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CRAFTING THE FUTURE OF FASHION WITH DATA, MATERIALITY, AND DIGITAL INNOVATION

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Patricia Wu Wu; Dust Enforcer; Point-cloud volumetric rendering of the choreographed performance, reworked by the editorial staff

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SURFACE SUSTAINABILITY

MAPPING CLIMATE CHIC ECO-AESTHETICS ON DIGITAL-ONLY FASHION PLATFORM DRESSX

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Abstract

This article explores the digital-only fashion platform DRESSX and its prominent role in shaping the narrative of sustainable innovation within the fashion industry. It investigates how DRESSX constructs and communicates its sustainability claims through aesthetic, discursive, and platform-mediated strategies. While digital fashion is often celebrated as an inherently sustainable alternative to physical garment production, this article questions the cultural and ideological assumptions underpinning such claims. Rather than treating DRESSX merely as a digital marketplace, the article approaches it as a curatorial and commercial ecosystem that performs sustainability through its interface and branding practices. It asks how sustainability is imagined, aestheticised, and commodified in a dematerialised, platform-based digital fashion economy.

Drawing from fashion media studies, critical platform theory, and innovation studies, this article maps the ways DRESSX blends commerce, curation, and affective visuality to promote “green” values tied to the digitalisation and so-believed dematerialisation of fashion. Through a mixed-methods approach combining platform analysis, interface reading, and discourse analysis, it reveals how sustainability operates more as a surface strategy than a systemic solution. The study ultimately questions whether the dematerialisation of fashion via digital platforms leads to a more ethical industry or simply a digitally displaced version of fast fashion.

Keywords: *Dematerialisation; E-commerce; Fashion ecosystem; Platform capitalism; Post-physical*

INTRODUCTION

Digital fashion has recently grown into a field of (digital) innovation in the fashion industry, promising reduced environmental impact by decreasing and sometimes eliminating physical materials (Baek et al., 2022; Periyasamy & Periyasami, 2023; Schauman et al., 2023). Central to this ecological narrative is *dematerialisation*: the shift from physical garments to data-driven designs, framed as a sustainable alternative to traditionally physical production and consumption. This shift reflects the increasing integration of immersive digital spaces into fashion systems, from AR/VR applications to gamified and metaverse environments where garments are visualised, worn, and circulated in non-physical forms (Boughlala & Smelik, 2024). As Periyasamy and Periyasami (2023, p. 3) argue, “the utilization of the metaverse in the digital fashion economy provides designers with the essential means to establish a brand that is environmentally sustainable and to support suppliers that adhere to sustainable practices.” Digital fashion platforms such as *DRESSX* position themselves at the forefront of this shift, presenting digital fashion as both technologically progressive and ethically responsible.

In this article, I investigate how sustainability is imagined, aestheticised, and commodified through digital fashion by focusing on DRESSX as a case study. Rather than measuring the platform’s material impact, I critically explore how sustainability is performed through DRESSX's interface, branding discourse, and commercial strategies (Fairclough, 1992; Galloway, 2012). Describing itself as "the largest digital fashion platform globally," DRESSX operates fundamentally as a *fashion-tech* company deeply embedded in platform capitalism and data-driven design. Its operations extend beyond garment creation to the infrastructure through which digital fashion is consumed, circulated, and monetised. Drawing from fashion media studies, critical platform theory, and innovation scholarship, I approach DRESSX not merely as a retail interface, but as a techno-cultural ecosystem that encodes ecological ethics into its commercial and ideological narrative (Srnicek & De Sutter, 2016; Van Dijck et al., 2018).

DRESSX offers digital garments for social media, gaming, and AR environments, and provides AI-powered tools for styling, virtual try-ons, and personalised garment visualisation. Its consumer ecosystem includes an AR fashion app, AI fashion game, virtual wardrobes, and avatar integrations across platforms such as *Roblox*, *Bitmoji*, *Meta*, and *Zepeto*. It also offers blockchain-based NFTs via its on-chain marketplace, positioning virtual garments as collectible and tradeable assets. On the business side, DRESSX develops AI styling tools, virtual try-on mirrors, branded wearables, digital trend reports, and platform utilities.

Products and services are accompanied by so-called *eco-metrics*: quantitative indicators of carbon savings and material reduction that position DRESSX as not only a pioneer in virtual aesthetics but also a leader in sustainable innovation. However, these metrics reflect a deliberate strategy to frame digital fashion as both technologically advanced and environmentally responsible (Creangă, 2019; Niessen, 2020). This raises questions about the robustness of such sustainability claims and their function within a broader entanglement of digital fashion, ecological ethics, and platform-driven innovation.

The leading question for this article is: how does DRESSX perform sustainability through its platform design, commercial discourse, and interface aesthetics? By critically mapping the visual, rhetorical, and infrastructural logics of the platform, I argue that sustainability here operates less as systemic intervention than as a branded, promotable surface that is visually polished, affective, and platformised. This argument centres on what I call *surface sustainability*: the performative deployment of green values that remain aesthetic and affective, rather than systemic or structural.

While this article focuses on DRESSX, the platform operates within a broader ecosystem of digital-only fashion initiatives, including platforms such as *XR Couture*, *Zero10*, and *Digitalax*. DRESSX is selected because its scale, commercial reach, and explicit sustainability branding make visible the dominant logics through which digital fashion platforms currently aestheticise and commodify environmental responsibility. Furthermore, DRESSX is not a single brand but a platform-based ecosystem that hosts multiple designers, collections, and technological services. The focus on DRESSX is therefore not aimed at generalising empirically across platforms, but to critically interrogate a paradigmatic case through which broader discursive and platform-mediated tendencies in digital fashion can be understood.

METHODOLOGY

To explore how DRESSX constructs and performs sustainability, I apply a mixed-methods approach combining platform and interface analysis with critical discourse analysis. Rather than assessing the platform's material environmental impact, I examine how sustainability is imagined, aestheticised, and commodified through visual design, discursive framing, and platform infrastructure. This includes platform ethics and data practices, which are increasingly recognised as integral to sustainability claims (Vänskä et al., 2024).

The methodological framework draws from media and platform studies to approach DRESSX not as a neutral digital marketplace but as a curated and commercial ecosystem (Riemens, 2025; Srnicek & De Sutter, 2016). Following Alexander Galloway's (2012) conception of the interface as a cultural effect, the platform interface is read as an ideological site that encodes sustainability through affective design, image curation, and user navigation. Building on Nanna Verhoeff's (2012) spatial and navigational reading of mobile screens, the interface analysis considers how the aesthetic organisation of sustainability guides perception and participation through product categorisation, imagery, and interactivity.

To complement this visual-infrastructural lens, I conduct a critical discourse analysis of

DRESSX's textual and visual messaging across its official communication channels, including the website, press releases, social media campaigns, mission statements, newsletters, blog posts, and collection announcements. Inspired by Michel Foucault's (1972) notion of discourse as a system of knowledge production, and Norman Fairclough's (1992) attention to institutional language, the analysis focuses on how sustainability is framed within broader narratives of innovation, digital dematerialisation, and ethical consumption targeted towards consumers (B2C) and businesses (B2B).

This approach is further informed by Rianne Riemens' (2024, 2025) model of tech-on-climate discourse, which foregrounds the strategic use of discursive coupling and decoupling to legitimise technological solutions to environmental crises. Her concept of "Platform Earth" frames digital platforms as actors in a green capitalist economy, where techno-optimism, planetary control, and immateriality obscure extractive practices and material entanglements (Riemens, 2025). Analysing DRESSX's sustainability rhetoric through this lens, I will examine how green values are encoded not only in language but also in platform architecture, functioning as both aesthetic strategy and ideological mythmaking device.

FRAMING SUSTAINABILITY IN THE DIGITAL FASHION ECONOMY

Before turning to the case analysis, I review and conceptualise dominant framings of sustainability within the digital fashion economy, focusing on their construction in both industry discourse and scholarly research. While recent research highlights the potential of digital innovation such as artificial intelligence to enhance sustainability in supply chain optimisation, defect detection, and consumer personalisation (Periyasamy & Periyasami, 2023; Ramos et al., 2023; Xin et al., 2025), there remains limited critical engagement with how sustainability is performed, aestheticised, and commodified by digital fashion platforms. The dominant framing tends to reproduce conventional narratives of technological solutionism, positioning innovation as inherently ethical. This uncritical alignment risks concealing the environmental and ethical implications of platform infrastructures and may ultimately reinforce unsustainable practices driven by the demands and dynamics of the digital economy.

Traditionally, sustainability in fashion is understood through material interventions: eco-fabrics, water reduction, circularity, and waste minimisation (Fletcher, 2014; Niessen, 2020). In contrast, digital fashion appears to circumvent these concerns altogether by eliminating physical production. Within popular media and marketing, dematerialisation is often framed as intrinsically sustainable. However, this framing overlooks the material realities of digital infrastructures: energy-intensive rendering processes, cloud computing, and the environmental toll of blockchain and NFTs (Schauman et al., 2023; Xin et al., 2025).

This is not to suggest that digital fashion is inherently unsustainable. When applied thoughtfully, it offers meaningful potential for environmental impact reduction. For example, 3D design supports zero-waste patternmaking and low-impact sampling (Rissanen & McQuillan, 2023). Virtual try-ons and digital showrooms can lower the carbon footprint of retail, shipping, and overproduction by encouraging more informed purchases. In such contexts, digital fashion may serve as a preventative tool for making less wasteful decisions. Still, its overall sustainability ultimately hinges on its integration into larger systems of production, consumption, and technological infrastructure.

Platforms like DRESSX have capitalised on the digital turn in fashion, a shift accelerated and brought to a peak by the COVID-19 pandemic (Boughlala & Smelik, 2024). Their branding draws on the language of sustainability, innovation, and empowerment, presenting digital fashion as a guilt-free alternative to fast fashion. In my view, this narrative masks a different kind of excess: not material, but visual, experiential, and digital. Consumers purchase digital garments to enhance online personas, clothe avatars, or post on social media (Choufan, 2022; Park & Chun, 2023). The value of these items is not in their utility but in their symbolic and affective appeal, often intended for ephemeral, single-use visibility in posts or games (Zhang, 2022). I therefore argue that digital fashion replicates the logic of disposability in dematerialised form, circulating within the same cycles of novelty, aesthetic trend, and obsolescence that drive fast fashion.

Importantly, DRESSX operates as a platform within the broader system of platform capitalism. Its sustainability discourse is not just an ethical claim, but it is a commercial strategy, a form of platform-native greenwashing. Carbon offset metrics, “eco-conscious” collections, and digital-only fashion drops, are framed as ethical innovations, yet they often serve more as affective signals than as structural interventions. Following Srnicek and De Sutter (2016), this can be understood as the commodification of ethical discourse within digital infrastructures: green values are encoded into user experiences (UX), algorithms, and marketing, not to reduce systemic harm but to differentiate the platform in a competitive digital economy.

While digital fashion may lower some material impacts, its sustainability is frequently aestheticised and commodified within platform logics. The literature discussed in this section suggests that green values are mobilised to enhance visibility, engagement, and competitive positioning within the digital economy, rather than to drive structural change. Ultimately, sustainability in this context is less a matter of material reduction than of narrative construction, where ethical claims serve brand identity and consumer affect, as much as environmental responsibility.

VISUAL AND COMMERCIAL LOGICS OF SUSTAINABILITY

Analysing the DRESSX interface reveals how it plays a central role in communicating sustainability to users. Through product labelling, navigation design, and curated categories such as the “Eco-conscious” collection, the platform fosters an image of ethical consumption. This collection presents garments as environmentally aligned, though the criteria for inclusion are rarely transparent. As I will show in this section, the interface, across both desktop and mobile versions, curates not only a browsing experience but an entire visual and ideological experience; one in which sustainability is rendered intuitive, immersive, and technologically progressive.

Let me show how the interface presents sustainability as an aesthetic and affective experience. At first encounter, green hues appear across the site’s visual design and in the logo. This strategic use of green, long associated with ecological responsibility, reinforces the perception that users are engaging in environmentally conscious consumption. Garments often feature shiny textures with ethereal and glowing effects that gesture toward a post-material, utopian future. (Fig. 01)[1]

Items like DRESSX’s “Blue Marble 2007”—dresses and shirts digitally wrapped in NASA satellite imagery of Earth—or Scotomalab’s “Save-Our-Planet” capsule collection exemplify how sustainability is visualised through direct symbolic references to environmental iconography. Beyond these explicit references, my analysis shows that the aesthetics of immateriality—metallic sheens, floating garments, dreamlike virtual environments—reinforce the perception that these clothes are clean, weightless, and guilt-free. This visual language distances users from the material realities of garment production while reinforcing a sense of participation in innovation and progress (Evans, 2013; Galloway, 2012). The promise of sustainability is conveyed not through material transparency, but through a speculative visual culture where dematerialisation becomes synonymous with ethical action.

The site foregrounds ethical action by presenting sustainability as a curated lifestyle choice. Categories such as “Eco-conscious” and “No More Plastic” are seamlessly integrated into the interface’s top-level menu, appearing alongside style-driven or occasion-based groupings. These remain accessible across devices through expandable menus, maintaining visibility regardless of screen size. Their strategic placement puts ecological awareness on equal footing with aesthetic taste under the header “shop now,” suggesting sustainability is no longer a niche concern but an integral part of contemporary fashion culture. Moreover, these sections are often accompanied by bold, motivational statements—e.g., “Eliminate your carbon footprint with every outfit” or “Communicate your sustainable goals through your new digital looks”—guiding users not just toward a product, but toward a desirable ethical identity.

Pushing the analysis further, this ethical identity is constructed through the procedural dimensions of the interface. Unlike e-commerce platforms of physical items, DRESSX does not

1 The design pictured in this image is accompanied with an artist and garment description. In this case, Lena Semenenko—Ukraine’s first digital designer to present at Ukrainian Fashion Week (2020)—imagines a speculative future in her DRESSX collection READY FOR FUTURE? Her designs envision smart, sustainable cities shaped by collaboration between designers, scientists, and bio-designers, using materials that “do not exist in reality” to propose new urban and ecological paradigms.

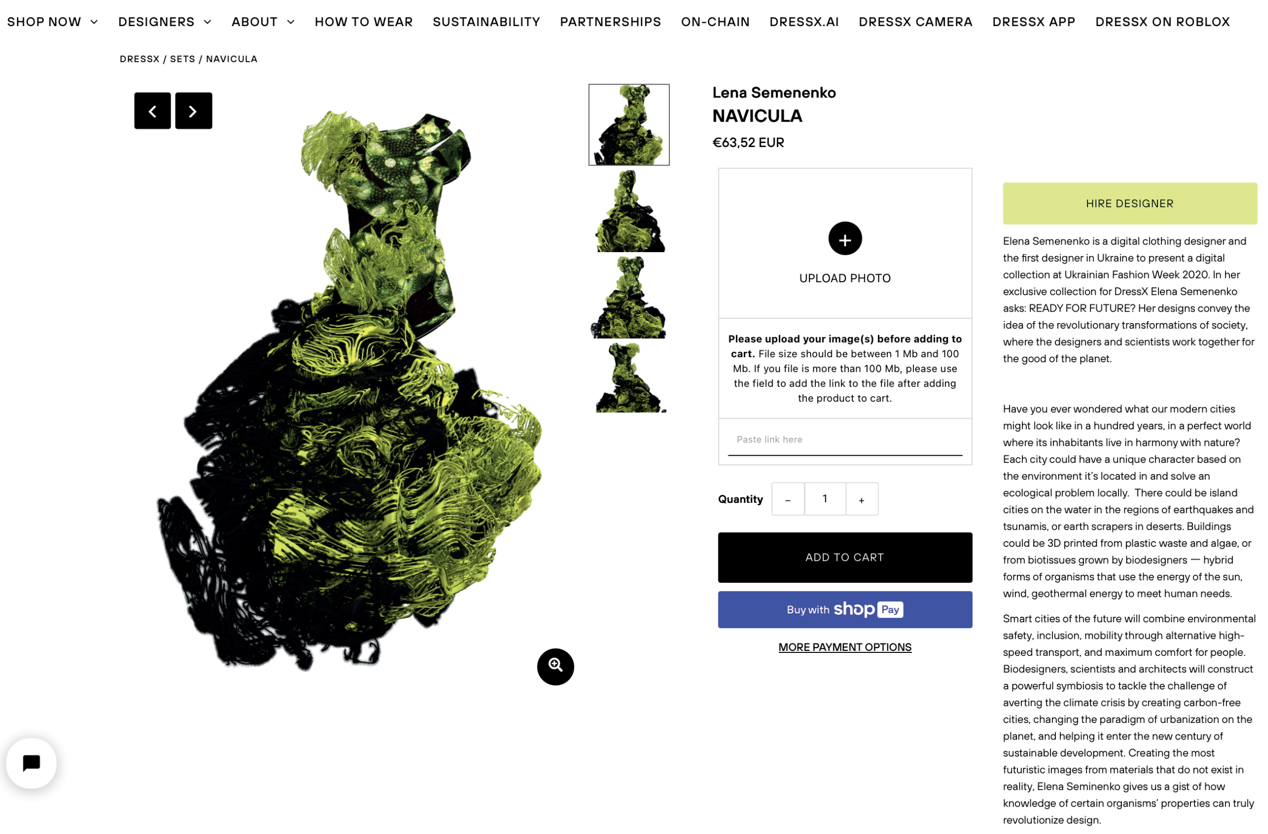

Fig. 01

ask users to select a garment size or shipping address. Instead, users are prompted to upload a photograph or try garments in Augmented Reality, built on the premise that "digital clothes fit all sizes." This shift symbolically reconfigures the act of consumption: the absence of shipping options or fabric descriptions is not a flaw but a feature; it is a visual and experiential cue that these clothes generate no physical waste. In fact, the "upload" button becomes an interface artifact of sustainability, replacing logistical friction with virtual immediacy—a form of "instant fashion" (Rocamora, 2013, p. 74)—ideologically aligning technological ease with ecological virtue.

As my analysis further reveals, this dematerialised ethos is reinforced by the absence of traditional material indicators: no fabric swatches, no garment tags, no sourcing notes. Though there are some tongue-in-cheek references to fictitious materials like "digital leather." Instead of actual material references, the interface prominently features bold infographics, claiming quantifiable environmental benefits such as kilograms of CO_2 saved or litres of water preserved. These figures are often paired with digestible comparisons (e.g., "equal to 968 days of phone charging"), anchoring abstract ecological metrics in everyday actions (Fig. 02). Visually, these statistics appear in stylised blocks, with icons like water droplets or CO_2 clouds, integrating the language of sustainability into the interface's design vocabulary.

For a discourse analysis, it is crucial not only to consider what is present, but also what is absent. While these eco-metrics suggest scientific legitimacy, they are presented without links to underlying data, independent verification, or lifecycle assessment. They operate less as rigorous environmental accounting than as performative markers of green intent, designed to reassure users immediately. In this context, eco-metrics serve as aesthetic cues rather than empirical tools, allowing sustainability to act as a commercial asset. Their presence blurs the boundary between ethical information and marketing strategy, reinforcing the idea that digital fashion consumption can be not only guilt-free but 'measurably' virtuous.

The broader aesthetic of the site supports this alignment of sustainable innovation. The layout privileges full-width imagery, smooth

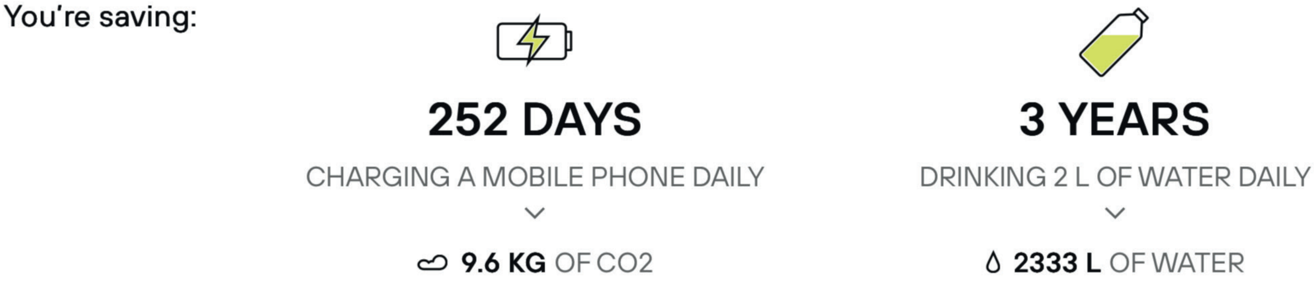

Fig. 02

animations, and dynamic interactions, enhancing the immersive experience of digital consumption. A clean, minimal colour scheme (white or black with neon highlights) evokes a technological clarity and futuristic optimism. There is a deliberate absence of fashion's usual environmental signifiers: no factories, no fibres, no supply chains. Instead, users encounter a streamlined interface where consumption is abstracted from material labour, and sustainability becomes a visual default.

This analysis shows that the DRESSX interface communicates sustainability not as ecological urgency or systemic critique, but as a desirable and rewarding lifestyle aesthetic. Users are not asked to reconsider consumption, but to redirect it; to "shop smarter" by moving from physical to digital wardrobes. Digital fashion is presented as ethical indulgence: a way to enjoy fashion's pleasures without planetary costs. The act of uploading a selfie, swiping through glowing garments, or dressing an avatar becomes imbued with moral and affective value.

"POST-PHYSICAL" BRANDING NARRATIVE OF DIGITAL FASHION

Moving the analysis beyond the interface, I argue that DRESSX constructs its sustainable identity through a broader discursive strategy rooted in aspirational sustainability, digital innovation, and personal empowerment. Across official communications, the platform consistently aligns itself with climate responsibility and technological transformation. Slogans such as "saving the planet one digital garment at a time" or "post-physical fashion" position digital fashion not merely as trend, but as cultural and moral imperative. These statements do more than market a product: they articulate a worldview in which fashion consumption becomes ethically regenerative, technologically advanced, and aesthetically liberating, in clear contrast to fast fashion's moral and environmental failings.

A key theme in DRESSX's sustainability discourse is dematerialisation as ecological salvation. The company foregrounds that digital garments "produce 97% less CO_2 and use 3,300 litres less water than physical clothing." These claims recur across their "Sustainability" microsite, which includes subpages on "People," "Planet," "Prosperity," and "Partnership."[2] Modelled on the United Nations Sustainable Development Goals (SDGs), this framework suggests accountability, but its application remains largely rhetorical. The platform's "Raw data & methodology" page references internal calculations and external estimates to quantify environmental savings. However, these figures are presented as infographics and simplified analogies ("equal to 968 days of phone charging") with no third-party verification or detailed lifecycle assessment. DRESSX thus *performs* transparency while affirming a pre-established belief in digital fashion's eco-virtue.

This emphasis on quantifiable impact legitimises ecological credibility while displacing the more complex realities of energy use, data storage, and platform infrastructure. Climate action is translated into user-friendly metrics, rendering sustainability legible as a lifestyle upgrade rather than a structural critique. Users are invited to participate in planetary care through consumption, marking an affective shift from guilt to empowerment. Slogans like "Don't shop less, shop digital fashion" invert the logic of sustainable restraint, reframing minimalism as abundance and sacrifice as indulgence. Here, digital fashion is not a reduction of fashion consumption, but a redirection into a supposedly immaterial domain.

This aspirational tone is reinforced by future-oriented language: "cutting-edge technology," "AR try-ons," and "Web3 solutions" are promoted as tools for climate-positive fashion. This language is ideological, inviting users to identify as responsible, early adopters of a new mode of ethical consumption. It encourages pride and momentum in aligning with digital change, cultivating what I term *climate chic*: a stylised, optimistic, and shareable form of ecological awareness.

DRESSX also mobilises identity politics in its branding narrative. They describe Gen Z, their largest consumer base, as digital natives driven by "climate anxiety" and a desire for "sustainable and expressive alternatives." This rhetoric positions digital fashion as both stylistic tool and political medium. Statements like "build your infinite wardrobe" or "explore trends guilt-free" invoke green consumer citizenship, where ethics are enacted through marketplace behaviour. Notably, the "People" page juxtaposes grim statistics on labour exploitation in the global fashion industry with celebratory descriptions of DRESSX's own remote workforce, complete with "delicious snacks" and co-working hubs. These contrasts produce a discursive split between analogue suffering and digital freedom, positioning DRESSX as a clean, ethical break from fashion's material past/present.

Strategic collaborations and curated collections further embed DRESSX's messaging in climate branding. Partnerships with initiatives like the *No More Plastic Foundation* and *Earth Month* campaigns anchor digital garments in environmental discourse. Collection names such as "Mass-Extinction Tee" or "Save the Ocean" stress symbolic value, while AR-enhanced campaigns promise seamless scalability. The refrain "no fabric, no pollution, no compromise" captures the techno-solutionist ethos at play: an imaginary in which innovation, rather than regulation or degrowth, becomes the preferred path to sustainability.

DRESSX's sustainability pages amplify this narrative, layering SDG references with broad claims like "all our activities have positive environmental and social impact." However, the engagement with these goals is largely symbolic. While the site references SDG 12 ("Responsible Consumption and Production") and SDG 13 ("Climate Action"), it offers no measurable progress or concrete targets. Sustainability functions here as a visual and discursive aesthetic, anchored in iconised metrics, elevated by slogans, and enacted through design. Features like the "upload" button, as mentioned before, or AR try-on are not merely functional but ideological: they embody the promise of ethical consumption without waste, labour, or delay.

My analysis shows that DRESSX's discursive strategy does not challenge structures of overconsumption but enables its continuation in digitised, aestheticised, and moralised form. Sustainability becomes an affective state: a stylish, intuitive experience that aligns consumption with virtue. By framing digital fashion as both technologically inevitable and ethically redemptive, DRESSX does not merely promote a product—it constructs a post-physical imaginary in which users dress themselves into a better future. In this framing, sustainability is less a goal to be achieved than an experience to be performed.

2 https://dressx.com/pages/sustainability

DISCUSSION: COMMERCIAL PERSISTENCE OF FAST FASHION

Bringing together the analyses, I argue that DRESSX reproduces many core logics of fast fashion: rapid turnover, trend-centric aesthetics, and a relentless emphasis on novelty. While its garments are virtual, the platform remains tethered to the fashion industry's accelerationist dynamics. New collections appear frequently, often tied to temporal events, celebrity collaborations, or digital "drops," echoing the micro-trend cycles of brands like *Shein* or *Zara* (albeit without the physical inventory). What distinguishes DRESSX is not a break from fast fashion's economic model, but its rebranding under the guise of digital dematerialisation. The earlier-mentioned slogan "Don't shop less, shop digital fashion" is telling: consumption is no longer constrained by storage, shipping, or wearability. Instead, users are encouraged to build "infinite meta-closets" filled with ephemeral looks for ever-changing platforms. This post-physical abundance sustains fast fashion's appetite for visual novelty while dressing it in a rhetoric of sustainability.

Yet, and this is paramount to my argument, dematerialisation does not equal impact-free. Emerging research shows the environmental cost of digital infrastructures is far from negligible (Che et al., 2024). Core processes such as 3D rendering, cloud storage, AR/VR, and blockchain minting consume significant energy. Even "lightweight" digital garments require GPU-intensive rendering, server capacity, and constant user engagement. As Xin et al. (2025, p. 5) put it, "the technological energy consumption of the production process of digital fashion products is invisible to the brand." In this light, DRESSX's claims of decarbonisation may obscure the redistribution of environmental harm from the sweatshop to the server farm.

These tensions reveal a central contradiction in the branding of ethical immaterialism. DRESSX's sustainability discourse promotes minimalist values like waste reduction, no shipping, carbon neutrality, yet invites users to accumulate maximalist digital wardrobes, often filled with garments intended for one-time use. This mirrors what Niessen (2020) calls fashion's "sacrifice zones": immaterial spaces that enable continued consumption while concealing its extractive conditions. In the case of DRESSX, I extend this to *digital sacrifice zones*: digital environments that enable continued hyper-consumption while masking their infrastructural, energetic, and ideological costs. Here, digital fashion functions as both absolution and incentive: a promise that users can consume more, more often, and more publicly, so long as they do so digitally, without cloth or carbon.

While DRESSX offers one of the most developed eco-metric interfaces, similar sustainability framings can be observed from other major digital-only platforms such as The Fabricant, Institute of Digital Fashion, and more. These likewise emphasise immateriality, reduced (or zero) waste, and ethical innovation without fully or explicitly accounting for infrastructural energy use or platform-driven consumption dynamics. This suggests that surface sustainability is not unique to DRESSX, but operates as a broader discursive and commercial strategy within the digital fashion economy.

CONCLUSION

I have shown that DRESSX does not break from fast fashion's logic, but it digitises and intensifies it. The platform transforms sustainability from a material practice into a marketing aesthetic, revealing the complexities and contradictions of consuming ethically in an immaterial economy. Far from being a neutral space of innovation, the analysis of DRESSX reveals how sustainability in digital fashion is constructed, curated, and commodified. I have mapped the visual, discursive, and commercial strategies through which the platform constructs its sustainability narrative. Rather than a systemic response to fashion's ecological crises, sustainability emerges as a surface strategy—polished, promotable, and platformised—embedded in the visual, affective, and commercial logics of the digital fashion economy.

By engaging critically with digital fashion as both a media interface and a commercial actor, we can better understand the layered nature of sustainability discourse in emerging fashion ecosystems. Rather than take claims at face value, it is essential to assess how platforms like DRESSX aestheticise, monetise, and algorithmically reinforce sustainability not as an end goal, but as a branded surface. This tension lies at the heart of digital fashion's promise and its paradox. If digital fashion is to contribute meaningfully to sustainable futures, it must move beyond surface claims and participate in this reinvention socially, ecologically, and structurally.

CAPTIONS

[Fig. 01] NAVICULA dress by Lena Semenenko, DRESSX website, screenshot by author.

[Fig. 02] Eco-metrics of Scotomalab's SAVE-OUR-PLANET digital T-shirt, screenshot by author.

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FINE-TUNING LARGE LANGUAGE MODELS FOR MULTI-TASK CONSUMER DATA ANALYSIS IN FASHION DESIGN PROCESS

A CASE STUDY OF CHINESE WOMEN'S FASHION MARKET

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Abstract

Artificial intelligence (AI) is rapidly growing within the fashion industry, with current attention primarily focused on image transformation and generation. However, the application of text comprehension AI in design processes, particularly in market research, remains insufficiently explored. This research fine-tunes RoBERTa models to construct an analytical framework including data cleaning, sentiment analysis, and topic classification for Chinese women's fashion analysis.The research analyzed 30,796 user comments from Bilibili. The fine-tuned models achieved strong performance: 95% accuracy for data quality classification, 97.65% for sentiment analysis, and F1-scores ranging from 0.70 to 0.97 across nine topic categories. Analysis of 6,029 high-quality comments revealed that 89.1% of consumers expressed negative or neutral sentiments, with size fit (43.5%) and gender differences (41.3%) being main concerns. The research identified nine systematic industry challenges, including size standards deficiencies, design practices that enforce traditional gender norms at the expense of functionality, and unfair pricing practices.This research shows that fine-tuning Large Language Models works for fashion processes analysis, providing evidence for widespread consumer dissatisfaction. The research fills the gap in applying fine-tuned LLMs to fashion design processes while demonstrating new ways for integrating fashion education with AI, contributing to digital transformation in fashion education and industry development.

Keywords: *Large Language Models (LLMs); Sentiment analysis; Topic classification; Women's fashion; Model fine-tuning*

INTRODUCTION

The fashion industry is closely connected to every individual and represents an essential sector for every nation. According to Statista, global fashion market revenue is projected to reach $920.19 billion in 2025 (Statista, 2025). In recent years, the advancement of AI technologies has transformed numerous industries (Rizzi & Casciani, 2023; Mohammadi et al., 2021). Among these developments, generative AI for image creation has had a major impact on the design industry, shown by its application in textile pattern creation (Jung & Suh, 2023). As industry rules frameworks develop, related legal and ethical issues have gradually emerged (Musmeci, 2024). Compared to the early start of AI research in autonomous driving (Forbes et al., 1995), the development of AI technology in the fashion industry has been relatively slow, initially being primarily utilized for image generation and personalized recommendation systems (Zou et al., 2021).

However, people have started questioning whether the final data is real and whether the creative work is truly original.Given these current conditions and challenges, research on AI technologies specifically designed for the fashion industry domain remains insufficient.

This research will employ Large Language Models (LLMs) to investigate the topic of “Current Development Status of Chinese Women’s Fashion” and attempt to fine-tune AI models within a “fashion industry context” to enhance the authenticity and reliability of both the analytical processes and outcomes when examining fashion-themed unstructured data(Liu et al., 2024; Fan & Wang, 2024; Liang & Chen, 2024). This methodology can be applied across different stages of design, such as the research phase targeting user sentiment analysis and the analytical phase examining potential topics related to products or brands.

