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Abstract

Today's fashion industry is marked by rapid production, early disposal and low-quality materials, resulting in environmental harm and social injustice. Denim production involves a resource-intensive and extended supply chain with entrenched design practices, leading to substantial pre-consumer waste. To address these issues, emerging design manufacturing techniques hold promise for fostering alternative sustainable fashion ecosystems yet remain largely underexplored by the industry. The current work focuses on 3D weaving, an innovative niche design manufacturing technique that enables the production of near-complete garments, facilitating zero waste and reducing labour-intensive steps at the cut-and-sew stage. Employing a qualitative approach informed by the literature and empirical research with denim industry professionals, this study investigates the potential of this novel design manufacturing technique in the context of systemic change beyond merely introducing technological advancement as an intervention in the existing industry. The analysis reveals four fundamental components: industry-led change, relocalisation, reimagining denim design roles and consumer communication. These key components, synthesised with the literature, are discussed respectively. We illustrate how the niche design manufacturing technique can shape novel fashion ecosystems by providing an exemplary concept which concerns the collaborative establishment of a small-scale local supply chain for 3D woven denim garments. Through this example, we aim to ignite discussions on a further reimagining of the fashion industry, utilising similar alternative lenses that prioritise sustainability over ultra-speed, high efficiency and mass production in alignment with the United Nations Sustainable Development Goals 9 (Industry, Innovation and Infrastructure), 12 (Responsible Consumption and Production) and 17 (Partnerships for the Goals).

Keywords: Local production, Sustainable fashion innovation, Systemic change, Zero waste, 3D weaving

Introduction

With brands driving mass-produced, trend-driven and seasonal fashion, a constant fast fashion cycle is perpetuated, in which clothing is rapidly produced and disposed of (Niinimäki et al., 2020). In denim, fashion brands have sought to reduce market risks and enhance profitability by shifting their apparel manufacturing to lower-income countries (McCormick et al., 2014). This strategic move allows them to optimise costs while disguising the resource-intensive, complex and geographically dispersed supply chain involved in denim production and the accompanying significant social and environmental implications (Bick et al., 2018). Moreover, consumer attitudes have shifted, prioritising price over clothing heritage, so that impulsive and fast purchases of low-priced, disposable fashion dominate the landscape (Allwood et al., 2006; Niinimäki et al., 2020).

Over the past decades, it has become evident that the linear economic model in the fashion industry, characterised by high resource consumption, significant pre- and post-consumer waste and social injustice, is unsustainable (Niinimäki et al., 2020). To address the issues embedded in the 'make-take-waste' system, the concept of a circular economy, which aims to close energy and material loops, thereby eliminating waste and pollution, has gained significant attention. However, the fundamental design of denim products raises a crucial question, as its aesthetic expression has remained unchanged over the past 150 years. Conventional patternmaking for garments generates significant pre-consumer waste, with estimates suggesting that 10%–15% of the fabric is discarded during this design process (Enes & Kipöz, 2019). The cut-and-sew stage accounts for 15.6% of a garment's overall environmental impact throughout its lifecycle (Wennberg & Östlund, 2019), and this pre-consumer waste is often immediately sent for incineration or to landfill (Enes & Kipöz, 2019; Niinimäki et al., 2020). The persistence of such practices can be viewed as a design flaw, where the significance of introducing changes from the design stage is reinforced due to approximately 80% of a garment's environmental footprint being solely determined during this stage (Östlund et al., 2020). Exposing this design flaw becomes even more critical with the growing enforcement of the EU Extended Producer Responsibility policy, such as the 2023 Dutch enactment, which emphasises transparency, waste management, eco-design and product redesign (Ministerie van Infrastructuur en Waterstaat, 2023). The current work addresses the subsequent need to reassess the design and manufacturing processes associated with this long-standing and current fashion staple.

