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Conformal, Seamless, Sustainable: Multimorphic Textile-forms as a Material-Driven Design Approach for HCI

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ABSTRACT

Technology embeddedness in HCI textiles has great potential for enabling novel interactions and enriched experiences, but unless carefully designed, could inadvertently worsen HCI's sustainability problem. In an attempt to bridge sustainable debates and practical material-driven scholarship in HCI, we propose Multimorphic Textile-forms (MMTF), as a design approach developed through a lens of multiplicity and extended life cycles, that facilitate change in both design/production and use-time via the simultaneous thinking of the qualities and behaviour of material and form. We provide a number of cases, textile-form methods and vocabulary to enable exploration in this emerging design space. MMTF grants insights into textiles as complex material systems whose behaviour can be tuned across material, interaction and ecological scales for conformal, seamless, and sustainable outcomes.

CCS CONCEPTS

• **Human-centered computing → Interaction design process and methods**.

KEYWORDS

HCI textiles, Sustainability, Textile-form, Material-driven design, Multimorphic textile-forms, Materials experience.

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1 INTRODUCTION

For 15 years Sustainable HCI (SHCI) has called for the decentring of human [94], the broadening scope beyond individual behavior, experiences, and persuasion [26, 50, 52], the questioning of the need for technological solutions [15], and the embracing of dynamic notions of material, time and scale. As in the broader design domain, there remains a gap between sustainable theory and its practice in HCI [138] centralized around these concepts, and HCI textiles is not exception. Issues of unsustainability are compounded in HCI textiles through its use of existing problematic industry processes [28, 141], and via the use of problematic smart and electronic materials [85, 86] that combine "disposable technology" [72] with textile waste. Modularity [155] is proposed to support the extension of technological relevancy, enabling obsolete hardware to be repaired or replaced, while design for disassembly is proposed as a solution for recycling [190]. However, neither of these approaches addresses the inherent unsustainability of existing systems for textile-based form manufacturing which divide and globally distribute the processes needed to make textile-based objects (fibre processing, yarn spinning, textile production, and form production). In other words, as textiles and the objects made from them are usually understood and designed separately this leads to inevitable overproduction and underutilisation of resources.

On the other hand, in response to problems of user-acceptance in HCI textiles [45], there is a push toward embedded materiality (e.g. [21, 64, 73]) which is at the core of the 'material turn' of ubiquitous and physical computing [145, 184]. Prominent in these lines of research is a growing interest in achieving design intent through understanding materiality [186] and a turn to material tinkering [123] and making [42, 46]. These material-driven approaches in HCI textiles unveil the potential for tuning textile qualities for desired experiences that make interactive textiles more relevant in our daily lives (e.g., [31, 58, 148]). However, this alone does not address the use of existing wasteful practices of form design and construction [140]. Moreover, addressing textile and form as separate components underutilises textiles' potential as inherently performative [58] and multi-situated materials [82], limiting the degree of seamlessness and embeddedness possible for interactive textile objects.

In this paper, we argue that the unfolding interaction design space between (technology) embeddedness, (form) seamlessness and (material) textileness has great potential for sustainable HCI textiles. To further this understanding, we propose Multimorphic Textile-forms (MMTF) for HCI as a design approach to evaluate and develop interactive three-dimensional textile-based objects through the lens of extended life cycles, on-demand local production, and zero waste. MMTF provides three contributions to HCI. First, it builds a vocabulary to discuss HCI textiles' sustainability alongside material-driven design practices as part of the same holistic

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approach. Second, with example cases, it provides inspiration for future research in HCI at this interwoven design space situated between form, textile and an expanded notion of temporality. Third, it identifies the opportunities and challenges HCI designers may encounter when working in this space which may be used as a place to start.

2 RELATED WORK

2.1 Sustainable HCI

Despite its obvious bracketing within the realms of the human, computing, and interaction, HCI has increasingly engaged with matters that go beyond immediate qualities of interaction, including social change, feminism, and sustainability. Since 2007, the call for integration and implementation of (what we will broadly call) sustainable thinking is supported by many HCI scholars [26, 38, 49, 68, 94, 100, 161]. Bardzell and Bardzell [14] present a feminist HCI methodology that argues for a simultaneous commitment to scientific and moral objectivities that challenges dominant notions of scientific objectivism within HCI. Light et al. [93] critique HCI's focus on human-centric technology in light of the accelerating race between climate change and the world's economic ambitions. They argue that Human-Computer Interaction as a term is no longer fit for purpose, in particular the "H" in HCI, since "all entities on the planet engage with (human-made) technology" [pg., 731.] so to counter the seductiveness of self/human-centredness we must be critical of the role and impact of humans within ecosystems.

In their introduction to the special issue on practice-oriented approaches for SHCI, Pierce et al. [126] identified three themes that continue to have resonance today: reframing materiality to decentre both humans and computers, the impact that dynamic notions of time and place have on the context of HCI practices, and the need to widen the scope of HCI practices when navigating complex sustainable challenges. Entwistle et al. [52] contribute to the call for a wider scope for HCI, calling for design for collective action rather than individual behaviour. Remy et al. [137] also critique the focus placed on (usually) individual usability when validating SHCI research, an especially valid critique given the much wider scope and scale that sustainability requires. Bremer et al. [26] in their critical review of SHCI efforts over the last 15 years identify essential new competencies and critiques, all of which are mirrored in the broader sustainability and circularity discourse [99, 162]. Within this corpus of research, it is clear that without holistic and actionable methods that decentring the human and the computer in HCI, the field risks treading the same path that has disheartened researchers for the last 15 years. We can view material-driven design and making as post-anthropocentric in nature - next we will explore how the discourse explores this connection.

2.2 Material-driven approaches for Sustainable HCI

Sustainable design discourse has argued that if we are to sustainably transition our material world [101, 121, 152, 178, 181, 188, 197] we need to change our perspective and expectations of the aesthetics of materials, including what we might normally consider such as "imperfection" [34, 147, 150, 152]. In this context, turning to new materialist scholarship from science and technology studies (STS) [11, 25, 79, 87], Rosner et al. [148] suggested critically examining material traces to understand attributes, entanglements, and trajectories in HCI. Subsequently research has explored material traces as a means to disrupt Borgmann's 'device paradigm' (in [144]), in the design of interactive patina [59], and the implementation of Wabi-Sabi in HCI [173]. These corpus of work in HCI bring forth the temporal expressions of materials, i.e., temporal form [177], where materials come to be, or become, only over time and in context [20].

In parallel, the drive for embedded material interactions, exemplified by the emergence of ubiquitous and physical computing [145, 176, 184, 186] has seen a reimagining of what we consider computational materials in HCI [56]. Notions such as hybrid ecologies [39], computational composites [175], radical atoms [75] and living bits [124] focus on the hybrid nature of new media compositions, supporting a move away from strong boundaries between physical, digital, and biological, and understanding all things as material in interaction design [145]. This thinking has broadened beyond sight and screens [71, 75, 76], to include touch [109] with textiles that remember [43], and other bodily sensations with materials as diverse as paper [107], glass [156], silicone [165], SCOBY leather [114], biodegradable clay [16], bacteria [63] and fungi [67]. This expanded materials palette in HCI offered novel possibilities for shape-changing [135] and deformable [23] interfaces.