The rest structure of this paper is organized as follows: Section 2 presents a literature review that examines the current development status of AI technologies in the fashion industry and their relationship with users, identifying research gaps in the field. Section 3 introduces the specific experimental methodology, including research design, data collection methods, sample selection, and analytical approaches. Section 4 analyzes the results from both methodological and experimental content perspectives. Section 5 provides a comprehensive discussion of the research findings.

LITERATURE REVIEW

AI AND THE FASHION INDUSTRY

In recent years, AI technology has experienced rapid advancement, with LLMs such as ChatGPT and DeepSeek, based on Transformer architecture, demonstrating significant advantages in "rapid generation," "automated analysis," and "personalized decision-making" (Kalinin et al., 2024; Ranjan et al., 2025). These advantages have different impacts across different stages of product development.

For instance, the design process for apparel products can typically be divided into several stages: the analysis phase (analyzing target groups), where companies like Zara use data mining methods through social media to better understand target consumers' preferences (Cao, 2024; Dang, 2022); the preparation phase (collecting trend information and other related data); the conceptualization phase (where designers organize information and derive inspiration); and the implementation phase (creating fashion illustrations and garment production). For example, Nike enhances consumer engagement and brand loyalty by adding user customization options that allow consumers to participate in the design process (Gan, 2023).

Consumers are both research subjects and end-users of garments (Sarkar, 2011; Schiaroli et al., 2024). Fine-tuned LLMs can extract design preferences from consumer reviews, identify popular design elements, and quantify consumers' perceived value differences across various price points for apparel (Yu et al., 2021).

However, fashion design students currently tend to focus more on the final presentation effects of products and personal artistic expression within the design process, while the user research phase often fails to receive adequate attention (Harvey et al., 2019; Murzyn-Kupisz & Hołuj, 2021). This includes, for example, the current development status and challenges of women's fashion from the consumer perspective.

LLMS AND ROBERTA

BERT (Bidirectional Encoder Representations from Transformers) is a pre-trained language model proposed by Google in 2018 that achieved significant performance improvements across various natural language processing (NLP) tasks (Devlin et al., 2019). RoBERTa (Robustly Optimized BERT Pretraining Approach) includes several key optimizations based on BERT. Current research demonstrates that fine-tuned pre-trained RoBERTa models can achieve superior performance compared to BERT across various downstream tasks, including sentiment analysis, textual entailment, and reading comprehension (Liu et al., 2019).In fashion industry text analysis, RoBERTa demonstrates superior feature extraction capabilities and enhanced performance when processing complex unstructured textual data, due to its stronger language understanding abilities and more stable training processes.

ChatGPT, DeepSeek, and Gemini represent new-generation LLMs that employ generative architectures and possess capabilities in conversational interaction, text generation, and complex thinking. For analytical tasks involving specific niche domains and deep textual understanding, encoder models such as RoBERTa continue to maintain advantages (Nielsen et al., 2024).

Compared to image-based AI models, traditional text understanding models (such as BERT and RoBERTa) are relatively straightforward in terms of data preprocessing and model fine-tuning. For instance, in the apparel development process, different pre-trained models can be selected based on specific objectives and subjected to domain-specific fine-tuning to obtain models that better align with particular domain requirements, allowing more accurate understanding of fashion industry terms and concepts (Chen et al., 2024). Though rigorous application in fashion market research remains limited.

In summary, to address this research gap, this research will employ a fine-tuned RoBERTa model using user comments about “Current Development Status of Chinese Women’s Fashion” from Bilibili, a major Chinese video platform, as the data source. Through sentiment analysis and topic modeling methodologies, this research examines users' emotional attitudes and focal concerns regarding this topic from a consumer perspective. This research aims to validate the application value of text-based language models in fashion industry market research and explores the following research questions:

- What emotional attitudes do young consumers hold toward the current development status of Chinese women's fashion?
- What are the core issues in Chinese women's fashion development that consumers focus on?
- Based on consumer feedback, what are the primary challenges facing the Chinese women’s fashion industry?

METHODOLOGY

To understand the current status of the Chinese women's fashion market, this research follows a five-step process for data collection and analysis, implemented using Python version 3.9.1. To validate model reliability, we employ Precision, Recall, and F1-score as evaluation metrics. These metrics represent established standards for machine learning model assessment (Goutte & Gaussier, 2005; Sasaki, 2007; Christen et al., 2023).

DATA COLLECTION, SOURCES, PLATFORM SELECTION, AND DATA SCOPE

The sample utilized user comments from Bilibili, a major Chinese video platform, as the data source. Compared to short-video-focused platforms such as TikTok, Bilibili specializes in long-form video content, providing more adequate time and space for in-depth topic discussions (Shang, 2025; Xia, 2025). According to Bilibili’s Q1 2024 investor presentation, the platform's user base primarily consists of individuals born between 1985 and 2009, representing 65% of total users, with female users comprising 48% of the overall user population. Notably, over 80% of students from China's Project 985 and 211 universities—elite higher education institutions designated by the Ministry of Education—are registered Bilibili users (Bilibili Inc., 2024). This demographic profile indicates a highly educated user base, which contributes to more substantive and articulate discussions in comment sections. Furthermore, the substantial female user presence (48%) ensures adequate representation of the target demographic for women's fashion discourse, making Bilibili an appropriate platform for investigating attitudes toward Chinese women's fashion.(Li et al., 2025).

For this research, searches were conducted on Bilibili using the keywords "women's fashion" and "women's fashion status," yielding 1,006 videos containing these terms. From these results, videos were ranked by view count (highest to lowest), and the 13 videos with the highest comment volumes were selected for analysis. The selected videos span a four-year period from May 13, 2021, to April 20, 2025. Comment data collection, including both original comments and replies, was conducted between June 5 and June 7, 2025, resulting in a total of 30,796 initial text data points (Fig. 01)

DATA PREPROCESSING AND CLEANING

Text Preprocessing

The preprocessing phase involved identifying and removing reply formats such as “Reply @username:”; cleaning HTML tags, URLs, email addresses, and phone numbers; normalizing consecutive repeated characters, words, and punctuation marks; and converting emojis to textual descriptions or removing them entirely.

In this process,a selective emoji protocol was applied: emojis conveying emotional states or emphasis were converted to textual equivalents, while decorative emojis inserted for platform reward purposes were excluded.

Intelligent Text Enhancement

For comments lacking subjects, contextual information was intelligently added (e.g., "too small" → “the clothes are too small”). Missing semantic components were added through pattern matching techniques.

Content Filtering

Short comments (fewer than 3 characters) were removed; pure punctuation, pure numbers, and

Selected Bilibili Video Dataset for Chinese Women's Fashion Analysis

No.	Video Title	Views (k)	Comments
1	High Return Rates for E-commerce Women's Fashion: You Really Can't Blame Others	78	1,234
2	Close Down Quickly! What Kind of Distorted Aesthetics Do Current Women's Clothing Stores Have?	5,212	1,768
3	Buy 10 Items, Return 8! Are Clothes Also Becoming Assassins?	523	2,273
4	Men's Cotton Jacket Only 69 Yuan... With Free Shipping... Is Women's Money So Easy to Earn? Reject Pink Tax!	1,639	2,818
5	Don't You Know Why Your Women's Clothing Has High Return Rates??	1,818	5,685
6	Differences Between Women's and Men's Pants	105	445
7	Women's Clothing is Expensive and Slow to Ship, Who Exactly is Discriminating Against Female Consumers?	929	7,721
8	Merchants Should Allow People Who Return Items to Post Buyer Reviews	4,864	1,018
9	Distorted Aesthetics! Current Women's Clothing Size L Can Only Fit Dogs, Isn't Anyone Managing These Merchants?	184	1,209
10	Isn't Anyone Managing the Sizing of Current Women's Clothing Stores??	841	2,543
11	Isn't Anyone Going to Manage Women's Jeans??	106	450
12	Expensive and Poor Quality: Chinese Women's Fashion Trapped in a Dead End	61	124
13	Question Men, Understand Men, Become a More Money-Saving Woman	1,309	2,936

Fig. 01

meaningless phrases were identified and deleted; complete duplicates were removed along with similarity-based deduplication.

Quality Assessment

A quality scoring system (0-6 points) was developed based on: length score (0-2 points), fashion relevance (0-2 points), subject completeness (0-1 point), evaluative content (0-1 point), with reply format penalties (-0.5 points). Using keyword dictionaries, the system decided and found whether comments contained clear subjects or referential objects. A strict filtering strategy was employed, requiring comments to be fashion-related with quality scores above 2 points.

Cleaning Results

Following completion of the above steps, a total of 10,594 processed comment texts were obtained.

ROBERTA-BASED DATA CLEANING

During manual checking of the preprocessed data, several low-quality comments were identified, primarily characterized by: (1) extensive use of emoticons as replacements for textual expression; (2) incomplete sentence structures lacking essential components such as subjects and objects; (3) fragmented expressions with ambiguous semantics or unclear logic. These issues primarily come from the complexity of internet language and the diversity of user expression habits, which traditional rule-based text cleaning methods struggle to effectively identify and address.

To more precisely identify and filter low-quality comments, 569 comments were randomly sampled from the preprocessed data for manual annotation. The annotation criteria were: 0 for meaningless comments (including semantically incomplete, off-topic, or pure emoticon content), and 1 for meaningful comments (complete in meaning and relevant to the research topic).

Based on the manually annotated data, the hfl/chinese-roberta-wwm-ext pre-trained model was employed for fine-tuning. The hfl/chinese-roberta-wwm-ext is a Chinese pre-trained language model based on RoBERTa architecture, developed by the Harbin Institute of Technology-iFLYTEK Joint Laboratory (HFL) (Cui et al., 2021). This model is widely applied in Chinese text classification and sentiment recognition, specifically optimized for Chinese text processing.

For model training, the data was split into training and validation sets at an 8:2 ratio. This training method was consistently applied to subsequent sentiment analysis and topic classification tasks.

Model Performance Evaluation

For the 'meaningless' class, the model achieved precision of 0.95, recall of 0.91, and F1-score of 0.93 (n=45). For 'meaningful' comments, precision was 0.94, recall was 0.97, and F1-score was 0.96 (n=69). Overall accuracy was 0.95 across 114 test samples (Tab. 01).

Full Dataset Filtering Results

The trained model was applied to all 10,594 preprocessed comments, with a confidence threshold of 0.7 for filtering[1].Ultimately, 6,029 high-quality comments were obtained, resulting in a data retention rate of 56.9% (filtering rate of 43.1%). During the filtering process, the model reached an average prediction confidence of 83.1% across all comments.

1 Confidence represents the model's certainty level when processing comments; higher values indicate greater model confidence in its predictions.

ROBERTA-BASED SENTIMENT ANALYSIS

For the sentiment analysis phase, this research employed the hfl/chinese-roberta-wwm-ext-large pre-trained model for fine-tuning. This model represents an upgraded version of hfl/chinese-roberta-wwm-ext, capable of capturing more complex linguistic patterns and semantic relationships, getting higher accuracy in text understanding and generation tasks. The manually annotated sample for sentiment analysis comprised 1,062 comments, categorized into three sentiment classes: positive, neutral, and negative.

Model Performance Evaluation

All three sentiment classes achieved F1-scores above 0.97, with the model reaching an overall accuracy of 97.65% across 1,062 validation samples (Tab. 02 for per-class details).

Full Dataset Results

The trained model was applied to all 6,029 data points. Among these, positive comments accounted for 10.9% of the total comments (660 comments), negative comments comprised 41.3% (2,487 comments), and neutral comments represented 47.8% (2,882 comments). The model's average confidence in sentiment classification was 90.8%, with high-confidence predictions accounting for 83.6% of the total, while low-confidence

RoBERTa Model Performance for Data Quality Classification

Class	Precision	Recall	F1-score	Support
Meaningless	0.95	0.91	0.93	45
Meaningful	0.94	0.97	0.96	69
Accuracy			**0.95**	**114**
Macro avg	**0.95**	**0.94**	**0.94**	**114**
Weighted avg	**0.95**	**0.95**	**0.95**	**114**

Tab. 01

RoBERTa Model Performance for Sentiment Analysis Classification

Class	Precision	Recall	F1-score	Support
Positive	0.9855	1.0000	0.9927	136
Negative	0.9833	0.9652	0.9741	488
Neutral	0.9663	0.9817	0.9740	438
Accuracy			**0.9765**	**1062**

Tab. 02

predictions comprised only 5.2%.

ROBERTA-BASED TOPIC CLASSIFICATION

Due to the increased complexity of multi-label topic classification and building upon the strong performance achieved in sentiment analysis (average accuracy of 97.65% across three sentiment categories), this section continued to employ the hfl/chinese-roberta-wwm-ext-large pre-trained model for topic modeling.

Initially, a subset of comments required selection for manual annotation. For this part, 380 samples were annotated using a mixed sampling strategy. An additional 249 comments were added to ensure training stability and maintain sample diversity and uniqueness. This resulted in a final dataset of 629 manually annotated samples.

The manually annotated samples revealed 9 distinct topic categories: price, quality, style design, size fit, shopping experience, industry environment, gender differences, repurchase behavior, and fabric materials.

Model Performance Evaluation

Optimal Performance by Topic Category (Tab. 03)

Among the nine topics, the model demonstrated the highest precision in identifying fabric-related topics, successfully recognizing all fabric-related comments. However, recognition accuracy for quality and style topics was relatively lower at only 0.75. The price topic exhibited the worst overall performance with an F1-score of only 0.69. Most topics achieved F1-scores ranging between 0.77-0.87, indicating relatively balanced overall performance.

Final Model Performance (Tab. 04)

Full Dataset Results

Total Sample Size: 6,029

The fine-tuned RoBERTa model was applied to 6,029 high-quality comments for topic classification, identifying a total of 8,862 topic labels with an overall coverage of 147.1%. Size Fit appeared 2,620 times (43.5%), Gender Differences appeared 2,492 times (41.3%), Style Design appeared 1,115 times (18.5%), Industry Environment appeared 752 times (12.5%), Shopping Experience appeared 604 times (10.0%), Price appeared 517 times (8.6%), Quality appeared 353 times (5.9%), Repurchase Behavior appeared 271 times (4.5%), and Fabric appeared 138 times (2.3%) (Fig. 02).

Analysis revealed that over half of the comments (56.8%, 3,426 samples) focused only on single topics. An additional 35.5% (2,141 samples) addressed two topics at the same time, while only 6.9% (413 samples) discussed three topics. Overall, 92.3% of consumers focused on one or two specific concerns in their comments (Fig. 03).

RoBERTa Model Performance for Data Quality Classification

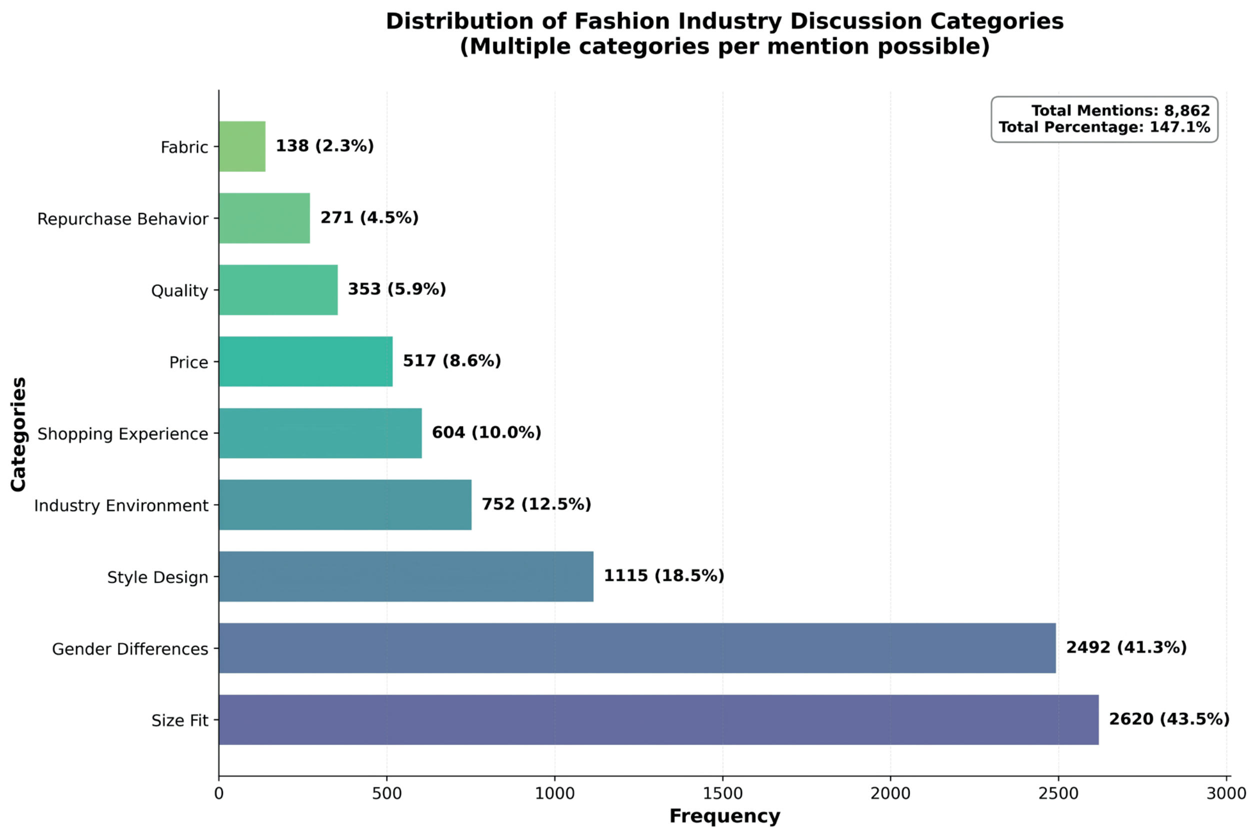
Topic Category	Precision	Recall	F1-score
Quality	0.7500	0.7895	0.7692
Price	0.8889	0.5714	0.6957
Industry environment	0.9048	0.7037	0.7917
Gender differences	0.8333	0.9091	0.8696
Style design	0.7500	0.8333	0.7895
Shopping experience	0.9091	0.7143	0.8000
Size fit	0.8667	0.7879	0.8254
Repurchase behavior	0.9091	0.8333	0.8696
Fabric materials	1.0000	0.9333	0.9655

Tab. 03

Overall Performance Metrics for Multi-Label Topic Classification Model

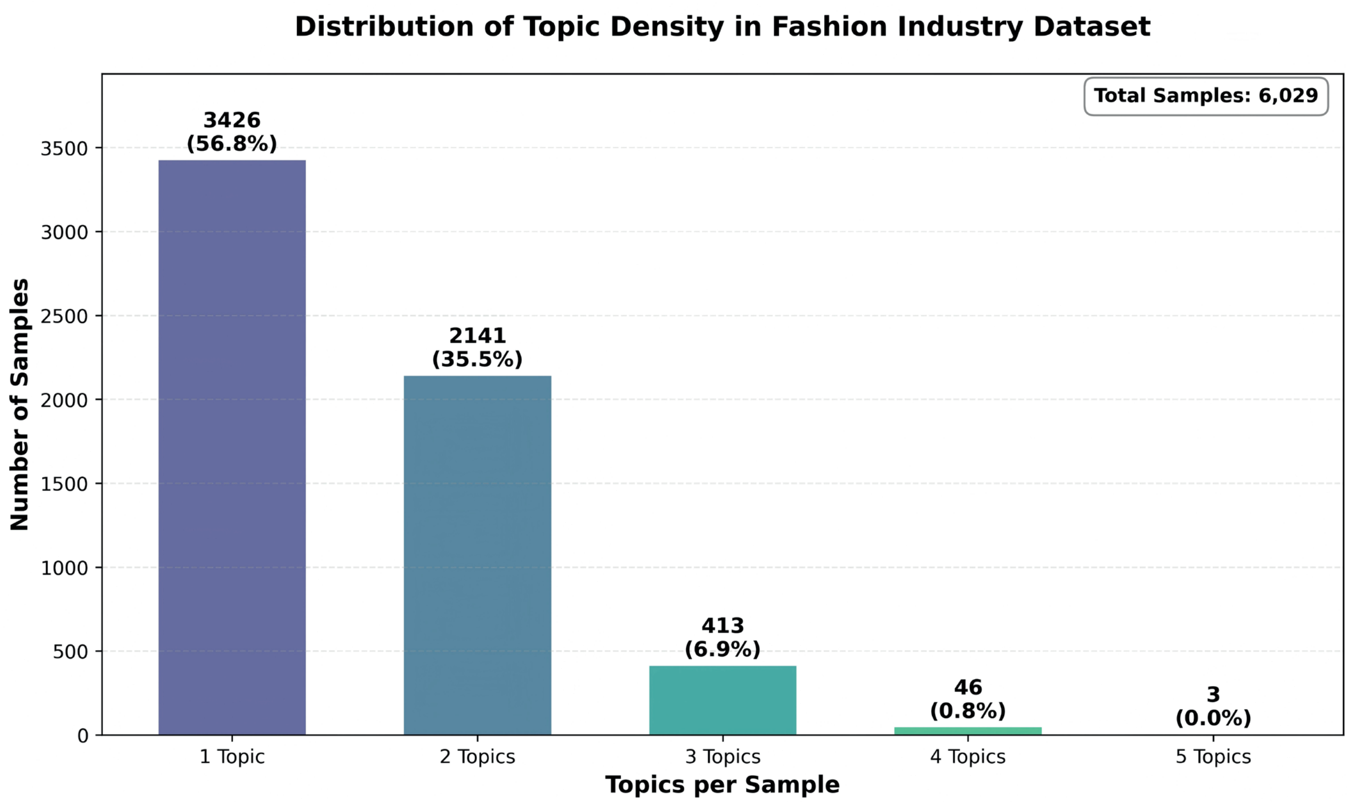
Averaging Method	Accuracy	Precision	Recall	F1-score
Micro Average	0.6293	0.8544	0.7377	0.7918
Macro Average		0.8503	0.7293	0.7801

Tab. 04



Distribution of Fashion Industry Discussion Categories
(Multiple categories per mention possible)
Total Mentions: 8,862
Total Percentage: 147.1%
Categories
Fabric
Repurchase Behavior
Quality
Price
Shopping Experience
Industry Environment
Style Design
Gender Differences
Size Fit
138 (2.3%)
271 (4.5%)
353 (5.9%)
517 (8.6%)
604 (10.0%)
752 (12.5%)
1115 (18.5%)
2492 (41.3%)
2620 (43.5%)
0
500
1000
1500
2000
2500
3000
Frequency

Fig. 02



Distribution of Topic Density in Fashion Industry Dataset
Total Samples: 6,029
Number of Samples
3500
3000
2500
2000
1500
1000
500
0
3426
(56.8%)
2141
(35.5%)
413
(6.9%)
46
(0.8%)
3
(0.0%)
1 Topic
2 Topics
3 Topics
4 Topics
5 Topics
Topics per Sample

Fig. 03

RESULTS

ROBERTA-BASED DATA CLEANING

The results demonstrate that initial filtering using self-defined criteria successfully removed 65.60% of low-quality comments. However, following further data cleaning with the RoBERTa model, an additional 43.1% of comments were identified as invalid content and removed. This phenomenon is mainly attributed to the complexity and diversity of Chinese comments on the Bilibili platform(Shang, 2025). As a breeding ground for numerous internet slang expressions, the platform has heavy use of online casual language, shortened expressions, and context-specific popular phrases in user comments. Ultimately, the fine-tuned RoBERTa model achieved 95% classification accuracy on the validation set, demonstrating its reliability and effectiveness in understanding complex online linguistic environments. The model successfully captured meaning features of comment content, accurately distinguishing between meaningful and meaningless comments, thereby establishing a high-quality data foundation for subsequent sentiment analysis and topic modeling tasks.

ROBERTA-BASED SENTIMENT ANALYSIS

Model Performance and Method Validation

The results demonstrate balanced performance across all three sentiment categories, with F1-score variations of only 1.87 percentage points between categories, indicating strong generalization capabilities and class balance..These findings demonstrate that fine-tuned RoBERTa models can accurately classify consumer sentiment (97.65% accuracy) in fashion-specific contexts, with balanced performance across sentiment categories.

Sentiment Distribution Characteristics and Industry Insights

The analysis reveals clear sentiment distribution patterns in discussions regarding the current development status of the Chinese women's fashion market: neutral and negative sentiments dominate, while positive sentiment accounts for only 10.9% of the total. This distribution reflects the predominantly negative attitudes held by young Chinese consumer groups toward the current state of women's fashion industry development. These findings indirectly confirm the existence of systematic industry problems, examined in detail in Section 5.2.

ROBERTA-BASED TOPIC CLASSIFICATION

Due to the significantly higher complexity of the nine-class multi-label task compared to previous binary and three-class classification tasks, individual comments may simultaneously address multiple topics. This complexity creates an inverse relationship between classification difficulty and accuracy, putting higher demands on the model's generalization and learning capabilities.

Performance Analysis

Compared to the previous data cleaning and sentiment classification models, the multi-label nine-class model demonstrated lower performance across precision, recall, and F1-scores, exhibiting relatively careful overall performance. The model displayed typical "high precision, low recall" characteristics, achieving an average precision exceeding 85% while maintaining an average recall of approximately 73%, reflecting a careful predictive tendency of "preferring false negatives over false positives."

Variation Analysis

The model exhibited significant variations in recognition capabilities across different topic categories, primarily attributable to two factors: first, with only 503 training samples split across 9 topic categories, per-category data was severely imbalanced. Second, inconsistent labeling quality caused uneven learning outcomes across topics.

4.3.3 Full Dataset Results

When the fine-tuned model was applied to all 6,029 samples, the results revealed core issues of consumer concern in the Chinese women's fashion market. The data indicate that size fit (43.5%) and gender differences (41.3%) constitute the two most frequently discussed topics, together accounting for 84.8% of comment content. In contrast, fabric (2.3%), repurchase behavior (4.5%), and quality (5.9%) demonstrated relatively low mention frequencies, suggesting limited consumer perception and attention toward these aspects. Analysis revealed that over half of the comments (56.8%) focused exclusively on single topics, indicating that consumers maintain clear and concentrated attention on specific issues, reflecting the high consistency and common nature of major problems within the industry.

CONCLUSION

METHODOLOGICAL CONTRIBUTIONS

This research applies text mining techniques to analyze unstructured consumer data in the fashion industry. Specifically, it employs a fine-tuned large language model based on the hfl/chinese-roberta-wwm-ext-large pre-trained model for sentiment analysis and multi-label topic classification.The results demonstrated the feasibility and accuracy of LLMs in design decision support, providing practitioners with demand-driven, customized AI experimental solutions (Bertacchini, 2023). This approach not only enhances the data-driven nature and clarity of design decisions but also advances methodological innovation and integration between AI technology and fashion design fields.

FINDINGS

Analysis of 6,029 Chinese social media comments revealed significant structural challenges in the women's fashion industry. Nearly 90% of consumers expressed non-positive sentiments, with sizing issues (43.5%) and gender representation concerns (41.3%) emerging as the most prominent pain points. Notably, while consumers demonstrate clear awareness of these problems through frequent and specific complaints, the issues remain prevalent in current industry practice. This disconnect between consumer recognition and industry status quo suggests systemic challenges that extend beyond surface-level concerns.

Combined with the previous sentiment analysis results, the data reveals several existing problems in the Chinese women's fashion market:

Absence of Size Standardization

Consumers universally face challenges with inaccurate sizing and poor fit. The current market lacks unified sizing standards, with different merchants and shopping platforms operating independently, resulting in significant variations of the same size across different brands (Workman,1991). More critically, influenced by societal aesthetic trends pursuing "pale, thin, and youthful" ideals (Liu & Li, 2024; Guo et al., 2023), women's clothing sizing is designed extremely small, leading to the unfortunate phenomenon of adult women being forced to choose children's clothing. This phenomenon reflects the industry's severe lack of recognition regarding women's body diversity (Hu et al., 2016).

Gender Stereotypes in Fashion Design

Women's fashion design exhibits deeply entrenched gender biases and stereotypes, primarily shown in: design ideas that force gender norms such as "women should wear skirts"(Cai, 2023); functional design deficiencies, including the removal or reduction of pocket designs with the excuse that "women have handbags"(Bolon, 2025); and severe pink tax issues(Brand & Gross, 2020), where female versions of products of the same type and quality are priced significantly higher than male versions. This pricing unfairness lacks reasonable cost reasons.

Forced Design Differentiation

This artificial differentiation has prompted consumer resistance, with increasing numbers of young consumers embracing gender-neutral fashion as a form of social practice (Jiang & Michelsen, 2024). Among these consumers, many women actively choose men's clothing for superior practicality and value. When consumers systematically prefer men's alternatives for everyday needs, this pattern reveals fundamental failures: inferior quality, reduced functionality, and poor value despite higher prices (the "pink tax"). The preference for men's clothing represents not merely individual choice but resistance against gendered design that sacrifices women's actual needs for prescribed femininity.

Vicious Cycle in Industry Ecosystem

The women's fashion industry is trapped in a negative feedback loop: (1) poor product quality, high prices, and inaccurate sizing lead to very high return rates; (2) rising return rates compress merchant profits, forcing further reductions in production costs; (3) platforms implement stricter return and exchange policies to protect consumer rights; (4) merchants transfer costs through extended pre-sale periods and increased selling prices; (5) product quality deteriorates further.

Deteriorating Shopping Experience

Consumers face multiple challenges throughout the entire shopping process: (1) very long pre-sale periods (often exceeding one month) during product selection; (2) receiving obviously second-hand returned merchandise; (3)

price manipulation practices in promotional campaigns (artificially raising prices before applying discounts). These issues seriously damage consumer confidence and patience in women's fashion shopping.

Systemic Price Discrimination

The pink tax phenomenon is especially obvious in the women's fashion industry, where female-related products are regularly priced higher than comparable male products (Fu, 2024). This price differential often lacks reasonable cost reasons and primarily reflects excessive taking advantage of women's purchasing power and the commercialization of gender bias.

Collapse of Quality Assurance Systems

In pursuit of short-term profit maximization, merchants universally compress production costs, resulting in the failure of quality control mechanisms in garment manufacturing processes. This cost compression manifests not only in declining craftsmanship standards but also in the relaxation of product durability and safety standards.

Distorted Market Competition Mechanisms

Quality-oriented merchants face structural disadvantage: fast fashion margins (16%) far exceed those of traditional quality retailers (7%) (Sull & Turconi, 2008), enabling a "bad money drives out good" dynamic (Akerlof, 1970) that further deteriorates the industry ecosystem.

Systemic Decline in Raw Material Quality

Closely linked to quality issues, cost compression directly results in narrowed fabric selection ranges and declining quality. Merchants are forced to choose cheaper and lower-quality raw materials, creating a comprehensive quality decline chain from source to end product.

INDUSTRY SIGNIFICANCE

As one of the world's largest garment production and consumption markets (Circular Fashion: Prospects for China's New Textile Economy), the developmental dynamics and structural issues of China's women's fashion industry hold significant international reference value. The data insights and analytical methods provided by this research not only offer precise guidance for international brands to improve product design but also provide scientific evidence for the global fashion industry to understand the Chinese market and formulate localization strategies.

CAPTIONS

[Fig. 01] Selected Bilibili Video Dataset for Chinese Women's Fashion Analysis.

[Fig. 02] Distribution of Fashion Industry Discussion Categories.

[Fig. 03] Distribution of topic density in Fashion Industry Dataset.

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TEXTILE MASKS

THE FABRIC OF IDENTITY. FROM POST-DIGITAL TEXTILE ARTISTIC CREATION TO ART-FASHION AS A TOOL FOR CRITIQUE AND SAFEGUARDING OF INTANGIBLE HERITAGE

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Abstract

This article examines *Textile Masks: The Fabric of Identity*, a series of contemporary textile art artefacts produced by the authors between 2024 and 2025, as a post-digital artistic expression situated within the field of art-fashion and engaged with social critique and the safeguarding of intangible cultural heritage. The series comprises handcrafted textile objects conceived as sculptural masks, developed through traditional textile techniques—specifically hand stitching and trapunto quilting—in dialogue with post-digital aesthetics. The analysis addresses two typological groups of artefacts: textile objects that incorporate technological components, namely augmented reality, and textile objects that, while materially analogue, critically reflect on processes of digital rematerialisation without embedding technology within the object itself. Drawing on works such as *Synthesis* and selected pieces from the *Textile Masks* series, the article explores how the convergence of textile practices and digital imaginaries generates hybrid artistic forms that challenge the boundaries between the tangible and the virtual. It is argued that these post-digital textile practices renew contemporary visual languages while operating as instruments of cultural critique and as mechanisms for safeguarding intangible heritage by reinscribing ancestral knowledge into contemporary artistic narratives.