Alternative approaches are increasingly being explored to mitigate pre-consumer waste in garment design and production. The innovative niche design manufacturing technique of 3D weaving has disruptive potential and remains somewhat underexplored. 3D weaving can generate complex textile-based forms while weaving by utilising contemporary jacquard machinery (i.e. looms) to produce multi-layered, locally varied textile structures. By incorporating woven 'seams' into the structure, cutting open specific layers can generate larger fabric pieces that would typically require the joining or sewing of separate panels. As a result, the garment's form and function is integrated into its textile design, reducing the need for machining, minimising material wastage and streamlining the lay-up process (McQuillan, 2020). Figure 1 presents a simplified overview of the fabrication process and its potentially disruptive qualities to demonstrate how the 3D weaving approach facilitates a more sustainable manufacturing process. The technique generates a unique aesthetic through a radically different approach to pattern creation and output, challenging the enduringly uniform appearance of denim over the past decades. Considering alternative perspectives allows for questioning not only the conventional methods of textile design and manufacturing but also how they might enable entirely new ecosystems. This opens an opportunity to fundamentally reimagine the fashion industry, diverging from the paradigm of large-scale and hyper-efficient global production.
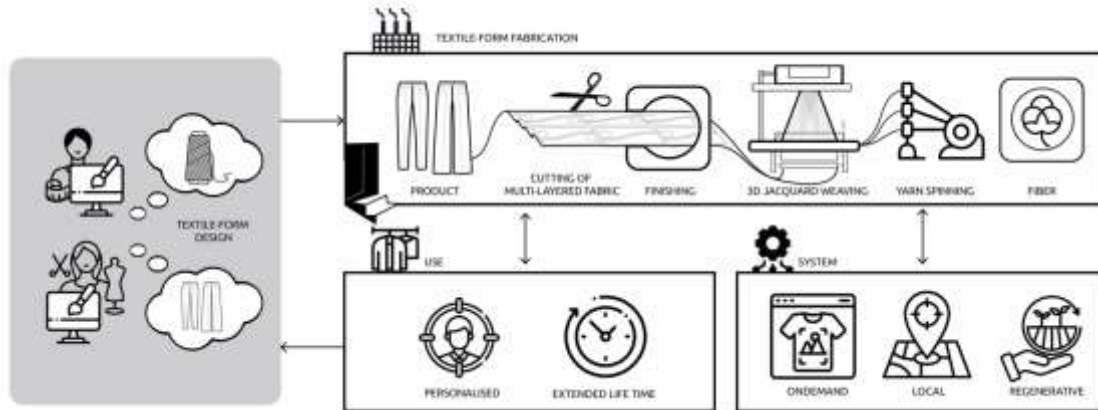
Figure 1: Simplified overview of the 3D weaving process and its potentially disruptive qualities.

Therefore, the current research aims to understand how a novel design manufacturing technique can shape more sustainable models for fashion through a systemic lens rather than relying solely on technological interventions within the existing fashion ecosystem, with the overall aim of fostering a debate on envisioning alternative pathways to industry transformation.

Related work

The next section introduces related work on 3D weaving and on systemic approaches toward fashion transitions, as well as on-demand production and relocalisation of supply chains.
The section concludes by identifying a knowledge gap.

3D weaving

Notably, researchers and professionals in textiles and fashion are increasingly intrigued by the possibilities of 3D weaving, as exemplified by the work of McQuillan (2020), who has conducted experiments in creating zero-waste garments using weaving techniques, such as a T-shirt and trousers. Similarly, Vroom's (2022; as cited in McQuillan et al., 2023) 3D woven denim jackets demonstrated promise for more sustainable denim design (see Figure 2). However, limitations within currently available looms prevented them from achieving complete zero-waste goals at this early research stage. Furthermore, Weffan's (Slater, 2023) endeavour to establish a consultancy for 3D woven garments and Unspun's development of a specialised loom for automating 3D weaving, alongside their recently secured funding of $32 million to support expansion (Ewen, 2024), show a commitment to advancing this innovative technique. It is crucial to note that the current exploration of 3D weaving remains primarily within the realm of research, concentrating on material-driven design and production process enhancements. This emphasis overlooks its potential for broader transformation within the fashion industry.

Figure 2: A 3D woven denim jacket designed by Vroom (2022).

Related work in systemic approaches toward fashion transitions

Numerous initiatives have addressed the present challenges within the fashion industry and achieved transformative goals through a comprehensive, systemic perspective. One prominent example is Mistra Future Fashion, an European Union (EU)-funded project congruent with the EU's ambitious objective of establishing a fully circular fashion system by 2050 (European Commission, 2022; Wennberg & Östlund, 2019). Mistra Future Fashion investigates the promotion of sustainable consumer behaviour, policy change and enhancement of recycling processes for post-consumer textiles, thereby facilitating the transition from a linear to a circular and sustainable industry (Wennberg & Östlund, 2019). However, absent from this comprehensive approach is the incorporation of innovative and distinct techniques that hold the potential to play a pivotal role in steering the fashion industry towards alternative, reimagined holistic design manufacturing systems.

Recently, the Ellen MacArthur Foundation published *The Jeans Redesign*, a resource offering guideline for redesigning jeans that conform to circular economy principles. This report outlines specific design requirements for achieving goals related to durability, material selection, labour, ecosystem well-being and user empowerment through repair knowledge, as well as services, recyclability and traceability (Ellen MacArthur Foundation, 2023). However, a significant aspect of the textile industry's journey towards circular economy goals remains unaddressed: the generation of pre-consumer waste during the cut-and-sew process. Consequently, the systemic approach employed in the report can be deemed not yet 'fully complete'.