Bringing to the fore the experience of such new and emerging materials in the everyday, the notion of materials experience [58], calls for HCI designers to pay attention to the active role of materials in shaping our ways of doing and ultimately, practice, next to the aesthetics of design. In line with new materialist figures such as Karen Barad [11] and Jane Bennet [18, 19], materials experience thinking suggests expanding the performativity beyond the social (human) to the material, aiming to show that material things are productive [19], and play an active role in public life. In an attempt to operationalize the materials experience thinking in design, Karana et al. [81] introduced the Material Driven Design (MDD) method. The method aims at supporting designers in structuring, communicating, and reflecting on their actions in bridging technical and experiential aspects of materials when materials are the departure point in the design process. The MDD method has been instantiated in designing, for example, with waste-coffee grounds [81], 3D printed textiles [167], electroluminescent materials [12], textiles [139], and living media including mycelium [122], plant roots [200], and flavobacteria [63]. Common to all, and in line with material-driven debates in HCI, the turn to materiality [51, 62, 187] and post-anthropocentric making approaches [6, 12, 46, 180] sees efforts aimed at understanding machines and materials as having agency in the design process and material engagement is a means to logically think, learn, and understand through sensing and immediate experience of materials [1, 74, 117].

In the MDD method, the authors urge designers to raise critical questions such as "in which contexts would the material make a positive difference?" [81] in formulating their material design vision. In design, researchers have also explicitly connected MDD to sustainable design [8] and designing upcycling systems [24]. The range of works explicitly connecting these in HCI or interaction design are relatively few. Some examples include biofoam presented as a sustainable material and is explored using MDD

[88], Dew's [47] PhD Thesis explores sustainable materials (waste) through interaction design practice using MDD, and Vogel et al. [179] present tools for embedding circular thinking in MDD for HCI. HCI researchers have also explored the replacement of unsustainable materials, including the use of biomaterials (e.g., [88–91]), DIY materials and fabrication (e.g., [7, 30, 57, 146]), making with waste [48], and deconstruction (e.g., [110, 111]).

We see a great potential for sustainability in the re-positioning of materials inherent qualities in the design process as the starting point. Additionally, a focus on enriched material experiences may make materials more relevant in our daily lives, revealing connection to the "broader context (society and planet)" [81]. However, a limited number of HCI studies (listed above) explored the intersection of material-driven practices and sustainability to date. The relatively limited scope so far can be partly explained by the technical challenges HCI designers face when designing with new and unfamiliar materials [12, 42, 63]. In such practices, the utmost attention is given to exploring tangible material qualities and performance, while its (un)sustainability often remains abstracted from its materiality or is an afterthought. Thus, an identified limiting factor in the implementation of sustainability in HCI research remains as the gap between theory and practice [138]; and HCI textiles is no exception.

2.3 HCI Textiles

Over the last two decades textile research in HCI has built discourse around the accessibility of textile knowledge [43, 134], including the development of DIY materials, open-source software or tools for designing [55, 103, 189] and manufacturing [5]. Many examples explore transferring the functionality of a screen or keypad to malleable textiles interfaces [119], use existing textiles as a substrate for active materials [142]. In other examples, textiles are used as part of a tool kit [131], or they are developed as a custom skin that interacts with technology [98], or in a composite with technology [60].

The malleability of textile-based interfaces enables complex interactions between users, textiles, and digital outputs [27] which move beyond the textile as a button or slider, and into a space where textiles might seem [102] or actually be alive [2]. As the research dives deeper into the textile hierarchy [64], we see that interactivity can be embedded within the colouration [17], fibre or yarn itself [95, 120, 159], in interaction with the textile structure [36, 44, 130]. The latter is an approach that requires deep textile-led knowledge, which can be missing in HCI [42, 172]. Some research has worked to address this gap through the development of a deeper understanding of the relationship between tools and technological assumptions [129], of wearable e-textiles using a 'textile-centric' approach [191], by supporting collaborations between HCI researchers and textile craftspeople [42], computer scientists [4], and material scientists [134], and the publishing of textile knowledge aimed specifically at the HCI community [43]. As a result of these long-standing endeavours, we are seeing increasingly complex interaction via the tuning of material behaviours in complex textile structures (e.g. [3]).

Devendorf et al. [45] acknowledge that the desire for interactive functionality in wearable textiles can lead to outcomes that disrupt users' expectations of ordinary textile interaction and the expression of identity so important in worn textiles. As HCI's concept of computational matter expands [170, 175, 176], and as textiles become alive [114] and active with computational, chemical, mechanical and biological means [31], leveraging the unique physical characteristics of textiles become increasingly important for interaction design [133]. The research to date demonstrates that with the right skills textiles can be complex multi-material systems of interaction, and as such the potential for tuning textile behaviour through its materiality in the context of HCI is exciting.

2.3.1 Textile-based form in HCI. To date, textiles in HCI are often used in 2D as a malleable and formable substrate [195] or skin for technology [196], and work on shape-change mechanisms [102] and materials [84, 172, 173] to achieve 3D shape change or form. Pouta and Mikkonen emphasize that the majority of explorations in 'smart' woven textiles in HCI are flat or exhibite minimal shape variations [133]. This tendency to explore interactive textile interfaces as substrates and in two dimensions, underutilises the potential for tuning textile systems for seamless and embedded form situated interactions in everyday products.

Usually textile-based form is produced either via cutting 2D fabric and assembling it into form, by deformation, or by utilising 'fully fashioned' textile construction methods (see Appendix (Table 4)). Conformal textiles are produced in the intended form during production (such as WholeGarment™ methods or McQuillan's 'textile-form' [104, 105] which we will unpack in Section 3.2). Primarily explored outside of HCI (e.g., [65, 69, 198, 199]), conformal production methods can be seen in HCI in examples for skin-situated sensors (e.g., [118, 183]), 3D printing (e.g., [160]), and for the production of 3D knitted (e.g., [83, 96, 97]) or woven (e.g., [73, 163]) sensors embedded in robot arms or applied on the skin. Interactive, conformal textiles require a simultaneous and iterative development of material qualities of textiles and form.

2.3.2 Sustainability in HCI textiles. HCI textiles has a sustainability problem. The composites commonly used, the interactive and conductive yarns, and electronic hardware embedded in many HCI textiles would contaminate textile recycling efforts [86] especially when scaled-up.

Project Jacquard [132], now sold as a Google Jacquard x Levi's collaboration, demonstrates some of the complex issues for Sustainable HCI textiles. In this smart garment, conductive yarn is woven directly into the cuff of a classic Levi's trucker jacket. It is designed to facilitate user engagement with digital apps and devices through touch gestures on the jacket sleeve. It utilises modularity to enable the removal of the 'Jacquard Tag' for washing and to physically update it. However, because of this modularity, the jacket remains tethered to hardware which the garment design is then required to disguise. Even with this functionality, care instructions recommend minimal laundering of the jacket, possibly undermining the cultural longevity of a denim jacket, while the end-of-life treatment of the smart garment is not articulated. Here the tensions between technological and aesthetic obsolescence, and durability in the context of HCI textiles are particularly evident and challenge HCI designers to consider time across multiple scales over design and use time.

In response, we see efforts to explore sustainable approaches for textile interaction that contribute to the dematerialisation of fashion [13], the repair of e-textiles [77], design for deconstruction [111], as well as bio-inspired design approaches [80]. However, when it comes to sustainable form-making practices, there are few examples that explore the intersection of interactive textile and form. Pouta and Mikkonen [133] mention the value for HCI designers in understanding the relationship between the shape of textile and the resulting form to better understand how textile deformations and interactions in relation to form, can aid in the development of that form. However, they do this via a suggestion for conventional sewing patterns which relies on a subtractive, wasteful and exploitative method of textile-based form production – cut and sew. Outside of HCI, McQuillan's work on Multimorphic Textile-form [105] situates the development of textile-based objects in the context of sustainable theory at the intersection of textile design and form-giving practices. However, while her work touches on time as a factor in her notion of multimorphism, there is a lack of clarity on the way in which time is a design element with equal footing to the development of textiles and form.