Keywords: *Post-digital artist creation; Textile art; Identity; Heritage; Art-Fashion*

INTRODUCTION

In contemporary contexts, textile artistic creation has established itself as a fertile field for the exploration of identity, political, and cultural issues, incorporating languages that intertwine tradition and technological innovation. Far from being limited to formal or decorative concerns, contemporary textile practice has increasingly consolidated itself as a critical territory, capable of intervening in broader debates on memory, cultural diversity, and processes of subjectivation.

This dynamic acquires particular relevance within the post-digital paradigm, a concept that emerged in the early 2010s to describe a critical shift in how the digital is understood and integrated into artistic and cultural practices. As proposed by Cramer (2013), the term post-digital does not designate a chronological phase following the digital, but rather an aesthetic and cultural condition in which digital technologies are no longer perceived as novelty or rupture, becoming instead a naturalised and structural element of artistic production. Within this framework, post-digital aesthetics are characterised by a renewed emphasis on materiality, manual gesture, and artisanal processes, in dialogue with digital imaginaries, logics, and modes of mediation. Artistic creation thus unfolds in a space of critical coexistence between the tangible and the virtual, where artisanal processes and digital references are articulated to generate hybrid practices that question traditional dichotomies and reconfigure the relationships between technique, aesthetics, and culture (Cramer, 2013; Pereira, 2018).

In the field of textile art, post-digital practices manifest themselves both through the direct incorporation of digital technologies and through processes of symbolic rematerialisation of the digital in materially analogue objects. Post-digital textile creation is therefore characterised by a productive tension between materiality, manual gesture, and technological mediation, enabling the questioning of dichotomies such as tradition versus innovation or materiality versus immateriality. In this sense, textiles emerge as a privileged medium for critically reflecting on the role of material practices within cultural contexts marked by the pervasive presence of the digital (Dormor, 2020).

It is within this framework that the present article analyses *Textile Masks: The Fabric of Identity*, a series of contemporary textile art artefacts produced by the authors between 2024 and 2025, understood as a post-digital artistic expression situated within the field of art-fashion and engaged with social critique and the safeguarding of intangible cultural heritage. The series consists of handcrafted textile objects conceived as sculptural masks, developed through traditional textile techniques—namely hand stitching and trapunto quilting—in dialogue with post-digital aesthetics and imaginaries.

The analysis addresses two typological groups of artefacts. On the one hand, it examines textile objects that incorporate technological components, specifically augmented reality and forms of digital interaction, activated through external devices. On the other hand, it considers materially analogue textile objects that, while not embedding technology within the object itself, critically reflect processes of digital rematerialisation at both conceptual and symbolic levels. This typological distinction allows post-digital practice to be understood not as dependent on the constant presence of technology, but as an expanded field of relations between materiality, mediation, and digital culture.

Within the scope of this research, intangible cultural heritage is understood as a set of knowledges, practices, and cultural expressions associated primarily with rural and minority communities and with forms of cultural diversity whose modes of production and transmission are frequently at risk of invisibilisation. These knowledges are articulated in the analysed works through manual textile techniques, as well as through the use of colour, pattern, and the representation of faces, which function as narrative and symbolic devices for the inscription of identity and cultural memory.

METHODOLOGICAL FRAMEWORK

This article adopts a practice-based research approach situated within the field of artistic research, in which creative practice functions simultaneously as a mode of inquiry and as a generator of knowledge. The contribution is grounded in a reflective and critical analysis of the authors' own artistic production, positioning the artworks not merely as illustrative examples but as central epistemic objects through which the theoretical questions under examination are explored and problematised.

The case studies analysed—*Synthesis* and the *Textile Masks: The Fabric of Identity* series—correspond to textile artworks developed by the authors between 2024 and 2025. The selection of these works is intentional and methodological, insofar as they materialise distinct, yet complementary, approaches to post-digital textile creation. Rather than pursuing an external or observational analysis, the article adopts a form of situated critical reflection, in which the authors' dual positioning as artists and researchers is explicitly acknowledged.

Beyond their materiality as artistic objects, the analysed works are also approached through their exhibition dimension. The artefacts have been presented in physical, virtual, and hybrid exhibition contexts, in which the relationship with space, mediation devices, and audience experience plays a central role in the activation of meaning. This exhibition dimension is understood as an integral component of the artistic research process, insofar as it enables reflection on how the objects operate as narrative, sensorial, and critical devices across different modes of presentation and reception.

From a methodological perspective, the analysis combines visual and material examination of the artefacts with theoretical reflection informed by scholarship in post-digital aesthetics, art-fashion, and intangible cultural heritage. This approach aligns with established models of artistic research, in which knowledge emerges through the articulation of practice, theory, and critical self-reflexivity. The aim is not to produce generalisable conclusions, but to contribute to contemporary debates in art, fashion and post-digital studies by articulating how specific artistic practices can operate as sites of cultural critique and as mechanisms for the symbolic safeguarding of intangible cultural heritage.

TEXTILE ARTISTIC CREATION

The emergence of the post-digital paradigm has profoundly transformed contemporary textile artistic creation, introducing hybrid scenarios in which material practices and digital imaginaries intersect, overlap, and mutually transform one another. Although multifaceted and still the subject of theoretical debate, the concept of the post-digital has become a fundamental interpretative framework for understanding artistic practices that operate at the intersection of material tangibility and digital virtuality (Cramer, 2013; Pereira, 2018; Pereira & Fernandes-Marcos, 2021). Within the field of textile art, post-digital practices do not merely blur material and symbolic boundaries; they also redefine aesthetic experience, authorship, and the role of the audience, opening up new modes of digital rematerialisation, sensorial engagement, and critical intervention in contemporary culture.

The notion of the post-digital originally emerged as a critical response to technological determinism and to the rhetoric of novelty traditionally associated with digital media. As articulated by Cramer (2013), the post-digital is situated at the intersection of digital and analogue cultures, signalling the dissolution of clear boundaries between traditional media and new media. From this perspective, the post-digital does not denote a historical period succeeding the digital, but rather a condition of coexistence in which physical and digital materials interpenetrate, generating hybrid aesthetic languages (Pereira, 2018).

In the textile field, this coexistence manifests itself through processes of rematerialisation, whereby the digital does not replace the material object but instead expands, reframes, and resignifies it. Textile practices operating within a post-digital framework foreground material presence, manual gesture, and embodied knowledge, while simultaneously engaging with forms of digital mediation and interaction. As Dormor (2020) argues, contemporary textiles transcend utilitarian or decorative functions, asserting themselves as discursive and epistemological media in which each stitch may operate as an inscription of memory, a political gesture, and an aesthetic performance.

REMATERIALISATION AND POST-DIGITAL AESTHETICS

One of the central contributions of the post-digital paradigm lies in its critique of the notion of immateriality traditionally associated with digital culture. Whereas earlier forms of technological modernism privileged virtuality and dematerialisation, post-digital practices signal a renewed engagement with the tangible, the haptic, and sensorial experience (Huhtamo, 2008; Manovich, 2001). In textile art, this shift becomes particularly evident through the creation of artefacts that combine traditional materials and techniques with digital layers, resulting in hybrid objects that extend aesthetic experience beyond purely visual regimes (Pereira & Fernandes-Marcos, 2021).

Post-digital textile rematerialisation encompasses both the physical presence of the artefact and its digital extension, activated through technologies such as augmented reality and forms of digital interaction. In these contexts, the textile object operates simultaneously as a material entity and as an interface for digital inscription, enabling expanded modes of perception and engagement. Artefacts such as Nature of a Digital Dream (Pereira & Fernandes-Marcos, 2021) exemplify this dialectic, in which the textile surface functions as a site of symbolic and sensorial convergence between physical and digital dimension (Fig. 01).

Within the framework of post-digital art-fashion (Pereira, 2018), textile creation inherits not only hybrid techniques and materials, but also performative and experiential dimensions traditionally associated with fashion systems. These include theatricality, ephemerality, embodiment, and desire (Lipovetsky, 2016). In this sense, post-digital textile art operates simultaneously as an aesthetic and a critical practice, intervening in collective imaginaries, questioning cultural norms, and proposing alternative modes of aesthetic experience grounded in material engagement and symbolic reflection.

A distinctive feature of post-digital textile practices is their interactive and participatory dimension. In such contexts, audiences are no longer positioned as passive spectators but may become active participants in the aesthetic experience, either through embodied interaction with the artefact or through digital interfaces that enable transformation and reconfiguration. Importantly, interaction is not presented as an end

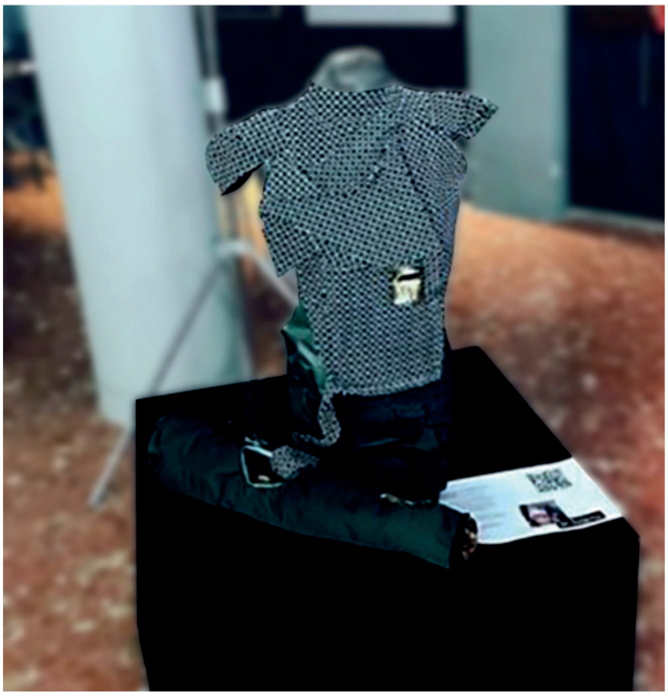

Fig. 01

in itself, but as a strategy for activating meaning, memory, and critical awareness within the artwork (Pereira & Fernandes-Marcos, 2021).

Post-digital textile aesthetics are thus characterised by hybridity, combining ancestral techniques with contemporary technological mediation to produce artefacts that oscillate between material permanence and digital ephemerality (Cramer & Jandrić, 2021). These artefacts function not only as aesthetic objects, but also as critical devices capable of articulating issues of identity, memory, gender, cultural sustainability, and aesthetic capitalism (Dormor, 2020; Pereira, 2018).

As argued by Pereira and Fernandes-Marcos (2021), post-digital textile art prioritises meaning over formal novelty, creating spaces in which relationships between tradition and innovation, the global and the local, and the human and the technological can be critically examined. This hybrid condition enables post-digital textiles to operate simultaneously as artistic objects, symbolic surfaces, and mediating interfaces.

Beyond their formal and technological characteristics, post-digital art-fashion artefacts operate as hybrid systems that integrate materiality, embodiment, interaction, and mediation. As noted by Fernandes-Marcos and Pereira (2021), these artefacts do not merely combine traditional textile techniques with digital technologies but activate experiential dimensions such as tangibility, ephemerality, wearability, immersion, and participation. Through haptic engagement and bodily or mediated interaction, they function simultaneously as sensorial objects and discursive surfaces. Within the field of art-fashion, these attributes intensify the capacity of textiles to articulate cultural memory and technological mediation. Post-digital textile art thus emerges as a critical framework through which tradition and innovation are negotiated in relation to identity and cultural sustainability.

TEXTILE MASKS: ANALYSIS OF THE ARTEFACTS

SYNTHESIS: MATERIALITY, AUGMENTED REALITY AND POST-DIGITAL INTERACTION

Synthesis (Fig. 02; Fig. 03) is a post-digital textile artefact composed of two interconnected dimensions: a textile bas-relief panel depicting half of a human face and a digital layer activated through an augmented reality application developed using Meta Spark. The very concept of synthesis that gives the work its title emerges from a process of formal reduction of the human face to its essential lines, seeking to preserve facial expressiveness and recognisability through a minimal set of visual elements.

In the material dimension of the work, these essential facial lines are translated into stitches, which simultaneously assume graphic, structural, and expressive functions. The face was entirely hand-stitched and three-dimensionally modelled using the trapunto quilting technique, a traditional method that creates relief and volume through localised padding between layers of fabric. This technique allows the stitches not only to delineate facial contours but also to shape the volume of the face, articulating surface, depth, and tactility. The manual act of stitching thus becomes a device of formal synthesis and identity construction, in which line, texture, and volume operate in an integrated manner.

Cotton fabrics were used throughout the piece, chosen for their association with textile traditions and for their sensory neutrality. For

Fig. 02

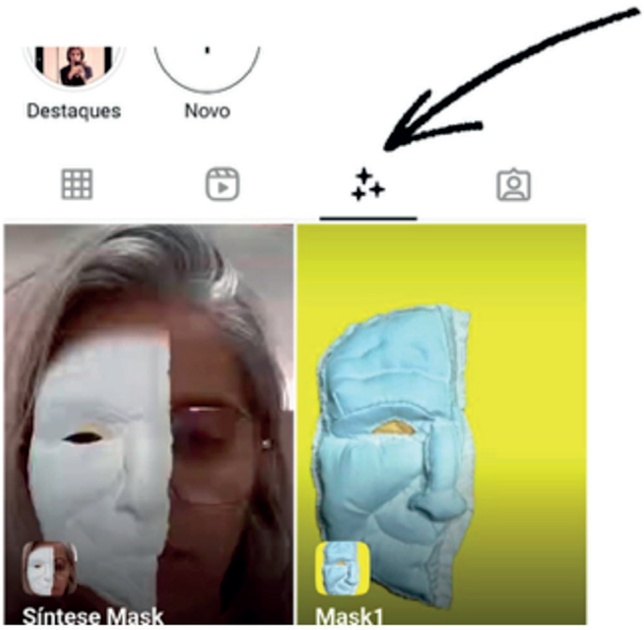

Fig. 03

the face, the deliberate choice of white carries symbolic meaning, understood as synthesis, origin, and beginning—the “blank page” upon which identity is inscribed. At the same time, white evokes a strong theatrical dimension, referencing the mime’s mask, a figure that conveys emotion and narrative through gesture, expression, and silence. This theatrical reference becomes particularly relevant as the mask is subsequently “worn” by the public through social media platforms.

The augmented reality component is accessed via social media, allowing audiences to use the artwork as a filter applied to their own images. By activating the filter, participants can photograph or record themselves with the virtual mask, which adapts to their faces and to different facial expressions. This dynamic adaptation introduces a performative and participatory dimension, in which the audience does not merely observe the work but temporarily embodies it within their own physical and digital identities.

Following this activation, participants may share their own version of the artwork on digital platforms, reinscribing *Synthesis* within networked circuits of circulation and extending the aesthetic experience into online space. Augmented reality thus functions not as an autonomous or dominant element, but as a relational extension of the textile object, activating processes of co-creation, mediation, and the multiplication of meaning.

In this sense, *Synthesis* exemplifies a post-digital approach in which technology does not replace textile materiality but critically expands it. The work articulates manual gesture, traditional technique, formal synthesis, and digital interaction, reinforcing the primacy of material presence while simultaneously proposing new modes of engagement, recognition, and sharing. The relationship between the physical object and its digital extension enables an exploration of identity, visibility, and performativity within a cultural context profoundly shaped by technological mediation.

This artefact was exhibited at Figures-International Exhibition, CICA Museum, South Korea, and Reflections of the Past, Visions of Tomorrow, Cista Arts Gallery, London.

TEXTILE MASKS: THE FABRIC OF IDENTITY: REMATERIALIZATION, IDENTITY AND ANCESTRAL KNOWLEDGE

The series *Textile Masks: The Fabric of Identity* (Fig. 04) consists of a set of sculptural textile objects that suggest only fragments of human faces. Rather than presenting complete faces, the works reveal partial elements—eyes, cheekbones, lines of the mouth—that evoke expressions of fatigue, restraint, and weariness. This fragmentation of the face plays a central role in the series, operating as a metaphor for contemporary identity as incomplete, multiple, and unstable.

The objects are made of wool felt, a material chosen for its sensory and symbolic qualities. The texture of the felt—simultaneously warm, porous, and imperfect—stands in contrast to industrial or technologically polished surfaces, reinforcing an aesthetic of vulnerability and imperfection. The colour palette comprises skin tones, oranges, and greys, evoking bodily diversity, emotional ambiguity, and psychological states associated with physical and emotional exhaustion. The textile material, in close proximity to the body, intensifies the affective dimension of the works, establishing a direct relationship between skin, fabric, and memory.

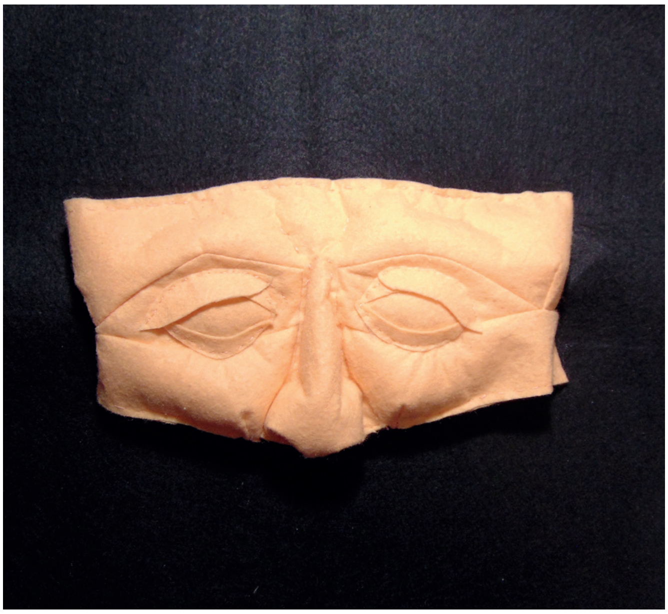

Fig. 04

Unlike *Synthesis*, this series does not incorporate embedded digital technology or interactive devices. Its inscription within the post-digital field is articulated through processes of symbolic and critical rematerialisation. The textile masks function as a material reflection on contemporary digital culture, particularly on mechanisms of avatarisation, filtering, and performative self-presentation associated with social media platforms. In this context, the textile mask emerges as a counterpoint to the glamour and idealised aesthetics of *Instagrammable* life, exposing a quieter, more fatigued, and less polished dimension of contemporary subjectivity.

The use of the mask as a form directly references the multiple social and digital masks individuals adopt in networked environments. Just as digital filters reshape, smooth, and transform faces on social media, these textile masks physically materialise the notion of filtered and mediated identity. However, in contrast to the digital logic of perfection and visual seduction, the masks foreground failure, wear, and incompleteness, asserting a critical stance towards dominant regimes of visibility and performativity in digital culture.

These artefacts assert themselves as a living homage to ancestral textile traditions, reactivating them through a contemporary perspective that honours the past while simultaneously projecting it into the future. This approach is rooted in a profound recognition of the symbolic, social, and cultural value embedded in manual skills transmitted across generations. Through the reactivation of traditional textile techniques and embodied knowledge, the series positions making as a form of cultural continuity and resistance within a rapidly dematerialising technological landscape.

The masks are produced at dimensions close to those of the human face, allowing audiences to touch them and place them over their own faces in an analogue manner. This possibility of physical use does not transform the works into utilitarian or spectacular performance objects but rather introduces a crucial experiential and relational dimension. By wearing the mask physically, participants are invited to confront the materiality of the object—its weight, texture, and proximity to the skin—activating a sensorial experience that stands in sharp contrast to the immaterial mediation of digital identities.

The textile techniques employed—namely hand stitching and *trapunto quilting*—enable the three-dimensional modelling of facial fragments, creating volume and expressivity through manual gesture. These techniques, associated with ancestral knowledge and intergenerationally transmitted practices, reinforce the embodied dimension of the works and their connection to forms of intangible cultural heritage often linked to rural, communal, and minority contexts. Manual making thus becomes a gesture of resistance against acceleration, dematerialisation, and cultural homogenisation.

The series has been presented in physical exhibition contexts, including the solo exhibition *Woven Realities: Bridging Threads and Pixels* at Cista Arts Gallery, London, and *Fresh Legs 2025* at Inselgalerie, Berlin. In these settings, the works were activated as sensorial sculptural objects, inviting proximity, contemplation, and critical reflection.

Taken together, *Synthesis* and *Textile Masks: The Fabric of Identity* articulate two complementary approaches to post-digital textile practice, revealing how the post-digital condition can be critically explored both through the incorporation of digital technologies and through their deliberate absence. While *Synthesis* mobilises augmented reality as an interactive extension of a materially grounded textile object, *Textile Masks* translates concerns associated with digital culture—such as fragmentation, filtering, and avatarisation—into analogue, tactile forms. This dual strategy demonstrates that post-digital artistic creation is not defined by technology itself, but by a critical awareness of how digital logics shape contemporary subjectivities, identities, and modes of representation.

Within the field of art-fashion, both artefacts operate at the intersection of textile sculpture, bodily extension, and symbolic surface. *Synthesis* foregrounds performativity and networked circulation, allowing the textile mask to be temporarily embodied, transformed, and redistributed through social media platforms. In contrast, *Textile Masks: The Fabric of Identity* privileges physical proximity, wearability, and sensorial engagement, inviting the public to encounter the mask through touch and analogue interaction. In both cases, the textile object functions as a mediating interface between body, identity, and cultural discourse, situating art-fashion as a hybrid practice that exceeds conventional distinctions between art object, fashion artefact, and technological interface.

Finally, both works reaffirm the relevance of textile materiality and manual knowledge within contemporary artistic practice. Through techniques such as hand stitching and *trapunto quilting*, the artefacts reinscribe ancestral textile skills into present-day visual languages, positioning making as a form of cultural continuity and resistance. Whether extended through augmented reality or activated through analogue use, the textile mask emerges as a critical device that negotiates visibility, identity, and memory in a post-digital context. Together, these artefacts demonstrate how post-digital art-fashion can operate as a site of aesthetic experimentation, cultural critique, and symbolic safeguarding, grounding contemporary concerns in embodied, material, and historically situated practices.

FINAL CONSIDERATIONS

This article has demonstrated that post-digital textile artistic creation constitutes a critical field for aesthetic experimentation, cultural inquiry, and the active safeguarding of intangible cultural heritage. Through the practice-based analysis of *Synthesis* and the *Textile Masks: The Fabric of Identity* series, the study shows that textile artefacts can operate as symbolic and experiential surfaces where identity, memory, and cultural negotiation are materially articulated.

A key contribution lies in clarifying that post-digital textile practice is not defined solely by the presence of digital technologies, but by a critical engagement with the cultural conditions shaped by digital environments. While *Synthesis* employs augmented reality as an interactive extension of a textile object, the *Textile Masks* series explores post-digital aesthetics through analogue rematerialisation, translating logics of fragmentation and avatarisation into embodied forms. This distinction demonstrates the conceptual breadth of post-digital aesthetics.

Within this framework, art-fashion is positioned as a critical category through which textile artefacts function as bodily extensions, performative interfaces, and discursive devices. At the same time, the reactivation of manual techniques such as hand stitching and *trapunto* quilting affirms textile practice as a form of symbolic safeguarding, ensuring the transmission of embodied knowledge through transformation rather than preservation. Taken together, these findings position post-digital textile art and art-fashion as multidimensional practices that articulate materiality, mediation, and cultural memory within contemporary global contexts

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CAPTIONS

[Fig. 01] Pereira (2019). Nature of a Digital Dream. Exhibition Artrooms Roma 2019 – International Contemporary Art Fair for Independent Artists, 22–24 July 2019, Rome, Italy. Courtesy of the authors.

[Fig. 02] Pereira (2024). Synthesis. Exhibition Figures – International Exhibition, CICA Museum, South Korea. Courtesy of the authors.

[Fig. 03] Pereira (2024). Synthesis – Augmented Reality application, available on Instagram and Facebook. Courtesy of the authors.

[Fig. 04] Pereira (2025). Textile Masks: The Fabric of Identity III. Courtesy of the authors.

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SITUATED TRACEABILITY IN POST-CONSUMER TEXTILE WASTE

INTEGRATING TECHNICAL DATA WITH THE BECOMING OF MATTER

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Abstract

Circularity has become a crucial topic in the textile sector, highlighting the need to rethink production models still rooted in linear logics. In this context, post-consumer textile waste represents one of the most pressing challenges, as it consists of heterogeneous, contaminated materials that often lack a recognizable identity. To address these issues, the European Union has introduced the Digital Product Passport (DPP), a tool designed to ensure transparency across the entire product lifecycle. However, in cases of open-loop recycling — where materials are radically transformed and lose all connection to their origin — the linear model of traceability proposed by the DPP reveals its limitations. This article offers a critical reading of these limits and introduces the concept of situated traceability, capable of also valuing the inherent opacity of post-consumer materials. Starting from a reflection on experimental waste transformation practices and from theoretical approaches that interpret materials as dynamic and relational entities, the article proposes a vision of the DPP as a potential narrative interface. In this perspective, tracing does not only mean identifying technical data, but making visible the contexts, relationships, transformations, and meanings that intertwine around the material.

Keywords: *Situated traceability; Post-consumer textile waste; Digital Product Passport; Material opacity; Open-loop recycling*

REIMAGINING TRACEABILITY IN THE END-OF-LIFE PHASE OF TEXTILE PRODUCTS

In recent years, the discourse on circularity in the textile sector has taken center stage in political, academic, and design debates, in response to a production system still largely based on linear models, with significant environmental, social, and economic impacts (Hole & Hole, 2019). Within this context, post-consumer textile waste emerges as one of the key challenges in the transition toward truly circular models. It represents the largest waste stream in the European textile chain (European Environment Agency, 2024; Eppinger, 2022), consisting of garments discarded after use by the final consumer. These are often characterized by high heterogeneity, contamination, mixed fiber compositions, and low quality (Johnson et al., 2020; Wang, 2010). Such features make these materials difficult to sort and recycle through closed-loop systems (Huang et al., 2024). Nevertheless, it is estimated that most discarded textiles retain over 70% of their remaining useful life, revealing a systemic paradox that the industry struggles to recognize and address.

In response to this scenario, the European Union's proposal for the Ecodesign for Sustainable Products Regulation (ESPR) (European Commission, 2022a) outlines an ambitious framework to reform the textile supply chain toward circularity. The regulation promotes the adoption of ecodesign criteria, the use of recycled and biocompatible materials, and the strengthening of practices such as repair, reuse, recycling, and industrial symbiosis. One of the key elements of this transition is the Digital Product Passport (DPP), a tool designed to ensure transparency along the entire value chain through a digital system that collects, stores, and provides access to standardized product information — from composition to manufacturing processes, usage guidelines to recycling options — accessible via a QR code or other digital identifier. However, where transparency becomes an imperative, the recycling of post-consumer materials reveals its opacity.

In cases of open-loop recycling — where materials are transformed into entirely different products, severing formal ties to their origin — the promises of the DPP risk collapsing under the impossibility of maintaining a linear, traceable genealogy. Although the DPP is also intended to support the retention of materials within closed-loop recycling systems, this goal is often constrained by technological and regulatory limitations. The closure of cycles cannot be infinite: with the progressive degradation of fibers, the loss of performance, or the contamination of materials, open-loop recycling becomes inevitable to avoid landfill or incineration. Several virtuous examples of open-loop textile recycling highlight how post-consumer waste can be reconfigured into neomaterials — a family of experimental, non-standardized materials newly defined and obtained from waste through processes that diverge from traditional recycling technologies, often as a result of regulatory constraints or technological limitations (Pellizzari & Genovesi, 2017). These practices are based on adaptive and non-linear approaches, in which material transformation does not rely on a single technology, but on processes using emerging techniques capable of responding to the heterogeneous nature of materials and generating new material identities.

What happens, then, when the origin is indecipherable, or when the material is the result of stratifications that are no longer distinguishable? This clash between normative ideals and operational reality generates a grey zone in which post-consumer textile waste emerges as a material "without origin," devoid of symbolic value and pushed to the margins of the official narrative of circularity. In response to this, the aim of this article is twofold: on the one hand, to explore the contradictions between the logic of total traceability and the complex, disorderly, and opaque reality of post-consumer recycling; on the other, to propose a reflection on the role of design in shaping forms of situated traceability that recognize opacity not necessarily as a system failure, but as an emergent quality. Specifically, the article suggests reimagining the Digital Product Passport (DPP) not merely as a repository of technical data, but as a potential narrative interface capable of conveying the transformability, trajectories, and relationships that characterize post-consumer textile waste as it takes on new forms and functions. In this perspective, recognizing opacity does not mean giving up on knowledge, but rather embracing the complexity of these materials in their processual and transformative dimension. The article is structured as follows. After framing the limits of linear traceability in the end-of-life phase of textile products, Section 2 critically examines the role and structural limitations of the Digital Product Passport (DPP) when applied to post-consumer textile waste and open-loop recycling. Section 3 articulates the concept of situated traceability through a theoretical dialogue with relational and material-driven approaches, addressing opacity as an emergent and generative condition of matter, and is supported by comparative diagrams illustrating the shift from linear to situated traceability models. Finally, Section 4 outlines the conclusions and discusses the implications of this framework for design practice and policy, proposing a pluralisation of traceability logics.

LIMITS OF LINEAR TRACEABILITY: THE DIGITAL PRODUCT PASSPORT AND POST-CONSUMER MATERIAL COMPLEXITIES

Traceability has become a key concept in the transition toward circularity in the textile sector. Understood as the ability to follow a product throughout its entire lifecycle — from raw material to end-of-life — it is promoted as a tool to ensure transparency, accountability, and to reduce the impact of our consumption. Within this framework, the Digital Product Passport (DPP) is positioned as a crucial informational infrastructure to enable a more circular textile sector, facilitating data sharing among producers, consumers, authorities, and third parties (European Commission, 2022b). The DPP is an integral part of the European Strategy for Sustainable Products and aims to make it mandatory to collect data related to composition, durability, reparability, and environmental impact of textile products. This information should be linked to each item through an interoperable digital platform, accessible at every stage of its lifecycle (EEA, 2024).

The DPP is expected to provide all relevant stakeholders with accurate information about the features and performance of textile products, offering useful specifications on materials and substances used (ETP, 2024; European Commission, 2022b; Rugi, 2024). Expectations for this tool are high: greater visibility into material characteristics could enable improved eco-design, reuse, and recycling practices (Carvalho et al., 2025). However, the DPP is based on the assumption of a traceable supply chain from the very beginning — relying on new, homogeneous, and standardized materials — and it remains unclear how this tool might adapt to the structural specificities of materials at end-of-life. In particular, post-consumer textile waste represents one of the most critical challenges in the shift toward a truly circular economy.

The DPP is intended as a key tool to direct such materials toward the most suitable recovery channels, providing useful information to sorters, recyclers, and second-life operators. Yet, as materials move further away from their point of origin, traceability tends to weaken, especially in the presence of complex supply chains, physical damage, or subsequent transformations that alter the material's structure and readability (Legardeur & Ospital, 2024). Data entered during the early stages of the lifecycle — such as composition, production processes, and performance — do not necessarily reflect the product's actual condition at the end of use. While the DPP represents an important step toward informational transparency, it alone cannot ensure effective cycle closure: it must be embedded in a broader ecosystem that includes design practices, distribution models, and social frameworks capable of activating new meanings and uses for discarded materials. Moreover, even when post-consumer materials are formally accompanied by a Digital Product Passport (DPP), this does not guarantee their continuous recyclability within closed-loop systems. As fibres deteriorate, and undergo treatments, these materials progressively lose compatibility with homologous processes and are often diverted toward open-loop recycling paths. In this transition, any connection to the original identity dissolves, rendering the retrospective traceability envisioned by the DPP ineffective. Unlike closed-loop recycling, which aims to maintain coherence between input and output, open-loop recycling transforms materials into semi-finished products and goods with entirely different forms and uses (Abrishami et al., 2024; Heikkilä et al., 2024; Huang et al., 2024). Through this process, textiles become something else: acoustic insulation, technical padding, building components. The original product becomes unrecognizable — shredded, remixed, pressed, or agglomerated with binders — losing formal traceability and often the ability to distinguish fibre composition.

The outcome is a hybrid neomaterial, seemingly anonymous. In such cases, the gap between data and material widens: the transformed material loses any formal connection to the product it originated from, making it impossible to trace back to its source. Additionally, the handling of these materials often occurs through informal, decentralized, or local networks that elude standardized industrial digitization frameworks. The risk, then, is that the DPP ends up excluding precisely those materials that are most in need of being revalued — too opaque to be recognized by official systems. Digital information collected along the supply chain should be integrated with situated assessments of the material, regarding its current condition, remaining quality, and actual recyclability. Only through such integration can the DPP evolve from a static information repository into an operational tool that concretely supports recycling and end-of-life management. Within this scenario, it is necessary to explore alternative forms of traceability, not based on a certain origin, but on coherence of use, functional value, and the relational quality of materials (Fletcher & Tham, 2019.