On-demand production and relocalisation

Given the lack of transparency and unethical practices in today's outsourced fashion supply chains, relocalisation is imperative. As Amed et al. (2019; 2022) emphasise, brands must reevaluate their growth strategies to suit specific geographic contexts better. Additionally, the problem of

overproduction - a staggering 30%-40% of all apparel (Magnusdottir, 2020) - stemming from brands creating consumer demand necessitates a shift towards on-demand production. On-demand production is well-suited for micro-manufacturing environments, where responsive, local demand-driven manufacturing is practical. This manner of production aligns with previous initiatives in reshoring textile production in the UK (Postlethwaite et al., 2022), emphasising the importance of establishing innovative, localised centres through reshoring efforts.

Due to its streamlined supply chain and integrated design manufacturing process, 3D weaving is well suited for micro-manufacturing and on-demand contexts. Exploring upskilling is essential for navigating the challenges of a forward-thinking industry (Postlethwaite et al., 2022). Establishing newly situated design-to-consumer models could serve as a foundation for further exploration of methods like 3D weaving, focusing on automation, efficient 3D prototyping, on-demand production and precise sizing requirements.

The examined related work suggests a gap. Effectively transforming the fashion industry demands a departure from current production practices and requires the redesign of multiple interconnected system facets (Murphy, 2022), redistribution of power dynamics, covering of actual costs and redefining perceptions of what is considered 'fashionable'. The related work shows elements of importance in moving towards a more sustainable fashion system, either through addressing circular economy approaches focused on closing loops in later stages or through systemic design approaches in general aspects of the textile system. However, explicitly investigating how these different approaches tie in together and how interconnected system elements can be leveraged to exhibit the potential of niche innovative methods like 3D weaving towards reaching a window of opportunity (Geels, 2002) has not yet been illustrated. The necessary considerations and steps remain unclear, especially within the context of the ubiquitous yet rigid and deeply entrenched denim industry, presenting a significant gap to explore.

Given the unsustainable nature of the present fashion industry and the growing demands for transparency, on-demand production and circular economy practices, the current work explores alternative models that respond to these needs rather than current fast fashion principles. As 3D weaving emerges as a promising example for displaying how emergent techniques can stimulate more sustainable fashion models, critical components to unlock its potential will be clarified within the context of systemic change.

Methodology
The current study employs a qualitative approach that combines the literature and empirical research with various experts in the denim industry, incorporating both semi-structured and unstructured interviews, as well as co-creative sessions. The research addresses the question: What critical components are essential to unlock the potential of 3D weaving for alternative fashion design-to-consumer models in the denim industry?

The literature review informed the setup of semi-structured interviews with denim industry professionals. We maximised opportunities for unstructured interviews in casual settings, allowing for spontaneous interactions, by bringing a sample 3D woven structure by Vroom (2022) to present

the technique (see Figure 3), while benefiting from the principal researcher's familiarity with the semi-structured questions.

Figure 3: Sample of a 3D woven denim structure.

Based on the findings, we conducted an expert session with the research team to distil the key components necessary for fostering new fashion ecosystems. To mitigate the influence of the principal researchers' subjective interpretation, the findings were cross-referenced with the existing literature and scrutinised by the research team. Following Guest and McLellan (2003), a thematic analysis was performed, applying inductive codes to the qualitative data and clustering them to identify themes and patterns.

The analysis revealed critical considerations for implementing novel sustainable fashion models and informed how 3D weaving can be systematically leveraged for its potentially disruptive capabilities, providing insights for the industry. Additionally, co-creative sessions were held with industry professionals during a field visit. The previous considerations and the results of co-creative sessions, which were analysed in keeping with Sanders and Stappers (2012), were translated into a design. The design illustrates how emerging techniques can stimulate more sustainable fashion models from fashion design to consumer, particularly in the form of a local 3D weaving ecosystem. The Netherlands, where the research was initiated, serves as a relevant exemplary context due to its specialised knowledge in 3D weaving and established partnerships within the local textile industry. The House of Denim, a Dutch foundation interviewed in the study, could serve as another leverage point, as it already supports innovation through collaborations with researchers, brands and mills in the Dutch denim community.

We used the collected data according to Table 1, which demonstrates an overview of the research activities of the broader study in chronological order. However, the research relating to a user study, autoethnographic research and an additional interview was used solely to validate the proposed local 3D weaving ecosystem. These activities are part of a larger study on fostering sustainable fashion models and will be discussed in future publications.

Table 1: Overview of qualitative research methods.