2.4 Summary of gaps and opportunities

The appeal of technological novelty, untethered by ethical concerns is strong, and there are few examples of material-driven research in HCI that successfully develop technical innovation, while addressing holistic sustainability goals. Material-driven approaches provide opportunities for uncovering unforeseen potentials of novel and emerging materials, however the newness of such materials and processes might give designers the impression that a mere transformation of a new material to any product has value and this view can hinder deeper investigation of its impacts. In HCI Textiles this has led to the presentation of the use of materials as a trade-off between sustainability, functionality, and novelty, where functionality or novelty wins, often compounding the joint issues of e-waste and textile waste. Furthermore, a lack of textile knowledge in such endeavours commonly results in textiles being treated as substrates, and an approach which leaves potential for enriched experiences via tuning textile systems underexplored. Furthermore, difficulties with technology integration leads to issues with user-acceptability – and to address this, researchers are seeking approaches that enable a greater degree of embeddedness. However, embeddedness without consideration of where materials come from, or how they might be recycled can result in highly problematic outcomes. The holistic, material-driven approach to HCI textile objects could be utilised to explore conformal, seamless, and sustainable outcomes, when temporality is carefully integrated within the approach.

3 MULTIMORPHIC TEXTILE-FORMS

Multimorphic Textile-forms (MMTF) (Fig. 1) are textile-based objects designed through a lens of sustainability via on-demand local production, extended life cycles and zero waste [105]. Originally, it was introduced to acknowledge the role of adaptation and conformal thinking in the design of textile-based objects, with a particular focus on shape changing textile-form in the design/production time. The approach focussed on enabling personalisation – through greater aesthetic and size diversity – and a reduction of waste in (over)production. However, in this introduction to HCI designers, we argue that the comprehensive definition of MMTF should also acknowledge the role of change (beyond shape change) in the use-time of textile artefacts. In other words, with the notion of MMTF we refer to textile-forms that are designed through simultaneous thinking of material (textile) and form (product), that change in design/production and/or use time, through a lens of multiplicity and extended life cycles, on-demand local production and zero waste. The term 'multi' refers to change over time across material, social and ecological scales, by considering material-textile-form relations, production, people, and ecosystems holistically. The proposed approach is, therefore, a bridge between the theoretical roots of material-driven design and making and sustainability, as already established fields in HCI research, with an emphasis on temporality.

Accounts of temporality in material-driven HCI (e.g., [177]) provide a useful entry point to articulate the capacity of a textile-form to afford multiple actions in the use-time (i.e., performativity [12]), to help them remain relevant with enriched experiences and resourceful in multiple situations of use. In Materially Yours, Karana et al. [82] – capitalising on 'resilience thinking' [35] that argues the most responsive to change will survive – propose multi-situated materials, advocating for change, ambiguity, flexibility, curiosity and openness as a means to develop resilient material relationships with everyday artefacts. In line with this thinking, morphic textile-forms, while enabling change in design/production and/or use time, must also deliver a material experience as close to the kind of malleable, natural, and expressive relationships that are currently mediated through the textiles we interact with every day.

To properly introduce multimorphic textile-forms and provide prompts for textile researchers in HCI, next, we will give definitions, a broad overview of textile-form methods with examples, and then define and present examples of morphic textile-form. Lastly, with an analysis of two cases we will instantiate how HCI textile researchers could move toward MMTF's and address, through practice, the wider needs of both human and non-human entities across multiple temporal and material scales.

3.1 Methodology

To provide prompts of how an HCI designer could implement morphic and multimorphic textile-form thinking through process and material perspectives in HCI, we undertook a non-exhaustive but comprehensive analysis of existing textile-based objects. We collected these objects from publications in HCI and design venues including the ACM Digital Library, and the libraries of ScienceDirect, and Scopus from the ten year period of May 2012 to May 2022. An initial keyword search of "textile" AND "3D" OR "three-dimensional" yielded 865 publications. By adding specific textile interlacement methods such as "3d print" OR "knit" OR "weave" OR "mould" OR "felt" OR "non-woven" OR "grow" OR "bio" we could exclude results that mentioned textiles only in passing without discussing the method of production. The results narrowed to 654 publications. Each of these was examined for duplication, and examples that did not describe an object/demonstrator, or where the object/demonstrator was not a textile or textile-proxy, were excluded.

Our first selection criterion for the textile-based objects was the conformal thinking in the production method of textile-forms (i.e.,

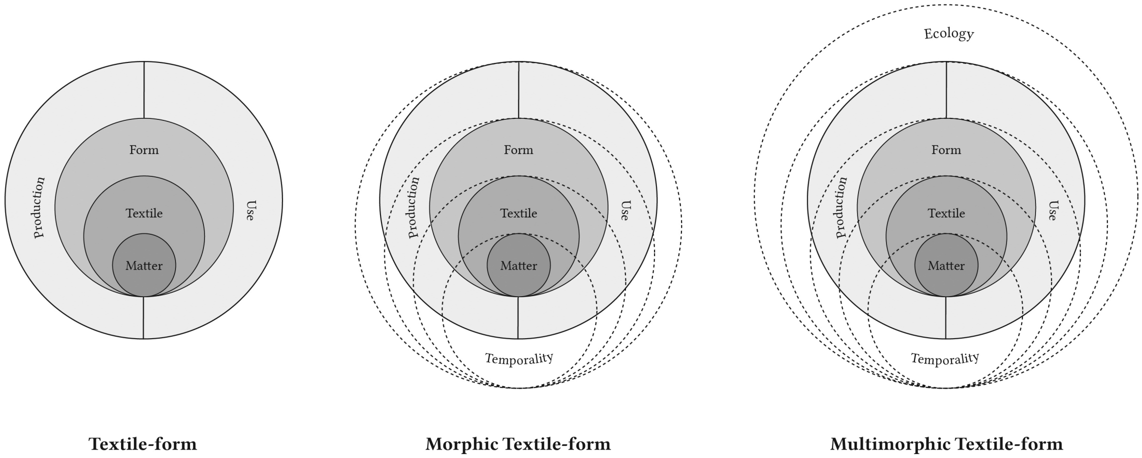


Figure 1: Textile-forms (left) are textile-based objects where textile and form are simultaneously constructed via the interlacement/deposition of matter/fiber/yarn. They include the consideration of material, textile, form, production and use. Morphic Textile-forms (centre) expand on textile-forms to material temporality/change in design/production and/or use time. Multimorphic textile-forms (right) are morphic textile-forms that consider temporality across material, production, use and ecological scales.

cases that seek to simultaneously make the textile and form). Initially, we used McQuillan's [105] categorisation of textile-forms as a lens. However it became clear that composite methods, although previously included in 'Flat Textile-forms', utilise existing textiles and therefore do not construct the textile and form simultaneously via the interlacement/ deposition of matter/fiber/yarn. Composite textile-based forms, while they have a great deal of value and are the most commonly used form-making method for textile-based objects, were therefore outside of the scope of our study. We also excluded cases of solely cut and assembled textile-based forms and included cases that illustrate a complex form topology that moves beyond surface texture. The differentiation of form in this context was challenging, as some textile-forms may utilise what is commonly referred to as '3D textiles', which often is limited to surface texture. Additionally, examples that do not exhibit or intend to exhibit textileness [31, 61] were also excluded. This first round yielded 24 textile-form objects.

We then expanded the initial search to the textile and fashion design venues and publications, including exhibitions/fashion shows (e.g., London Design Week, Paris Fashion Week, Dutch Design Week) and popular magazines (e.g., Dezeen). We found extensive examples of textile-forms - particularly knitted textile-forms as WholeGarment™ or 3D knitting technology commercially available, and a relatively large number of both 3D printed textile-proxies, and woven textile-forms of varying complexity. In order to have a manageable list of representative cases, we clustered them based on the methods used to make textile-forms, such as flat textile-form, knitted textile-form and 3D textile-form [105]. Together we discussed the initial categories and undertook a second investigative round using this initial taxonomy, identified sub-categories, and added additional relevant examples from the above-mentioned sources. For example, we divided the examples of 'Flat Textile-forms' into sub-categories of weaving, growing, etc., and '3D Textile-forms' into moulded and 3D printed textile-forms. The definitions of terms used in this study are outlined in the appendix. This phase resulted in five textile-form methods and 26 textile-form objects. Thus in total, we had 50 textile-form objects from the first two rounds of selection.