TOWARDS SITUATED TRACEABILITY: TRANSPARENCY IN THE COMPLEXITY OF MATTER

The byproducts of our everyday lives, when no longer used or usable, are commonly referred to as "waste", a term that carries with it a sense of passivity and obsolescence, as if their value were exhausted with their original function. In French, *déchet* means "that which has fallen": something produced as a residue of constructing something else, destined to be hidden or eliminated (Paoletti, 2021). This notion of falling or invisibility echoes the challenges that post-consumer infrastructures. Within the framework of the Digital Product Passport (DPP), transparency is promoted as an essential value. However, as Mattern (2017) argues, transparency is not a neutral concept: it is a technopolitical construct that defines what can be made visible and what remains excluded from knowledge systems. This observation becomes particularly relevant when addressing the issue of post-consumer materials, whose trajectories — marked by contamination, transformation, and repeated use cycles — often render them incompatible with the standards demanded by digital infrastructures. Rather than an anomaly, the opacity that emerges may be interpreted as a different kind of knowledge, one that challenges the linearity and stability upon which conventional traceability tools are built.

Tim Ingold (2007) contributes to expanding this perspective by proposing a view of materials not as static elements, but as entities in becoming, whose qualities emerge over time through relationships with the environment, tools, and people. The properties of materials, he argues, cannot be objectively determined or simply imagined; rather, they are practically experienced as the outcome of encounters and transformations. Each quality, in this sense, can be read as a condensed story, an expression of what happens to the material as it changes, blends, and deforms. To describe a material, for Ingold, is to narrate its lived experience, to trace a situated and open-ended genealogy made up of gestures, agents, and contexts. This approach encourages moving beyond fixed taxonomies and reading matter through its transformative trajectories (Ingold, 2007), aligning with an idea of traceability that is not linear but relational. This line of thought is echoed in the metaphor proposed by Ezio Manzini (1986), who suggests that describing a material is like trying to take a family photograph when all the members are moving. As Manzini points out, matter resists being fixed in a stable definition: it is mobile, relational, and its meaning takes shape over time through dynamic and layered processes. For both Ingold and Manzini, materials should be read as living phenomena, whose value does not lie in intrinsic properties, but in the transformative trajectories they undergo.

Following Karen Barad's (2007) perspective, the knowledge of materials is not objective or absolute, but emerges as an intra-active, relational, and situated process. Material truth is constructed through the interaction of things, contexts, and the transformative acts that involve them. In this view, designing within opacity means letting go of the ideal of total transparency and recognising opacity itself as a generative ground, where material qualities are not predefined, but continuously taking shape. Matter should not be understood as a set of fixed properties, but as the materialisation of phenomena, where each configuration results from evolving relations (Barad, 2007, p. 210). Materiality is therefore emergent, shaped by ongoing interactions, and materials do not have absolute ends, they undergo multiple transformations.

In line with Haraway's concept of situated knowledges, the object of knowledge must be understood as an actor and an agent, rather than as a passive resource to be represented (Haraway, 1988). Applied to post-consumer textile waste, this implies rethinking the Digital Product Passport not as a system that merely records information about inert materials, but as a device that interacts with active, transforming matter whose properties and meanings continuously evolve. Alternative forms of traceability exist that are not based on codes or databases, but emerge through sensory and transformative narratives of materials. In some cases, it is the textures, smells, density, or reaction to certain stimuli that tell the story of a material. In others, it is the gestures, tools, and local contexts that leave traces, generating forms of situated traceability. These forms of recognition do not necessarily reveal *where* a material comes from, but rather *how* it has been transformed, *by whom*, with which resources, and for what purposes. From this perspective, the Digital Product Passport (DPP) could be reimagined not as a mere technical archive, but as a narrative interface, one capable of conveying the complexity of material metamorphoses and the relationships that have made them possible. Rather than ensuring a closed and univocal genealogy, a reconfigured DPP could activate plural and localized narratives, supporting contextual interpretations and recognition practices that help guide the use and reuse of materials outside dominant industrial paradigms. This type of approach would be particularly relevant in contexts where post-consumer materials are recovered, transformed, or reconfigured in the absence of structured technical information, for instance, in local initiatives, circular micro-economies, or socially-driven design projects.

In this scenario, the principles proposed by the Earth Logic Plan (Fletcher & Tham, 2019) offer a valuable framework for rethinking the concept of traceability. While the dominant logic is grounded in linear, centralized models of data collection — oriented toward performance and control — the Earth Logic approach promotes a relational, situated, and plural vision. From this perspective, traceability is not merely the accumulation of technical information, but a construction of meaning over time and space: a participatory practice that emerges from places and is nurtured by relationships. Situated traceability thus becomes a form of knowledge embodied in processes, one that follows the material through its transformation, reflecting not only its origin but also its context. In this light, traceability could evolve from a tool of control into a practice of situated attention, attuned to the ways matter transforms and survives. Design practices, in this scenario, can play a decisive role in restoring meaning and value to textile waste materials, even when they fall outside the normative parameters of traceability. The goal is not to reconstruct a lost origin, but to recognize the trajectory the material has undergone, what it has become, how it has acted, and what relationships it has activated along its path. These reflections suggest the possibility of reimagining the Digital Product Passport as more than a registry of technical and standardized data, integrating narrative, sensorial, and relational dimensions capable of conveying the transformability and situated trajectories of post-consumer materials. This approach does not strive for total knowledge, but rather acknowledges — as Barad emphasizes — that matter is constantly becoming, and that all traceability is always partial, situated, and contextual. A DPP conceived in this way could help enable new forms of circularity, not grounded in absolute transparency, but rooted in careful attention to what transforms, escapes, or is reinvented. The conceptual shift from linear to situated traceability is synthesized in (Figure 01) and (Figure 02), which compare the standard Digital Product Passport model with the proposed integration of situated micro-archives. To clarify the operational implications of situated traceability, one may consider the case of a batch of post-consumer garments initially documented through a standard Digital Product Passport. Once these materials enter an open-loop recycling process and are transformed into a new composite material for a different application, the original DPP data are no longer sufficient to describe the material metamorphosis. At this stage, a situated micro-archive can operate as a second level of traceability, documenting not only the identity of the original material, but the transformation process itself (Fig. 02), marking the passage from what the material was to what it has become. Such a micro-archive may record information related to the transformation — including the quantity of material processed, the type of process adopted, the site and the actors involved (for example social cooperatives or design-driven initiatives), the post-transformation composition (textile fraction, binders), as well as the main process parameters (mixing ratios, temperature, pressure, processing time). It may also collect the characteristics of the resulting neomaterial, both in terms of sensory properties (surface texture, rigidity, chromatic variations, odour release) and in terms of technical performances (response to humidity, sound absorption properties, mechanical behaviour, etc.). Finally, the micro-archive may include information concerning the output and the use scenarios activated — who uses the material, in which context, and through what type of exchange — as well as indications regarding possible future scenarios of reuse, repair, reprocessing, or further open-loop cycles. In this way, the micro-archive does not aim to preserve a linear genealogy of origin, but to sustain the continuity of material knowledge across transformations, enabling situated decision-making processes even when the identity of the original product is no longer fully retrievable. From a DPP perspective, this means that a passport informed by situated traceability would contain not only origin-based product data, but also process-based records of transformations, material

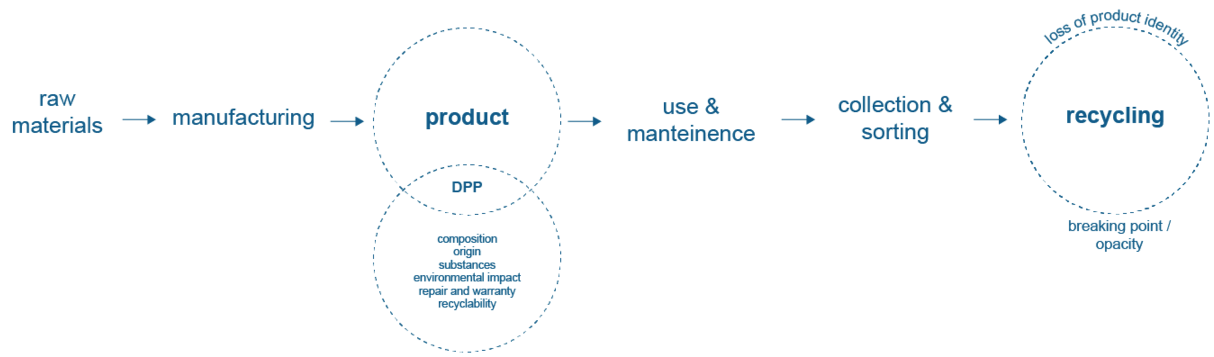

Fig. 01

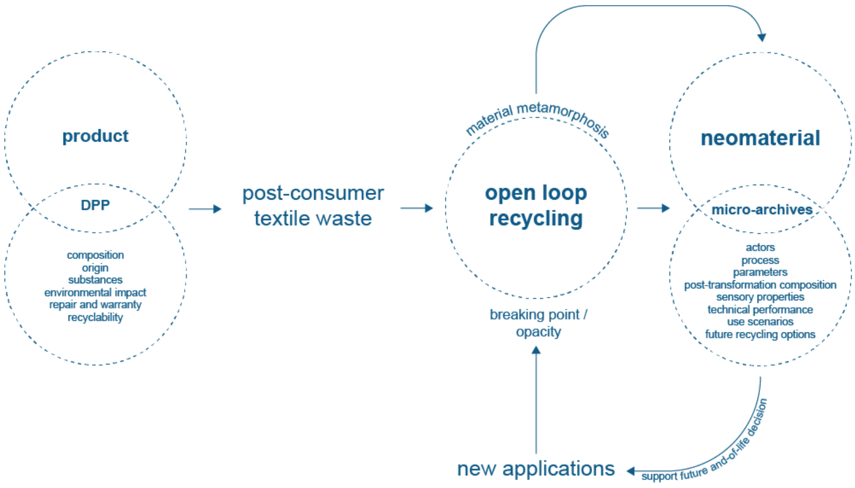

Fig. 02

performances, and use contexts, extending traceability beyond the first product life and following materials through successive open-loop transformations. Such practices of situated traceability would legitimise partial, local and experimental forms of documentation, also supported by digital tools, operating in dialogue with official infrastructures.

CONCLUSIONS: PLURALISING THE LOGICS OF TRACEABILITY

The reflection developed in this article aims to show how traceability, despite being one of the cornerstones of the circular transition envisioned by European policies, is neither a neutral nor an exhaustive process. The case of post-consumer textile waste emblematises the limits of a traceability system conceived through linear, codifying, and standardized logics. When materials lose their original form, pass through multiple cycles, or are combined with other substances, they escape digital codes and conventional taxonomies. Yet within this opacity, rather than an error to be corrected, one can recognize a different condition of understanding. As discussed, matter should not be considered a passive substrate but rather an active, relational entity capable of carrying stories, gestures, and contexts. Authors such as Mattern (2017), Ingold (2007), Manzini (1986), Barad (2007), and Fletcher & Tham (2019) invite us to rethink materiality as a process, a becoming, a transformative force. From this perspective, knowledge of textile products and materials does not coincide solely with the availability of objective, centralized data but emerges through situated and partial interactions that can activate new forms of understanding. In this framework, opacity is not the opposite of transparency, but its complementary condition: a space in which forms of situated knowledge can be activated.

From an epistemological perspective, in open-loop recycling processes — where materials are contaminated, mixed, and reconfigured — opacity does not simply signal a breakdown of traceability, but marks the transition toward other states, uses, and values of matter. In this sense, traceability can no longer be conceived solely as a backward-looking operation anchored to the identity of the previous product, but instead unfolds through transformations, following materials across successive states and uses. Within this framework, design is not understood as a neutral recorder of data, but as an epistemic mediator operating within material indeterminacy. By translating opacity into practices of situated documentation, micro-archives, and material narratives, design sustains the continuity of knowledge across cycles of transformation and enables informed decisions on future scenarios of reuse, repair, and further recycling. Following this line of thought, we propose an evolution of the

Digital Product Passport (DPP) capable of integrating qualitative, narrative, and relational dimensions. A DPP reframed through a situated lens could become a device that not only records technical data, but also incorporates material narratives, sensory cues, and local practices. This transformation calls for a revision of related policy frameworks: instead of focusing solely on maximizing data collection efficiency, it would be more appropriate to promote the coexistence of digital infrastructures and decentralized knowledge practices, rooted in contexts of production, transformation, reuse, and recycling. For example, the recognition of contextual forms of traceability could be supported through micro-archives, self-documentation tools, and open, accessible protocols, tools that could also valorize experimental materials, or neomaterials, such as those derived from open-loop recycling and non-standardized processes. In this transition, design can play a crucial role, not only as a technical enabler, but as an epistemic practice capable of mediating between the visible and the invisible, between systems and margins. Design practices can contribute to making such materials legible not through the imposition of labels, but by constructing interpretive frameworks, sensory experiences, and relational devices. In this sense, design becomes an agent of recognition, able to accompany materials into their second life without erasing their complexity. It is not about tracing back to the origin, but about building coherence of use, meaningful connections, and plural narratives. Finally, it is important to stress that situated traceability does not exclude digital traceability, it complements it, providing depth and context to what databases alone cannot register. In a time when environmental urgency demands that every material fragment be valued, even what falls, mixes, or transforms deserves attention. Only by acknowledging this plurality of logics — epistemic, material, and political — can we build a form of circularity that is not only technical, but also cultural and social.

CAPTIONS

[Fig. 01]Standard Digital Product Passport (DPP) model based on linear, origin-based traceability across the product lifecycle, from production to end of life. (Authors' Own Model).

[Fig. 02] Situated traceability model integrating a micro-archive within an open-loop recycling process, documenting material transformations, performances, actors, and use contexts beyond origin-based data. (Authors' Own Model).

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THE GENERATIVE ADVERSARIAL NETWORKS AND TEXTILE DESIGN

TOWARDS AN AUGMENTED CRAFTSMANSHIP IN THE CONTEXT OF DIGITAL AND SUSTAINABLE FASHION

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Abstract

This contribution investigates the application of Generative Adversarial Networks (GANs) to the generation of textile patterns, aiming to evaluate the technical and design feasibility of an AI-driven approach in the context of digital and sustainable fashion. A hybrid visual dataset was constructed, comprising historical ornamental motifs and contemporary patterns, carefully selected to ensure morphological coherence and modular repeatability. This dataset was used to train a GAN model on Google Colab, monitoring the visual evolution of the generative outputs at different stages of training. Preliminary results show the emergence of recognizable structures potentially applicable to textile design; however, technical issues persist, such as digital noise, edge discontinuities, and insufficient resolution for fabric printing. These findings indicate the need for architectural and parametric optimizations, as well as specific evaluation criteria for seamless patterns. The study also highlights the importance of considering the computational costs of generative models from a sustainability perspective, outlining future directions aimed at improving visual quality, scalability, and integration into the industrial fashion design workflow.

Keywords*: Generative Design; Algorithmic Craftsmanship; Textile Heritage; Computational Aesthetics; Data-Drive Fashion.*

INTRODUCTION

The growing integration of artificial intelligence into design processes is significantly transforming both fashion aesthetics and the operational workflows of textile design. In particular, Generative Adversarial Networks (GANs) have demonstrated an emerging ability to synthesize complex images from structured datasets, offering new scenarios for material and formal exploration of textile surfaces.

Although the literature indicates growing interest in the use of GANs in the visual domain, research in textile design still exhibits limitations in three crucial areas: (i) the integration of cultural repertoires into generative training; (ii) the evaluation of pattern quality in terms of modular continuity and industrial applicability; (iii) the analysis of the computational impact of generative pipelines from a sustainability perspective.

In light of these challenges, the present research aims to assess the technical and design feasibility of using GAN models for generating patterns intended for digital fashion and textile printing. Specifically, the work investigates how hybrid datasets, based on historical ornamental motifs and contemporary patterns, can inform the synthesis of new surfaces through GANs.

The following research questions were defined:

RQ1. To what extent are GANs capable of generating modular patterns with visual coherence and potential seamlessness?

RQ2. What technical limitations emerge in the preliminary results, and which optimization strategies prove most effective?

RQ3. What computational implications arise from adopting GANs in a textile design workflow oriented toward sustainability?

The contribution of this paper lies in providing a preliminary experimental assessment of the potential of GANs for textile design, through a comparative analysis of the generative results and a reflection on the needs for optimization.

THEORETICAL BACKGROUND

The integration of artificial intelligence into design processes represents a structural change in the textile-fashion sector, affecting both aesthetic logics and design and production workflows. Among emerging technologies, Generative Adversarial Networks (GANs), introduced by Goodfellow et al. (2014), stand out for their ability to synthesize visually coherent images from reference datasets, opening up innovative scenarios for visual experimentation in textile design.

The approach adopted here is based on a co-creation paradigm in which AI does not replace the designer but expands their exploratory and interpretative capabilities. This dialogic vision is rooted in theories of situated and relational design (Manzini, 2015; Norman, 2013), which posit that design arises from the continuous interaction between material culture, data, and digital tools. In this perspective, AI acts as an epistemic partner (McQuillan, 2022), stimulating non-linear processes that are open to the emergence of unexpected forms.

The Italian textile tradition constitutes a dynamic and stratified visual heritage, increasingly accessible today thanks to the digitization of historical archives and industrial collections. Their transformation into computational datasets configures the archive as a living dataset (Collet, 2019), in which images cease to be static objects and become visual materials ready to be reworked in a generative way. This model follows the logic of aesthetic recombination (Shanken, 2014), according to which innovation arises from the semantic re-articulation of pre-existing forms.

The textile surface generated algorithmically introduces a new dimension of digital materiality: although not physical in its initial phase, it possesses an operational and symbolic potential that anticipates its future material incarnation (Ferraris, 2021; Baurley et al., 2017). Here, the designer's curation is not a subsequent phase, but a continuous action that guides the semantic value of the pattern through dataset selection, parameter modulation, and aesthetic validation of the output.

Finally, the issue of computational sustainability emerges as a new critical front in generative design. The need to understand the energy impacts, operational logics, and life cycle of AI models is part of the regulatory and methodological framework promoted by sustainability in contemporary fashion (European Commission, 2022; Fletcher & Tham, 2019). This perspective confirms the relevance of a transdisciplinary approach in which digital innovation, environmental responsibility, and cultural valorization coexist within a conscious design ecosystem.

METHODOLOGY

The experimentation was structured as a four-phase pipeline: (i) construction and curation of the dataset; (ii) training of a Generative Adversarial Network (GAN) model; (iii) qualitative evaluation of the generative results; (iv) exploratory classification via a convolutional neural network (CNN) to support visual curation.

DATASET

The dataset was constructed through the collection and curation of ornamental motifs from both historical and contemporary sources, in order to explore a diversified range of visual grammars relevant to the fashion sector. In total, approximately 200 digitized textile pattern images were selected: ornamental motifs drawn from Italian historical archives and stylistic samples recurrent in current textile design.

All images were preprocessed to 256×256 px (RGB) format, with square cropping, noise reduction, and pixel value normalization. 15% of the images were discarded due to lack of modularity or the presence of visual artifacts. The curation ensured morphological coherence and ornamental repeatability, essential prerequisites for evaluating the potential seamlessness of the generated patterns.

GAN MODEL AND TRAINING PARAMETERS

A Deep Convolutional GAN (DCGAN) model (Radford et al., 2016) was used in a Google Colab environment. The model was trained for 100 epochs and monitored through the periodic generation of samples to evaluate the generator's

Deep Convolutional GAN (DCGAN) model

Parameter	**Value**
Input/Output resolution	256x256 px
Batch size	64
Learning rate	0.0002
Beta1 (Adam)	0.5
Latent noise (z-dim)	100
Output save frequency	every 20 epochs

Tab. 01

ability to learn the dataset's modular structure (Tab.01).

The configuration adopted follows best practices for GAN training stability: a low learning rate and using Adam with $\beta 1 = 0.5$ reduce the risk of mode collapse, while a batch size of 64 provides a balance between gradient quality and the computational limits of the cloud platform. This setup allows for the progressive observation of the morphological emergence of the generated patterns.

QUALITATIVE EVALUATION AND CATEGORIZATION

The quality of the outputs was evaluated through visual analysis based on three criteria:

- Ornamental coherence (legibility of form, symmetry)
- Modular continuity (absence of visible seams)
- Digital noise and artifacts (spurious pixels, distortions)

A CNN was trained in a supervised manner to classify the images from the dataset and the synthesized samples into ornamental macro-categories (geometric, floral, mixed), achieving a preliminary accuracy of 79%. This classification supported the curatorial analysis of the patterns, highlighting cases of semantic failure that should be addressed in future optimizations.

METHODOLOGICAL LIMITATIONS

The training was conducted on a small-scale dataset and in a computational environment with limited resources. The output resolution, while sufficient for a preliminary analysis, does not yet meet the industrial requirements for textile printing (≥ 300 DPI). Furthermore, in the current phase, no mechanisms have been implemented to guarantee perfect tileability (e.g., periodic padding); such mechanisms will be integrated in future developments to improve seamlessness.

RESULTS

The analysis of outputs generated by the DCGAN model highlights the progressive emergence of ornamental configurations over the course of training. In the initial epochs, the synthesized samples are dominated by visual noise with low formal coherence; subsequently, the network partially learns the dataset's modular syntax, generating patterns characterized by rudimentary symmetries and basic geometric repetitions (Fig. 01).

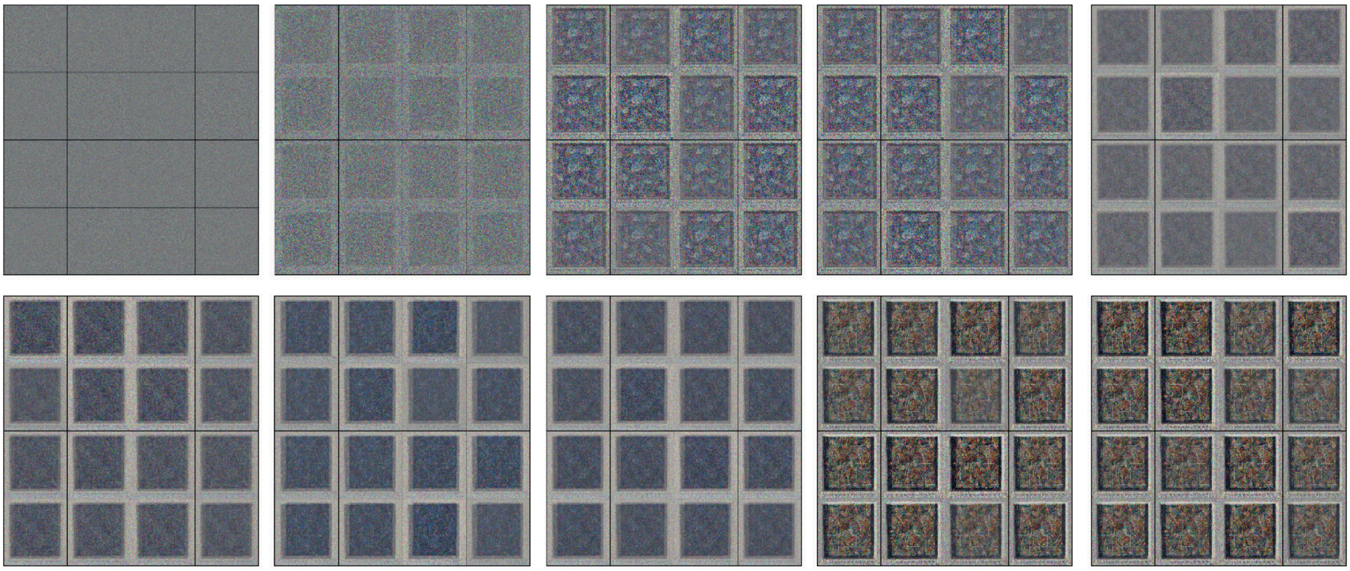

Fig. 01

The qualitative evaluation indicates that the model tends to recognize geometric motifs more consistently than floral ones, which undergo more pronounced morphological distortions. In general, ornamental legibility remains limited, and the lack of modular continuity prevents the immediate usability of the patterns on large surfaces (Tab. 02)

The results confirm the preliminary nature of the experiment: although the GAN shows signs of learning the ornamental grammar, the current quality does not meet the aesthetic and technical requirements of the fashion sector, which demand high resolution, guaranteed seamlessness, and visual coherence of the repeated module.

DISCUSSION AND IMPLICATIONS

GENERATIVE AI AS A CRITICAL AND RELATIONAL PARTNER

The use of Generative Adversarial Networks (GANs) in textile design is not limited to the automatic production of images but introduces a transformation of creative processes and the designer's role itself. GANs operate as epistemic partners (McQuillan, 2022), capable of activating design modes that are non-linear, exploratory, and open to the unexpected. Algorithmic generation temporarily suspends authorial intent, fostering an interaction that is not a delegation of creativity but a continuous negotiation between constraints, data, and human intentionality (Terzidis, 2006).

This configuration aligns with theories of relational design, in which authorship is distributed among a multitude of material and digital actants (Manzini, 2015). In this sense, GANs are not mere visual production tools, but apparatuses of revelation capable of deconstructing and recombining the ornamental codifications of tradition, projecting them into a new computational imaginary.

DATA-DRIVEN FASHION AND RELATIONAL SUSTAINABILITY

The experimentation fits into an emerging paradigm where fashion is understood as a connective and narrative system, no longer merely aesthetic or functional, but one permeated by information and interaction (Wakkary, 2021). In this context, the digital materiality of computational images assumes a primary role: they are not simple virtual simulacra, but cultural artifacts endowed with symbolic intensity, capable of

Qualitative evaluation

Criterion	Preliminary outcome	Observations
Ornamental coherence	2/3	Recognizable forms only in some cases
Seamlessness (edge continuity)	1/3	Edges are still unstable and misaligned
Digital noise and artifacts	3/3	High presence of stray pixels and distortions
Textile applicability	1/3	Outputs not yet printable

Legend: 3 = critical; 2 = medium; 1 = weak.

Tab. 02

generating emotional attachment and interpretive processes (Ferraris, 2021; Baurley et al., 2017).

This opens important prospects for relational sustainability in fashion: if a pattern is culturally recognizable and emotionally resonant, the usage life of a product increases and perceived obsolescence decreases (Fletcher & Tham, 2019). Artificial intelligence, if guided critically, can thus become a catalyst for a more ethical, participatory, and durable fashion, in dialogue with European sustainability policies (European Commission, 2022).

COMPUTATIONAL AESTHETICS AND ALGORITHMIC CURATION

The adoption of GANs requires questioning the cultural role of the generated patterns: if they express new formal possibilities, they must nevertheless undergo continuous critical curation to acquire meaning. In line with interpretative design principles (Krippendorff, 2006), every image is a sign that requires context to be read and valued.

The designer thus assumes the role of a semantic mediator, orchestrating the relationship between the dataset, algorithms, and symbolic codes. Without this human filter, the results risk straying from the reference ornamental repertoires, yielding forms that are culturally neutral or incoherent. Algorithmic curation is therefore a continuous act that preserves and renews the cultural relevance of the pattern.

MADE IN ITALY AND FUTURE HERITAGE: OPPORTUNITIES AND RISKS

The integration of AI into textile design processes raises questions about compatibility with the identity values of Made in Italy, which are historically rooted in craftsmanship, cultural supply chains, and material care. This apparent gap can be bridged by considering that craftsmanship itself has, over history, incorporated innovative technologies without losing its identity (Antonelli, 2020). The Jacquard loom, a precursor to programming, stands as a symbolic precedent.

Following the logic of future heritage (Collet, 2019), GANs can contribute to the regeneration of ornamental heritage, provided that the designer acts as a guarantor of the stylistic recognizability of the territory. The greatest risks concern cultural decontextualization and the loss of ties to material roots: identity sustainability requires a mindful and situated digitalization that valorizes traditions while incorporating innovation.

CRITICAL IMPLICATIONS AND TRANSFORMATIONS UNDERWAY

The conducted experimentation shows that the relationship between designer, dataset, and algorithm is not a neutral operation, but a practice of cultural translation in which values, aesthetics, and memories are constantly negotiated. The integration of GANs into textile design is not limited to the generation of new forms, but opens a critical terrain in which to redefine the logics of meaning-making and quality production in contemporary fashion.

In this scenario, the relational dimension of the algorithmic surface implies a rethinking of the role of pattern within the fashion system: it is no longer a merely decorative element, but a semiotic device through which plural identities, social expectations, and territorial affiliations are articulated. GANs do not replace the artisanal gesture, but rather relaunch it in a computational horizon, enhancing its ability to create connections between past and future, between the local and the global.

The possibility of generating patterns as emerging repertoires from historical archives encourages us to recognize artificial intelligence not as an extractive technology, but as a facilitator of cultural continuity.

CONCLUSION AND FUTURE WORK

CRITICAL OUTCOME OF THE RESEARCH

investigating not only the technical potential of ornamental synthesis but above all the epistemological, cultural, and design implications of adopting artificial intelligence as a creative partner (McQuillan, 2022; Terzidis, 2006). Generative AI emerges as a device that is simultaneously generative and curatorial, capable of triggering a deep dialogue between historical archives and new emerging visual grammars (Manzini, 2015; Collet, 2019).

The project demonstrates how the textile pattern, traditionally tied to manual craftsmanship, supply chain, and territoriality, can be reinterpreted as a relational surface where memory, computation, and human intentionality intertwine (Baurley et al., 2017; Ferraris, 2021). In this perspective, GANs become epistemic allies, capable of expanding formal exploration and supporting processes of augmented craftsmanship, in continuity with the identity values of Made in Italy (Antonelli, 2020).

Computational aesthetics is therefore not merely an experimental domain, but a critical field within which to redefine the material culture of fashion in a horizon of sustainability, circularity, and responsible innovation (Wakkary, 2021).

LIMITATIONS AS GENERATIVE CONDITIONS

The exploratory nature of the experimentation implies the presence of limitations that do not represent a shortcoming, but rather the very condition of possibility for the inquiry (Suchman, 2007; Wakkary, 2021). The restrictions imposed by the dataset's small scale, the image resolution, and the available computational resources have directed the focus toward what constitutes the heart of textile design: ornamental recognizability, the relationship with tradition, and the designer's critical role in selecting outcomes (Krippendorff, 2006).

Far from weakening the contribution of the research, these limitations highlight the need for a broader involvement of institutional and industrial actors, archives, manufacturers, museum hubs, so that the experimentation can evolve into a fully situated design practice in the context of Made in Italy (Collet, 2019; Antonelli, 2020).

PERSPECTIVES FOR A SITUATED AND CO-AUTHORIAL

The next developments of the research will unfold along dimensions that are not only technological but, above all, cultural (Manzini, 2015; Wakkary, 2021). The expansion of the dataset is not driven by a principle of computational efficiency, but by the need to map the identity complexity of Italian ornamental languages (Collet, 2019).

Similarly, the adoption of advanced architectures or more robust production pipelines is not aimed at mere technical optimization, but at strengthening the co-authorial nature of the process, in which the designer assumes the role of semantic director of visual heritage in transformation (McQuillan, 2022; Krippendorff, 2006).

In this way, the project aims to contribute to the creation of data-driven design ecologies in which fashion once again becomes a medium for connection, memory, and collective invention. In this perspective, the collaboration between artificial intelligence and contemporary craftsmanship does not replace Italian material culture, but expands it, preserving its heritage while imagining its future.

CAPTIONS

[Fig. 01]Evolution of samples generated during DCGAN training in Google Colab. The progression from initial noise to the formation of modular structures is visible, although still marred by visual artifacts, chromatic instability, and edge discontinuities that hinder the seamlessness required for industrial textile applications.

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COMPOSITIONAL SENSING

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Abstract

This paper explores how fashion design can critically engage with contemporary sensing technologies, not merely as tools for measurement, but as an active medium that shapes how bodies are seen and known. It proposes compositional sensing as a methodological framework in which sensing is treated as a dynamic, co-constructed process rather than a passive act of data capture.
This approach is demonstrated through Dust Enforcer, a choreographed performance between a human wearing a reflective foil suit and a forensic grade lidar scanner. Rather than recording a static body, the scanner captures fluctuating densities, gaps, and spatial anomalies produced through movement, reflectivity, and interference. Each gesture becomes a compositional input, inscribing spatial data through a recursive feedback loop between the body and machine. What emerges is not a coherent silhouette, but a field of conditional appearances.
Reframing fashion through Stan Allen's 'field conditions', the paper argues for a shift from designing objects to composing responsive environments for data generation. This offers new possibilities for designers to critically interrogate the epistemic assumptions embedded in sensing technologies, and to intervene in how bodies are constructed, represented, and governed through data.