Data collection method	Research source	Duration	Data analysis
1. Literature review	A broad range of empirical and theoretical articles selected.	-	Integrative review (Kutcher & LeBaron, 2022), deductive analysis for interview themes.
2. Semi-structured interviews	Industry experts at Kingpins Show: denim designers and brands, mills, sustainable material experts, traceability and certification experts, House of Denim and 3D weaving experts (n = 15).	20–90 minutes	Interpretivist, inductive coding, thematic analysis.
3. Unstructured interviews	Denim designers, representatives from Tonello and members from the educational field associated with two UK universities present at the Blackhorse Lane Ateliers (a UK-based denim mill) during an event (n = 18). Denim design and history professional (n = 1).	10–30 minutes over 4 hours Approximately 8 hours	Interpretivist, inductive coding, thematic analysis.
4. Co-creative sessions and semi-structured interviews	Industry experts during a field visit to Diamond Denim by Sapphire, a vertical denim mill based in Lahore, Pakistan (n = 8).	60–120 minutes	Interpretivist, inductive coding and thematic analysis according to "Analysis (clustering) on the wall" (Sanders & Stappers, 2012).
5.Semi-structured interviews	Users of 3D woven denim jacket (n = 20).	45–60 minutes	Interpretivist, inductive coding, thematic analysis
6.. In-depth auto-ethnographic research	Users of 3D woven denim jacket (n = 10).	4 weeks	Deductive analysis, autoethnographic research diary; interpretivist, inductive coding, thematic analysis.
7. Semi-structured interview	Expert in supply chain traceability (n = 1).	60 minutes	Interpretivist, inductive coding, thematic analysis.

Towards sustainable fashion ecosystems

Figure 4 displays the four key components – industry-led change, relocalisation, reimagining denim design roles and effective consumer communication – found essential for unlocking the potential

of 3D weaving through implementing alternative fashion models in the denim industry, with some components addressing multiple topics.
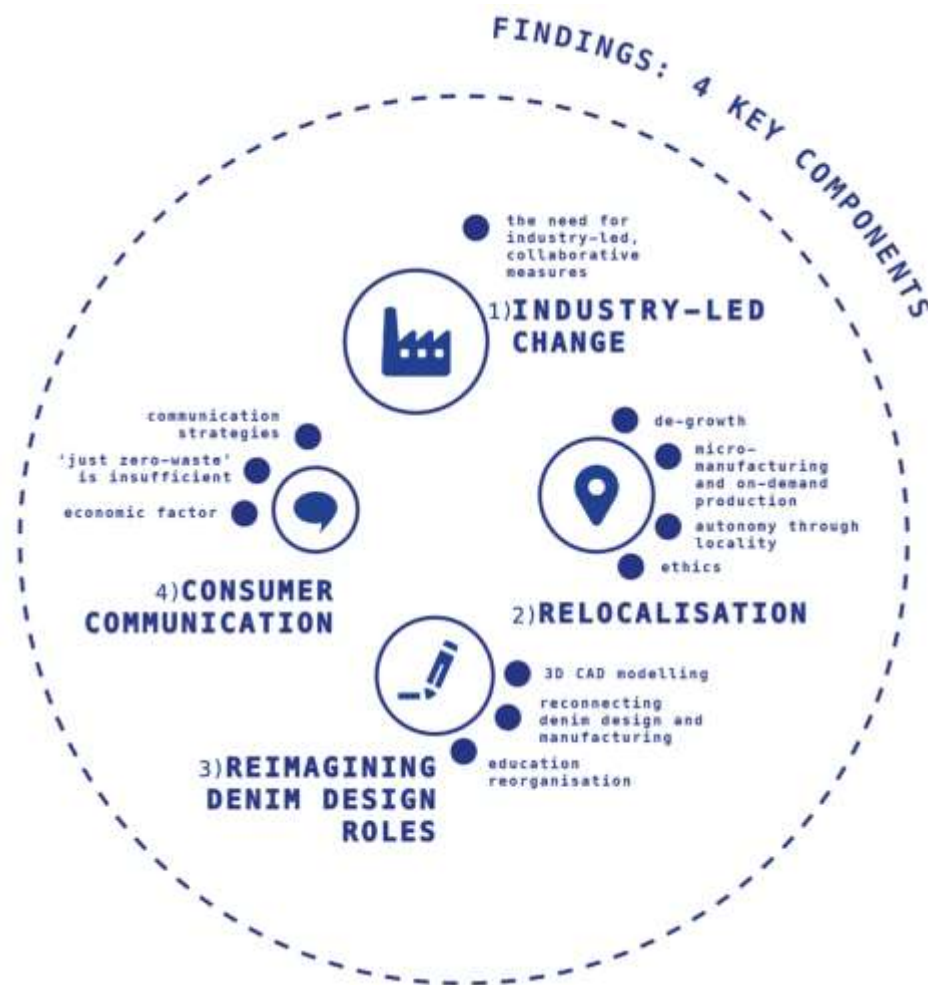

Figure 4: Four critical components unlocked the potential of the 3D weaving technique towards systemic change.