We analysed these 50 objects further. Where there were multiple similar examples related to a specific process, we used the following criteria to select a representative example: (1) the clarity of description of the object provided by authors/designers, (2) availability of multiple images of process, (3) and the existence of a fully developed prototype. We also gave attention to include a diversity of application domains (i.e., not only garments).

This process resulted in 18 examples of textile-forms (Fig. 2). 10 of those were categorised as static examples of textile-form production methods (e.g., woven, grown, etc.). Some textile-form practices utilise methods from multiple categories, for example, in some cases categorised as moulded (Fig. 2.04, and 2.11) and grown textile-forms (Fig. 2.15), 3D printing processes are used in addition to growing or moulding. However, Peterson's Medium cotton non-woven dress (Fig. 2.11), for example, is classified as a moulded textile-form, as the 3D printing is used as a tool for process preparation, not the textile-form construction itself.

The remaining eight cases are morphic textile-forms (MTF) that take temporality as a design element, activating change in form, colour, scent, texture, sound, or energy for example, either in design/production time and/or use time. Examples where change only occurs via 'ordinary' physical textile-form based methods such as flipping, cutting, folding, stitching, and pulling are excluded. In morphic textiles-forms one process can be used to make the textile-form with active material embedded, to then utilise a second textile-form method to further manipulate the outcome. As such, the examples are not grouped by process, instead by when the change occurs, in use time, design/production time, or both. Examples such as Bio-Logic [195] and "This is GMO" [108] are not included in morphic textile-forms, as cut and assemble production methods are used to

Figure 2: 1: The Bunny [3]; 2: DefeXtiles [53]; 3: 3D Woven Shoe [69]; 4: MycoTEX [70]; 5: Unfoldable Cube [78]; 6: Zero Waste Weavers [106]; 7: CTT: Trouser Experiment [31]; 8: H|H Collection dress [105]; 9: Kinematics Petal Dress 2 [164]; 10: Knitted Bunny [112]; 11: Medium cotton non-woven dress [125]; 12: Active Textile Tailoring [168]; 13: Programmable Knit [158]; 14: WholeGarment™ knitted sweater [192]; 15: InterWoven [154]; 16: Form from Flat [182]: 17: Dynamic Folding Knits [151]; 18: Biocouture™ BioBomber Jacket [41]. All images reproduced with permission from copyright holders.

make the 3D form – in both change occurs at a textile-surface level and so can be considered animated textiles [31] but not morphic textile-forms. However, we can look to such examples for further development in the morphic textile-form space, which we will touch upon in the Discussion section. Similarly, Climate Active Textiles [169] from Self-assembly Lab at MIT is also not included as the 3D form appears to be constructed from planar textiles.

From these 18 examples, we selected two morphic textile-forms (Fig. 2.06 and 2.13) that explicitly address a holistic approach to sustainability, illustrating a move towards multimorphic textile-form (MMTF).

3.2 Textile-forms

A Textile-form (Fig. 1, left) is a textile-based object where textile and form are simultaneously constructed via the interlacement/deposition of matter/fiber/yarn. A key motivation in the development of textile-forms is the move toward zero waste conformal textile-based outcomes, while leveraging automation to enable relocalisation of on-demand manufacturing close to the communities that will wear and use the outcomes.

Weaving and knitting are the most commonly used textile production methods, and both usually make flat rectangular fabrics that are later cut and constructed (usually sewn) to make a 3D form. This multi-step, largely manual process usually divides textile and form production across multiple countries, contributing to the textile industry's carbon emissions [116, 153]. Textile-forms in contrast, emerge directly from the interaction of molecules, fibres, yarns, textile structures and finishing processes, into 3D form such as garments, chairs, or perhaps even architectural elements. In contrast to the subtractive and manual cut and sew methods used in industry, textile-forms move closer to, or achieve, additive and automated manufacturing processes.

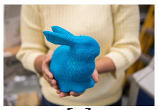
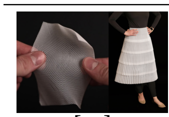
The most obvious existing example of a textile-form method is 3D knitting, or WholeGarment™ knitting, where the 3D form of a knitted object emerges directly from the knitting machine, with little waste or post-knitting processing required. Other less known textile production methods are 3D printing, moulding, and growing form in the context of bio-design. Table 1 provides examples to illustrate some of the possible approaches in the making of textile-forms. Later, in the discussion on morphic textile-forms, this boundary is further blurred.

3.2.1 *Moulded textile-forms.*

Moulded textile-forms are produced as a finished 3D object and encompass some of the oldest textile production methods – such as the use of felting and shaping wool fibre for 3D form. Novel approaches include Karin Peterson's [125] use of 3D moulds, silk, wool, and cotton fibre, with a bio-plastic binder (Fig. 2.11). The development of moulding methods and materials that maintain textile pliability or textileness [31, 61] is an important factor. The MycoTEX dress (Fig. 3) by Aniela Hoitink [70]provides a moulded textile-form example that grows mycelium textile 'disks' that are then bonded together on a 3D mould. Other examples include Suzanne Lee's work (Fig. 2.18) with bacteria cellulose [41] and Fabrican by Dr Manel Torres [171].

Figure 3: Moulded textile-form example. MycoTEX jacket (right) by Aniela Hoitink [70] is made from grown mycelium 'disks' (left), then bonded on a 3D mould. Image credit: MycoTEX by Aniela Hoitink.

Table 1: Textile-form examples

Example case	Type of textile-form	Textile-form process description
 [125]	Moulded textile-form	Simultaneous design and production of textile and form using a 3D moulding process. May include the use of felting, binders or bonding to directly make the 3D form.
 [4]	Knitted textile-form	Simultaneous design and production of textile and form using knitting, crochet or other looped textile structures.
 [69]	Woven textile-form	Simultaneous design and production of textile and form using the interlacement of two (or more) yarn systems perpendicular to each other.
 [53]	3D printed textile-form	Simultaneous design and production of textile and form using a 3D printer.
 [200]	Grown textile-form	Simultaneous design and production of textile and form via the growing of living material/organism.

3.2.2 Knitted textile-forms. 3D or WholeGarment™ [192, 193] knitting are the most understood and well-developed example of designing and producing textile-form (Fig. 2.14). Other related methods such as crochet (see [185]) and lace making, can also be used to make form and textile structure simultaneously. The knit or loop structures can be controlled to manifest 3D form during textile construction, therefore reducing post-knitting finishing, as such, knitting is often presented as a method to automate the production of 3D form. Access to WholeGarment™ knitting is sometimes problematic for novice HCI researchers, so work on design-production tools [103, 112, 113] for enabling complex 3D knitted forms (Fig. 2.10) has the potential to enable further exploration of conformal knitted textile-forms.

3.2.3 Woven textile-forms. Weaving a textile almost always produces a (relatively) flat rectangle, which usually needs to be cut and sewn or deformed in order to make complex 3D forms. The digital jacquard loom enables (Fig. 2.08) the embedding complex topological form in the interstitial spaces within the rectangular cloth through the manipulation of the structure of the woven textile. 3D looms are utilised in technical textile applications to make lightweight complex rigid forms for the automotive industry, however, they have also been used to make outcomes such as a 3D Woven shoe (Fig. 2.03 [69]). Standard industrial jacquard looms can also be used to make woven textile-forms through the application of multi-layer textile structures (e.g.,[40, 92, 104, 127]). Other related methods include braiding [66], and basket weaving.

