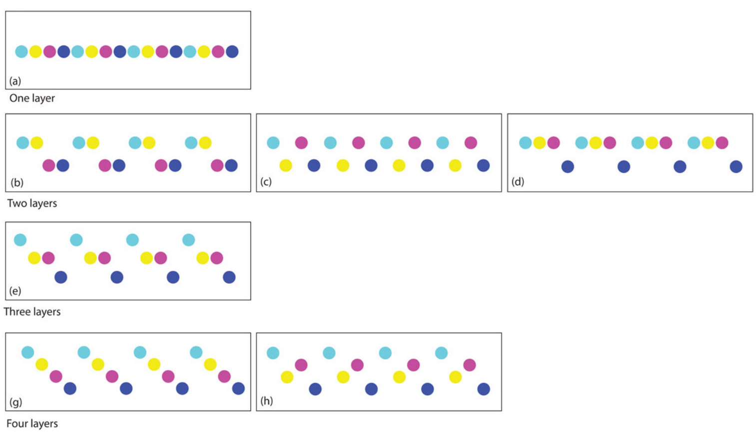

Figure 15.
Options for warp and weft sequences.

and Kapsali 2023), floating threads) in combination with non-compressing interlacements. To illustrate the use of compound weave structures in seams, Figure 16 shows a textile that transitions from a single-layered zone on the left (1A2B) to a double-layered zone on the right (1 A/2B). In WTf's, It is important that these compression properties are considered at structure, zone and form levels. At a form level, it can result in weaving whole products that are not the correct length. At a zone level, where exact shapes are important, for example, crotch seams in trousers, compression and elongation must be accounted for when designing the MoB. Furthermore, a sufficient number of interlacements per cm is required in areas such as seams to ensure stability.[23]

The flexibility in selecting yarns for each layer, along with the capability to construct layers that incorporate multiple warp and weft systems, opens up avenues for altering the order in which yarn systems are interwoven. A fundamental application of this is the rearrangement of yarn placement within a compound structure, a technique frequently employed by jacquard designers to create visual patterns, as demonstrated in Figure 17. Our research has revealed an additional practical advantage: seams woven in this manner tend to exhibit reduced fraying and slippage depending on the choice of fibre/yarn type and weave structure used. For instance, in the scenario depicted in Figure 17, layers 2B and 3 C are interlaced within the middle layer, with yarn C being positioned at the top of this layer, and yarn B at the bottom. In most examples presented in this paper, we have chosen to weave all fabric layers in a zone with the same weave structures,[24] however, it is possible to choose the type of weave structure in each layer. In some examples, we experimented with alternating weave structures to create a cohesive surface pattern across the folds (Figures 17 and 18).

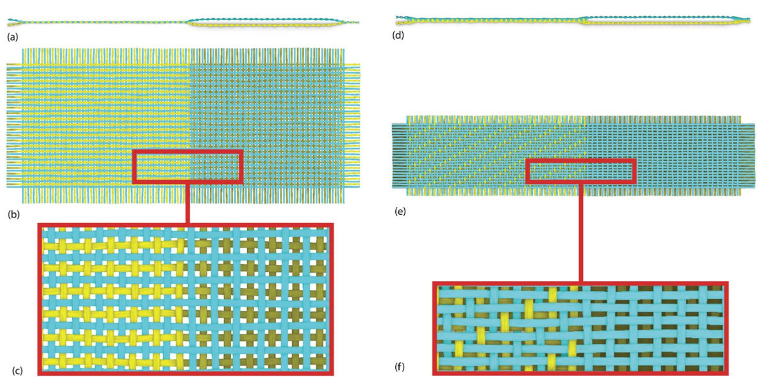

Figure 16.
Textile where the weave structures are unbalanced. Left section plain weave, right zone double cloth with plain weave (a) Cross-section of the two zones (b) Face view of fabric structure (c) Detail of face fabric structure (d) Cross-section of the two zones (e) Face view of fabric structure (f) Detail of face fabric structure.

Figure 17.
Iteration four (a) the fourth trouser iteration in flat fabric state (b) the cut and unfolded garment (c) Detail of the pocket.