The industry-led change component emphasises the necessity for proactive and coordinated efforts within the denim industry to drive sustainable transformation, fostering collaboration and incentivising brands to initiate change rather than solely relying on shifting consumer behaviour. Relocalisation involves shifting production and sourcing practices to local or regional contexts, aiming to reduce mass production cycles, lower the transport footprint, enhance transparency, ensure supplier autonomy, employ micro-manufacturing contexts and support self-sustaining local economies. Reimagining denim design roles highlights the importance of redefining the responsibilities of denim designers within the context of manufacturing, embracing a holistic, creative and multidisciplinary approach that integrates sustainability considerations into the design process. Effective communication with consumers is crucial for successfully utilising 3D weaving practices in the denim industry in alternative fashion models of implementation in a transparent and informative manner to raise awareness, educate consumers about sustainable choices and enable higher trust in the sustainable information conveyed. We elaborate on each critical component and its sub-elements in the next section.

Industry-led change (1): The need for industry-led, collaborative measures
Through the literature research and the interviews conducted in this study, it was found that overall, consumers need to recognise fashion as a practical and meaningful necessity rather than objects of short-lived pleasure (Allwood et al., 2006; Niinimäki et al., 2020). However, relying solely on changing consumer behaviour through sustainability narratives to disrupt the fast fashion ecosystem was found to be insufficient. An example is the prevalence of unverified sustainability claims by many brands, which has resulted in greenwashing practices and, subsequently, consumer scepticism (Marrucci et al., 2021). The findings of the expert interviews match this connotation.

Another finding from the expert interviews is that most consumers are currently not inclined to pay a higher price for sustainable garments, as stated by the denim mill Diamond Denim by Sapphire, the denim designers from Endrime and Wrangler and the Blackhorse Lane Ateliers owners. The study reaffirmed that consumers cannot be easily categorised, and even those with a higher perception of sustainable awareness can find themselves making consumption choices based on price rather than sustainability considerations, pointing to a value–action gap (McDonald et al., 2012). Similarly, Niinimäki (2010) suggests that the abundance of cheap clothing deters consumers from buying pricier options, while misaligned expectations around eco-fashion between brands, designers and consumers may also contribute to this gap.

The interviews with industry experts revealed that consumers are not solely responsible for driving demand in the fashion industry. Fashion brands play a pivotal role by constantly fuelling the market for new cycles and seasonal trends, resulting in mass-produced and overstocked items, with marketing techniques employed to stimulate the psychological needs of the consumer. Moreover, mills were found to be highly responsive to and dependent on the demands of fashion brands, yielding to their influence in every decision they make. This dynamic persists even when mills actively strive to invest in sustainable technology and practices on their own accord. Despite their efforts, the ultimate authority lies with brands, exerting significant control over supply chain choices and operations.

While brands retain significant control over supply chains, the current study revealed that a small and tightly knit community of modern denim mills and designers associated with established denim brands actively collaborate and are willing to invest in sustainable practices. This level of collaboration within a small community is unique in the textile industry and present behind the most globally spread fashion staple. By leveraging this collaborative mindset and the shared commitment to sustainability among this group of modern denim mills and designers, innovative approaches and alternative models for denim can be explored.

Relocalisation (2a): De-growth
Globalisation often leads to a decrease in centralised manufacturing clusters as labour-intensive processes are outsourced to various subcontracting chains in countries with lower associated costs, resulting in a dispersion of economic activities. The resulting problems, such as overproduction, transparency, unregulated work environments, cultural appropriation and a high distribution footprint in garments, show the need for localising supply chains. While some advocate the concept of "de-growth" as a beneficial solution for the environment, it may not provide practical strategies

for redefining the fashion industry. The interviews with industry professionals showed that the notion of de-growth fails to motivate proactive measures towards change. This is due to the perceived absence of clear benefits, with many believing it would ultimately result in diminished business opportunities. It was also clear that any incentive implemented is recommended not to undermine the powerful hedonistic and psychological enjoyment derived from fashion at the consumer end (Environmental Audit Committee, 2019). Hence, a more favourable approach would involve considering the relocalisation of structures across the globe, forming new self-sustaining economic ecosystems. This argument suggests that future leading fashion brands could proactively optimise the value chain by focusing on two key aspects: nearshoring and automation.