3.2.4 3D printed textile-forms. 3D printed textile-forms apply 3D printing in the context of textile-form design. The rigidity of many 3D printing materials can result in a lack of pliability in 3D printed textiles - a limitation commonly addressed by utilising a chainmail-like (Fig. 2.09) approach [33] to enable flexibility in rigid materials. Also of particular interest to textiles is the development of pliable 'yarn-like' extrusion materials and processes [166]. Additionally, due to the limitation of printing bed size, modular or collapsible approaches are commonly used to circumvent the difference between bed size and body/object. In addition to new material development, exploration of design and process interventions such DefeXtiles [53] can enable flexible and extensible textile-forms (Fig. 2.02) to be manufactured utilizing existing 3D printing materials and equipment.

3.2.5 Grown textile-forms. Often living or bio-material approaches utilise post-growth joining methods, however, a growing space of exploration relevant to the field of textile-forms is the use of living material to grow 'textiles' [37] directly into a form. Diana Scherer's work is an excellent example of this approach where the root structures of plants are trained via moulds to create interlaced patterns that resemble lace [200]. Once fully grown, the grass, soil and roots are harvested (Fig. 4, left), the grass removed and soil washed out, leaving the root structure as 'textile'. This approach has been expanded to interlace roots structures for a Grown textile-form [154] – Grown Plantrootsculpture (Fig. 4).

These examples provide HCI designers with novel production methods and ways of thinking about the relationship between

Figure 4: Grown textile-form example. Diana Scherer's Grown Plantrootsculpture [154] - harvested soil and plant matter (left), cleaned of glass and soil to reveal dress (right). Image credit: InterWoven by Diana Scherer.

Figure 5: Form from Flat by Kathryn Walters [182] is an example of morphic textile-forms that change in design/production-time. The woven textile-forms use elastic and paper yarn and so can be shaped over a form after weaving. Image credit: Kathryn Walters.

textile and form, however, none address the core concern of HCI – interaction. Next, we introduce the opportunity that time can provide in the development of textile-forms.

3.3 Morphic textile-forms

As explained in the previous section, a key motivation in developing textile-forms is the move toward zero waste outcomes and automation to enable re-localisation of on-demand manufacturing close to the communities that will wear and use the outcomes. In HCI this opportunity is expanded through its combination with animate materials [10] and animated textiles [31], enabling the personalized, conformal production of interactive textile-based form - morphic textile-form (Fig. 1, centre).

Morphic textile-forms (Table 2) combine elements of temporality, textile design and form design. The key distinction between textile-forms and morphic textile-forms is that the design process enables change in design/production time and/or during use-time. As with the original definition of animated textiles [31], this activation can be done via physical, biological and/or computational means. Morphic textile-forms that change in design/production-time can address sustainability through the simplification of on-demand production leading to an increase in diversity and personalisation in conformal textile-based form manufacturing. Morphic textile-forms that change in use-time address sustainability through enriched experiences and extended multiple lives. Morphic textile-forms that change both in design/production and use time compound the benefits of both.

3.3.1 Textile-forms that change in design/production-time. This group of morphic textile-forms utilise computational, physical, or biological means to change shape, colour, smell, taste, texture, energy in design/production time. In this way uniform production can be personalised by utilizing textile structures and materials that enable change.

Form from Flat (Fig. 5) by Kathryn Walters [182] explores the use of multi-layer jacquard weaving and paper yarn to make sculptural forms. The 3D form is flattened in the woven structure when the yarns are interlaced on the loom, and when activated in a post-weaving process involving water the static 3D form emerges.

Dynamic Folding Knits (Fig. 6) by Victoria Salmon [151] are inspired by origami folding and use knit structures with thermoplastic stiffening yarn to activate the 3D form. They are relatively flat off the knitting machine and once steamed (Fig. 6 left) the form emerges (Fig. 6 right). While the resulting forms are designed for interaction by flipping and folding between form-states through the use of colour and texture, the material does not change after production and so are not classified as morphic textile-forms that change in use-time.

3.3.2 Textile-forms that change in Use-time. This group of morphic textile-forms utilise computational, physical, or biological means to change shape, colour, smell, taste, texture, energy in use-time. Use-time can be extended through utilizing textile structures and materials to enrich material-user interactions.

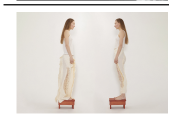
Unfoldable Cube (Fig. 7) by artist and designer Hella Jongerius [78] is a rich example of a morphic woven textile-form that weaves photovoltaic strips into a multilayer weave structure to harvest energy from the sun, which then activates mechanical shape change in the form via servo motors. When activated, the flat textile opens to make a cellular structure that Jongerius proposes as a new category of transformative, responsive, and pliable architecture.

The Bunny [3] is one of a set of morphic knitted textile-forms presented in HCI that explore the potential for inlaid tendons in 3D knitted form to enable mechanical shape change when the tendons are pulled and released (Fig. 8). The tendons are embedded in the 3D knitted form as it is knitted, resulting in an output that is entirely soft to the touch, while also achieving significantly more variability in shaping and texture than other approaches [143] that use off-the-shelf textiles and components in composites.

3.3.3 Textile-forms that change in both design/production and use-time. This group of morphic textile-forms integrate the benefits of both change in design/production and change over time. Here, change is leveraged as a design tool for innovation in production while leaving further user interaction open-ended.

Active Textile Tailoring [168] utilises a low-melt polyester yarn to knit the textile-form. In production time the low melt polyester enables personalisation of a base size for a specific fit via heat application using a robotic arm (Fig. 9, right). At home, heat can be applied directly by the user to further tune the fit of the garments. The knitted structures enable variable fibre and yarn behaviour to be expressed, and later textile experiments (Climate Active Textiles [169]) demonstrate that this principle can be applied to enable the

Table 2: Morphic Textile-form examples

Example case	Change in...	Description
	Design/production time	Form from Flat [182]. These sculptural woven forms come flat off a loom and their final and irreversible 3D form emerges with the application of heat.
	Design/production time	Dynamic Folding Knits [151]. Interactive textile objects inspired by origami and knitted with thermoplastic yarns that permanently stiffen the folds programmed into the knit structure.
	Use time	Unfoldable Cube [78]. An exploration of future shape changing architecture that responds to light. Results in reversible and dynamic mechanical and material shape change.
	Use time	The Bunny [3]. A soft toy that is 3d knitted with actuation 'tendons' and sensors inlaid to enable reversible and dynamic mechanical shape change.
	Design/production and use time	Active Textile Tailoring [168]. 3D Knitted sweater that can be shrunk to fit utilising heat gun on a CNC robotic arm. Results in material shape and density changes that are irreversible.
	Design/production and use time	CTT Trouser Experiment [31]. A multi-layer jacquard woven textile makes a pair of trousers that can be shrunk to fit a range of forms and body sizes. The material shape and density change is open to interaction, but irreversible in one direction.