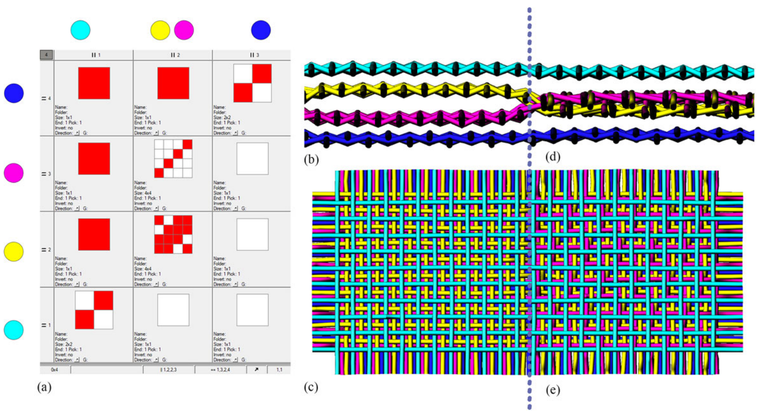

Figure 18.
Table weave and resulting interlacements (a) the table weave for 1 A/2C3B/4D (b) Cross-section of 1 A/2B/3C/4D (c) top view of 1 A/2B/3C/4D (d) Cross-section of 1 A/2B3C/4D (e) top view of 1 A/2B3C/4D.

Weaving and Finishing

Upon completion of the jacquard design process, the designer is able to export their design to a loom file, which typically comprises the design, weft selection order, and additional information regarding density and the regulator. Unless meticulously calculated, weft density necessitates iterative finetuning for the specific combination of materials and weave structures. Thus, it may prove useful to develop a sample blanket prior to weaving the design to test multiple densities, in order to reduce the need for multiple alterations to the final design.

While most variables are predetermined in the jacquard design process, some variables require fine tuning on the loom. For example, a reduced weaving speed may be required[25] when weaving a WTf, particularly during the sampling phase. Another important variable to attend to in the weaving process is how the loom handles the tension of the warp while weaving complex MoB with variable weave structures comprised of different layers. When the multi-layered fabric zones are relatively large, and/or a big production of garments is woven, the designer needs to consider different yarn consumption of the different zones, particularly involving long vertical lines (ref warp tension/consumption paper). The more irregular and non-linear a MoB is, the more likely these differences in warp tension can be managed by the loom.[26] If warp tension problems are noticed while weaving, the weave structures used and/or the MoB zone shapes can be adjusted to better balance warp tension.

Loom Constraints

While there are looms that are specifically designed for 3D weaving, in general, the majority of industrial jacquard looms are developed and configured for weaving flat fabrics. Therefore, most likely, the designer will encounter some challenges regarding density, fabric take-up and warp tension specific to conventional looms.[27] A common constraint of the machine setup can be the repeat of the jacquard, which can vary in width and repeat direction. Some trousers we have developed (Appendix A) were developed on a loom where the repeat was unequal in size—making a zero-waste pattern impossible. In general, a jacquard with a full width repeat will be the most flexible set up for WTf [28] that is still somewhat commonly available.

Fabric Finishing

In many industrial mills, fabric undergoes a step known as fabric finishing after the weaving process. The primary objective of finishing is to augment the fabric's properties to meet specific functional or aesthetic requirements for its intended use. For instance, some trouser examples (Appendix A) utilized standard industrial finishing processes like singeing, sanforization, and garment washing to achieve common denim material experience expected of jeans.

While our exploration hasn't delved deeply into finishing processes for WTf's, these iterations gave us some insights in the challenges and opportunities for WTf's. Given the complexity of multi-layered fabrics, there are opportunities to fine-tune shrinkage and leverage differences in shrinkage to shape the fabric. For example, one layer could be woven with a fibre and structure that shrinks more than another layer, allowing for the creation of non-developable surfaces (Xiaogang Chen and Ebru Tayyar 2003). While this technique can aid in shaping, it also presents challenges. Conventional finishing processes aren't optimized for multi-layered fabrics, leading to slight movements and folds during finishing. Moreover, when more than two layers are woven, it's essential to investigate if the finishing process adequately penetrates the inner layers of the fabric.

Cutting

After weaving and finishing the WTf, certain predefined zones must be cut to separate the layers and allow the intended form to emerge. This cutting process can be carried out manually or with the aid of automated machinery such as a laser cutter or CNC machine. The cutting process differs significantly from conventional fabric cutting processes, particularly in the fashion industry, where many ply's of fabric are stacked and multiples of each pattern piece is cut simultaneously. In WTf, automated cutting processes should be daisy-chained after the weaving process (and fabric finishing if used) so that single-ply lays can be automatically cut.