Keywords: *Compositional sensing; Lidar scanning; Fashion design as field conditions; Design with data*

FROM MANNEQUIN TO CORPOREAL SENSING

In *Crafting Anatomies,* Joanne Entwistle and Katherine Townsend's (2020) concluding statement open a conceptual space of inquiry, "what a body is, what a body can do" (p. 301). This question frames fashion design's relation to corporeal knowledge along two interdependent registers: *ontological* (what constitutes bodily being) and *operational* (what capacities emerge from it). Fashion design materialises these registers. Ontologically, the body becomes a spatial form with measurable boundaries, proportions, and orientations. As Ingrid Loschek (2009) observes, the body is configured through its surface conditions: skin becomes a threshold, and clothing extends this boundary into external space. Operationally, garments act on the body's capacities by shaping posture, regulating mobility, and enforcing or releasing constraint. Fastenings, structure, and material behaviour determine how a body performs within its designed envelope. Through these mechanisms, fashion establishes a regime of corporeal knowledge grounded in intervention rather than representation. What the body is becomes inseparable from what it can do within designed systems.

The mannequin serves as fashion's primary instrument of knowledge, abstracting bodily variation into standardised parameters[1]. Its

1 While this critique centres on Western industrial fashion systems, other sartorial traditions—such as the

underlying logic derives from Vitruvian principles of symmetry and proportion still embedded in contemporary sizing systems (Atkinson, 2017). Such a framework establishes what might be termed as *metric epistemology*: a way of knowing the body that presumes it to be stable and spatially contained through cardinal measurements. In condensing bodily complexity into a set of normative dimensions, the mannequin becomes a reproducible template for mass production whilst simultaneously determining which bodies can be registered or accommodated.

For Caroline Evans (2013), the mannequin presents a deeply ambivalent figure. Its status as both inert (static object) and animate (living body) creates a 'disturbing alliance' between the living and the lifeless, thereby producing a body that is both idealised and disavowed. The mannequin, in this sense, is not simply a tool of representation but a mechanism of bodily regulation and visual discipline. The conformity required for fashion display extends to living bodies, made to behave as if inert. What appears as standardisation is sustained by deeper fantasies of control and erasure. The mannequin shapes the ontological boundaries of fashion itself—defining what can be seen, measured, and made.

Contemporary sensing technologies—motion capture, biometric tracking, thermal imaging, 3D scanning—do not replace fashion's metric paradigm; rather, they extend and intensify it. As Shane Denson (2021, p.69) argues, the shift is scalar in "speed, scope, and degree", expanding the reach of measurement into the micro-temporal and infrastructural dimensions of everyday life. What emerges is a computational ecology of capture, wherein bodily presence becomes a continuous stream of data, parsed in real time and redistributed across technical systems for evaluation, prediction, or optimisation.

Within this ecology, two epistemic tendencies emerge: the measured body and the sensed body. The measured body is discretised and anticipatory—a fixed template for drafting and replication. Edmund Husserl's (1989) distinction between Körper and Leib is useful here: Körper *names* the objectified body that can be observed, measured, and analysed from the outside, while Leib *names* the lived body that experiences sensations, emotions, and actions. The measured body presumes *Körper* as a stable template that precedes abstraction: a body capable of being mapped once and applied across contexts. The sensed body, by contrast, is emergent and event-based, constituted through real-time capture of thermal gradients, movement trajectories, and physiological fluctuation.

While imaging mediates as an interface—converting raw sensor data into visual representations—it also determines which dimensions of bodily life become computationally actionable. Data is not neutral but an extracted artefact, produced through layers of selection, abstraction, and exclusion. As Shoshana Zuboff (2019) argues, the logic of surveillance capitalism turns lived experience into behavioural surplus: profiles, predictions, and risk scores that circulate across opaque infrastructures of value extraction. Denson (2021) extends this into what he calls "metabolic capitalism," wherein the body becomes a node in an infrastructural network of affective and energetic throughput (p. 67). Computation interfaces directly with flesh—not simply visualising it but shaping its conditions of sensation, movement, and social readability.

This has profound implications for fashion design. Traditional design tools—mannequins, blocks, grading systems—presume a stable body that persists across time. Sensing systems displace this presumption, revealing a body that is computationally composed, temporally distributed, and infrastructurally mediated. Designing for such a body requires a reorientation: from encoding forms based on dimensional constants to negotiating signal thresholds and temporal variabilities. The task becomes not simply to design for the body, but to engage critically with the technical conditions under which the body becomes perceptible.

What does it mean to design for a body that exists not as a fixed form, but as fluctuating streams of data? Several research-based fashion practices signal a shift in how bodies can become sites of interrogation and speculation. Kat Thiel's I:*OBJECT series* playfully explores the limits of "what is it to have, clothe and perceive a body" (2017, p.162) through garment making, performance, installation and 3D scanning. In *Bodies of Work*, the scanner becomes an instrument to be worked against and with, whose capacities and blind spots

Japanese kimono or Indian sari—employ garment-wearer relationships not governed by the mannequin. These approaches often emphasize relational fit, embodied construction, or adaptive tailoring over standardized abstraction.

produce a feedback relation in which capture is not an endpoint, but a parameter of (re)making garments. Taking this line of inquiry into a political terrain, Thiel's *Disembodied Female* addresses the asymmetries of online exposure and surveillance by treating visibility itself as something that can be inverted through hacking, turning technologies against their own logics of datafication and control to reclaim agency over how bodies are made to appear.

Elsewhere, Jan Tepe's (2022) *Wearing Digital Bodies* extends this speculative approach through a different configuration of tools and encounters, using 3D scanning, CAD, and AR to test how digital dress reorganises relations between body, garment, and space. The project explores "alternative morphological relations between the physical human body and digital dress" as a route to more body-diverse design practices (2022, p. 298). The works treat the digitised body as a transitional design material that can be fragmented, multiplied, hollowed, or reoriented—staging design decisions outside a standardised silhouette logic. The AR stage projects the digital dress onto the physical body whose morphological qualities are felt and evaluated simultaneously physically and digitally.

Read together, these practices exemplify Denson's (2021) concept of "dis/correlative counter-capture"—appropriating the tools that underpin biometric standardisation, optimisation and surveillance exposure while redirecting them to destabilise its epistemic grounds[2]. In Thiel, this manifests through iterative deformation, where the scanner's machinic gaze is folded back into making as a generative constraint. In Tepe, counter-capture appears as a reformatting of body–dress relations and renders the apparatus's affordances as designable parameters. What unites these approaches is their tactical engagement with sensing technologies, staging moments where the correlation between bodily referent and measured output becomes unstable, negotiable, and ever shifting.

The term compositional sensing is introduced in the next section to formalise this emerging orientation as a methodological framework to fashion design practice. Where counter-capture describes a strategic posture—operating within and against capture infrastructures—compositional sensing specifies how design can actively orchestrate these conditions. This shift extends beyond destabilising existing correlations to propose an alternative epistemic stance: one where the designer intervenes within the sensing event as it unfolds.

TOWARDS COMPOSITIONAL SENSING: A METHODOLOGICAL FRAMEWORK

Compositional sensing redefines sensing in design as a compositional event rather than a passive act of capture[3]. Drawing on David W. Bernstein's (2015) account of indeterminacy in John Cage, composition is understood as "a process through which the performer creates a piece" (p. 557). Composition becomes inseparable from its realisation: it provides structured conditions—constraints, durations, probabilities—within which form emerges through performance. What is composed is not the work itself but a system of possibilities.

This processual understanding shifts composition from object to event, from prescription to potentiality. Applied to sensing, it suggests that what can be designed is not the body-as-data but the apparatus of intelligibility through which certain aspects of bodily presence register while others remain occluded. Erin Manning's (2013) concept of 'pre-acceleration' deepens this temporal logic: movement does not pre-exist its capture but becomes determinate through the technical and perceptual thresholds that sense it. The body sensed is not prior to but co-emergent with its conditions of registration. Sensing becomes participation—an encounter that constitutes what it purports to record.

Compositional sensing operationalises this insight as a design methodology. It treats the sensing apparatus as co-composer: material properties, temporal rhythms, and systemic thresholds become designable variables rather than fixed constraints. The designer's role shifts accordingly—from one who captures bodies

2 There are a number of practices across art and architecture exploring counter-capture approaches through lidar, facial recognition or biometric sensors. see: Zach Blas's *Facial Weaponisation Suite*, Hyphen-Labs' *Hyperface*, Liam Young's *Where the City Can't See* and *Choreographic Camouflage.*

3 Comparable methodological approaches can be found across architecture, dance, and critical software studies—where artists and researchers use data not as output but as a medium for intervention. For example, works by Tega Brain or Kate Sicchio foreground live data as material for real-time, situated co-composition.

to design for them, to one who composes the technical, spatial, and durational conditions through which bodies and data co-emerge.

The framework proceeds through three integrated dimensions. Material intervention involves designing artefacts—wearables, surfaces, spatial constraints—that modulate the parameters of what can be sensed. Temporal orchestration introduces duration and sequence as compositional variables, synchronising the rhythms of sensing with the dynamics of movement or interaction. Systemic reflexivity brings the sensing system's own behaviours, its latencies and processing protocols into the compositional field, amplifying or subverting these as parameters. Together, these dimensions shift sensing from a logic of extraction to composition.

Two interlinked questions structure this approach: how do sensing systems delimit what becomes legible as a body; and what design affordances emerge when the sensing apparatus is treated as a co-composer rather than a neutral instrument of capture? *Dust Enforcer*, discussed in the following section, exemplifies this methodology through a coupling of fashion, real-time sensing, and choreographic performance. Garment, movement, and apparatus form a feedback ecology where what emerges is not a visualisation but a field of conditional appearance. Here, design operates not as response to captured data but with data, anticipating as Chris Speed and John Oberlander (2016, p. 2999) state, "the disruptive potential that is produced from streams of live data" as a constitutive element of the design process itself. The technical, operational, and methodological implications of this approach are examined in detail in what follows.

DUST ENFORCER AS RESEARCH APPARATUS

Dust Enforcer is a choreographed performance that examines the ontological status of the fashioned body when subjected to the technical scrutiny of remote sensing. At its core, the work intervenes in a broader epistemological field, where the convergence of sensing apparatus, gesture, and reflectivity generates new conditions for corporeal intelligibility.

The setup is deliberate: a single performer, dressed in a tailored foil suit, engages with a terrestrial lidar (Light Detection and Ranging) scanner configured for forensic-grade resolution. Each element is calibrated to the operational parameters of the other, acting as mutually conditioning variables in a closed feedback loop.

Lidar—is a remote sensing method that actively emits laser pulses and computes distance by measuring the time it takes for each pulse to reflect off a surface and return to the sensor. Each successful return is transformed into a spatial coordinate (x, y, z) through time-of-flight calculation (Royo & Ballesta-García, 2019). Unlike cameras, which produce images through lens-based optics, lidar produces dense point clouds: three-dimensional datasets composed of millions of discrete coordinates assembled sequentially over time. These coordinates may also include attributes such as timestamp, return number, and intensity values.

Applications in lidar range in fields from autonomous vehicle navigation and climate science to forensic analysis and architectural preservation, where its capacity for spatial accuracy and depth resolution is central (Shan & Toth, 2018). Forensic grade lidar scanners typically operate with sub-centimetre precision, capturing high-density scans suitable for courtroom evidence or archaeological reconstruction.

The decision to use foil as the primary material emerged through a series of experiments. Prior to the performance, a range of materials—bubble wrap, translucent fabrics like organza, and plastic bags—were evaluated for their interaction with lidar (Fig. 01). These tests assessed material behaviours such as laser absorption, scattering, occlusion, and refraction. Each material produced distinct signal responses, resulting in varied distortions, voids, or intensities in the point cloud. However, aluminium exhibited the most volatile interaction: a combination of high reflectivity, surface instability that introduced complex feedback effects into the sensing process.

Aluminium foil reflects incident laser pulses along narrowly directed specular paths. Depending on the angle of incidence and curvature of the surface, pulses are either deflected away from the sensor—resulting in data dropouts—or reflected directly back, producing intensity spikes. Because the foil deforms continuously with movement, each gesture reconfigures surface topology in real time, altering reflection angles and disrupting return trajectories. These changes introduce non-linearities into the point cloud data, manifesting as spatial discontinuities, duplicated contours, or high-frequency noise artefacts.

To further investigate lidar's response to

MATERIAL	SURFACE PROPERTIES	LIDAR INTERACTION	CAPTURE ACCURACY
Aluminium foil	High specular reflectivity, metallic, crinkled surface	Causes beam scattering and deflection; frequent dropouts and false depth readings	Low accuracy; significant artefacts and signal loss
Bubble wrap	Textured, translucent, air pockets	Partially diffuse reflection; inconsistent returns depending on surface tension and curvature	Moderate; returns unstable depending on curvature
Organza	Lightweight, semi-transparent, fine mesh weave	Low reflectance; partial returns with low intensity; penetrable depending on weave tightness	Low; limited visibility, variable detection
PVC (clear plastic)	Smooth, transparent or semi-transparent, flexible	High transmission; weak or missed returns; often registers as void or background	Very low; minimal capture, often undetected
Mirrors	Perfectly reflective, smooth, rigid	Reflects beam away from sensor; produces ghost points or absent returns	Extremely low; typically unregistered or misregistered
Plastic bags	Thin, semi-glossy, deformable	Moderate reflectivity; partial returns with noise due to surface deformation	Moderate; noisy returns with deformable geometry
Black velvet	Non-reflective, matte, deep black, absorbent	Absorbs light; returns are extremely weak or absent	Very low; often invisible to sensor
Reflective tape	Engineered reflectivity, smooth, directional surface	Strong return when aligned; highly angle-dependent	High; strong when properly aligned with sensor
Acrylic sheet (opaque)	Rigid, opaque plastic, high surface uniformity	Stable returns; surface accurately registered under normal incidence	High; well-captured under stable conditions
Mylar film	Thin, metallic polyester film, glossy and flexible	Prone to scattering; may produce streaks or false depth	Low to moderate; artefacts frequent under motion
Cotton fabric	Woven, diffuse, high-texture textile	Diffuse returns; good surface coverage, moderate noise	Moderate; structurally accurate with minor gaps
Tulle	Lightweight netting, open weave, low density	Sparse returns; inconsistent signal due to open weave	Low; patchy visibility, dependent on density and angle

Fig. 01

extreme reflectivity, mirrored surfaces were selectively incorporated into the suit. Unlike foil, which flexes and shifts with the body, mirrors maintain fixed geometries, amplifying multi-path reflection effects. In such cases, a single laser pulse may reflect off the mirror, strike a secondary object, and return along an indirect path—producing two or more return points from one emission. During motion, these effects compound, generating ghost geometries (duplicated structures) and mis-registered boundaries that fragment the scanned body into layered or conflicting spatial figures (Fig. 02).

In the performance, the lidar device does not passively register the body; it actively co-produces it. Gesture, reflectivity, and sensor resolution operate as interdependent variables within a closed feedback system. To appear before the scanner is to enter an infrastructural choreography in which each movement perturbs the laser's path, shaping and altering what and how is sensed. The scan does not represent the body—it materialises through it. Embodiment, here, becomes a function of modulation: produced through continuous interference between surface behaviour, movement, and machine logic.

This modulation is not improvised but choreographed in response to the sensor's technical constraints—angular resolution, scan velocity, and return thresholds. Preliminary experiments revealed that movement exceeding specific velocity thresholds, particularly when moving with the foil suit, disrupted the sensor's ability to register consistent photon returns. Rapid gestures scattered or deflected the emitted laser pulses beyond the sensor's receptive field, often yielding incomplete or imperceptible point cloud data.

To remain perceptible, the performer modulated movement through iterative calibration. Movement was slowed to maximise return density yet varied enough to activate the reflective instability of the foil suit. Each bodily adjustment—torsion, flexion, shift—reconfigured surface angles and disrupted the sensor's beam path. These micro-perturbations redistributed point density across the scan field, producing spatial differentials patterned by signal behaviour. Gesture thus became a compositional input, not merely altering what was captured but actively reshaping the architecture of capture itself (Fig. 03).

What the scanner records is differential

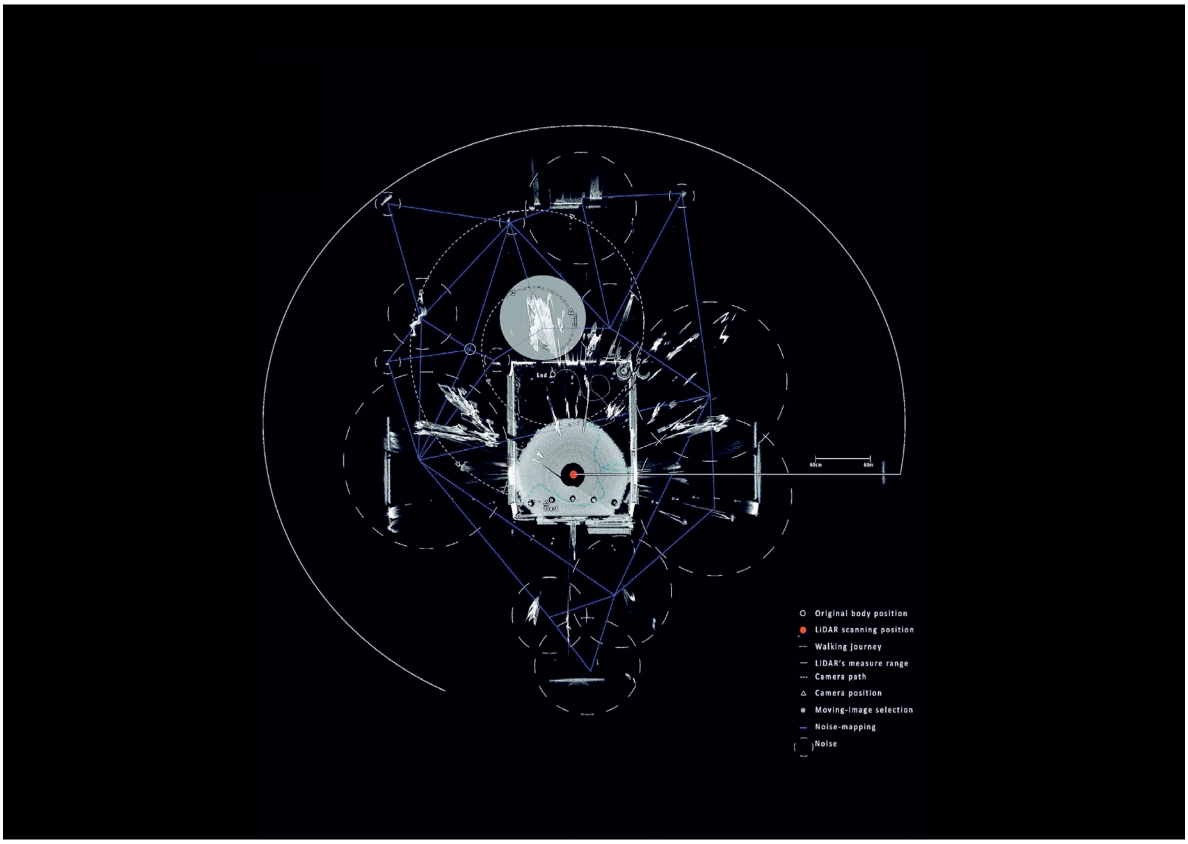
60cm
60m
Original body position
LiDAR scanning position
Walking journey
LiDAR's measure range
Camera path
Camera position
Moving-image selection
Noise-mapping
Noise

Fig. 02

Fig. 03

change. The point cloud becomes a durational archive of perturbation: indexing relations between surface, beam, and time as they shift across the scan. Gesture inscribes temporality into space, generating layered, partial or overlapping clusters that distribute form across latency and dropout. As the scan unfolds, the body does not resolve as a bounded object within space; it appears as a volumetric distribution structured by the recursive reorganisation of sensing thresholds.

In this context, noise does not interrupt signal, it acts as "the condition of all signal's emergence" (Hainge, 2013, p. 35). The scan's anomalies—voids, ghost geometries, misregistration—do not signal failure. They articulate a body that exceeds capture: one whose material presence overwhelms the limits of resolution and protocol. The reflective suit, by refusing signal regularity, enacts a body without contour—a body that is legible only as disruption. Here, visibility is not given; it is negotiated through the friction of interaction.

For Michel Serres (1995, p.13) "noise is the background against which any form must be perceived". In *Dust Enforcer*, photonic noise becomes an epistemic substrate: the condition through which the body is fashioned, not through its silhouette or anatomical continuity, but through occlusion, instability, and saturation. The scan functions as a surface of speculation, composed through the relational excess between sensing infrastructure and material performance.

This recursive interplay between sensing, movement, and instability enacts the compositional sensing framework introduced earlier. Gesture becomes a vector of modulation; surface instability a structural mechanism; noise, a generative principle. The choreography does not submit to the logic of capture—it intervenes in it. *Dust Enforcer* does not perform for the sensor; it composes the sensor's performance. What emerges is not the body as a captured entity, but the body as a contingent negotiation between signal and its excess, between legibility and the noise that makes it possible.

The dataset generated by Dust Enforcer does not yield a stable object but a volumetric condition—a mutable field of fluctuating densities, emergent voids, and spatial contradictions. *Volumetric rendering*—a physics-based method in computer graphics is used here, where each point in the cloud becomes a discrete volumetric unit, assigned depth, transparency, and spectral colour based on signal and voxel density.

Processed through a custom Python interface, the point cloud data coordinates enriched with intensity and timestamps—are voxelised into a three-dimensional grid. Each voxel encodes local density and reflectance-derived opacity. Unlike mesh-based reconstruction methods, which impose topological closure, this technique preserves the fragmentation within the data. Voids, outliers, and noise remain visible, exposing the epistemic volatility of capture. The resulting visualisation functions both as a spatial artefact and a diagnostic layer—indexing how material behaviour, movement, and sensor logic condition the body's appearance.

What emerges is not a coherent silhouette. Internal and external coordinates collapse into one another, dissolving the distinction between surface and volume (Fig. 04). The body is rendered as a topology of fluctuating intensities. In Dust Enforcer, this inversion turns the body inside out, collapsing visual hierarchies into new forms of infrastructural intimacy (Colomina, 2015). Resisting anatomical coherence, the resulting data-body cannot be reconciled into a singular bounded figure. Composed of millions of non-uniform coordinates, the scans become a constellation of positional contingencies, co-produced through motion, reflectivity, and dropout.

What, then, becomes of silhouette—so central to the logic of fashion—when the body no longer resolves as outline but emerges as volumetric flux?

CONCLUSION: FROM SILHOUETTE TO FIELD CONDITIONS

The silhouette has historically served as fashion's epistemic anchor: a visual schema that stabilises the body by drawing boundaries—between figure and space, garment and skin, interior and exterior. *Dust Enforcer* challenges this logic through a distinct sensing ontology in which form does not appear through outline but emerges as a topology of spatial contingencies. Here, the silhouette is redistributed across a fluctuating, probabilistic resolution.

Stan Allen's (1997) theory of *field conditions* provides a conceptual scaffold for this reframing. Rather than imposing form from above, field-based design proceeds from situated constraint and local interaction. Form becomes an emergent property of material behaviour, temporal process, and responsiveness. *Dust Enforcer* enacts this paradigm: the reflective foil suit, lidar scanner, and perform-

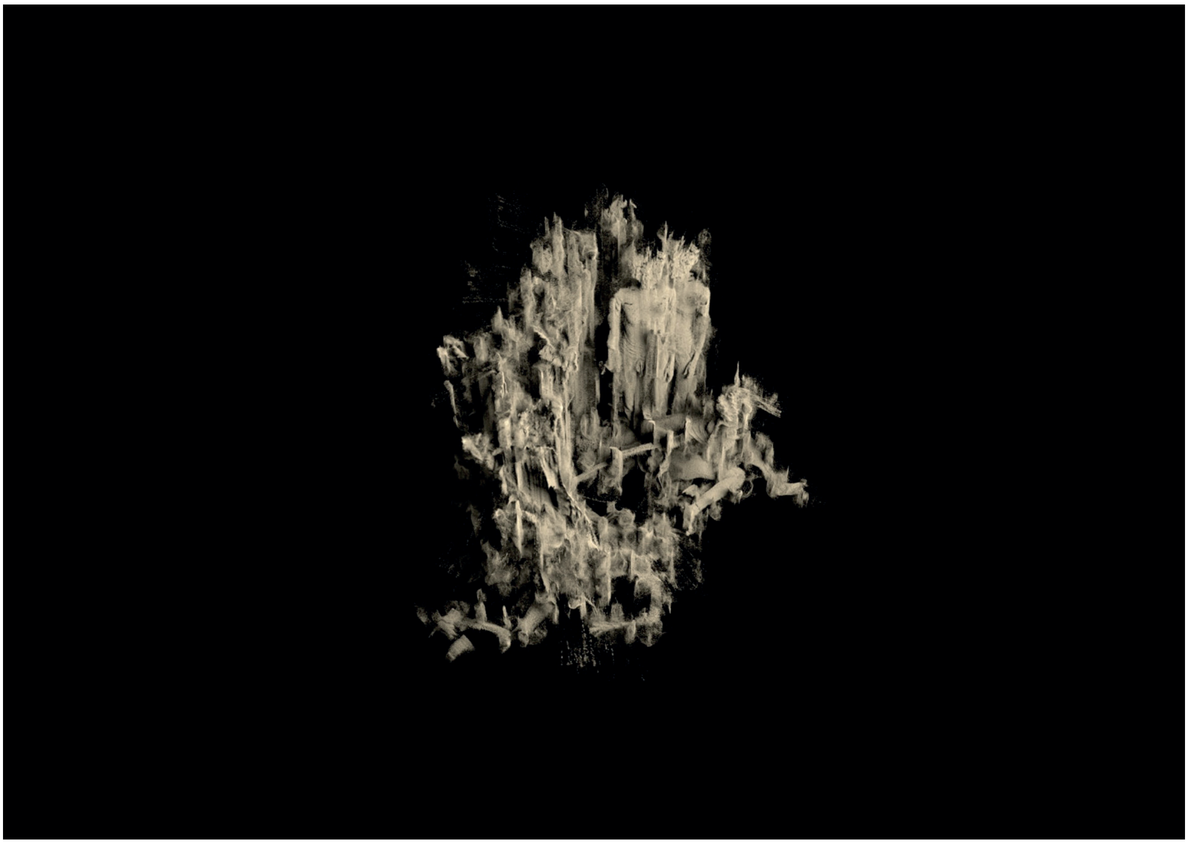

Fig. 04

er's movement constitute a distributed system of mutual inscription. There is no fixed garment or neutral body; what appears is a co-constructed resolution of sensor, material, and gesture.

The lidar point cloud abandons the edge in favour of return probability. Without outlines, the body becomes a spatial distribution where each lidar point inscribes an event, a discrete encounter where light meets matter, reflects and returns. Space becomes a site of inscription; the scan is a durational archive of interference. Gesture writes across the (x, y, z) axes, composing form through a choreography of light.

In this visual regime, voids and anomalies become structurally significant. The spaces between points—gaps, overlaps, misregistration—participate in the construction of form. To be fashioned is not to occupy a finished form, but to exist within a fluctuating matrix of registration events, a phase space. The silhouette then, becomes a contingent threshold—reconstituted moment to moment by reflectance, angle, and algorithm. Fashion, in this sense, ceases to condition visibility through outline; it becomes an electromagnetic calculus, orchestrating what forms of spatial coherence can briefly emerge before the next pulse rewrites the sensing condition.

Dust Enforcer positions the fashioned body as an instrument of inscription. Choreography becomes compositional: not the enactment of a predefined shape, but the modulation of an evolving dataset. Movement writes into space, producing a temporal regime of interference and resolution. Each shift in position or reflectivity reconfigures the point cloud, the fashioned body is composed within and as a durational condition of sensing.

The transition from object-based to field-based thinking in fashion entails a comprehensive shift. Under this model, design becomes an ongoing, situated engagement with distributed systems, material contingencies, and dynamic relations. What is designed are not garments but conditions: of legibility, interference, emergence. Under these conditions, fashion becomes an interpolative practice[4]. Between the

4 Interpolation is widely used in computational imaging and point cloud processing to estimate spatial information between known data points—often to fill gaps, smooth noise, or simulate continuity. In the context of Dust Enforcer, this principle acquires conceptual weight: the absence of data is not merely a technical limitation, but an epistemic space in

captured points lie infinite un-captured positions; meaning emerges through what is inferred, interpolated, or suspended in latency. The body is fashioned in a continuous process of becoming, distributed across photonic events and detection thresholds.

The stakes of this shift are not confined to the ontology of the scan; they re-specify where fashion design can intervene under contemporary regimes of capture. In an era of metabolic capitalism—where sensing infrastructures anticipate, predict, and pre-format bodily behaviour—*Dust Enforcer* advances a counter-capture approach that repurposes such logics from within (Denson, 2021). The practice-level contribution shifts from making garments to staging encounters through which bodies become measurable and actionable. Here, the designer is no longer positioned as a sovereign author who imposes form onto a stable anatomy, but as an orchestrator of situated constraints and feedback relations—working with apparatus, movement, and material behaviour as a dynamic system of emergence.

Fashion scholarship has long privileged signification—identity, consumption, display—treating dress as a communicative and socio-cultural system (Carter, 2003; Barnard, 2002; Barthes, 1990). Compositional Sensing shifts the frame to an infrastructural prior: how bodies are rendered perceptible and governable within regimes of capture that increasingly organise social life through prediction and algorithmic observation. This shift aligns with the rise of critical and expanded fashion practices that work across multiple media and treat fashion as a research apparatus to generate new forms of knowledge outside the industrial horizon of garment-making (Torres, 2017).

Situated within urgent conversations on embodiment, perception, and digital materiality—where bodily presence is increasingly operationalised as data—the paper interrogates the conditions under which embodiment is registered, processed, and acted upon within computational infrastructures. To ask what a body is, or what a body can do, is therefore to ask how it is made to appear as evidence. *Dust Enforcer* exemplifies this orientation by composing those conditions directly, positioning fashion as a critical practice of perception, registration, and reconfiguration.

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which meaning is constructed by the system and viewer alike.

CAPTIONS

[Fig. 01] Patricia Wu Wu; Dust Enforcer; Table documentation categorizing material properties and their interaction with lidar.

[Fig. 02] Patricia Wu Wu; Dust Enforcer; Point-cloud diagram visualization analysing bodily movements and gaps.

[Fig. 03] Patricia Wu Wu; Dust Enforcer; Photographic documentation of the performance set up process and movements prior to scanning.

[Fig. 04] Patricia Wu Wu; Dust Enforcer; Point-cloud volumetric rendering of the choreographed performance.

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BODILY PAIN

TEXTILE STRUCTURES OF BREATH AND REPAIR

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Abstract

This paper investigates sculptural knit as a site of somatic memory and embodied intelligence, proposing tenderness as an infrastructural logic within fashion textile technology. Grounded in lived experiences of chronic pain, sensory difference, and care, the research adopts a practice-based, research-through-design methodology to examine how industrial knitting and weaving can register breath, pain, and protection through material form. Through the case study *Pain Bodies*, the paper analyzes how knit architectures—through cavities, inlay, and compression—hold, archive, and respond to bodily states that resist linguistic expression. Inlay is articulated as both technique and ethical gesture, embedding memory, grief, and attentiveness directly into textile structure. Drawing on somatics, care ethics, and textile interaction design, the research reframes smart and adaptive textiles not as systems of optimization or spectacle, but as supportive companions for embodied regulation and persistence. By foregrounding inclusive craft, emotional durability, and responsiveness felt rather than measured, the paper contributes an alternative paradigm for fashion technology. It proposes textile technology as tender infrastructure—capable of listening to the body, sustaining vulnerability, and expanding how responsiveness is understood within future fashion textile systems.

Keywords: *Sculptural knit; Somatic textiles; Tender infrastructures; Architectures of care; Pain bodies*

INTRODUCTION: TEXTILES AS EMOTIONAL ARCHITECTURE

This research begins with the body, grounded when it falters—through grief, pain, and the quiet negotiations of breath and pressure. Drawn to soft architecture and tender structures, the work is grounded in warmth.

Knitting is positioned as a way to hold on — an instinctive wrapping, a gesture of protection, a second skin to contain and release. From this grew *Pain Bodies*[1], a body of work in which sculptural knit forms act as architectures of memory, sheltering and revealing the body's vulnerabilities. While these works arise from lived experience, they also ask a broader question: how might knit function as a responsive healing structure for the body?

This paper proposes textile as infrastructure—an intimate architecture capable of care, repair, and memory (Townsend, Solomon, & Briggs-Goode, 2022). Historical precedents, notably Bauhaus body culture, similarly frame textiles and movement as sites of somatic training, ritual, and care (Ackermann, 2019; Burchert, 2019). Kathleen James-Chakraborty (2016) and Elizabeth Otto & Patrick Rössler (2019) extend this lineage by situating the body within Bauhaus culture as a site of design, discipline, and

1 *Pain Bodies*, a contemplative textile series that transforms bodily pain into soft architecture, gesture and emotional membrane.

performance.