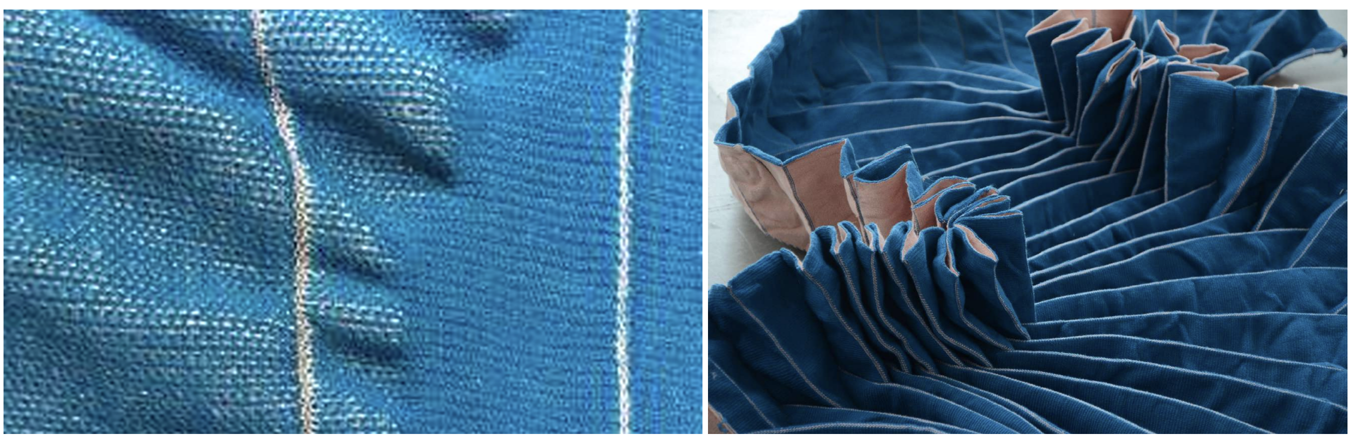


Figure 6: Dynamic Folding Knits by Victoria Salmon [151] is an example of a morphic textile-form that changes in design/production-time. The density of the knit structure is transformed (left) when heat is applied to the thermoplastic yarn used. This stiffens the structure and enables the embedded folds (right) to activate. Image credit: Victoria Salmon.

responsive opening or closing of textile structures for ventilation or warmth when worn on the body.

The second example CTT: Trouser experiment [31], takes a similar approach but explores via woven textile-form (Fig. 10), and utilises variations in weave structures to pre-program variations in shape change across the surface of the textile. It uses low-melt polyester yarn in combination with stable yarns (cotton), in multi-layer textile structures to transfer uniform shrinking yarn between layers enabling both the localised tuning of textile behaviour and the generation of complex woven form in a single step. The outcome can be shrunk on or off a mould as part of a production process or directly on the body for user interaction.

3.4 Building toward Multimorphic Textile-forms

MMTF is a practice that bridges the theoretical roots of material-driven design and making, and sustainability, via an understanding

Figure 7: Unfoldable Cube by Jongerius [78] is an example of morphic textile-form that changes in use-time. The woven form has photovoltaic strips embedded in the weave structure which power a servo motor to expand the multilayered textile into a 3D box-like frame. Image credits left to right: Jongeriuslab, Laura Fiorio, and Magdalena Lepka

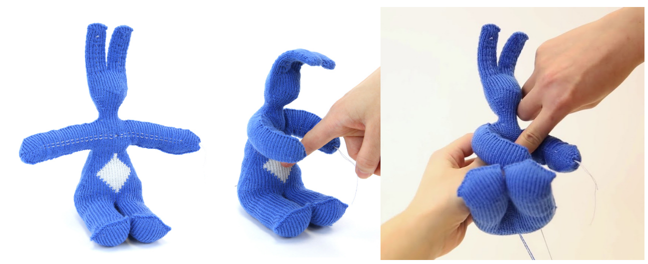


Figure 8: The Bunny by Albaugh, Hudson and Yao [3] is an example of morphic textile-forms that changes in use-time. The knitted form has both tendons and sensors integrated within the machine-knitting process which could enable the arms to hug. Image credit: Lea Albaugh, Scott Hudson and Lining Yao

Figure 9: Active Textile Tailoring [168] is an example of a morphic textile-form that changes both in design/production and use time. The knitted textile-form (a sweater) uses heat reactive yarn in a knit structure that contracts when heat is applied. This can be activated either during production or by the user. Image credit: Lavender Tessmer and Skylar Tibbits.

Figure 10: CTT: Trouser Experiment [31] is an example of a morphic textile-form that changes both in design/production and use time. The woven textile-form uses heat reactive yarn to locally tuned shape change while weaving, to be activated during production, or in the application of heat by the user. Image credit: Holly McQuillan, Karin Peterson and Kathryn Walters. Photography by Amanda Johansson

of temporality across material, social and ecological scales. Building on morphic textile-forms, the elements that interact in the design of a multimorphic textile-form include material, textile, form, production, and people, but widen to include how these things interact with ecosystems (Fig. 1, right). All of these elements are already interconnected in design, so even if it is convenient to treat them separately, it is necessary to consider them all in order to develop outcomes that are situated between social foundation and ecological ceiling [136]. Textile-forms enforce a level of holism through the tandem production of textile and form, morphic textile-forms expands this holism to include use and/or design/production time, while multimorphic textile-forms acknowledge material and social practices operate in the environmental context. A designer of morphic textile-forms will delve into the near-field scale of matter (fibre and yarn), into the context of its interaction with textile structures at a variety of axis; and to the far-field human-scale of how structures allow for form-making and how this form is desirable and needed in the social context of designed objects (its materials experience), and how it may change over time. In multimorphic textile-forms, each of these bracketed contexts then need to undertake a process of consequence scanning [29, 174], where an analysis, evaluation and reflection on the short and long-term environmental and social impacts takes place as part of the research, design, and prototype development. Next, we will outline two example cases (Table 3) that could be considered as building toward multimorphic textile-forms by their engagement with some of these challenges.

3.4.1 Programmable Knit. Programmable Knit [157, 158], is a morphic textile-form made from biodegradable and/or mono-materials (Fig. 11). The shape change behaviour of the textile structure is engineered at the intersection of hygromorphic fibres, yarn twist, and knit structures which enable shape change behaviour to be expressed when exposed to moisture (Fig. 11, left) and is applied in a garment context (Fig. 11, right). In industry, these fibre properties are considered detrimental and something to be minimised (see also: [128]), however, in Programmable Knit the natural behaviour of cellulose and protein-based fibres is tuned through yarn twist and knit structures to develop surprising interactive experiences that are entirely biodegradable.

3.4.2 Zero Waste Weavers: Planet City Costumes. These costumes (Fig. 12) were developed by McQuillan et al. [106] for the speculative film Planet City. Four morphic textile-forms made from recyclable mono-material (polyester), where shape-change is engineered at the intersection of heat low-melt polyester yarn, and multilayer woven structures that program variable fibre/yarn behaviour when

Table 3: Multimorphic Textile-form examples

Example case	Change in...	Description	Ecological considerations
	Use time	Programmable Knit [158]. Knitted morphic textile-form that changes shape when exposed to moisture.	Mono-material, biodegradable, reversible form-change
	Design/production and Use time	The Zero Waste Weavers [106]. Woven morphic textile-from that changes shape when exposed to heat.	Mono-material, recyclable, zero waste

Figure 11: Jane Scott's Programmable Knit [157, 158] emerges of the knitting machine relatively flat (left) and after exposing the knitted textile to moisture, dramatic peaks are formed (centre) (Image credit: Cristina Schek). The knitted dress (right) utilises the methods explored (Image credit: Jane Scott).

exposed to heat (Fig. 12, left). Conceptually the polyester fibre used would be 're-mined' from the detritus of previous civilisations and produced in a hyperlocal, automated, and vertical manufacturing facility. The garments are intended as 'special event' garments, costumes that are handed down through generations for repeated use, a long lifespan supported by their adaptability and the use of highly durable polyester fibre. Additionally, as a recyclable mono-material, these costumes can be - in theory - recycled several times.

4 DISCUSSION

In this section, we will discuss the opportunities that Multimorphic textile-form processes could provide for HCI designers, and outline the challenges facing HCI in developing this complex and emerging design space.