While cut lines can be either be on the inside or outside of the fabric, through our exploration, we recommend that layers or yarns that need to be cut be transferred to the outside/topside of the fabric.[29] This enhances efficiency and accuracy in fabrication and enables automated cutting. These cut layers can either be floating (without interlacement), or integrated into a woven structure, each approach offers distinct advantages. For instance, floating yarns, result in a more visible cutting line, while a woven structure facilitates a slightly easier cutting experience,[30] particularly when done manually due to reduced risk of missing a thread.

Assembly

Once the WTf is finished and cut, some assembly may be required—such as sewing with a manual sewing machine. The extent of assembly required is dependent on the approach taken in prior steps, and requires balancing between desired design requirements such as adhering to norms (in terms of outcome form or detailing), seeking a reduction in manual labour, and waste minimization. While woven (instead of sewn) 'seams' may fray when cut, this can be mitigated with the use of composite weave structures designed to lock in yarns, consideration of angle of the cut line relative to the warp, and the use of cutting methods such as pinking shears. Trousers woven and cut as described in Appendix A are undergoing user testing in ordinary use and care processes. While some of the woven seams show a degree of fraying, the integrity of all seams is maintained (see Figure 19 for photo of washed trouser seams) at a high enough standard for continued use. Furthermore, weaving processes such as shuttle insertion and leno weaving can be explored together with the methods presented in this paper to arrest the unravelling of seams fully.

The WTf trouser was initially designed for 4 layers, enabling the assembly steps to be significantly reduced. A cut and sew trouser of a comparable design would require approximately 7 pattern pieces each overlocked to prevent fraying, and 14 plain sewn seams: Leg side seam (L + R), Patch pocket opening hem (L + R), Patch pocket

Figure 19.
Close-up of the outside leg woven seam after 3 months in ordinary wardrobe rotation (worn ~20 times, and washed ~5 times).

sewn to trouser leg (L + R), Leg inseam (L + R), Crotch seam, Zipper insertion, Waist band (attach to body and turned over), Leg hem (L + R). In contrast, the 4-layer Woven Textile-form trousers are a single interconnected pattern piece, and only require 5 plain sewn seams to achieve the same level of finish: Leg hems (L + R), Patch pocket opening hem (L + R), Zipper insertion, and Waistband turndown. Additionally, compared to cut and sew garments which almost always require overlocking on all cut edges to prevent the fraying seen in most ordinary woven fabrics, the woven seams in WTf reduce or eliminate the need for overlocking - further reducing assembly steps. In later 2 layer iterations the right and left legs were designed to be woven as subassemblies that were sewn together at the crotch seam while the zipper was inserted.[31] This approach also enabled the trouser legs to be woven inside out and the seams located internally after assembly (Appendix C) which results in a more normative garment aesthetic.

While other product finishing processes such as garment washes are able to be applied as in conventionally constructed textile products, there is potential to integrate such effects within the textile and weaving process. For example, denim wear patterns can be woven into the fabric, rather than achieved through water-intensive washing processes. Consideration for how product finishing approaches are optimized, and when they are applied is a key part of the design requirements identified earlier. How consumers experience the material and outcome, what is possible in the context of this technology, and how social and environmental concerns can be addressed, comes together holistically in the final outcome (Figure 20).

Discussion

This paper introduced the WTfD method, developed to help designers enhance their skills in creating Woven Textile-forms on industrial jacquard rapier looms. WTfD aims to deepen designers'

Figure 20.
Iteration 10 of the WTf trouser. This is a zero-waste.

understanding of how the various facets of WTf's, such as outcome, form, textile and weaving are interconnected. The WTfD method has been developed through a four-year-long design research project focused on creating WTf trousers, collaborations with industry parters, developing different products (e.g. bags, denim, RTW, interiors, costume design), as well as extensive experience teaching students (Arts 2022; de Jager, McQuillan, and Mulder 2024; Groskamp 2024; Vroom 2022), and is underpinned by theories from textiles, material science, and HCI.

A key factor that emerged in the development of the WTfD method is the importance of understanding textile and form holistically and as interconnected parts of a socio-technical context beyond design and use-time, and extend to ecological time (McQuillan and Karana 2023). Embedded in textile thinking, we consider woven textiles a system of materials and processes in interaction, and the act of designing WTf's equally involves cognitive and physical processes (Albers 2017; Igoe 2021). In addition, it includes considerations of the body and/or object, systems of production and supply chains, and understanding dress as an important socio-cultural signifier (Crane 2000).