Often, fashion textiles are framed within discourses of optimization and enhancement, where technology extends the body's capacity by regulating function and improving performance (Smelik, 2018a, 2018b; Loke et al., 2021). Within this paradigm, textiles are positioned as instruments of efficiency, while the body is treated as a site of measurement and control. Alongside these approaches, this research situates knit as tender matter—a practice of care within fashion technology debates that are increasingly expanding beyond computation. Holly McQuillan and Elvin Karana's research on multimorphic textile-forms argue that responsiveness can be understood beyond computational layering—emerging instead from textile materiality and structure, a quality which can be poetically understood as material vitality, a liveliness (McQuillan, 2020; McQuillan & Karana, 2023). Tim Ingold (2012) describes materials as "substances-in-becoming," alive with histories and tendencies, while Karen Barad (2003) frames matter as "a doing, a congealing of agency," always active in its becoming. Through inlay, cavity structures, and compressive forms, this practice investigates quiet technologies of care—gestures that register breath and pain. Ingold's notion of "meshwork"—entangled lines of material flow and bodily movement—provides a framework for understanding these practices as forms of responsiveness grounded in tenderness rather than optimization. This positioning situates the work within ongoing debates between computation and materiality, and between optimization and care. These questions of responsiveness and care return the analysis to the body itself: the intangible pressing into the physical, asking to be held. Trauma lives in the body, unique to each, where it resists linguistic expression and imprints itself through sensation (van der Kolk, 2014). Textiles, with their ability to press, hold, and shelter, can hold what words cannot. Mengqi Jiang et al. (2021) extend this argument further, showing how movement-based interaction with smart textiles can actively regulate emotion, reframing textiles as affective co-regulators—a logic *Pain Bodies* extend through tenderness and embodied vulnerability. They offer a material language for the invisible: traces—faint, residues—the weight that clings and accumulates. *Pain Bodies*—sculptural knits—attempt to give these forms space, holding what words cannot. Knitwear stretches, compresses, and yields, mapping the body's vulnerabilities. As residue, it archives pain in hollowed cavities and bulging forms—a sculpting of grief into matter, absence and excess entwined. As protection, it shelters, molds and embraces—an architecture of care. Anchoring in this duality of residue and protection, the garments both remember and hold.

Feminist craft traditions offer a further conceptual grounding for understanding textile as infrastructure of care. The methods employed in this research align with this lineage—textile as storied and labored, anatomical and somatic. Jessica Hemmings (2015) and Katherine Townsend and colleagues (2022) suggest fashion textile practices hold what cannot be spoken; *Pain Bodies* operate as extensions of living anatomies. Anusha Alamgir (2022) positions the body as a site where narratives are speculatively redefined, challenging the bodily form. Tenderness here is a dialogue with the body, the haptic—the emotional framework in designing for and with embodied vulnerability. This articulation of lived transformation resonates with the practice underpinning this research, in which knitwear is conceived as an infrastructure of care. Though *Pain Bodies* first arose from grief and somatic inquiry, the research was subsequently reshaped by what is now understood as chronic pain. Experiences of nerve pain and compromised breathing necessitated a slower, more attentive engagement with the body as both fragile and persistent. *Pain Bodies* materialize this condition dually—through sculptural knit structures—as residue, archiving trauma and memory; and as protection offering shelter to embrace, dancing with pressure to steady the body. This duality forms the central analytical thread of the paper, situating the practice within physiological, feminist, and performative frameworks while remaining grounded in lived experience.

METHODOLOGY: KNIT AS SOMATIC REGISTER

This research adopts a practice-based, research-through-design methodology, structured through iterative cycles of somatic inquiry, material experimentation, and performative refinement. The approach draws on Sir Christopher Frayling's (1993) articulation of research through art and design, and is situated alongside contemporary applications of this framework within textile and material-led practice, including Claire Felicity Miller's (2025) experimental materials research and Silke Hofmann's (2025) practice-based investigations into material systems and embodied design. Rooted in human factors, this methodology extends beyond optimization to include tenderness as a mode of responsiveness. Knitting is situated as a somatic register, something tender—a slow, embodied practice tracing breath, pain, and pressure. As McQuillan & Karana (2023) note, responsiveness can be lived through material itself. The practice is autoethnographic, grounded in bodily experience, extended through dialogue with dance and architecture—blurring boundaries between discipline and living collaborator. Within this research, the act of knitting is less about production than correspondence. Gilles Deleuze and Félix Guattari (2004) describe it as "matter in movement, in flux, in variation," a flow to follow. Ingold (2012) extends this, framing making as "intuition in action," an attunement with materials in their unfolding. To knit is to accompany matter, to listen as it stretches, gives, or resists—an ethic of tenderness. In this sense, methodology becomes continuous with the same negotiations of breath and pressure that shape *Pain Bodies*; it is methodology as practice. *Pain Bodies* inscribe somatic states—softness as technology where inlay lingers like scars, cavities holding breath, and compression steadies through pressure. The Pain Body process material—archival scans, body mappings, cavity formations, inlay tests, and bulging structures—makes visible these somatic negotiations (Fig. 03). A practice translating sensation into form—gestures not of ornament, but of register.

Industry paradigms explore responsiveness through data-driven precision. This research positions material responsiveness itself as a technological capacity, expanding fashion technology beyond computation toward embodied, material intelligence. Vidya Narayanan et al. (2018) automated 3D mesh workflows; Shahar Asor and Yoav Sterman (2023) created parametric punchcard frameworks; Zishun Liu et al. (2021) advanced 4D knits with controlled elasticity; Katja Wolff et al. (2023) developed personalized garments adapting in real time. These projects broaden understandings of responsiveness through precision and adaptability. This contribution enters into a dialogue with such work, reorienting industrial knitting—also drawing from weaving discourse—toward tenderness—translating bodily fragility into architectures of care, locating responsiveness in stretch, compression, and yield in dialogue with the body. Such projects illustrate how computation and craft need not be opposed. Bine Roth and Kaori Ueda (2023), for instance, extend Nishijin weaving through generative design, not as disembodied code but as a bodily practice. Their work shows how digital logics can remain embedded in tradition and material intimacy—a resonance with this research's turn from optimization toward tenderness. Performance is central to the methodology, when knit is not only a material but a performer in dialogue with the body. Berit Greinke et al. (2021) extend this logic, showing how knit garments for orchestra conducting perform as co-agents with the body, transforming gesture into shared musical performance—garment as co-performer rather than passive tool. Dance, as Olivia Foster Vander Elst et al. (2023) describe, is purposeful and structured movement that entwines perception, action, and emotion. In working with dance, the sculptural knits of *Pain Bodies* register this embodied temporality: cavities stretch with breath, compressions shift posture, and weight choreographs grief across gesture. Here, textile is not passive but kinesthetic—joining the body's rhythms of expansion and constraint. Lara Conte and Francesca Gallo (2023) frame performance design as a negotiation between body, material, and environment. In this sense, *Pain Bodies* is an architecture approached not only as built environment but as knit's own structuring principle—inlays, cavities, and compressions acting as skeletal frameworks that both shape and respond to motion. The textile performs as infrastructure—a stage that moves with the body even as it constrains or supports it. *Pain Bodies* thus move between stage and scaffold, a duality between choreography and structure, cultivating tenderness as a relational practice of textile and body. Underlying the methodology is a commitment to accompaniment. Each stitch is small, repetitive, and durational, embedding attention as its own form of care. To knit in this way is to resist speed and optimization, embracing slowness as both practice and ethic; tenderness as method, a way of attending through soft attention to material, body, and breath. Knitting becomes ritual. The repetition of loops is akin to meditation or prayer, each pass of yarn marking time through touch. It's not about mastery but about staying-with—allowing material and body to unfold together. The practice holds grief and pain without seeking resolution. Here, methodology itself becomes an ethic: craft as care, method as tenderness, practice as accompaniment—offering an alternative model for responsive fashion textile technology grounded in embodied and material intelligence.

The wearable and adaptive textile systems discussed in the literature above are referenced as conceptual and contextual precedents, informing *Pain Bodies* possible future orientation toward responsiveness and care, drawing on novel technologies.

CASE STUDY: *PAIN BODIES*, THE HAPTIC AND THE HEALING

When the body falters—through grief, breath pressed thin—*Pain Body* 'One' (Fig. 01) stages responsiveness through softness. Delicate cavities of silk and cotton expand; the knit stretches and grips, tracing weight and respiration in pliable form along the chest and abdomen. Flavia Mancini et al. (2014) describe how the body is mapped differentially by sensation, neuropathways of haptic acuity—some regions tuned to the faintest brush of touch, others sharpened to pressure and pain. They frame softness as a design quality that exceeds comfort, shaping relation through pliability, pressure, and yield. Within *Pain Bodies*, softness operates as a technological capacity: not passive comfort, but an active system that senses, responds, and stabilizes. And so, knit's pliability becomes a partner in that cartography: registering respiration through cavities and steadying the body with gentle compressions. This haptic sensitivity stages what others have called textile vitality (McQuillan & Karana, 2023): *Pain Body* structures that yield and press, choreographing absence and pressure as gestures of care. Responsiveness is felt—body and textile listening in tenderness.

If pliability registers touch and pressure, then cavities register breath. Here, the cavities in *Pain Bodies* are a deliberate design strategy, translating physiological respiration into a spatial and tactile structure. Regulating the body, these voids are architectures of respiration, contracting with each breath. Bruno Bordoni et al. (2018) demonstrate how breath extends into the central nervous system, shaping posture, emotion, and pain perception. Valentin Magnon et al. (2021) and Marc Russo et al. (2017) show how slow deep breathing modulates the vagal tone, reducing anxiety and stabilizing cardiovascular rhythms. Apostolina Foskolou et al. (2022) explain how abdominal breathing grounds postural stability

Fig. 01

and engages muscular activation, while Marcin Sikora et al. (2024) reveal how patterned breathing reshapes pulmonary function and endurance. *Pain Body* cavities embody this notion: each hollow a dwelling for breath, an expansion of architecture and persistence—breath becomes physiological and poetic, an intimate infrastructure steadying a faltering body.

If cavities hold breath, compressions embody pressure. Compression is employed here as an infrastructural element, modulating bodily perception through sustained, distributed force rather than rigid constraint. The bodily folds of *Pain Body* 'draped' (Fig. 02, Fig. 04) weigh from below, across the shoulders and down the torso as grief made material. *Pain Body* 'draped' is a developed configuration of *Pain Body* 'One', intensifying compression and weight to foreground gravity and suspension as modes of tender support. And yet, ever so steady, a counterforce constrains as it supports. Marianna Halász et al. (2021) show compression garments shape physiological response—modulating circulation and stabilizing recovery. Jonathon Weakley et al. (2022) frame compression as infrastructure influencing

Fig. 02

hemodynamics, recovery, and proprioception. Trevor Barss et al. (2018) show compression alters the transmission of sensory feedback in the upper limb, re-tuning the body's haptic dialogue. Eric Harbour et al. (2025) show sports bra tightness alters respiratory muscle fatigue, breathing patterns, and subjective perception—reminding us that compression is never neutral but always embodied and contingent. Tomas Venckūnas et al. (2014) further highlight its cardiovascular dimensions: lower-body compression garments enhance venous return and circulation during running, integrating pressure as a mode of efficiency. By contrast, Theodora Kyrgia & Marina Toeters (2014) treat wearables as social-expressive companions in dance; these compressive knits reorient that performativity toward tenderness. Stitched bulges, tightened gathers, and weighted shoulders make compression visible, surfacing pressure as both care and constraint. These are not mechanical braces but tender architectures from within. To wear *Pain Bodies* is to experience compression not only as regulation but as kinship: an embrace that steadies as it remembers the body's fragility.

Pain is not only neurological but relational. Maral Tajerian & Jaqueline Garcia (2021) argue that environments and objects shape how pain is lived, expanding therapy beyond medicine into companionship. Garments are not inert layers but partners in care. *Pain Bodies* embody this: folds press, cavities respond, and compressions steady, creating structures that sustain rather than restrain. They do not demand but hold, offering continuity when the body falters. To wear these garments is to experience care, the tactility of weight. They do not erase pain but accompany it, shifting endurance from solitary struggle to shared persistence. This companionship is haptic, material, lived. *Pain Bodies* thus act as therapeutic companions, architectures of tenderness that intervene not with cure but with presence. The performative is approached not as presentation layered onto dress but as a register where body and garment co-become. Corneliu Bodiciu (2022) introduces symbiosis as a paradigm for understanding dress: the body is never isolated from what it wears, and garments are not inert shells but active companions. The dressed body is an ecosystem of material and immaterial agencies, where fabric, posture, memory, and sensation form a living whole. *Pain Bodies* echo this symbiotic entanglement. Each gesture subtly redirected, each inhalation finds a cavity that responds, each compression steadies movement. To perform in these garments is to enter a dialogue: not a theatrical projection, but a mutual becoming where grief, tenderness, and resilience are co-written by body and textile. Tenderness is not fragile—it is tensile, reconciling residue and protection. Resilience emerges where the folds and hollows accumulate the weight of memory; they are traces of what the body has endured. It is the grief that lingers, the embrace that steadies it, the inlays running deep. This duality aligns with vestments, amulets, and ritual garments—clothes that carry residues of belief while protecting the wearer. They sanctify vulnerability, reframing care in fabric and form. *Pain Bodies* join this lineage, reframing fashion as infrastructure of tenderness: remembering and protecting at once. Through *Pain Body* 'One', tenderness is demonstrated as a viable infrastructural strategy in fashion design—materializing care through breath, pressure, and proximity rather than through optimization or control. Through these material strategies, *Pain Bodies* demonstrate how tenderness operates as

Fig. 03

infrastructure: not as sentiment or aesthetic quality, but as a distributed system of breath, pressure, and support that stabilizes the body while holding traces of what it has endured.

THEORETICAL FRAMEWORK: BREATH, PRESSURE, AND MEMORY

Pain Bodies are also situated within broader dialogs of breath, pressure, and memory. Bessel Van der Kolk (2014) argues that trauma imprints itself into the body, shaping sensation and memory beyond language. Textiles archive this somatic memory, offering material forms for what resists. James Krasner (2020) shows how Lia Cook's textiles hold memory and emotion in fiber as sites of embodied craft. Jessica Bugg (2014) frames clothing as performance that stores affective residues of lived experience; and Laura Salisbury (2021) extends this by studying knitted wearable technologies as therapeutic systems, evaluating how softness mediates recovery with stroke survivors. *Pain Bodies* inhabit this lineage: cavities and bulges archive grief, folds retain weight, and compressions remember pressure. They are but mnemonic architectures, holding traces of pain, offering shelter. Within fashion technology debates, this framing extends textiles beyond surface or spectacle: they become archives that both remember and respond, proposing material memory as a form of digital craft.

Breath, too, is a site of memory and regulation. Bruno Bordoni et al. (2018) demonstrate respiration as it extends into the central nervous system—shaping posture, pain, and emotion. Roderik Gerritsen & Guido Band (2018) describe the "respiratory vagal stimulation model," showing how controlled breathing modulates vagal tone to support resilience. Neil Cherniack (1990) intricately traces the coordination of respiratory muscles with neural control, situating breath as both physiological and neurological. The knitted cavities of *Pain Bodies* materialize this regulation. Structures expand with inhalation, contract with exhalation, embodying respiration as both infrastructure and intimacy. They do not adorn but register—a somatic architecture where physiology and poetics meet. Joan Tronto (1993) articulates an ethic of care grounded in attentiveness, responsibility, and responsiveness. Sonja Jerak-

Zuiderent (2018) drawing on Maria Puig de la Bellacasa (2017) expands this toward speculative ethics in more-than-human worlds, where care is not sentimental but infrastructural. Within this framing, tenderness becomes ethical and material: each stitch a residue of care, each compression a trace of accompaniment. *Pain Bodies* embody this ethic. They reconcile protection with residue, holding vulnerability without erasing. Knit becomes a practice of tenderness: sustaining presence, sanctifying fragility, and embedding care in form.

Breath is not only physiological but ritual and spiritual. Ute Ackermann (2019) shows how early Bauhaus body culture linked breath and nudity to ideals of freedom, framing respiration as transformation. Otto & Rössler (2019) and Juliet Koss (2006) extend this lineage, documenting how Bauhaus body culture engaged sexuality, movement, and design as inseparable—an important context for situating my practice in care and somatics—linking body, movement, and breath. This practice holds breath as a site of personal ritual. Kristina Höök (2024) aligns with this in somaesthetic interaction design, grounding bodily technologies in contemplative, felt practices. Aglaia Zafeiroudi (2021) extends breath into choreography, showing how yoga and dance interlace respiration with spirituality. *Pain Bodies* join this lineage: cavities expand with inhalation, compressions steady exhalation, garments acting as ritual architectures. These perspectives frame breath as an infrastructural, ritual, and relational phenomenon. *Pain Bodies* becomes vestment—an infrastructure of tenderness where breath is sanctified, grief is carried, and persistence is honored.

Fig. 04

DISCUSSION: RESPONSIVENESS, TENDERNESS, AND ETHICS

Fashion textiles have often been defined by optimization, positioning garments as tools for efficiency, measurement, and control. Yet lived experience of pain and fragility demands another register—one where responsiveness is not calculated but cared for, where tenderness itself becomes an infrastructure. In this discussion, this paper reframes responsiveness, craft, and durability through the lens of care ethics, situating *Pain Bodies* as counterpoints to paradigms of optimization.

Smart garments frequently pursue responsiveness through optimization. Catherine Elliot et al. (2019) validate the Hexoskin biometric vest by measuring its accuracy during maximal aerobic testing, framing textile as an instrument of performance and control. Alice Haynes & Jürgen Steimle (2024) extend this paradigm with Flextiles, programmable shape-changing textiles designed with actuators—garments that move because computation instructs them to. In each case, responsiveness is measured, calibrated, and validated through efficiency. This research enters into dialogue with these approaches, proposing tenderness as a complementary mode rather than an oppositional one. *Pain Bodies* depart from this paradigm. Responsiveness here is tender, grounded in the lived body. By shifting emphasis from performance toward care, this research reframes responsiveness as accompaniment—garments that sustain the body through attentive material presence. Responsiveness becomes less about ‘what the garment does’ than about ‘how it listens.’ This listening is haptic intelligence—responsiveness felt through touch, not measured in data. If optimization frames responsiveness as data-driven control, this work situates it in sensation itself. Responsiveness is not computed but felt: the stretch of knit, the pressure of compression, the hollow that registers breath. This is a form of haptic intelligence—body and textile co-sensing, co-responding—what McQuillan & Karana describe as textile vitality. *Pain Bodies* are activated through cavities, folds, and compressions—structures that sense through touch. This resonates with Ruojia Sun et al. (2020), who describe woven “second skin” interfaces that collapse body and textile into a single haptic infrastructure. Haptic intelligence is relational, not instrumental. It is a dialogue of steadiness and care, where textile and body listen together in tenderness. Yet such computational approaches need not stand apart from tenderness. Liu et al. (2021) show how elasticity-controlled 4D knits merge precision with pliability, suggesting optimization can be reoriented through care. Building on this, Luo et al. (2021) propose conformal tactile textiles that learn from human–environment interactions, pushing responsiveness into adaptive, intelligent terrains. Even as these examples are framed within optimization, they can be read as invitations to rethink responsiveness as accompaniment: textiles that learn with us, shaping tenderness through shared adaptation.

Tenderness is tensile, not fragile. Tronto (1993) defines care as attentiveness and responsibility, while Puig de la Bellacasa (2017) reframes it as speculative and infrastructural. These ideas are extended materially through garments of *Pain Bodies*: folds archive grief, compressions steady breath, cavities sanctify fragility. In doing so, they echo ritual garments—vestments and amulets—that hold belief, memory, and protection together. If optimization offers precision and control, *Pain Bodies* tenderize, introducing tenderness as a parallel choreography of responsiveness. Responsiveness here becomes less about calibration than accompaniment, less about efficiency than intimacy. Tenderness itself emerges as an infrastructure—haptic, ethical, spiritual—that reframes what it means for fashion to care. Taken together, these threads articulate an alternative paradigm for fashion textile technology: responsiveness as accompaniment, craft as care, and durability as attachment.

CONCLUSION: TOWARD RESPONSIVE CRAFT

In concluding, this paper returns to the central provocation: what if textiles, rather than optimizing performance, could sustain tenderness as infrastructure? The following reflections draw together the strands of responsiveness, memory, and care, situating this practice within both historical and visionary lineages. Knitwear is often framed as surface—decoration, fashion, or spectacle—but here it becomes infrastructure: an intimate architecture that steadies and shelters the body. Townsend et al. (2022) describe textiles as anatomical, working not only across but with the body, embedding themselves into lived experience. Where buildings enclose, knit enfolds; where scaffolds brace, knit yields and compresses. Its loops create elastic architectures that move with the body, shaping touch, breath, and pressure. *Pain Bodies* extend this infrastructural quality. Cavities are not ornament but breathing chambers; folds are not drape but weights that anchor posture; compressions are not restraints but steadying forces. These garments do not sit outside the body but act as companions—an intimate support. Knit here is less of a garment than it is an architecture—it is composed of an elastic infrastructure that listens, steadies, and remembers. This reframing of knit resonates with broader conversations in fashion and design, yet redirects these logics toward tenderness rather than performance.

Tenderness emerges through a duality: residue and protection. Folds and hollows accumulate the weight of memory, carrying grief and traces of what the body has endured—compressing, enclosing, and steadying. Tenderness is tensile rather than fragile: it reconciles memory with shelter, grief with embrace. In *Pain Bodies*, this duality becomes tactile. Hollowed cavities archive breath, while weighted folds embrace fragility. The garments sanctify vulnerability rather than erase it, reframing fashion textile as a structure where residue and protection coexist. This duality of residue and protection echoes long-standing histories of garments as spiritual infrastructures. Throughout history, garments have operated as spiritual infrastructures of care: vestments, amulets, and ritual attire carry residues of belief while protecting the wearer. Their sanctity lies in their dual role as both material protection and symbolic memory—linking Annette Messager (1992) speaking of the evaporated body, Julia

Bryan-Wilson writings of Ana Mendieta (2013), and Johnson and Bayley speaking of Carolee Schneemann (2022). This practice joins this lineage. Each stitch in *Pain Bodies* is labored attention, a haptic act of accompaniment. Like amulets, the garments carry grief and memory; like vestments, they enfold the body in protection. protection. This spiritual and ritual dimension is extended in the installation of *Pain Bodies*, where the suspended knitted forms hover above madder root and powder, staging textile as residue, offering, and protective presence (Fig. 05). Knit here is sacred labor, embedding tenderness in form.

If ritual garments anchor tenderness in tradition, visionary designers push it into futurity. *Pain Bodies* stand in dialogue with both—and within a lineage of visionary design that reconceives garments as infrastructures of life. Issey Miyake et al. (1999) sculpted pleats and folds as living forms, architectures in dialogue with the body. Marta Muñoz and Ángel Cordero (2024) deepen this by showing how Miyake's folds resonate with architectural strategies, shaping garments as spatial environments. Nicholas de Monchaux's Spacesuit (2011) reminds that even technologies of survival are crafted with care: the Apollo suits embody how intimate labor and somatic understanding underpin structures of protection. Neri Oxman's contribution to CNSILK (Tsai et al. 2013) and her project The Wanderers as discussed by Yasmine Chacour (2020) extend this futurity, proposing garments as material ecologies, symbiotic organisms at once biological, computational, and architectural. Within this visionary lineage, this practice contributes tenderness. Alongside Miyake, Monchaux, and Oxman—who propose infrastructures of efficiency or futurity, *Pain Bodies* offer infrastructures of care. They reframe knit not as surface but as memory-bearing shelter—garments that archive grief while steadying the body.

At the end of this inquiry, *Pain Bodies* are understood as carrying forward propositions for futures of care in textiles for the body, in all of its diverse forms. Sculptural knits as proponents of tenderness in a multidimensional sense, bridging the poetic and the scientific, the crafted and the physiological. It is the linking of the artist's labor with meaning and memory, *Pain Bodies* is the connecting of performance and somatics with rehabilitation, breath, and resilience. In them, textile art, fashion, craft, design, and science meet—not as separate categories but as collaborators. A terrain in which practice and research reside: tenderness as infrastructure—remembering, protecting, and accompanying the body through responsive craft.

Fig. 05

CAPTIONS

[Fig. 01] *Pain Body 'One'*; Emily Sarah Trenton

[Fig. 02] *Pain Body 'draped'*; Emily Sarah Trenton

[Fig. 03] *Pain Body process*—archival scans, iterations, inlay tests; Emily Sarah Trenton, *Pain Bodies* is a compilation of my practice and research investigating the dialogue of knitted textile structures through body, movement, and pain. It is a contemplative textile series that transforms bodily pain into soft architecture, gesture and emotional membrane.

[Fig. 04] *Pain Body 'draped'*—archival scan; Emily Sarah Trenton

[Fig. 05] *Pain Bodies* (Left-right—*Pain Body 'Two', Pain Body 'draped', Pain Body 'One'*); Emily Sarah Trenton; *Pain Bodies* installation, suspended over madder root and powder.

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AGILE PRODUCTION NETWORKS

AI AND WHOLEGARMENT® KNITTING FOR DECENTRALISED FASHION SYSTEMS

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Abstract

WHOLEGARMENT® knitting enables the production of complete, 3D seamless garments in a single automated process, offering highly programmable textile manufacturing. This practice-based research investigates the feasibility of a decentralised production model—the Future Factory Network (FFN)—using existing industrial 3D knitting infrastructure. Early-stage knit trials were conducted at production sites equipped with WHOLEGARMENT® systems, alongside hypothetical network modelling based on international trade data and offshore manufacturing data from an Australian apparel brand. A varied set of products was produced to examine system adaptability, reconfiguration time, and operational stability under decentralised conditions. The study focuses on operational performance, framing knitting machines as networked production nodes within a potential distributed manufacturing system. Findings suggest that WHOLEGARMENT® technology provides a viable foundation for low-waste, low-labour, just-in-time production when applied across multiple localised sites. The research situates WHOLEGARMENT® systems within an emerging AI-enabled manufacturing context, indicating how future integration could further enhance responsiveness and coordination across decentralised networks. This study contributes to ongoing discussions on hyperlocal production and digitally enabled manufacturing, proposing a structured pathway for reconfiguring fashion production toward modular, decentralised systems.

Keywords: *3D knit; Localism; Advanced manufacturing; Industry 5.0; Sustainability*

INTRODUCTION

Traditional offshore manufacturing systems have proven increasingly fragile in the face of geopolitical instability, pandemic-related disruption, and extreme climate events (Ivanov, 2023). At the same time, regulatory developments—such as the European Union's Ecodesign for Sustainable Products Regulation (ESPR) and the Digital Product Passport (DPP)—are placing new demands on fashion brands for supply chain transparency, traceability, and responsiveness (Quantis, 2018). Together, these pressures foreground a central challenge for the fashion industry: how to improve sustainability and production flexibility while relocating manufacturing closer to the point of demand.

Within this context, WHOLEGARMENT® knitting technology, developed by Shima Seiki, offers a distinct production paradigm. By producing complete, seamless garments in a single automated process, WHOLEGARMENT® systems reduce material waste and minimise reliance on post-production operations such as cutting, sewing, and linking (Choi, 2005; Pavko Čuden, 2022a). In contrast, fully-fashioned knitwear production depends on multiple labour-intensive post-knit stages, which introduce additional time dependencies and constrain responsiveness, particularly in on-demand or small-batch production settings (Larsson et al., 2012; Peterson et al., 2008).

Previous case-study research has demonstrated that on-demand WHOLEGAR-

MENT® production can support order-driven manufacturing without cutting or sewing, enabling relatively short fulfilment lead times in retail contexts (Peterson & Mattila, 2010). Such findings are particularly relevant given ongoing global shortages of skilled textile labour and the growing need to accommodate smaller, more diverse order volumes—conditions under which traditional assembly-based knit production models are increasingly difficult to sustain (Pavko Čuden, 2022a).

Building on this background, this research investigates the feasibility of utilising WHOLEGARMENT® knitwear technology within a distributed manufacturing network. The proposed Future Factory Network (FFN) model conceptualises a decentralised system of production hubs equipped with WHOLEGARMENT® machines, each capable of fulfilling orders locally while sharing digital infrastructure, programming logic, and material inputs. Rather than concentrating production in a single factory, the FFN model examines whether programmable knitting systems can be more efficient and responsive when dispersed across multiple sites.

The study is informed by theoretical frameworks on modular manufacturing platforms (Gawer & Cusumano, 2014) and digitally enabled local production ecosystems (Larsson, 2018), extending these perspectives through practice-based production trials and system-level analysis. The aim is not to evaluate knitwear aesthetics or design processes, but to assess whether WHOLEGARMENT® machines—already established in niche and design-led applications—can serve as the technical foundation for scalable, decentralised knitwear production.

Ultimately, this paper proposes that WHOLEGARMENT® knitting, supported by targeted automation and local infrastructure, presents a viable pathway toward more responsive, low-waste manufacturing systems. By shifting away from centralised, labour-intensive production models, programmable knit production offers the potential for improved resilience, traceability, and adaptability in fashion manufacturing, particularly in markets characterised by volatile demand and increasing regulations.

RECONFIGURING FASHION MANUFACTURING THROUGH PROGRAMMABLE TEXTILE SYSTEMS

The contemporary fashion industry is undergoing a transition from the long-established manufacturing models, which are increasingly challenged by geopolitical instability, environmental pressures, and market volatility. For decades, apparel production has been organised around large-scale, centralised offshore systems designed to maximise economies of scale (Pouillard & Dubé-Senécal, 2023). While effective under conditions of stable global trade, these models have proven vulnerable to disruption, including climate-related events, labour volatility, trade tensions, and the systemic impacts of pandemics (Ivanov, 2023). At the same time, rising expectations for traceability and verifiable data have exposed the limitations of supply chains reliant on geographically dispersed, opaque production processes (Abreu et al., 2012).

In parallel, shifts in consumer behaviour are reinforcing the need for alternative production approaches. Growing awareness of environmental impacts, alongside increasing demand for product customisation and rapid response cycles, has rendered traditional mass-production systems less competitive (Kozinets & Handelman, 2004). Shorter lead times and more adaptable product development structures are increasingly required, signalling a broader reconfiguration of the relationship between design, production, and market demand (Pucker, 2022).

Labour constraints further intensify these pressures. Global shortages of skilled textile workers—particularly in technically specialised and repetitive roles—with younger generations increasingly disengaging from manual textile labour (Pavko Čuden, 2022a; Stevick, 2023; Taylor & Townsend, 2014). Even in historically low-cost manufacturing regions, labour scarcity has eroded many of the economic advantages traditionally associated with offshore production. Against this backdrop, programmable and automated textile technologies have emerged as viable alternatives. Digitally controlled systems, exemplified by WHOLEGARMENT® knitting, significantly reduce reliance on manual assembly, minimise material waste, and support greater production agility through integrated, single-process garment construction (Cerulo et al., 2022; Larsson, 2018).

The adoption of such technologies enables a shift from centralised factory models to distributed, and in some cases hyperlocal, production structures. By relocating manufacturing closer to the point of consumption and leveraging automation to reduce labour dependency, these networked models offer improved resilience, operational transparency, and reduced environmental impacts—particularly in relation to transport emissions and material handling (Ivanov, 2023). Rather than representing incremental technical upgrades, programmable textile systems facilitate a systemic reorganisation of fashion manufacturing, reshaping how production capacity, responsiveness, and sustainability are configured within contemporary constraints.

Taken together, regulatory pressures, evolving consumer expectations, labour shortages, and advances in digital manufacturing converge to signal a decisive shift in the global fashion production landscape. The proposed network is characterised by agility, digital integration, and sustainability, positioning programmable textile technologies as a critical foundation for more interconnected, adaptive, and future-oriented manufacturing networks.

DISTRIBUTED AND HYPERLOCAL MANUFACTURING NETWORKS

Distributed and hyperlocal manufacturing models have emerged as potential responses to contemporary challenges in manufacturing and supply chain management. Distributed manufacturing refers to decentralised production organised through networks of smaller, geographically dispersed units, often located closer to points of demand (Gawer & Cusumano, 2014). Hyperlocal manufacturing represents a more specific configuration within this broader category, in which production occurs within a narrowly defined geographic area, enabling rapid and flexible responses to local or regional needs (Langvik, 2022).

These networked production models offer several advantages over traditional centralised systems, including improved resilience to disruption, reduced transportation impacts, and greater responsiveness to fluctuating consumer demand (Ivanov, 2023). In the context of textile and knitwear manufacturing, the application of 3D knit technologies within distributed and hyperlocal frameworks presents a further opportunity to reduce material waste and supply chain emissions while supporting smaller batch sizes and variable production volumes (Cerulo et al., 2022; Larsson, 2018). Such models are developing in response to mounting pressure on global supply chains and increasing demand for adaptable, locally responsive manufacturing systems.