4.1 Opportunities in Textile-form for HCI designers

4.1.1 Tuning localised behaviour in textile-based form making. The simultaneous construction of textile and form provides many opportunities for HCI. The majority of examples of textile-based objects in HCI are composites made from existing planar textiles, and utilised existing or bespoke components. As such, the potential for tuning localised behaviour are limited to the addition of additional elements onto or between existing textiles that have predefined behaviours. Even in cases where a textile-form production method is theoretically tunable - such as WholeGarment™ knitting, for example - due to the blackbox nature of the design software, this capacity is underexplored. To exploit the potential for tuning textile-forms further, there remains a need for accessible programming tools and production equipment for HCI designers. To that end, 3D printed textiles forms offer a large-design space, and it is worth exploring the 3D printing of circuits and conductive components, for example, directly into a 3D printed textile-form as a way to enable seamless embedded outcomes for HCI.

4.1.2 Animate materials for morphic textile forms. There are many exciting developments in the use of animate materials [10] in textiles which deserve discussion and further exploration in textile-from space. The use of animate materials in on-demand production of HCI textile products can help tune textiles specifically to individual users' needs to further enrich user experience. Many of the examples found use heat reactive yarn as the animate material - often these are animate only in one direction which limits the diversity of interactions possible. The re-framing of traditional textile materials, such as wool or cellulose fibres, in the context of reversible animate materials, can open up a design space where the inherent temporality of many natural materials is encouraged, like in the case of Scott's Programmable Knit. As new materials are developed for use in textile products, radically different means of production become available that take advantage of these material properties. For example, the manipulation and development of materials for 4D printing [22, 120] or programmable yarn spinning [194]) enable change in behaviour down the length of the filament or yarn, which in combination with textile-form methods can result in complex behaviours from mono-material textile-forms. There are opportunities for further exploration of morphic textile-forms in a wide array of materials, and HCI textile designers can lead the development of new processes and animate materials.

The potential for integrating living materials into textile-forms is also a rich area for exploration in this space. A radical example is This is GMO [37, 108] which utilises synthetic biology to genetically modify bacteria to produce both cellulose and melanin in a morphic grown textile approach. Using a "microbial weaving" process a sneaker upper is "woven and coloured by a single genetically modified organism" [108]. Herein, the form-making process is more akin to fully fashioned approaches, where only the material needed is constructed and grown as a 2D shape, while the 3D form still needs to be moulded and stitched to a sole to make the whole shoe

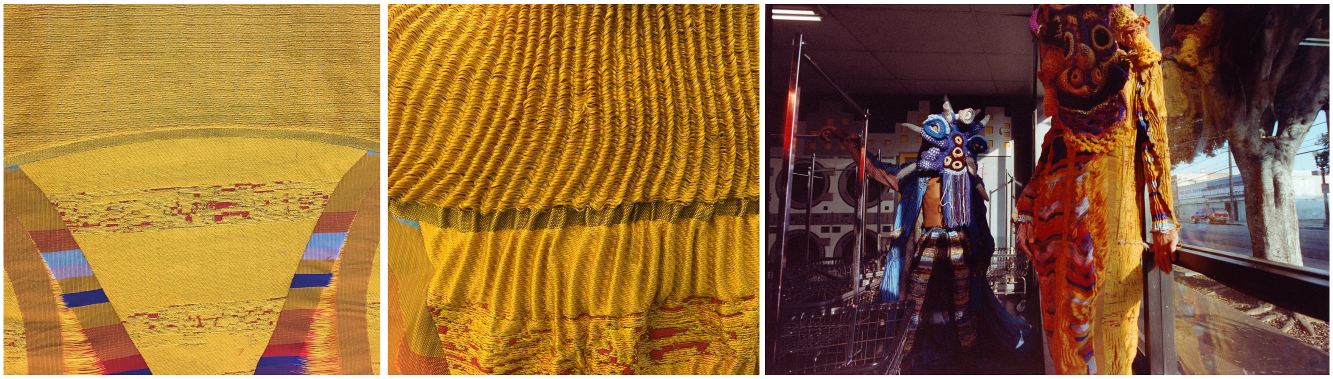


Figure 12: McQuillan et al. Zero Waste Weavers costumes [106] (right) are made from polyester monomaterial (Image credit: Holly McQuillan, Kathryn Walters and Karin Peterson for Planet City, a film directed by Liam Young, Costume direction by Ane Crabtree, Masks by Zee Monday, Photograph by Driely Carter). The untreated woven textile-form is shown left while the centre shows the same section of the textile-form after applying heat (Image credit Holly McQuillan).

form. Time is an active element in the growth of the bacteria 'textile' in the interlaced substrate, and the colour changes while this process occurs, however once produced, the upper is sterilised, and all the bacteria are washed out before leaving production, removing the possibility for interaction during use-time via ongoing colour change or growth. Recent developments in Engineered Living Materials [115] will increase the possibility of realising textiles that are alive, change and evolve at the use time (see e.g., [9]). When paired with textile-form design and production methods, such materials could aid in the development of sustainable production methods producing living outcomes, that afford radically different functions and user experiences.

4.1.3 Building behaviour over scale for sustainable HCI. Kapsali [80] argues that the lesson from biology is that textile designers need to "shift from designing with substance and energy to designing with structure and information" [p.g., 9.]. With the notion of MMTF we argue for HCI designers to synergistically build behaviour (i.e., change of information over time) throughout the textile system, while evaluating and responding to the impacts of material extraction, use and context (i.e., energy source and scale of technological, production, and sociocultural context), to make the rewarding, safe and just futures that are needed.

In MMTF, the motivation for tuning a textile system across scales is extended beyond use and interaction, to ecological time. Ordinarily, an HCI textile designer would evaluate performance for conductivity or degree of shape change (for example) when selecting a fibre or yarn for interactivity. In MMTF, the designer would also evaluate the context and impact of this materials extraction and if it can be recycled (or not). At the scale of the textile structure, consider if it can be disassembled, for example, through innovative use of stitches that unravel. How do you imagine the textile being used - is it ultimately for a body or other 3D form, and if so, how is that form constructed – does it reinforce inefficient and exploitative models of form production? What is the ultimate interaction goal? What (human/other) need is being served? Does this need to be achieved via the materials and processes selected, or is there another innovative approach possible? How long will this need be served by this product? Can it be upgraded, adapted, or modified? Designers of MMTF should critically iterate on their ideas with these questions in the design process. The two examples of MMTF presented both have potential issues when evaluating the outcomes with a holistic perspective of ecological time. In the case of Zero Waste Weavers [106] for example, even though the garment is recyclable in the short term, the production of micro-plastics might be of concern in the long term, and so HCI designers could look to new wool-based, shape change materials [32] used in combination with conventional wool as an alternative. By exploring temporal qualities throughout the interconnected scales of textile systems [149], from molecule, fibre, yarn, textile and to form, the underexplored synergies can be utilised in HCI for generating seamless and embedded interaction in morphic textile-forms. Furthermore, by evaluating these decisions and synergies through the MMTF lens, the outcomes HCI textile designers develop may avoid the perpetuation of existing unsustainable systems.

4.2 Challenges for HCI designers

While material scales are hierarchical in such textile systems (fibre is small and form is relatively large), the impact of each part of the textile system is symbiotic and flattened [31]. Therefore, to design for change over time from material to ecosystem, a deep understanding of the interrelationship between fibre, yarn, textile, form, and context is required. In addition to the added complexity that ecological time brings to materials in HCI, textiles - as malleable, relatively unpredictable soft material systems - could be perceived as somewhat imperfect mediators of technology. While overlaying predictable technology on a textile substrate can help to satisfy the desire to smooth out these 'messy' interactions, and ensures they work-as-intended, it also diminishes the potential utility and rich interactions textile complexity and malleability provides HCI designers. To fully utilise the potential of textiles in HCI we need to be critical of the criteria used to evaluate textile interfaces, and instead celebrate the properties we chose them for. This approach requires the simultaneous commitment to scientific and moral objectivities that Bardzell and Bardzell [14] encourage and an openness toward risk and uncertainty that is more commonly seen in craft practices, a value that is acknowledged by HCI discourse [42, 54]. While this process might inspire novel application ideas for long or short-term use, to develop further, it requires time and experience to build the necessary skills, or effective collaboration to manage the complexity across scales with confidence.