Relocalisation (2b): Micro-manufacturing, on-demand production and autonomy through locality
The interviews conducted with the denim mills and a 3D weaving expert also revealed that apart from facilitating the exploration of innovative production methods, 3D weaving has the potential to support process automation in micro-manufacturing contexts. By consolidating multiple steps in traditional supply chains, such as weaving, cutting and sewing, into a single process (i.e. a highly reduced number of steps), 3D weaving could serve as an example of localised innovation hubs that integrate design and manufacturing. This aligns with McQuillan's (2020) approach to zero-waste system design in a similar context. Moreover, local material opportunities could be explored. By bringing users, makers and the production process closer while integrating their values, a stronger symbolic bond could be formed between garments and consumers, potentially leading to a desirable shift in consumer behaviour, such as extended garment use (McQuillan et al., 2018). Accordingly, exploring how 3D weaving could enable on-demand approaches in local contexts and establishing a system for user participation could be valuable. It is important to note that 3D weaving alone may not provide a comprehensive solution for system change, relocalisation and user involvement, but it could serve as an initial case example, potentially initiating a catalysing effect in the broader industry.

The Blackhorse Lane Ateliers, operating as a smaller-scale, locally based denim mill in London, has demonstrated that more significant control over the supply chain can be achieved within this locality. Notably, their recent adoption of Tonello's ozone and laser machines and their autonomy in fabric selection highlight independence from their client brands' influence.

Relocalisation (2c): Ethics
While reshoring outsourced manufacturing may seem promising, it carries ethical risks. Bringing production back without careful planning could harm overseas businesses and workers, endangering their livelihoods. Although retraining programmes are suggested, it remains unclear who will hold responsibility, what they would include or which markets workers could be retrained for. Additionally, "rebuilding" can be misleading, as many former industrial districts no longer exist, requiring new supply chains to be created from scratch. Instead of abruptly withdrawing from existing arrangements, a collaborative approach involving knowledge transfer and partnerships with overseas mills could be pursued. Cultivating immaterial resources such as knowledge, design, information and logistics could stimulate and prevent the decline of traditional manufacturing industries in industrial districts and help form new economic, decentralised models.

Reimagining denim design roles (3a): 3D CAD modelling and reconnecting design and manufacturing
In recent times, denim designers have become increasingly aware of the rising prominence of emerging 3D software, which offers notable cost-effectiveness and creative freedom. They acknowledge that this development will likely change their work methodologies significantly. Anticipated shifts in priorities and company initiatives are already on the horizon. The use of 3D prototypes will redefine the sampling process. Furthermore, brands are expected to redirect their attention towards core products and embrace the concept of capsule collections, emphasising on-demand, true-to-size production.

Incorporating 3D weaving as part of currently evolving design roles can be seen as an opportunity within the denim industry, as it coincides with emerging perspectives. However, denim designers have highlighted the challenges of adapting to new tools, innovative manufacturing methods and 3D prototyping, especially when there is a significant disconnect from the production process. Traditionally, denim design has been relatively detached from manufacturing, suggesting a need for future integration. A report addressing the reshoring of supply chains to the UK, co-authored by one of the interview participants, calls for the establishment of open-access labs, Living Labs and networked collaborative manufacturing models (Postlethwaite et al., 2022). These initiatives could provide the necessary upskilling opportunities to meet the challenges of a forward-looking industry. Establishing such models could provide a platform for further exploring methods like 3D weaving in the context of automation, efficient 3D prototyping, on-demand production and accurate sizing requirements.

Reimagining denim design roles (3b): Education reorganisation
There is increasing recognition that educational restructuring is necessary to keep pace with the evolving role of denim design. In the UK, universities and prominent denim designers have acknowledged this need and are actively promoting the challenge of redesigning education by introducing integrated master's programmes tailored to this purpose. The significance of educational restructuring is evident in other instances, such as fashion designers pursuing double major programmes to cultivate cross-disciplinary skills and drive innovation (Faerm, 2018). The University of Leeds has provided another notable example of educational involvement in fashion design through the establishment of a collaborative research centre dedicated to 3D weaving, supported by the European Regional Development Fund (University of Leeds, 2023). Weffan, a 3D weaving expert interviewed in this study, has previously partnered with this centre. In the Netherlands, the team of innovative fashion design researchers is growing in the context of industrial design engineering. For the Dutch denim and fashion market, this notion could be an opportunity for similarly partnering industry and education with the innovation centre of Leeds.

The success of a denim designer extends beyond technical skills. It is crucial for students and established designers to join transdisciplinary programmes that offer a strategic balance between building new skills, integrative design manufacturing methods and unique storytelling. This equilibrium between the 'what' and the 'how' enables future denim designers to effectively translate societal trends and emotional values into fashion design trends in alignment with the evolving nature of the industry (Faerm, 2018).