WTf designers need to hold in mind and shape many things simultaneously (ref simultaneous design, multimorphic design). For example, WTf designers consider the loom width and properties, material selection, alongside how the form is flattened and arranged in order to reduce waste and fabrication steps, while also ensuring the structures and form are designed so that the fabric hand and final aesthetic is suitable for the intended application. Designers wanting to explore WTfD should leverage their existing strengths and skills, such as fashion designers' pattern cutting skills and textile designers' understanding of woven structures. However, WTfD requires a fundamental reimagining of how textile-based form can be developed; what a textile is, and how they are both designed and fabricated. Designing each in isolation is difficult, likely to fail, and limiting. Thus, challenging disciplinary hierarchies and opening textile discourse to broader conversations is needed (ref. Igoe). In developing this design method, we worked as a team, one of us with a fashion design background, the other a professional jacquard designer, and in this paper, we present the tools and processes used to effectively collaborate and communicate. Leveraging differences in designer's experience in textile and/or form design can mean that the WTfD process is approached differently. In our experience, juggling these multiple factors and engaging in these collaborations becomes easier with time, as initially novel processes become established ways of working. This paper aims to support designers navigating this steep learning curve, and a priority of our future research is to develop software and tools in support of these complex cognitive processes. Additionally, while we have presented a sequence of steps based on a form or outcome-driven scenario; following other textile design-centric scenarios might alter the way in which the steps are conducted or the depth to which they are explored. Therefore, each design process can follow its own non-linear path through the design method.

In addition to being non-linear, WTfD is also multi-scalar and temporal. Designers are navigating materials over time at different scales, in interaction with novel technology and systems of production, existing and changing user expectations, industry norms and requirements, societal needs and ecological limits. This complexity is both an opportunity and a challenge. Generalized frameworks such as circular design (McArthur 2017) or those specific to textile-form such as multimorphism (McQuillan 2020) can aid in determining appropriate motivation, contexts, and evaluation approaches used within WTfD. Our experience so far has shown that the process of creating WTfD and the resulting artefacts can facilitate deep reflection of the norms of existing systems, and provide a tangible demonstration of other ways of designing, making and experiencing textile products.

One practical challenge designers might face is expensive and hard-to-access industrial machinery and software. Although it is possible to prototype WTf's with accessible tools like Adacad (Devendorf et al. 2023; Friske, Wu, and Devendorf 2019), Photoshop, the TC2,and shaft-looms this process can be time-consuming and, at times, incompatible with industrial processes. However, producing textile forms on these tools offers hands-on experience that allows designers to reflect on industry norms and thus enhances valuable knowledge for future industrial applications. Furthermore, there are also significant limitations posed by current textile technology. While many loom configurations are possible, looms and software utilized in the weaving industry have predominantly been developed to weave flat, uniform fabrics. Understanding and utilizing the capabilities of existing industrial machinery (such as the trousers presented in this paper), and exploring the potentials of advanced and lesser-known or utilized weaving processes or components (see DIS paper for explorations toward this area) should be further explored, and this is the basis of current work (ongoing Ph.D. project Milou Voorwinden TU Delft).

It is important to recognize there are dominant assumptions and biases regarding textile and garment fabrication that may need to be addressed. One assumption, for example, is that a woven fabric will unravel and therefore must always have additional edge finishing, such as overlocking, applied for the seam to be strong. While this might be the case in traditionally designed flat textiles, in our research, we have developed seams that barely fray by engineering the textile structures and seam zone size and placement. Additionally, as woven seams interlace yarns at multiple "stitch" points, instead of just one or two rows of stitching in a conventional seam, the woven seams can be stronger than the fabrics they interlace (McQuillan et al. 2023). In undertaking this research, there were many things we needed to unlearn, and as the critical zone of both textile and fashion design is expanded, there may be many more opportunities revealed when interrogating the underlying assumptions of established textile-based form design processes.

Conclusion

In this paper, we have presented a design method entitled Woven Textile-form Design (WTfD), which represents our first attempt to facilitate such projects, considering the technical, aesthetic and sustainability aims. The method suggests that when a woven textile-form is designed, the textile and form should be considered equally. It should reflects the interconnected nature of the different variables in the design process and aims to support sustainable manufacturing while considering technical and aesthetic aspects.