The shift toward distributed manufacturing represents a structural departure from industrial models historically organised around economies of scale. Instead, networked production structures prioritise economies of scope and adaptability, enabling rapid reconfiguration of production flows and closer alignment with market demand (Gawer & Cusumano, 2014). Advanced digital fabrication technologies play a central role in this transition, supporting flexible production, reduced waste, and improved coordination across dispersed manufacturing sites (Cerulo et al., 2022; Larsson, 2018). As Pavko Čuden (2022) notes, traditional textile manufacturing has long relied on centralised facilities, extended supply chains, and large-scale volume production. These arrangements are increasingly problematic in relation to environmental sustainability, transparency, and responsiveness to volatile consumer demand (Quantis, 2018). Distributed production offers an alternative approach, using strategically located smaller facilities to manufacture garments closer to the point of use, thereby reducing transport-related emissions and supporting just-in-time production models that minimise excess inventory and material waste (Larsson, 2018; Swanson & Lankford, 1998).

However, implementing distributed manufacturing in textile production requires more than geographic dispersion alone. Effective coordination across multiple production sites depends on digitally enabled infrastructure, logistics, and process integration (Ivanov et al., 2016). Industry 4.0 technologies—including the Internet of Things (IoT), cloud computing, and data analytics—enable real-time communication, monitoring, and coordination across distributed networks, supporting production efficiency, material traceability, and reduced downtime in decentralised environments (Frank et al., 2019; Simonis et al., 2016).

Hyperlocal manufacturing represents a more constrained form of distributed production, though not all distributed systems operate at a hyperlocal scale (Srai et al., 2016). In textile manufacturing, small-scale urban and regional facilities—including microfactories—are increasingly adopting WHOLEGARMENT® 3D knitting technology. These sites can produce a diverse range of knit products with minimal machine reconfiguration, enabling production closer to the point of consumption and aligning with just-in-time manufacturing principles.

By embedding circular economy principles within local production ecosystems, hyperlocal models extend the benefits of distributed manufacturing further (Langvik, 2022). Advances in knitting technology—particularly seamless construction and digitally driven workflows—have created new conditions for integrating sustainability, responsiveness, and low-waste outputs into production systems. Within this context, hyperlocal knit manufacturing offers an alternative to high-volume models dependent on specialised labour and extended lead times, supporting scalable production with fewer logistical constraints and reduced material waste (Pavko Čuden, 2022b). Taken together, distributed and hyperlocal manufacturing networks represent both a relocation of production and a reorganisation of manufacturing logic within the fashion industry. By leveraging advanced digital technologies and intelligent management systems, these networked models provide a viable pathway toward more resilient, transparent, and responsive production systems capable of addressing contemporary economic, environmental, and logistical challenges (Ivanov, 2023).

AI-ENHANCED KNITWEAR PRODUCTION

Artificial intelligence (AI) is increasingly recognised as a transformative component of advanced manufacturing, with growing relevance for knitwear production systems. Broadly defined, AI encompasses computational systems capable of tasks associated with human cognition—such as pattern recognition, prediction, and optimisation—through learning from data inputs and prior outcomes (Hassani et al., 2020). Within textile manufacturing, AI applications have been explored across operational efficiency, predictive modelling, design support, and sustainability-related decision-making.

In knitwear production, AI has been shown to support efficiency gains through predictive analytics and parameter optimisation. Developments in machine learning (ML) enable data-driven modelling that can reduce reliance on physical sampling by predicting fabric behaviour and performance prior to production. This approach has the potential to shorten development cycles, reduce material waste, and improve alignment between design intent and manufacturing outcomes. Experimental studies using artificial neural networks (ANNs) have demonstrated the ability to predict mechanical and sensory properties of knitted fabrics—such as drape, elasticity, and tensile behaviour—based on yarn type, stitch configuration, gauge, and machine parameters (Singha et al., 2022). While these studies are dataset-based rather than industrially deployed, they provide a foundation for understanding how AI could support future knitwear optimisation.

These capabilities are particularly relevant to WHOLEGARMENT® systems, given their fully programmable structure and reliance on digital knitting instructions rather than manual assembly. The elimination of cutting, sewing, and linking enables a tightly controlled production environment in which machine parameters, material inputs, and structural variables are digitally defined, creating conditions well suited to AI-assisted analysis and optimisation (Pavko Čuden, 2022b).

One of the most immediate and practical applications of AI within knitwear manufacturing is predictive maintenance. When integrated with sensor systems and Internet of Things (IoT) infrastructure, AI-enabled monitoring tools can detect deviations in machine behaviour and identify maintenance requirements before failures occur (Ivanov et al., 2016; Simonis et al., 2016). This capability is particularly significant in decentralised and hyperlocal production networks, where technical staff may not be continuously present on site, and machine downtime directly affects production continuity across multiple nodes. Ensuring machine uptime is therefore critical to the viability of distributed manufacturing models, and AI-supported maintenance offers a means of stabilising production across geographically dispersed facilities.

Beyond maintenance, AI has potential applications in real-time process optimisation within WHOLEGARMENT® knitting systems. Prior research suggests that AI-assisted adjustment of parameters such as yarn tension, loop size, and stitch density could improve material efficiency, fabric consistency, and production speed, while reducing waste through more precise control of yarn utilisation (Cerulo et al., 2022; Scheidt et al., 2020). In this research, such applications are framed as prospective capabilities rather than validated outcomes.

AI-driven design and pattern generation also represent a promising area of integration. Intelligent systems capable of generating or adapting knitting patterns based on defined constraints—such as performance requirements or sustainability objectives—have been proposed to reduce the technical complexity traditionally associated with knit programming (Scheidt et al., 2020). Techniques such as long short-term memory (LSTM) neural networks have demonstrated potential in modelling sequential stitch relationships and generating knit structures, potentially reducing the translation gap between design intent and machine programming (Eckert, 1999). In hyperlocal production contexts, where adaptability and rapid iteration are critical, such tools could enable faster development cycles with reduced reliance on highly specialised programming expertise.

In addition, AI-enabled data tracking supports the traceability and transparency requirements of emerging regulatory frameworks, including the Digital Product Passport. By recording material usage, production parameters, and process data throughout the manufacturing lifecycle, AI systems can contribute to greater accountability and alignment with sustainability and circular-economy objectives (Pavko Čuden, 2022b; Quantis, 2018).

Despite these opportunities, significant barriers to AI adoption remain. Effective implementation requires access to high-quality data, reliable predictive models, and appropriate digital infrastructure, alongside the expertise needed to interpret and manage AI outputs (Singha et al., 2022). These challenges are particularly pronounced for smaller manufacturers and geographically isolated production sites. However, as AI tools mature and become more accessible through cloud-based platforms and open-source frameworks, these constraints may lessen, enabling broader adoption across diverse manufacturing contexts.

In summary, while AI was not implemented within the applied trials of this research, existing research outcomes and modelling-based studies indicate a clear role for its strategic integration in future knitwear production systems. When aligned with programmable technologies such as WHOLEGARMENT® knitting, AI offers a pathway toward more efficient, adaptable, and sustainable manufacturing—particularly within decentralised and hyperlocal production networks where responsiveness and resource efficiency are critical.

METHODOLOGY

This research employs a practice-based methodology to evaluate the feasibility of deploying WHOLEGARMENT® knitting technology within a hyperlocal, distributed 3D knit manufacturing framework. While the initial research design considered the integration of artificial intelligence (AI), AI tools were not implemented due to resource constraints. Instead, the study examines the operational performance of programmable knit technologies across decentralised production settings and evaluates the resilience of a simulated Future Factory Network (FFN). Analysis focuses on system adaptability, production responsiveness, and logistical viability, excluding aesthetic or stylistic outcomes.

As the second phase of a broader doctoral investigation, this stage builds on earlier conceptual work through applied experimentation and data modelling. Trials were conducted across two urban manufacturing sites—University of Technology Sydney (UTS) and Knovus in Melbourne—both equipped with WHOLEGARMENT® machines, including the Shima Seiki SWG-XR, MACH2XS, and MACH2VS. Each site operated as a production node within the simulated FFN, enabling testing of decentralised manufacturing portability.

A diverse range of products—including garments, blankets, and technical items such as ankle supports—was produced to assess system flexibility under variable, real-world production conditions. Trials comprised single-product runs to establish baseline efficiency, alternating-product runs to examine reconfiguration time and responsiveness, and integrated batch sequences to simulate continuous, demand-driven production. Operational data collected during the trials included machine setup and programming time, digital file transfer and adjustment durations, knitting time, product changeover downtime, yarn consumption, fabric weight, and post-production quality observations. Production time definitions were informed by prior simulation-based modelling of knit-on-demand WHOLEGARMENT® systems, which reported preparation times of approximately 11.5 minutes per order and total lead times of 165.5–187.5 minutes (Peterson et al., 2008). Knitting duration was modelled within a 35–70-minute range, with a typical value of 55 minutes, to reflect normal operational variation, such as yarn breaks or minor machine interruptions. Quantitative analysis focused on production efficiency, machine uptime, throughput, and flexibility, assessed through setup duration and ease of transition between product types. Sustainability was examined through material efficiency, waste generation, and energy use, while operational stability was evaluated via downtime logs, maintenance events, and recorded fault occurrences. Qualitative observations complemented this analysis by documenting workflow patterns, operator interaction, and procedural friction points.

The FFN was further examined using spatial modelling of a hypothetical distributed production nodes approach developed within a digital design environment. The models represent production as a network of geographically distributed sites connected through transport relationships, enabling comparison between centralised and decentralised manufacturing configurations. A reference scenario informed by international knitwear trade data was used to characterise conventional offshore production, against which a distributed, locally oriented network was conceptually compared.

Modelling was used as an exploratory tool rather than a predictive one, supporting comparative discussion across broad performance dimensions including time, distance, resource use, and capacity. In this way, the approach provides a structured means of examining the potential characteristics of hyperlocal production networks—such as adaptability and resilience—without specifying technical or operational parameters reserved for later publication.

The findings from this phase provide practice-based evidence supporting the viability of integrating WHOLEGARMENT® knitting within decentralised production models. While not presented as a comprehensive solution to broader industry challenges, the framework demonstrates how programmable knitting systems may support more responsive, localised, and resource-efficient manufacturing, establishing a foundation for future AI-enabled system development.

DISCUSSION

This study evaluated decentralised knit production using WHOLEGARMENT® technology within a simulated Future Factory Network (FFN). While artificial intelligence (AI) was not implemented in the applied trials, empirical and modelling-based evidence from the literature highlights its potential role in optimising future decentralised knitwear systems.

Prior simulation studies of knit-on-demand WHOLEGARMENT® production provide a useful benchmark for interpreting the operational performance observed in this research. Peterson et al. (2008) report preparation times of approximately 11.5 minutes per order and total customer fulfilment times ranging from 120 to 301 minutes, with mean values of 191 minutes for wool and 206 minutes for cotton garments. Knitting duration in these simulations was modelled using a triangular distribution of 35–70 minutes, with a modal value of 55 minutes, explicitly accounting for operational variability such as yarn breaks and minor machine interruptions. Machine utilisation across fifteen simulations ranged from 79.1% to 90%, with an average of 86%, indicating relatively high and stable equipment use within a knit-on-demand context. These results reinforce the importance of accounting for interruptions, setup time, and utilisation when assessing decentralised production performance.

Within the FFN context tested in this study, such findings underscore why predictive maintenance represents one of the most immediate opportunities for AI-supported optimisation. As demonstrated in Industry 4.0 research by Ivanov et al. (2016) and Simonis et al. (2016), sensor-driven monitoring systems can identify changes in machine behaviour before faults occur, reducing unplanned downtime. This capability is particularly relevant for decentralised and hyperlocal manufacturing environments, where technical staff are not always on site, and machine downtime directly affects production continuity across multiple small nodes.

Beyond maintenance, AI has demonstrated potential to improve programming efficiency, optimise parameters, and predict fabric properties in knitwear production. Experimental modelling studies using artificial neural networks (ANNs) have shown that fabric mechanical behaviour can be predicted based on stitch type, yarn characteristics, and gauge parameters (Singha et al., 2022).

While these studies were conducted on experimental datasets rather than deployed industrial systems, they provide evidence that AI tools could reduce reliance on physical sampling and manual parameter adjustment in future implementations of the FFN. In this research, such capabilities are positioned as prospective enablers rather than validated outcomes.

The suitability of WHOLEGARMENT® systems for AI integration is further reinforced by their high level of programmability and digital precision. Review-based research with strong industrial grounding documents that WHOLEGARMENT® technology eliminates linking and assembly processes, reduces dependence on scarce skilled labour, and supports small-batch, variable production (Pavko Čuden, 2022b, 2022a). Linking, in particular, is identified as a persistent bottleneck in fully fashioned knitwear production, both due to its labour-intensive nature and the declining availability of skilled operators. These documented industry constraints help explain why programmable, single-process production systems are structurally better suited to decentralised and hyperlocal manufacturing models.

Simulation-based studies further suggest that digital interfaces and automation can significantly influence output capacity in customised knitwear environments. Peterson et al. (2011) demonstrated that order-made WHOLEGARMENT® systems supported higher volumes of customised products over equivalent simulation periods compared to manual co-design processes, particularly when configuration interfaces replaced reliance on sales staff. Total co-design time was reduced from an average of 57.5 minutes in manual processes to 39.5 minutes in digital WHOLEGARMENT®-based configurations, while overall production output increased when additional configurators were introduced. Although these findings are simulation-based, they provide insight into how interface design and automation choices may affect scalability within distributed production networks.

From a workforce perspective, the integration of AI should not be framed as a threat to employment but as a response to structural challenges facing the textile industry. As Pavko Čuden (2022a) notes, younger generations are increasingly disengaging from repetitive, labour-intensive textile roles, contributing to skills shortages that constrain production capacity. AI-assisted systems have the potential to lower technical barriers, enabling smaller teams to operate complex production equipment with greater confidence and consistency. Within a hyperlocal manufacturing context, this may also support the re-emergence of textile production in regions where traditional skill bases are no longer available.

However, the implementation of AI within decentralised knitwear networks remains constrained by data availability, interoperability between production nodes, and the need for domain-specific expertise to interpret and act on algorithmic outputs.

In summary, while AI was not implemented in the applied trials of this research, existing empirical and modelling-based studies indicate a clear role for its strategic integration in future iterations of decentralised knitwear manufacturing systems. As the FFN model develops, AI is likely to function as a critical enabler—supporting machine reliability, production responsiveness, and resource efficiency—while reinforcing the broader shift toward localised, flexible, and digitally coordinated manufacturing networks.

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INTEROPERABLE IMMERSIVE FASHION

VR IDEATION TO DIGITAL PATTERN PROTOTYPES

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Abstract

This paper addresses the limited integration of virtual reality (VR) within fashion design workflows, where it is typically used for visualisation rather than creation. Through a practice-led methodology, the study develops and tests a hybrid digital workflow that connects immersive sketching in VR with technical refinement in 3D CAD (Computer Aided Design) software. By translating sculptural garment designs into flat patterns, the workflow enables a streamlined transition from early ideation to production preparation. The method was validated through cross-platform experiments and the creation of physical garments, revealing its potential to improve efficiency, reduce sampling and support more intuitive collaboration. The findings suggest VR's functionality as a real-time design tool, one that enhances spatial judgement, accelerates feedback and supports sustainable garment development. This paper contributes a scalable, practice-based model for hybrid digital fashion design that addresses current inefficiencies in design-to-production pipelines.

Keywords: *Virtual reality; Digital fashion workflows; 3D CAD; Immersive design; Garment development*

INTRODUCTION

Digital technologies are transforming the fashion industry, however it remains tied to traditional workflows. Conventionally, early design remains anchored in flat, 2D processes, while digital 3D tools can demand technical precision too early in the cycle. This misalignment slows development and limits collaboration. The fashion industry requires more agile and digitally fluent fashion practices (Karell & Niinimäki, 2020).

The potential for virtual reality (VR) as a creative design tool remains underutilised. While VR platforms such as Gravity Sketch and CAD packages like Clo3D are gaining traction, they often serve separate functions: VR for visual exploration and CAD for technical sampling.

This research explores how the fashion industry can adopt digital workflows and demonstrate a coherent design-to-production pipeline answering the following research questions:

- Can VR function as a tool for spatial garment ideation?
- What adaptations are needed to convert VR outputs into simulation-ready CAD patterns?
- How can this improve design efficiency and sustainability?

The project aims to create a scalable workflow that begins with VR sketching and ends with functional pattern outputs.

FRAGMENTED DIGITAL WORKFLOWS IN FASHION

Although digital tools are now embedded in many parts of the fashion industry, core design workflows remain fragmented. Digital sampling and visualisation tools in current workflows are persistently inefficient (Papachristou & Bilalis, 2017). Misalignment between conceptual and technical stages lead to redundancy and waste which create negative environmental impacts.

Digital garment development in the fashion industry often begins with manual 2D and 3D ideation. Often 2D digital design involves sketching via a tablet to visualise garment concepts and 3D development begins with draping sample fabrics. Translating freeform, unconstrained designs into more mature technical concepts relies on transitioning to CAD tools. The technical design is developed in CAD to produce a set of digital assets in the form of a 3D model and 2D digital patterns.

Digital fashion system challenges

Current digital workflows present several challenges that contribute to waste and inefficiency in the fashion industry. Transitioning freeform 2D designs into technical 3D CAD creates barriers within an iterative design process by demanding technical precision before creative ideas are fully resolved. These technical demands limit creative exploration and lead to inefficiencies through unnecessary sampling and revision cycles (Dumitrescu & Motta, 2022). Transitioning between digital tools also creates toolchain complexity navigating between platforms that do not share data fluently (Kumar et al., 2017). These barriers interrupt workflow and lack of integration reinforces linear design mentality despite the digital-first design environments. By contrast, integrated systems provide efficiencies through compressed development cycles and supporting the creative process by enabling earlier and faster decision-making.

In the current digital workflow, a number of sampling rounds are often required. There are several such as during pattern drafting, digital to physical discrepancies in the fabric selection, quality issues in construction.

Interoperability between digital design tools

One of the most consistent barriers to digital workflow integration is the technical incompatibility between digital design tools. Kumar et al., (2017) outline how unit misalignment, scale distortion and mesh fragmentation can create breakdowns in cross-platform workflows. In fashion design, these issues are especially disruptive, as CAD platforms rely on construction data (such as seam direction, grainlines and internal pressure points) that freeform VR models do not contain.

Most immersive design tools were initially created to facilitate artistic exploration, not the structural logic required for garment design (Dumitrescu & Motta, 2022). While they allow for fast, expressive form exploration, they lack an understanding of construction constraints. Without embedded rulesets for sewing logic or fabric behaviour, garments drawn in VR are conceptually rich but technically fragile.

VR IN FASHION

Although both VR and CAD tools exist, they are rarely used in sequence or with structured handover, creating disjointed pipelines where designers must choose between intuitive ideation and production viability (Gupta, 2024).

The use of VR in the fashion industry is predominantly for consumer experience as a communication or marketing tool (Sarakatsanos et al., 2024). Kim (2023) explores its use in immersive retail environments, where virtual spaces enhance emotional connection and brand engagement. Renault (2023) documents the rise of avatar dressing and virtual wardrobe curation across digital platforms. Similarly, (Jin et al., 2021) investigate the role of VR in virtual runway presentations, arguing that these settings support experiential storytelling. These studies position VR as a cultural interface rather than a working space for designers. The challenge is to integrate VR as a component of technical design and production workflows. Within educational contexts, VR has historically been used as an isolated visualisation tool, where immersive technologies are introduced separately from the technical systems, for interoperability more integrated teaching is required (Radianti et al., 2020; Rega et al., 2025) to align with industry 5.0 (see 1.4.1).

In creator-focused contexts, VR's offer great potential as a design environment, where form, proportion and silhouette can be explored spatially. By treating virtual space as an active design environment, real-time modelling and parametric adjustments can occur within the immersive setting (Coppens et al., 2019). However, existing studies rarely address how such immersive ideation environments can be systematically translated into CAD-based garment development, leaving a critical gap between spatial creativity and production viability.

FASHION INDUSTRY FUTURES

The future of fashion is being increasingly shaped by the convergence of digital technology and systemic sustainability, prompting a fundamental shift in how garments are designed, produced and consumed (Gupta, 2024). Across the industry, emerging technologies such as 3D simulation, artificial intelligence (AI), and VR are reshaping workflows, whilst more circular design principles and lifecycle thinking are becoming embedded in both education and production strategy (Aakko & Niinimäki, 2018). As these tools evolve, so too does the role of the designer, requiring not only technical creative skill, but the ability to navigate complex systems and ethical decision-making. This transformation signals a move from aesthetic output to an integrated, digitally fluent and environmentally responsive fashion system (Miah & Salgado, 2024)

FASHION INDUSTRY 5.0

Industrial development is commonly framed through models such as Industry 4.0 and 5.0, which help contextualise technological shifts and align practices with wider economic and societal aims. Traditional pattern cutting aligns with Industry 2.0-3.0 due to its reliance on manual tools and basic machinery, while digital fashion reflects Industry 4.0 through the use of CAD systems and simulation technologies (Grice, 2019). As immersive platforms and AI enter mainstream use, parts of the sector are now moving toward Industry 5.0, which re-centres human creativity within digital workflows (López, 2024).

Unlike the automation-driven ethos of Industry 4.0, Industry 5.0 promotes collaboration between people and machines, valuing adaptability, sustainability and personalised design (Donmezer et al., 2023).

Specifically, Industry 5.0 within a fashion context involves integrating technologies into design and production (Donmezer et al., 2023). 3D body scanning can be used to aid fit analysis and pattern cutting (Casciani & Bertolini, 2025) while digital twins enable improved digital accuracy and iterative garment evaluation across physical and virtual contexts, streamlining development timelines (Papacharalampopoulos et al., 2025). Case studies of mass customisation platforms like Future Fashion (Grosso & Boselli, 2022) demonstrate how digital platforms enable designers to adjust fit and materials in response to user inputs while maintaining control over manufacturing. It is also recognised how AI will play an increasing role is mass customisation (Nain & Samal, 2026). This collaboration between human individuality and digital systems in the fashion industry exemplifies Industry 5.0's focus on enhancing creativity and responsiveness in an increasingly digital market.

Immersive tools such as VR and digital twins are expected to facilitate real-time decision-making without compromising creative autonomy (Donmezer et al., 2023).

From an educational standpoint, this shift calls for educational models that emphasise workflow understanding and decision-making in interconnected systems. Hartmann et al. (2023) stress the importance of hands-on learning environments that foster human-machine collaboration and improved digital literacy. Immersive tools embedded in production workflows help learners connect design intent with production strategies, reinforcing Industry 5.0 as a human-centred paradigm (Martínez-Gutiérrez et al., 2024; Rega et al., 2025; Tóth et al., 2023).

Sustainable workflows

Digital fashion provides an sustainable alternative with accurate 3D simulation reducing the need for sample rounds. Black (2012) and Nahid-Ull-Islam et al., (2025) both document how virtual prototyping can reduce waste, accelerate development, and limit dead stock. However, these studies focus primarily on substituting physical steps with digital equivalents. Transforming the workflow to an industry 5.0 model may further improve sustainability, with as much as 80% of a product's environmental impact is determined during the conceptual design stage (Karell & Niinimäki, 2020), early decision-making is critical to sustainable outcomes. However, most digital workflows still embed sustainability only at the sampling or manufacturing level.

METHODOLOGY

This pilot study adopts a practice-led research methodology conducted through design of immersive garment workflows. designer-led enquiry provides insights that are difficult to access through theory alone (Nimkulrat, 2012; Rust, 2007). This study uses direct experimentation to surface problems and test solutions to establish protocol for transferring spatial VR designs into production-ready patterns.

The study progressed through four distinct phases, based on the Lewinian experimental learning model (Kolb, 1984), to ensure the development was both technically and practically viable.

ITERATIVE EXPERIMENTS

Tool calibration focused on identifying compatibility between platforms, testing data formats and resolving early-stage interoperability issues.

Reflection focused on assessing the outcome from each experiment and making informed decisions based on findings.

Workflow refinement involved iterative testing of methods to create a structured, repeatable pipeline from VR sketching to simulation-ready patterns informed by reflection.

Physical validation assessed the accuracy and production potential of the outputs through: garment sampling measured against two representative industry quality assurance (Amrod, 2019; TFG, 2012) tolerance charts. Additionally real-time client collaboration was used to assess and evaluate the garments. These two methods ground the digital process in tangible outcomes.

DIGITAL FASHION TOOLS

Three tools were selected for their complementary roles and relevance to current or emerging industry practice:

- **Gravity Sketch (GS)**: widely adopted in 3D concept design for its intuitive spatial modelling interface, making it suitable for immersive garment sketching. Gravity Sketch offers volumetric freedom without precision.

- **Blender**: initially used for UV unwrapping and scale checking; while not yet a fashion industry standard, it is increasingly being explored by companies such as Adidas and offers accessible, open-source functionality ideal for pipeline experimentation.

- **Clo3D**: a recognised industry standard in digital garment simulation and pattern development, enabling accurate testing of fit, structure and material behaviour.

REFLEXIVITY AND RESEARCHER POSITIONALITY

This practice-led study was conducted by a designer-researcher with prior familiarity with the tools used, which may introduce bias through tool preference and tacit skill. To mitigate this, decisions were documented across Tests A–D (including unsuccessful outcomes), supported by notes recorded after each phase. Outputs were evaluated using garment measurement checks reported in the Results, and a co-viewed session with an external stakeholder (SCIMM) to broaden judgement of fit and silhouette during live iteration.

RESULTS

This section outlines the outcomes of an iterative testing process designed to evaluate the technical viability of a VR-to-CAD garment workflow.

ITERATIVE WORKFLOW EXPLORATION

A series of structured tests were conducted using Gravity Sketch (GS), Blender and Clo3D to assess interoperability and traceability.

Test A: Direct Interoperability
Geometry exported from Gravity Sketch (.FBX/.OBJ) was imported directly into Clo3D. The geometry appeared intact but failed to produce editable patterns. Mesh structures were fragmented and the files lacked seam logic, resulting in simulation failure.

Test B: UV Mapping via Blender
VR garments were passed through Blender to generate UV layouts. These were imported into Clo3D as graphic overlays and manually traced using internal lines. Pattern traceability improved, but UV distortion and scale inconsistencies were observed.

Test C: Scaffold-Based Sketching
Test C introduced skeletal scaffolding, defined here as the use of a simplified 3D garment exported from Clo3D to serve as a proportionally accurate reference within Gravity Sketch. Simplified garments were exported from Clo3D and used in Gravity Sketch as proportionally accurate scaffolds. The designer drew new VR forms around these scaffolds, which were reimported into Clo3D for manual tracing using UV mapping from test B. Alignment improved and traced shapes more closely resembled the intended fit.

Test D: Avatar-Based Tracing
VR garments designed using scaffolding for fit were imported into Clo3D as avatars. Designers traced internal lines directly over these forms using the "3D Pen (Avatar)" tool followed by the "Flatten" tool to create 2D pattern pieces (Fig. 01). The resulting patterns were editable and compatible with full simulation.

EXPERIMENTAL RESULTS

The results of the four tests are summarised in Table 01, which compares import methods, traceability, simulation support and overall technical viability.

Across tests, several recurring technical issues were observed:

- Geometry from Gravity Sketch lacked construction-aware data, preventing pattern generation in Clo3D.
- UV mapping introduced scale distortion and required advanced cleanup in Blender.
- Manual tracing remained necessary in all methods except avatar-based tracing.
- Clo3D's native avatar tool provided the most consistent results for generating editable, simulation-ready patterns.

PILOT STUDY: VR-TO-CAD WORKFLOW

This pilot study documents the development of a garment workflow connecting immersive VR sketching with CAD-based pattern generation (Fig. 02). The objective was to create a pipeline that retained the spatial creativity of VR while producing structured outputs suitable for simulation and manufacturing. Through staged experimentation, the system evolved from initial object imports to a refined, replicable method based on avatar tracing.

WORKFLOW VALIDATION

The final workflow was validated through physical construction and live client testing. Two garments created using the avatar-based tracing method were successfully printed and assembled using standard garment production techniques (Fig. 03). No additional sampling rounds were required beyond the first prototype for either garment, confirming the accuracy of the pattern logic and reducing material waste.

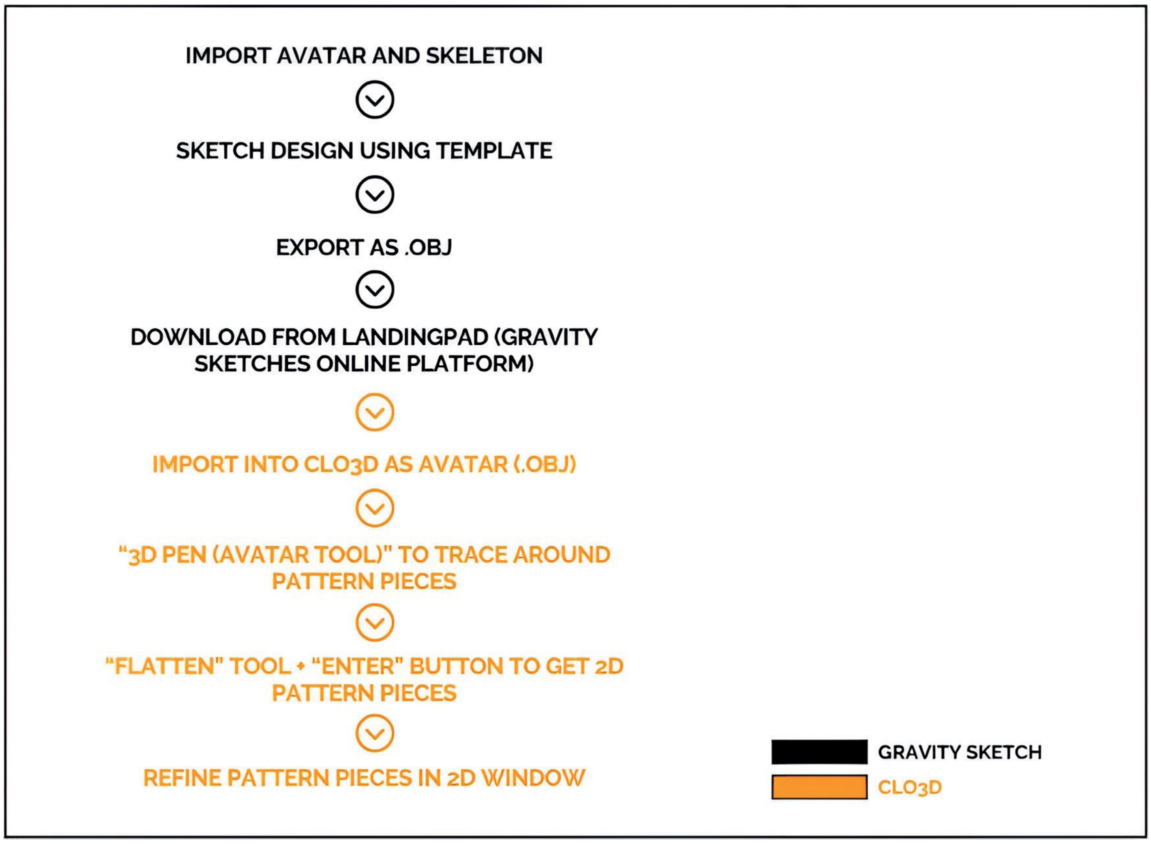
Client testing took place in a live session with SCIMM (Fig. 04), where the VR garment was reviewed via screen share. Edits to colour, branding and fit were requested and applied in real time. Minor adjustments were finalised in Clo3D, and no further revisions were needed. The session

Summary of workflow testing across three development phases

Test Phase	Tools Used	Import Method	Pattern Traceability	Simulation Support	Technical Viability
A: Direct Interoperability	GS + Clo3D	Object import	Poor	No	Not Viable
B: UV Workflow	GS + Blender + Clo3D	Graphic overlay + manual trace	Moderate	Yes (with errors)	Partial
C: Scaffold Based Sketching	GS + Blender + Clo3D	Graphic overlay + manual trace	Moderate	Yes	Viable
C: Avatar Trace	GS + Clo3D	Avatar import + internal trace	High	Yes	Viable & Scalable

Tab. 01

Fig. 01



IMPORT AVATAR AND SKELETON
SKETCH DESIGN USING TEMPLATE
EXPORT AS .OBJ
DOWNLOAD FROM LANDINGPAD (GRAVITY SKETCHES ONLINE PLATFORM)
IMPORT INTO CLO3D AS AVATAR (.OBJ)
"3D PEN (AVATAR TOOL)" TO TRACE AROUND PATTERN PIECES
"FLATTEN" TOOL + "ENTER" BUTTON TO GET 2D PATTERN PIECES
REFINE PATTERN PIECES IN 2D WINDOW
GRAVITY SKETCH
CLO3D

Fig. 02

Fig. 03

Fig. 04

Results from tolerance test comparing digital sample vs physical outcome for garments 1 and 2

Shirt Measurement	**Nominal Digital measure** (cm)	**Tollerance** (cm)	**Garment 1**			**Garment 2**		
			Physical measure (cm)	Difference (cm)	Accept / Reject	Physical measure (cm)	Difference (cm)	Accept / Reject
Back Shoulder Length		0.5	46.1	0.3	A	46.2	0.2	A
Back Neck Rib Band	16	0.5	16.2	0.2	A	16.1	0.1	A
Full Back Length	130	1	129.7	0.3	A	130.1	0.1	A
Sleeve Length	18.3	1	18.5	0.2	A	18.3	0	A
Cuff Length (1/2)	18.5	0.5	18.5	0	A	18.2	0.3	A
Chest Circumference	46.5	1	47.2	0.3	A	46.5	0	A
Back Middle Circumference	48.2	1	48.6	0.4	A	48.3	0.1	A
Underarm To Cuff	5.8	0.5	6	0.2	A	6	0.2	A
Opening Back Under Rib	21.5	0.5	21.5	0	A	21.5	0	A
Hem	48.9	1	49.4	0.5	A	49.2	0.3	A

Tab. 02

confirmed the workflow's ability to support direct design feedback without relying on static presentations or asynchronous communication.