Consumer communication (4a): Communication strategies

Reliable communication is crucial to support consumer understanding and the acceptance of new sustainable products and models. In this study, the literature findings and interviews with industry experts further reestablished this topic of importance. There is limited knowledge regarding the precise reporting and communication of sustainability efforts within fashion brands (Watanatada & Mak, 2011; Yan et al., 2010). This scarcity of knowledge is compounded by the lack of a standardised definition of sustainability at the EU level (Marrucci et al., 2021). Furthermore, Chan and Wong (2012) suggest that fashion consumers are often unfamiliar with the availability of sustainable fashion, indicating the need for relevant information to be easily accessible. Without sustainability knowledge, many people still rely on environmental messages by fashion brands regarding this topic at the time of purchase (Teona et al., 2019). Consequently, with the upcoming EU-wide Green Claim Directive (European Parliament, 2023) prohibiting misleading environmental claims, attention could shift to developing effective communication strategies.

Consumer communication (4b): 'Just Zero Waste' is insufficient

Sustainability information about 3D woven garments needs to encompass material choices, origin, chemical usage and labour practices to build consumer trust. As many industry and user participants reported, consumer scepticism may stem from awareness of greenwashing. Trust erodes when a brand's sustainability claims conflict with its actual practices, leading to perceptions that sustainability efforts are merely reactive to consumer demand (Ellen et al., 2006). Regarding 3D woven denim, collaborating with value-driven brand partners and ensuring full transparency across the supply chain is crucial.

Consumer communication (4c): Economic factors

Consumers can be willing to pay more for well-supported sustainable garments but may still resist excessively unreasonable prices, as noted in the literature and in the industry discussions with Diamond Denim by Sapphire and Blackhorse Lane Ateliers (Chan & Wong, 2012). Beyond affordability, sustainable products can gain value through design and quality (Camacho-Otero et al., 2019). A favourable combination of low price and appealing design might lead to a preference for garments that reflect sustainable fashion attributes but are in fact not sustainable. However, the latter indicates a strength of 3D woven garments, forming a distinct product category due to their unique visual appearance compared to traditional denim, making them not easily replaceable.

Some consumers seek to construct an ethical identity, fulfilling psychological needs and a desire for self-expression. Consumers perceive an advantage in a socially responsible lifestyle when purchasing branded products they associate with sustainable activities (Niinimäki, 2010). This suggests that the unique visual appeal of a 3D woven garment could be effectively combined with a compelling and transparent sustainability narrative. However, this sustainable narrative needs to address all life cycle stages – from design decisions to garment disposal. Making consumers part of the decision-making process by bringing them closer to the origin of their garments through local production and adapting marketing content to be informative and educational in terms of sustainability could help build stronger relationships between stakeholders and begin to encourage responsible consumption habits.

These findings represent important considerations for the industry as a whole and demonstrate how techniques can contribute to systemic change.

Exemplifying an alternative fashion ecosystem through 3D weaving denim
To showcase the transformative potential of innovative design manufacturing techniques, the findings have been translated into the design of an alternative, local fashion ecosystem for 3D woven denim situated in the Netherlands. Central to this design is the idea of new forms of collaboration, where relevant ecosystem actors find and support one another. Figure 5 presents a simplified overview of these actors, where 3D weaving serves as the focal point of the local research lab. The stakeholders displayed include governmental and non-governmental actors, educational institutions, denim brands and denim suppliers.
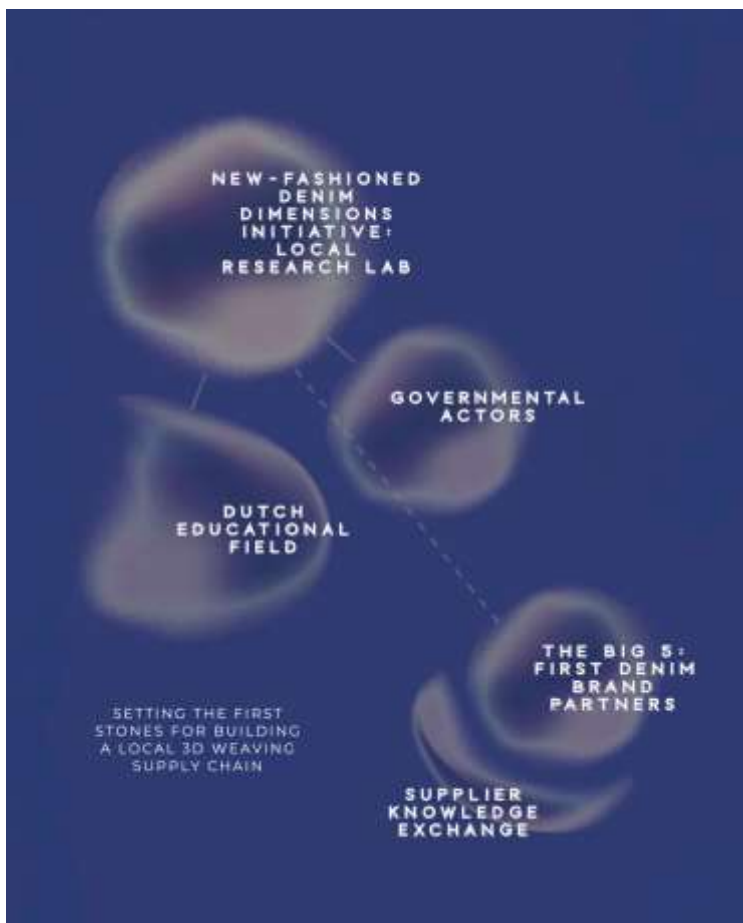