Disclosure Statement

No potential conflict of interest was reported by the author(s).

Notes

1. While in textile design, all textile expressions that are not planar are described as 3D textiles, in textile engineering there are distinctions between 2D woven 3D textile, 2.5D textile and 3D woven 3D textile (Khokar 2001).
2. In 2024 Unspun announces a partnership with Walmart to develop circular woven chinos (Unspun 2024).
3. They provide services for designers and brands wanting to produce woven textile-form for the fashion context.

4. While this approach is fundamentally the same for any WTfD that is produced on a side-by-side warp arrangement on the loom (including shaft looms), recent developments of circular jacquard looms (unspun) mean the notion of flatness as described in this paper, may require adjustment. For example, flattening may not be required for the main tubular subassemblies (such as a leg), but can be used to provide more complex form and detail (such as pocket bags).
5. Such as the convention that garment forms should be segmented to have side seams.
6. In the 4 layer WTf trouser example woven seams must be added to the inside of the concave crotch line, and the outside of the front and back of each leg segment otherwise the layers will fall apart when cut and won't unfold into form.
7. Tools that support this process include those used for cut and sew form visualisation for garments such as CLO3D or V-Stitcher, 2D software such as Illustrator, and analogue design processes using sketching, ready-made garments, paper models and cut and sew prototypes. Vector-based software (eg. Illustrator) is often utilized for the final MoC/MoB as it enables fine control of complex 2D shapes, and clean, solid colors (required for layer separation to be maintained through the jacquard design process and weaving).
8. In the WTf trouser (Figure 11), the overall flattened layout was preliminarily arranged based on the jacquard repeat width determined by the loom we planned to used (150 cm) and utilized ZWD strategies to nest one trouser next to another.
9. The MoC can be utilized for other flattened textile-form construction processes such as Lazerbonding (Goldsworthy 2012).
10. Often called "Artwork" in textile design.
11. But not the sequence or how it is interlaced - a plain weave or a compound twill for example.
12. Therefore it can be beneficial to draw the transitional cross-section.
13. The "/" symbol indicates separation of layers. In AdaCAD parentheses are used for this purpose, resulting in a notation such as (1A)(2B3C)(4D).
14. Can be used to ease cutting processes - see Finishing section.
15. See Appendix B for information about the loom and software used for the examples in this paper.
16. The logic of the steps in the method can also be translated to other loom configurations.
17. The table in Appendix A shows how we have explored different combinations of yarn weight and warp and weft density to compensate for fractional density.
18. Weaving fabrics with a uniform weft density is one option, but it's also possible to incorporate variable weft densities that can be programmed using variable densities or a regulator.
19. This can be either color changes, such as used in tartan, or houndstooth fabrics, or changes in fibre or spinning type of the yarn such as some tweeds.
20. However in some trouser iterations, we experimented with inserting melting yarn in bands aligned with the waistband and bottom hem to prevent the fraying of the fabric in those areas to simplify post-processing. See attachment B.
21. When programming the jacquard design there may need to be translation from the layer notation shown here to the system used in the industrial weave software. For example, a layer arrangement of 1a/23bc/4d, often needs to be articulated as a warp sequence of 1/22/3 and the weft sequence as a/bc/d. In the open source software AdaCAD, the programming language for this would written as (1a)(23bc)(4d).

22. A weave interlacement using only one warp and one weft is called a basic or simple weave, and when multiple warp and wefts are used, they are called complex weaves. There are three basic (simple) interlacement types from which most others are derived: the tabby, twill and satin weave. It is possible to make various modifications to these structures, such as enlarging, inverting, and interlacing them.
23. For example, if the width of a zone is 0.5 cm and the EPC of the fabric is 40, the total thread count would be 20. However, if two layers are woven within this zone, only 10 EPC threads would be available for constructing the textile. Therefore, it might be advisable to consider increasing the width of the seam.
24. Using a plain weave (a basic/simple weave) in each layer of a 2 layer structure, results in a complex weave.
25. Most weaving mills weave simple structures on high speeds, so initial caution is recommended due to the high density of many WTf.
26. If not, then the weave structures need to be redesigned to compensate.
27. For example, one of the looms we utilized for projects outlined in this paper were equipped with a full-width temple, meaning that the thickness of the fabric we could process was limited to the space between the top plate, base and steel rod. While this does not pose any significant challenges in creating single-layered fabrics, for textile forms, which rely on weaving many layers simultaneously, this is a limitation.
28. There are many other additional loom configurations, such as a creel, that would provide opportunities for WTf.
29. Starting from trouser iteration 6, we've capitalized on the flexibility of altering the layer order to relocate yarns—both in warp and weft—that need to be cut to the outermost surface of the fabric.
30. However, achieving precision in the exact cutting line may require more attention.
31. Ensuring desired garment finishing processes can be completed (such as providing sufficient seam allowance) should be considered when developing the MoC and MoB.