As discussed earlier, the use of animate materials [10], such as living materials, offers possibilities for the transformation of manufacturing processes so that finishing processes activate material behaviours programmed into the textile-form. This is an approach that can enable personalisation and reduce waste. However, without applied examples and detailed techniques, HCI will continue to utilise existing known processes. Furthermore, if the right balance between innovative production processes, novel material use and sustainability is not found, function and user-acceptability may be impacted. For example, a fully automated, zero waste and single step process for growing a textile-form may result in an outcome so far removed from current expectations that social acceptance is hindered. Furthermore, tools that help us evaluate these decisions, or that model change-over-time so we can better understand the outcomes is limited to non-existent for textile systems. The field needs more tools to support researchers and designers to manage, visualise and predict the multiple and ever-changing factors of these material systems.

As these tools are developed and textile knowledge increases, HCI Textiles will move further toward desired levels of embedded seamless integration of technology into textiles. The more successful these experiences are, the more problems of disassembly and recycling will be entrenched. So, there is a clear need to put sustainability at the forefront of these emerging fields. However, putting sustainability at the forefront of HCI textiles is not straightforward. Within HCI is a human-exceptionalism driven reluctance to allow for more-than-user needs to impact on innovation and 'scientific progress' (as evidenced in the corpus of sustainable discourse in HCI). Since it is already difficult for some to work with these technically challenging fibre, yarn, and textile structures from a functional perspective for users, adding sustainability into the design and evaluation process may feel daunting and limiting. Additionally, the newness of such material systems might seduce designers into believing that using morphic textile-form approaches is enough – an assumption that could hinder a deeper investigation of the possible impacts of the outcome on people, society, and ecology. While MDD methods [81] could help with practical tools to zoom out to bridging technical and experiential qualities of materials for HCI textiles, when it comes to MMTF, which includes change over time up to ecological scale, one might expect difficulties due to the technical challenges, novel skills and broad scope of understanding needed. It is clear that tools to support designers to understand materials and processes over ecological time that work to reveal interconnections between all entities are required.

4.3 Limitations and Future Works

This study introduces Multimorphic textile-forms to the HCI community as an approach that aids in reflecting on existing projects and research, provides prompts and language for their further development, and opens new design spaces where textile and form are simultaneously constructed for enriched textile experiences. There are a number of limitations to this study. First, there are few examples of some textile-form approaches. Many of the morphic textile-form examples shown use heat-reactive animate materials (such as CTT: Trouser Experiment [31], Active Textile Tailoring [168] and Form from Flat [182]), or mechanical/digital change mechanisms (such as Unfoldable Cube [78] and The Bunny [4]. Research (such as [149]) helps to broadens the shape-change material palette for MTF. Related to this is the high number of examples that use shape-change as the primary expression of temporality, and the limited examples of morphic textile-forms using biological mechanisms for change, likely due to the emerging nature of biodesign. Some examples of animated textiles such as This is GMO [108] points toward possible futures for textile-forms that utilise a broad range of emerging materials and mechanisms. Furthermore, due to the limited number of exiting MTF cases that explicitly address sustainability, there are few tangible MMTF examples to learn from. We hope that this approach informs HCI designers to view their own and others work in a different light and inspire novel seamless, conformal, sustainable solutions in HCI textiles so that there are many more examples of MMTF in the future. Secondly, we do not yet provide an explicit design method to guide HCI designers in their design process towards MMTF - this is a task we intend to pursue. As others have articulated [43, 133], we see that there is a clear need for mutual skill building, vocabulary and tools to enable effective collaboration between experts, and, eventually, application at a scale that transforms the industry and wider society. These are the challenges we want to tackle in our future work.

5 CONCLUSION

In HCI textiles the entwining of textile and e-waste reveals the need for methods situated at the intersection of sustainable theory and material practices. To fully realise their potential textiles should be considered as conformal, multi-material systems of interaction, building behaviour across the non-hierarchical and symbiotic material interactions of fibre, yarn, textile, and form. Material-driven approaches in HCI textiles unveil the potential for tuning the complex and interdependent qualities of textiles as inherently performative and multi-situated material systems. In this paper, we introduce Multimorphic Textile-forms (MMTF) as a material-driven design approach grounded in the practice of sustainability. MMTF utilises sustainability as a decisive constraint to develop novel HCI textiles, ensuring the solutions and technology that the field develops will avoid known environmental problems, and may also inspire technological innovations that might otherwise have never occurred. Developed through a lens of multiplicity and extended life cycles, MMTF facilitates change in both design/production and/or use-time via the simultaneous thinking of the qualities and behaviour of material and form. By providing a critical review of textile-based research and practice and textile-forms across design and HCI, a vocabulary and prompts for MMTF, we hope to inspire HCI designers to develop tools, collaborate on new materials and processes that enable the tuning of textile-form behaviour across material, interaction, and ecological scales for conformal, seamless, and sustainable outcomes.

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A APPENDIX

A.1 Definition of terms

Table 4: Definition of general terms

Term	Definition
Textile	A (often malleable) material made from the interlacement/deposition of fibres, filament and/or yarn into a matrix. The most common interlacement methods used include knitting, weaving and non-woven methods (felting, bonding etc), and there are also examples of 3D printed or grown/cultivated materials that are designed to be textile-proxies. Most often, textiles are understood as a planar material, however many textiles are 3D by design.
Textileness	The experience of textiles currently mediated through qualities such as softness, flexibility, durability, and comfort [31, 61].
Textile embellishment	Addition of decorative or functional elements onto the surface of existing textiles, such as embroidery, printing/dyeing, foiling, flocking, applique. Textile embellishment is widely used in HCI textiles to animate textile substrates.
Animated textiles	Textiles which change in use-time via physical, biological or digital means. [31]
Cut and Sew/Assemble	Where textiles are produced in rectangles and the shapes needed to make a 3D form are cut from this rectangle. These 2D shapes are then constructed (usually sewn) into the desired 3D form (such as a garment).
Composite textile-based form	Textile-based objects that use existing textiles and components to generate form.
Composite preform	A rigid textile-based object where textile and form are simultaneously constructed via the interlacement of matter/fiber/yarn which becomes the reinforcement for a composite.
Fully fashioned	Planar textiles that are produced to the desired 2D shape - resulting in minimal waste - these shapes are later constructed (sewn/linked) into the desired 3D form. Knitting is the most common textile interlacement method used to make Fully Fashioned objects.
Textile-form	A textile-based object where textile and form are simultaneously constructed via the interlacement/deposition of matter/fiber/yarn.
Flat textile-form	A textile-form made using a flatbed production method [105]. For this study we have divided this category group based on the methods for interlacement/deposition, (see woven textile-form and grown textile-form) and excluded composite methods.
3D textile-form	A textile-form produced in 3D [105]. For this study we divided this category based on the methods for for interlacement/deposition (see grown, 3D printed and moulded textile-form).
Knitted textile-form	A textile-form produced using knitting, crochet or other looped textile structures.
Woven textile-form	A textile-form produced via the interlacement of two (or more) yarn systems perpendicular to each other. Can also include other methods such as hand woven seamless garments, 3D weaving, braiding and basket weaving.
Grown textile-form	A textile-form produced via the growing of living material/organism.
Moulded textile-form	A textile-form produced using a 3D moulding process. May include the use of felting, binders or bonding to make the 3D form directly.
3d-printed textile-form	A textile-form produced using a 3D printer.
Morphic Textile-form	A textile-form that considers material temporality/change in design/production and/or use time.
Multimorphic Textile-form	A morphic textile-form that considers temporality across material, social and ecological scales.