*Figure 5: Simplified collaborative ecosystem structure to foster pathways
to alternative fashion ecosystems.*

To turn vision into action, ecosystem actors need access to the strategies required to navigate the complexities of redesigning the fashion industry. An essential first step is identifying other stakeholders within the local context to be explored and within the broader industry. Engaging in dialogue with stakeholders through immersive fieldwork, where both systemic change and perceptions of the innovative technique are addressed, will enable the identification of critical components for transformative leveraging.

In this novel ecosystem, only small-scale, fully transparent and vertical production (from spinning to final garment) takes place, adhering to the highest sustainable production standards at every production step. The concept reflects considerations of material, environmental, financial, technical, ethical, communicative, consumer, educational, governmental, business and circular aspects. Through the collaboration, denim brands are granted access to the distinctive 3D weaving technique under certain conditions, incentivising them to pursue and drive local, sustainable and transparent practices. However, the ecosystem could serve as a starting point for brands to adopt holistic approaches encompassing various operations, catalysing forward-thinking and localised design strategies beyond 3D woven denim as a singular product category.

To clarify the actions needed to establish the collaborative ecosystem structure, the design includes a comprehensive road map with specific, actionable steps[1]. This road map guides actors through the actions of co-creating a 3D woven denim ecosystem dispersed on a timeline, highlighting practical aspects such as funding, branding, retail, certification, knowledge partnerships and consumer communication. An additional overview further specifies the responsibilities of each ecosystem actor[2]. This road map offers resources to help stakeholders define roles and collaborate in leveraging innovative techniques to reimagine the industry, serving as a pioneering example rather than a universal blueprint.

Conclusions and recommendations

The current work explores leveraging emerging fashion design manufacturing techniques to shape novel and sustainable fashion ecosystems. In recognition of the adverse environmental and social effects of modern fashion production, we underscore such techniques' broader significance beyond technical innovation in driving meaningful transformation. This study combines empirical research from the denim industry with a review of the literature to identify four key components for implementing innovative fashion models. The work focuses on the niche technique of 3D weaving as an exemplary case for addressing the industry's prevailing challenges through its zero-waste, on-demand and local production capabilities, fundamentally challenging traditional denim design practices and enabling reimagining of supply chains. The findings inform the creation of an exemplary local, sustainable and collaborative fashion ecosystem centred around 3D woven denim in the Netherlands, as part of a broader study exploring additional vital aspects of developing alternative fashion ecosystems.

Given the limitations within the timeframe of the current research, it is advisable to expand the scope of investigation by exploring local contexts beyond the Dutch market, incorporating diverse geographic, political, socioeconomic and cultural considerations. Future research could delve deeper into establishing knowledge exchange partnerships with current fashion suppliers to facilitate an ethical transition towards localised and self-sustaining ecosystems worldwide. Furthermore, exploring alternative economic models for driving industry-led change that depart from the current capitalist system might offer more unconventional solutions to sustainability concerns beyond relying on new product creation, profitability and reputation. Additionally, testing on-demand production models locally can yield insights into personalised, made-to-measure principles and

enhance consumer engagement, fostering stronger emotional connections to garments. Further exploration of 3D woven zero-waste design opportunities in textile industries outside denim or fashion, such as architectural and automotive textiles, is also recommended.

Existing knowledge about resource and energy usage in denim production – for instance due to high transport footprints, commonly used materials and resource-intensive supply chain steps – highlights the need to reconsider production methods. 3D weaving could serve as a less energy-intensive option by preventing unnecessary fabric production, reducing the number of supply chain steps and facilitating local production. However, we recommend conducting a lifecycle assessment (LCA) in the future to compare the two approaches.

We demonstrate how fashion ecosystems can emerge by integrating novel techniques within local, on-demand and collaborative contexts to reduce pre- and post-consumer waste while enabling small-scale sustainable fashion production infrastructures close to consumers. With elaborate critical considerations and an exemplary design with actionable steps, aimed at opening avenues for future investigation and advancement in the field beyond 3D weaving, the current research particularly contributes to Sustainable Development Goal (SDG) 9 (Industry, Innovation and Infrastructure), SDG 12 (Responsible Consumption and Production) and SDG 17 (Partnerships for the Goals) (United Nations Secretary-General, 2024).

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