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Appendix A. Design details WTF trouser iterations

Iteration	1	2	3	4	5	6
Outcome	Design requirements were to develop a WTf trouser "block" that could be the basis for other variations. This foundation design was developed to require minimal post-weaving construction. And with minimal design details, have a regular fit with a slightly tapered leg, mid waist and hip pockets.			Same as Iteration 1–3 but explored the use of surface patterns to improve the fabric stability and aesthetic qualities of the WTf.	Same as Iteration 1–3 but explored the use of yarn properties to reduce fraying.	Same as Iteration 1–3 but changed to natural fibre to improve the material experience.
Form	MoB V1: The trouser form was flattened along the Z axis by folding the form at the front and back of each leg. This axis resulted in a maximum of 4 layers that accommodated the extreme gausian curvature where the two legs join at the crotch generated a negative space in layers 2 and 3 that made a pocket with layers 1 and 4. As segmentation is not required when using this axis the majority of post-weave assembly is eliminated increasing automation.					
Textile	Fine polyester warp was available at the weaving mill. To keep the variables the same, and to create a mono-material garment the same weft yarns were chosen. A high density was chosen, with two weft yarns for each layer that are weaving in a compound structure (8 wefts in total). Two colors were chosen to indicate the outside of the trousers to communicate the concept.		The weft yarn weight was increased to improve the fabric's stability, while other variables remained the same.	Explored the use of surface patterns to improve the stability and aesthetic qualities of the WTf. The weft yarn was the same but the picks per CM was lowered.	Melting yarn was added in sections to prevent unravelling in the waistband and hemline, with the aim of reducing or easing the garment's construction. The weight of the weft yarn was increased,	Switched weft material to a recycled cotton, to improve the material qualities. In addition to changing the fiber type, the amount of weft systems we worked with changed to 4, with each weft yarn weaving one layer

(*Continued*)

(*Continued*).

Iteration	1	2	3	4	5	6
					and the density was lowered.	and the weight of the yarn also increased, lowering the weft insertions per cm. In this iteration the cutting layers were moved to the outside (top and bottom) of the fabric.
Weaving and finishing	All these iterations were woven on the same loom, a rapier jacquard loom without a repeat. No fabric finishing was applied in these iterations. The cutting was all done by hand, and there was no assembly done. The seams that needed to be cut to release the form were placed on the inside of the garment making cutting difficult.					This iteration was woven on the same loom, but changes were made in the cutting procedure and the garment was assembled; hemming, waistband and zipper.
Key insights	During the weaving process, it became clear that	The density appeared to improve	In this iteration, the fabric is more stable. However,	The surface pattern enhanced the yarn stability within the	Despite the increased yarn count in this iteration, the	The modifications in this iteration significantly

(*Continued*)

(*Continued*).

Iteration	1	2	3	4	5	6
	the combination of weft density and yarn count was inadequate to achieve the desired fabric density and stability. As a result, the density was increased during the weaving of the first iteration. Additionally, due to a mistake in the weft sequence, the weft colors were not correctly positioned on the intended side of the fabric layers.	significantly during the weaving process. However, it became evident that despite being dense enough, the stability did not meet our expectations. Upon inspection, we found that this was a result of a combination of factors, including the slippery nature of the polyester yarns and the relationship between yarn weight and fractional density.	the machine faced difficulty processing the material due to the high weft density and increased yarn count.	fabric layers, as the weft yarns alternated between layers. However, despite the improved aesthetics, the presence of polyester yarns diminishes the overall tactile experience of the material. The stiffness of the yarns, their high density, and their synthetic nature collectively result in the fabric feeling less like conventional trousers.	fabric's stability did not improve significantly, prompting a further increase in yarn count.	enhanced the garment's overall quality. By increasing the weft yarn count, using cotton fibre, and employing one weft yarn per layer in a plain weave, each layer of the textile closely resembled a conventional textile. Furthermore, relocating the cutting layers to the garment's exterior substantially simplified the post-weaving process.

Iteration	7	8	9	10
Outcome	Same as but for denim jeans. Material qualities needs to align with expectations of denim	Same as Iteration 7, but aimed to bring overall design details and aesthetic closer to conventional jeans. Some increase in post-weave construction was accepted.	Aimed to demonstrate that this method and trouser 'block' could be 'graded' - be applied to make the same trouser design in different sizes.	Aimed to demonstrate that the WTf trouser 'block' could be modified to develop variations on fit, in a similar way to conventional pattern blocks.
Form	Same as MoB and form design as iteration 1–6, but the textile is divided in two layers so crotch seam is not woven	MoB V3: Based on iteration 7. To bring outcome closer to conventional jeans a front fly was integrated into design utilizing space in the crotch/pocket area from MoB V1. Additionally a separate pocket/waistband MoB was designed as a subassembly.	MoB V4: 4 layer trousers, two different trouser fits are designed to nest with each other across the width of the loom. Waistband modified to result in more normative aesthetic at the fly.	
Textile	These iterations were constructed on a different loom. Due to the lower warp density, the yarn count was higher, and the same in warp and weft. Therefore, the textile was constructed in two layers. To keep the blue indigo color in the garment, $1/2$ of weft yarns inserted were indigo. A similar approach to iterations 1–5 was applied, with having two weft yarns each weaving one layer		The textile was constructed with the same arrangement and structure as iteration 6. In this iteration, the cutting layers were all moved to one side, reducing the cutting processing time, and allowing for automated cutting.	

(*Continued*)

(*Continued*).

Iteration	7	8	9	10
	in a compound structure. The seams were constructed in a inverted compound structure.			
Weaving and finishing		The air-jet loom used in this iteration had a smaller repeat and a lower warp thread count compared to the previous loom. The fabrics underwent a complete denim-finishing process, including singeing, seizing, and sanforization. The construction of the garments involved sewing together the two legs, adding a waistband and hemming, and finishing with the addition of a zipper and button.		Same weaving and finishing procedures as iteration 6
Key Insights	The repeat on the loom in combination with the shrinkage of the fabric limits the size range of these trousers. The change of material (cotton in both warp and weft) and weight of the yarn improves the fabric experience. Fabric shrinkage had large effect on garment size and should be better inorporated into the form stage by scaling MoB based on % shrinkage.	Separating trouser into leg and pocket subassemblies aids in achieving an outcome closer to conventional jeans.	With a full width repeat jacqard there is a lot of flexibility in arranging MoB for different styles and sizes of garments while maintaining zero waste. Small adjustments can be achieved within the cross section of the WTft which provides further opportunities to tune garment fit that is not possible in conventional zero waste design methods.	

Appendix B. Technical details WTF trouser iterations

Iteration	1	2	3	4	5	6	7	8	9	10
Photo										
Total design hooks	11520						2400		11520	
Fabric width	151,57						144,27		151,57	
Repeat	No repeat						Main repeat in the centre (59.5 cm), two partial repeats on left and right		No repeat	
Software	EAT Designscope						NedGraphics		NedGraphics	
Warp materials	78 Dtex Polyester						Ne20 Indigo dyed cotton		78 Dtex Polyester	
Warp density	76						40.31		76	
Weft materials	78 Dtex Polyester		110 Dtex Polyester		167 dtex Polyester	20 Nm recycled denim	Ne 8 60%HA 40%CO yarn. Weft 1 and 3: undyed, 2 and 4 indigo dyed		20 Nm recycled denim	
Weft density	192	384	384	320	160	128	50		88	
Max Number of layers	4						2		4	
Weft density per layer	48	96	96	80	40	32	25		32	
Number of weft yarns	8						4		8	

Appendix C. Technical details student projects

Student work 1	Student work 2
	
2400	
144,27	
Main repeat in the centre (59.5 cm), two partial repeats on left and right	
NedGraphics	
Ne20 Indigo dyed cotton	Ne 10 Indigo dyed coton
40.31	
Ne 8 60%HA 40%CO yarn. Weft 1 and 3: undyed, 2 and 4 indigo dyed	Ne 8 60%HA 40%CO yarn
50	34
2	2
25	17
4	2