Whilst a virtual garment is built to a nominal size, a physical garment requires technical specifications to incorporate defined tolerances that account for material behaviour, machine variation and human execution during construction. Industry-standard tech packs for the T-shirt garment type in this study typically specify acceptable measurement deviations between ±0.5 cm and ±1 cm depending on style, fabric and construction complexity (TFG, 2012) (Tab. 02).

Sample vs physical outcome for garments 1 and 2

The measurements of the physical garments created during this workflow are shown in Table 02, all measurements are well within the specification with a maximum deviation of 0.5cm. Within this context, the constructed garment in this study demonstrate the viability of the VR-to-CAD workflow for physical sample production. In this study, the refined digital pattern outputs produced through the spatial-to-CAD workflow were assessed against predicted specification measurements and found to fall within accepted industry tolerances (Table 2). This alignment indicates that the proposed workflow supports production-ready pattern accuracy comparable to standard digital and physical sampling processes, reinforcing its reliability for technical garment development.

ANALYSIS

The results of this study demonstrate how a layered VR-to-CAD workflow can address critical inefficiencies in digital fashion development. Traditional digital workflows often rely on material-specific simulation too early in the process, limiting creative freedom and increasing sample iterations. This study presents an alternative: a pipeline that enables early spatial judgement in VR and structured refinement in CAD, maintaining creative agility while reducing waste. Rather than correcting the limitations of VR tools, the workflow embraces their strengths, using sketches as guides for pattern development. By enabling co-viewed, real-time design sessions, it also replaces asynchronous revisions with live iteration, significantly reducing feedback cycles.

REAL-TIME FEEDBACK AND COMPRESSED ITERATION

This study demonstrates that immersive workflows enable earlier and more collaborative decision-making, reducing repeated sampling and accelerating refinement cycles. Rather than relying on static sketches or asynchronous reviews, design decisions were made live as the garment was developed in VR, streamlining feedback and minimising iteration. Compared to traditional digital workflows, which separate ideation and sampling into linear steps, this approach compresses the cycle into a single collaborative session.

This efficiency has significant sustainability implications. As McFall-Johnsen, (2020) highlights, the fashion industry is responsible for immense environmental damage, contributing to high carbon emissions, material waste and water consumption. Garment overproduction has become routine, with billions of unsold items discarded annually (WRAP, 2022). While digital tools are often promoted as sustainable, they are increasingly used to speed up production rather than reduce waste (Pucker, 2024). In contrast, the immersive approach proposed here allows for earlier judgement and reduces the need for physical prototypes, offering a genuinely sustainable alternative.

At scale, this workflow could increase transparency and responsiveness across distributed teams. By reducing reliance on static decks and bridging creative and technical phases, it not only improves communication but also supports more sustainable practices. Designers shift from generating static outputs to facilitating real-time co-creation.

IMMERSIVE SPACE AS A SITE OF DESIGN JUDGEMENT

This study shows that VR can act as a practical site for structural garment evaluation, not just a space for visualisation. Designers working within immersive spaces are able to assess silhouette and proportion volumetrically, forming judgments typically reserved for later stages in CAD. Because design and judgement happened in parallel, decisions can be made earlier and with greater confidence. In contrast, conventional CAD systems require precision early on, discouraging intuitive exploration. By combining immersive sketching with later CAD refinement, this approach supports spatial judgement without sacrificing technical rigour. This hybrid mode may be particularly valuable for complex silhouettes or bespoke garments, where proportion is difficult to visualise flat.

INCLUSIVE ACCESS FOR NON-TECHNICAL STAKEHOLDERS

This study demonstrates that immersive workflows can be structured to include collaborators without technical expertise or access to specialist software. By separating authorship (designing in VR) from feedback (observing via screen share), the process enabled meaningful input from clients who might otherwise be excluded from digital design workflows.

In the SCIMM testing session, the client observed the design process via video call and provided live feedback on fit, silhouette, and branding. They did not require a headset or any direct interaction with the software. The designer made real-time adjustments in response, collapsing what is typically a multi-step review process into a single collaborative exchange. This approach removed the need for formal presentations or post-session revisions and allowed the client's perspective to shape the garment as it was being created.

This structure responds directly to accessibility critiques in the literature. Creed et al., (2024) highlight how many immersive pipelines embed high technical thresholds, excluding non-specialists from participating meaningfully. By reducing the interaction requirement to observation and verbal feedback, the workflow lowers barriers and supports co-creation across technical divides.

The broader significance lies in its adaptability. For clients with mobility or cognitive impairments, or for distributed teams working across time zones, this format reduces friction. It eliminates the need for platform onboarding or file exchange while increasing transparency and speed. In doing so, it promotes a more democratic design process, one where insight is not limited by software fluency but enabled through shared visibility and live communication.

SPATIAL-TO-PRECISION INTEGRATION

Rather than treating VR sketching and CAD pattern development as separate phases, the process demonstrates how form and function can be developed in parallel, bridging intuitive design with simulation-ready output. Tests B and C revealed that direct geometry exported from Gravity Sketch lacked the structural logic required for CAD interpretation. However, when used as an ideation tool through garment scaffolds and imported into Clo3D, the resulting silhouettes aligned closely with the avatar and could be traced into accurate, editable 2D patterns. This allowed the designer to preserve spatial intent while working within the parameters of garment construction software. Crucially, the final method did not require post-processing steps such as UV mapping or mesh repair. Instead, the tracing was done directly in Clo3D using its native tools, enabling rapid pattern creation without technical overhead. The efficiency and accessibility of this approach improved overall workflow speed while maintaining fidelity to the designer's original vision.

This finding supports Sarakatsanos et al., (2024), who note the potential for VR tools to enable meaningful garment evaluation before physical sampling. While many systems support visualisation, few offer a seamless bridge between immersive ideation and technical execution. The avatar-trace method fills this gap by creating a viable pathway from volumetric design to functional garment data. This highlights VR's potential to unify creative and technical tools. By reducing friction between stages, the method encourages early spatial design without compromising production logic. For freelancers, small teams, or educational contexts, this means a faster, more accurate route from concept to prototype, supporting cost estimation, design communication and sustainability.

LIMITATIONS AND STRUCTURAL GAPS

Gravity Sketch is a spatial modelling tool, not a garment design environment, it lacks built-in logic for drape, stretch, seams, or gravity. This limits the designer's ability to judge how a garment will behave in real-world conditions, making early-stage material decisions difficult. Yet, this absence also provides creative freedom. Without embedded constraints, designers can explore exaggerated volumes and sculptural forms unconstrained by physical limitations. In this context, VR becomes a space for ideation rather than prediction.

However, the lack of garment-aware functionality means all structural information must be reconstructed in CAD. Designers are required to interpret and translate their work between platforms, a process that adds friction and reduces scalability, especially for less technically experienced users.

These limitations reflect wider interoperability issues across fashion technology. Kumar et al., (2017) highlight how exchanging files between CAD systems can significantly alter part accuracy and compromise integrity. Until VR platforms incorporate garment logic or standardised export and import protocols are adopted, these hybrid workflows will remain partially improvised. In educational contexts, this lack of interoperability has direct implications for how digital fashion workflows are taught, as students must rely on informal workarounds rather than stable, repeatable processes, making it difficult to develop consistent technical understanding across platforms.

A final constraint lies in the perception of VR itself. It is still widely viewed as a visualisation tool, not a developmental one. This limits industry adoption and slows platform evolution. However, this study demonstrates that with the right workflow, immersive sketching can move beyond spectacle and serve as a credible stage in garment development.

KEY FINDINGS

This research demonstrates how VR enables early volumetric judgement of silhouette and proportion. The workflow moves beyond visualisation, supporting fluid early exploration and collaboration before concepts are introduced to the precision constraints of CAD. It also supports meaningful input from non-technical stakeholders through observation and live feedback, without requiring headset access.

This study proposes a novel workflow logic rather than a new tool or interface. VR is used deliberately for 3D ideation and a space to make design decisions, while CAD is used for garment logic, construction and refinement. The pipeline formalises VR sketches as scaffolds that can be interpreted and resolved downstream in CAD, creating a clear digital 3D workflow pathway from ideation to pattern production.

The study shows this approach can reduce development time by enabling key decisions to be made in real time during co-viewed VR sessions, reducing the traditional cycles of reviews and repeated sampling. It also shows that viable, editable patterns can be produced when VR sketches are processed through avatar-based tracing in Clo3D.

CONCLUSION

This pilot study has developed and tested a hybrid digital workflow that positions immersive sketching as a credible and practical tool within garment development. By connecting spatial ideation in VR with technical refinement in 3D CAD, the workflow offers a clear alternative to the fragmented processes still common across much of the fashion industry. It enables designers to move fluidly between creative exploration and production logic, producing simulation-ready outputs that are suitable for manufacturing. By reducing the number of physical sampling rounds and enabling earlier, real-time feedback, the method offers a more responsive and resource-efficient pathway that aligns closely with broader sustainability aims across fashion design and production.

The research confirms that VR can be used as a legitimate environment for spatial ideation. It allows designers to shape form, proportion and silhouette directly in scale and in volume, accelerating early decision-making compared to conventional 2D sketching and digital refinement workflows. In this context, immersive tools become more than just aesthetic platforms; they offer a practical contribution to both design speed and sampling efficiency. Through physical prototyping and real-time industry testing, it demonstrated its functionality across educational and commercial contexts.

The framework developed is deliberately modular and adaptable. While it requires a base level of technical fluency and access to specific platforms, it reduces process complexity by using in-platform features and avoids additional technical steps such as UV mapping, preserving creative freedom during early-stage design. Through structured testing, the workflow was refined into a clear and repeatable process, avatar-based tracing within Clo3D, that effectively bridges expressive VR sketching with the pattern logic needed for 3D garment construction.

The workflow created during this research depends on the designer's garment-making knowledge and digital literacy to successfully translate immersive design intent into viable pattern data. To educate designers in these industry 5.0 skills, they require expertise in technical skills, reinforcing the role of embodied knowledge in digitally mediated fashion practice. Taken together, the findings suggest a need for a pedagogical shift from teaching immersive technologies as isolated digital skills towards cultivating workflow fluency. Aligning with Industry 5.0, designers should be trained on continuity, translation and decision-making across connected design workflows.

FURTHER WORK

In the future, this workflow could inform the development of garment-aware VR platforms that embed construction logic directly into spatial modelling environments, reducing the need for manual reconstruction in CAD software's. As demand grows for more sustainable, collaborative and agile design systems, industry adoption of immersive workflows like this could become part of standard digital practice. Ultimately, the framework offers a foundation for building infrastructure that links creativity and construction within a single, adaptable pipeline.

CAPTIONS

[Fig. 01] 3D Avatar Pen Tool and results in Clo3D.

[Fig. 02] Novel VR to CAD Digital fashion 5.0 workflow.

[Fig. 03] Worlds first VR created garments made physically through VR-to-CAD workflow.

[Fig. 04] Screenshot from live session with SCIMM exploring colour wheel in Gravity Sketch for pocket colour.

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FASHION AS ARMOUR

REINTERPRETING PROTECTION THROUGH CULTURAL HERITAGE AND INNOVATION

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Abstract

This essay explores the evolving relationship between fashion, material culture, and digital technology through the conceptual and formal legacy of historical armour. Positioning clothing as a symbolic and communicative system, the study interprets armour as a paradigmatic object – simultaneously protective, aesthetic, and identity-forming. A critical historical and semiotic analysis of selected European armours from the Stibbert Museum in Florence investigates their material composition, craftsmanship, and cultural significance, identifying them as early examples of wearable design where function and ornament converge. This historical inquiry is complemented by an experimental application of 3D laser scanning on reflective metal surfaces, assessing the potential of digital technologies to document, preserve, and reinterpret heritage artefacts. These research phases inform a design-led practice that translates the symbolic and structural qualities of armour into a contemporary fashion collection. Employing advanced materials, modular construction, and digital fabrication, such as 3D modelling and printing, the garments propose an adaptive, emotionally responsive model of protection. This interdisciplinary investigation highlights fashion's potential to function as a dynamic interface between cultural heritage and technological innovation, positioning it as a medium for both continuity and transformation in the construction of identity.

Keywords: *Digital Heritage; 3D Printing; 3D Modelling; Digitalisation; 3DeVOK MT*

INTRODUCTION

Since its origins, clothing has served as far more than a simple covering for the body: it has fulfilled roles of protection, distinction, and communication, becoming a medium for individuals to express identity, assert presence, and tell their stories. Within this complex cultural and symbolic framework, armour occupies a pivotal position. Conceived initially as a defensive device, armour gradually evolved to encompass aesthetic, representational, and identity-related functions, anticipating many of the expressive roles now attributed to contemporary fashion (Di Carlo, 2022).

This research seeks to investigate and reinterpret the enduring relationship between armour and fashion, weaving together insights from history, art, technology, and design. The study begins with a theoretical and visual in-depth analysis of the historical evolution of armour, highlighting its dual function as both utilitarian protection and ornamental display. Over the centuries, armour mirrored the fashion of its time, adapting its forms, silhouettes, materials, and embellishments to prevailing aesthetic codes (Kim et al., 2023). Beyond its defensive function, it became a symbol of status, power, and social belonging. The use of precious materials, refined craftsmanship, engravings, and gilding elevated armour to the realm of art, signifying the prestige and identity of the wearer (Thomas, Gamber & Schedelmann, 1965).

Exploring the relationship between fashion and armour requires a critical examination of the foundational concepts involved – namely, functionality and aesthetics. In this context, we propose a deliberate reversal of the conventional hierarchy between these terms, adopting a holistic approach that considers the interplay between meaning and signifier (Barthes, 2006). Here, fashion is understood as meaning: the idea, concept, or mental representation attached to a material expression – what clothing communicates. In contrast, armour assumes the role of signifier: the tangible form through which meaning is articulated and projected into the world.

Fashion, ultimately, is a language – a system of signs through which individuals communicate with the world, their communities, and themselves. Within this dialogic process, aesthetic form and functional purpose merge, generating a conception of beauty inseparable from the object's role. Historically, armour was developed as a protective apparatus for warfare. However, over time, it evolved into a complex cultural artefact, enriched with symbolic and aesthetic value far beyond its original purpose.

The protective function of clothing – universal in scope and transcending cultural, temporal, and geographical boundaries – has always gone hand in hand with psychological and identity-driven dimensions. As Cabrices (2022) insightfully observes: "[…] we turn to our clothes, expecting them to solve our problems. We leave to the garments in our wardrobe the almighty job of answering our questions, making our lives and ourselves better, and standing up for our looks and beliefs". Since its earliest incarnations, clothing has protected the human body from environmental threats. Initially purely functional, garments gradually took on symbolic, decorative, and social functions.

Armour has historically embodied a dual role: both protective device and communicative artefact (Krause, 2017). Beyond its capacity to shield the body from physical harm, armour has consistently conveyed symbolic meanings (Breiding, 2004). The materials selected, the craftsmanship employed, and the decorative intricacies of historical armour were strategically designed to generate psychological impact and visual authority (Breiding, 2023a; 2023b). The origins of protective wear can be traced to classical antiquity, notably within Greek and Roman civilisations. However, the conceptual impulse behind such artefacts – the human desire to protect and fortify the body – predates recorded history and continues to shape clothing design in the Modern Age. These early forms evolved significantly during the Middle Ages, culminating in the 15th-century development of full plate armour, an intricate ensemble of articulated components designed not only for maximum defence but also as a display of artisanal and symbolic sophistication (V&A Museum of Art, 2023).

As military technology advanced and the practical utility of traditional armour diminished, its representational and ceremonial functions gained prominence. Armour increasingly came to symbolise personal prestige, institutional authority, and sociopolitical identity, foreshadowing the expressive and aesthetic roles of modern fashion. From the 14th century onward, European armour began to reflect, and at times influence, civilian fashion trends, incorporating the silhouettes, proportions, and decorative motifs of contemporary dress. These stylistic evolutions, much like modern fashion cycles, were visible, rapid, and culturally resonant.

The enduring significance of armour's aesthetic and conceptual legacy is evident in its continual reemergence within contemporary fashion (Rall, 2014). Modern designers reinterpret its forms, materials, and metaphoric aspects to engage with current themes of resilience, vulnerability, and transformation.

While recent studies in digital heritage and fashion archives primarily focus on digitising historical designs, garments, and armour for documentation, conservation, or virtual exhibition, such approaches often remain limited to communicational and marketing purposes (Vacca, 2024). This research advances the field by framing digital technologies as interpretive and creative tools within a design-led exploration. Instead of viewing digitisation as a final goal, the study uses 3D scanning, modelling, and additive manufacturing to transform historical armour into a modern, wearable artifact. In doing so, it connects heritage preservation with material experimentation, highlighting fashion design as a vital practice that generates new cultural meanings from historical sources.

FASHION AND ARMOUR: AN AESTHETIC AND FUNCTIONAL CONNECTION

While historical armour gradually evolved from a war apparatus to a symbol of authority and identity, contemporary fashion has inherited and reinterpreted its forms and meanings. In this context, modern clothing can be viewed as a conceptual evolution of armour: no longer solely focused on physical protection but also on identity, narrative, and emotional expression.

Seen through a contemporary lens, armour and fashion are both means of engaging with the world. Clothing covers the body, regulates exposure in accordance with social codes of propriety, offers environmental protection, and serves as a nonverbal communication tool. It attracts attention, builds identity, and reflects moods, values, and desires. In some cases, fashion even takes on controversial dimensions, especially regarding the environmental and ethical challenges facing the textile industry. Even garments derived from technical or protective contexts, such as military jackets, hazmat suits, and face masks, have been symbolically appropriated by fashion. Designers integrate these elements into their collections, transforming them into visual metaphors for resistance, crisis, and adaptation. Contemporary figures like Craig Green and Demna Gvasalia have explicitly drawn on protective forms and materials, suggesting that fashion can respond – sometimes critically – to the anxieties of our time.

In today's sociopolitical climate, fashion increasingly emerges as a new kind of armour not made of steel, but of textiles, signs, and symbolic structures. Clothing and accessories serve as tools of empowerment and self-expression, while also revealing the tensions between identity, conformity, and resistance. The relationship between fashion and armour is not only historical or formal; it is a living, dynamic language that reflects the emotional and cultural battles of each era. In the contemporary landscape, armour is reimagined: softened, internalised, and adapted to confront the conflicts, both visible and invisible, of our time.

The idea of clothing as armour – whether physical, psychological or identity-based protection – has been explored by numerous designers who reinterpret its forms, materials and meanings through collections that are often theatrical and scenographic. While some adopt rigorous, concept-driven approaches, others privilege their visual, narrative, or emotional impact. The motif of armour in contemporary fashion operates as a powerful visual and conceptual device, embodying themes of protection, identity, and transformation (Fig. 01). A paradigmatic figure in this discourse is Alexander McQueen (Guerisoli, 2024), whose designs integrate historical references with material innovation to reimagine armour through a dramatic couture lens. Notable examples include his SS2024 collection, where the traditional cuirass is reconstructed using non-traditional materials, plaster, leather, acrylic, and glass, signifying vulnerability and strength. Similarly, collections such as Joan (FW1998) and Eye (2000) articulate complex narratives through the fusion of military, religious, and cultural iconography. Alongside McQueen, Paco Rabanne emerges as a seminal figure in redefining femininity through metallic and synthetic constructions (Mariani, 2022). His 1966 collection, 12 Unwearable Dresses in Contemporary Materials, challenged fashion orthodoxy by assembling garments from metal and plastic, advocating for fashion as both modular and sculptural (Fabbri, 2021). This legacy continues under Julien Dossena, whose FW 2023-24 collection revives Rabanne's aesthetics through chainmail, bustiers, and metallic fringes. The symbolic function of armour extends across numerous fashion houses. Dolce & Gabbana, Balmain, and Saint Laurent have all reinterpreted chivalric and metallic motifs, often integrating historical references with opulence and modern tailoring (Trevisson Zardini, 2024). Saint Laurent's collaboration with Claude Lalanne, whose galvanised metal body moulds blurred the line between fashion and sculpture, remains particularly influential. Contemporary designers continue this dialogue with new materials and digital aesthetics. Nicolas Di Felice's minimalist chainmail for Jean Paul Gaultier and Demna Gvasalia's dystopian, game-based presentation for Balenciaga (FW2021-22) reflect evolving interpretations of armour in relation to futurism, sensuality, and spectacle. Likewise, designers such as Jonathan Anderson, Dries Van Noten, Simone Rocha, and Iris van Herpen (Smelik, 2018) explore armour's conceptual terrain through sculptural silhouettes and experimental fabrics, often emphasising the tension between fragility and strength.

One iconic manifestation of this thematic lineage is Issey Miyake's thermoformed acrylic bust, worn by Grace Jones in 1995 and now housed at

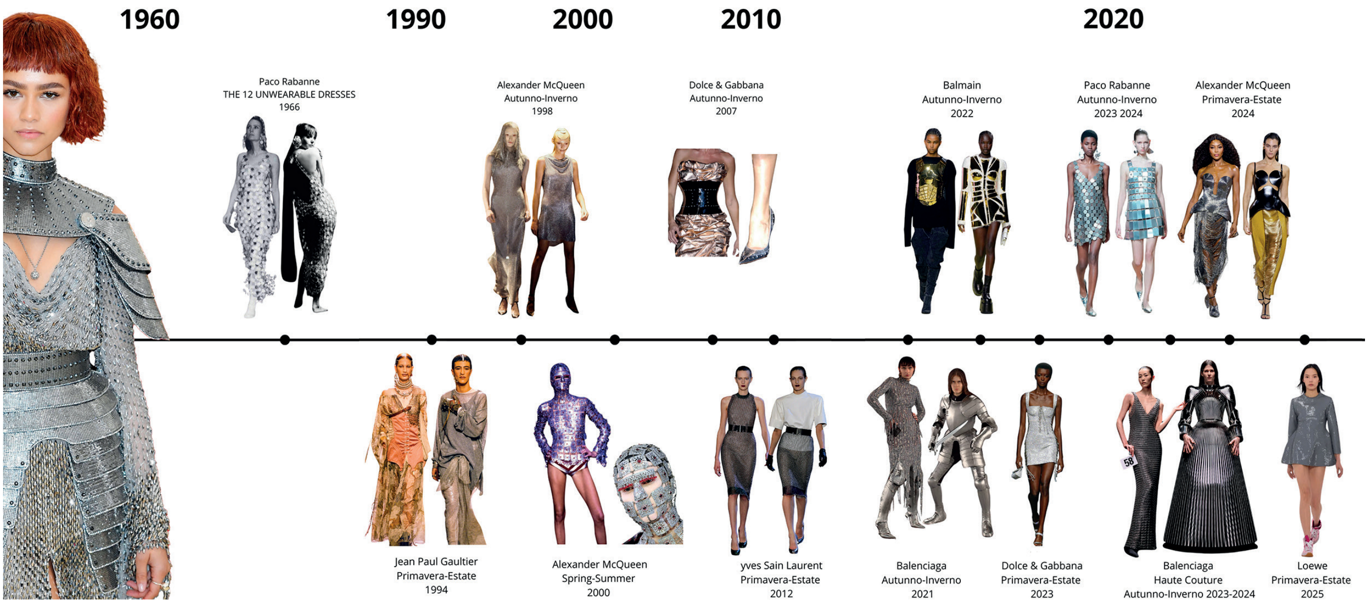

Fig. 01

armour-inspired design (Villanova, 2023). The increasing popularity of medieval and chivalric aesthetics beyond the runway has fostered dynamic interactions among fashion, visual culture, and contemporary media. Fantasy representations serve as powerful cultural vehicles that reframe the iconography of armour, blending historical influences with a spectacular, hyper-stylised modern aesthetic.

In essence, the resurgence of armour in contemporary fashion reflects a cultural moment in which clothing is invested with intense symbolic value. No longer relegated to ornamentation or seduction, garments act as devices for psychosocial protection and identity expression. Armour, in this context, becomes an evolving aesthetic code through which individuals and communities renegotiate their relationship with the body, power, and vulnerability. As fashion incorporates and reinterprets this imagery, it continues to function not only as a mirror of the times but as a language of resistance, transformation, and survival.

DIGITALISATION AND 3D MODELLING

This study forms part of the outcomes of the thematic seminar Heritage and Innovation, conducted within the framework of the bachelor's degree programme in Textile and Fashion Design at the Department of Architecture (DIDA), University of Florence. At the core of the research is a case study of the Stibbert Museum in Florence, which houses one of the most extensive and visually compelling collections of European armour worldwide (Becattini, 2010). The museum is currently engaged in a digitisation project to produce high-resolution digital surveys of both its architectural spaces and individual artefacts (Cottini et al., 2025). In contemporary design and heritage studies, digital surveying techniques have become indispensable tools for acquiring and processing complex geometries, enabling the creation of high-fidelity three-dimensional models applicable across a wide range of disciplines, including morphological analysis, cultural heritage conservation, industrial design, and creative prototyping. Among the most widely adopted technologies are digital photogrammetry and 3D scanning, using either structured light or laser-based systems. Although both methods enable non-invasive data acquisition, they differ in their operating principles, levels of accuracy, processing workflows, and ideal contexts of use.

Within this context, the research investigates how historical and artistic cultural heritage can serve not only as a source of creative inspiration but also as a direct component of the contemporary design process through the application of advanced digitisation technologies (Schactler, 2022). The study examines selected artefacts to analyse the structural complexity and symbolic significance of historical armours, considering their lasting impact on contemporary visual and material culture.

Furthermore, the project is aligned with the broader convergence of fashion and digital fabrication. Recent developments in the fashion industry – such as 3D scanning, modelling, and additive manufacturing – demonstrate how heritage references can be reinterpreted through technological innovation. A notable example is Balenciaga's iconic armour dress from the Haute Couture FW2023-24 collection, fabricated using galvanised resin and polished chrome printing. Inspired by historical armour and recently exhibited at the Louvre, the piece exemplifies how fashion design can intersect with both historical reference and digital experimentation.

The scope of three-dimensional digitisation today extends far beyond documentation or preservation (Parrinello & Dell'Amico, 2019). These technologies are now central to interactive museology, virtual reality experiences, digital fashion, and experimental design. Within this framework, the present research explores the integrated use of photogrammetry and 3D scanning to digitise historical armour, to reinterpret its forms in the context of contemporary fashion design. The aim is to establish a multidisciplinary dialogue between technology, history, and creative practice, in which historical memory serves as a catalyst for innovation.

The initial phase of the research involved an in-depth analysis of the materials conserved at the Stibbert Museum, intending to establish a conceptual and formal framework for the development of a fashion collection. The investigation aimed to identify visual, structural, and decorative elements that could inform the design of nine original outfits, drawing inspiration from historical references in terms of silhouette, ornamentation, and construction techniques. Attention was devoted to the suits of armour displayed in the Sala della Cavalcata (Boccia & Probst, 2004), whose scenographic arrangement and typological variety offered a rich source of morphological and symbolic motifs for reinterpretation within a contemporary fashion context.

The Stibbert Museum represents a paradigmatic case of 19th- and early 20th-century historical collecting, shaped by the intellectual and cultural milieu of its founder. By the late 1850s, Stibbert had begun acquiring objects through European markets, particularly in London, with the explicit aim of establishing a public museum. This vision was realised in the architectural transformation of his Florentine villa into a museum complex, featuring purpose-built galleries. Central to the collection is the European Armoury[1], which comprises over 8.500 artefacts dating from the late 15th to early 19th centuries, arranged in display environments inspired by dynastic armouries of Central Europe. The Sala della Cavalcata exemplifies a museographic mise-en-scène in which mounted mannequins evoke the performative and symbolic dimensions of chivalric warfare. By the time of his death, Stibbert had assembled approximately 12.000 items, including around 1.400 Islamic and a comparable number of Japanese artefacts. However, the enduring value of his legacy lies not merely in the scale of the collection but in his conception of a comparative, cross-cultural museum. His curatorial vision – anchored in both scholarly ambition and museographic innovation – established a framework for interpreting the material culture of warfare as a dialogue among aesthetic, technological, and historical traditions. Today, the Stibbert Museum stands as a foundational reference point for the study of arms and armour, historical museology, and the transformation of private collections into public cultural heritage.

Following the identification of key formal and decorative elements for the collection's development, a photogrammetric survey campaign was undertaken using Structure-from-Motion (SfM) techniques. Data acquisition was conducted both from the ground and via a telescopic pole, to digitise selected armours and generate high-resolution 3D models for subsequent processing

1 While the collection's nucleus remains European, Stibbert's interests later expanded to include Islamic and Japanese martial cultures.

and during the documentation process, primarily due to the complex geometry of the artefacts, the highly reflective nature of metallic surfaces, and the constraints imposed by the museum's exhibition layout. To address these limitations and improve data fidelity, an experimental test was conducted using a next-generation laser scanner on a metal helmet borrowed from a theatre costume workshop. This preliminary test allowed for a comparative evaluation of scanning technologies and informed the methodological refinement of future digitisation strategies.

The survey was conducted using an instrument 3DeVOK MT[2] on a reflective metal helmet, assessing the potential of 3D digital surveying for capturing the intricate, shiny surfaces typical of armour (Fig. 02). The focus was on digitising a highly polished helmet to evaluate the feasibility of integrating this device into a digital workflow for non-invasive surveying of historical artefacts. The 3DeVOK MT is a high-performance scanning system that combines three advanced light sources: 34 blue laser lines, 22 infrared laser lines, and a wide-area IR speckle pattern. This hybrid configuration allows for scanning in multiple modes, enhancing precision and adaptability across a range of operational conditions. One of the device's most valuable features is its ability to scan without markers, a critical advantage when working with fragile or delicate surfaces. Additionally, it employs hybrid alignment algorithms that maintain high accuracy even with low-feature or straightforward geometries. Crucially, the device proved capable of scanning reflective and dark surfaces without the use of matting sprays and demonstrated full operability even in low-light conditions or outdoor settings. These features were fundamental in confirming the scanner's suitability for non-invasive documentation of historical metal objects, which typically present technical challenges due to their glossy finishes and complex geometries. This preliminary experimentation confirmed the efficacy and reliability of the 3DeVOK MT system for capturing the detailed morphology of historical armour. The resulting data not only supports digital conservation and archiving but also enables new

2 Key technical specifications: resolution: up to 0.05 mm; accuracy: up to 0.04 mm; acquisition speed: 4.5 million points per second; scanning area: up to 1100 × 1000 mm; working distance: up to 1500 mm.

Fig. 02

approaches to design-driven reinterpretation, in which historical artefacts serve as direct inputs to the creative development of contemporary fashion and conceptual garments.

This study adopts a hybrid epistemological framework that combines historical and semiotic analysis with practice-led design research. Knowledge is generated not only through critical interpretation of archival and museological sources but also through material experimentation and prototyping. Within this framework, design is understood as a form of inquiry, in which the act of making becomes a means of reflection, allowing theoretical insights and technical processes to inform one another in an iterative, integrated manner.

3D PRINTING AND COLLECTION DEVELOPMENT

The project entailed the design and development of nine original garments, each conceptually and formally inspired by a specific suit of armour housed in the Stibbert Museum (Fig. 03). The creative process was articulated through the production of flat sketches, technical construction drawings, and the prototyping of a top garment as a tangible outcome of the research. A key focus of the project was the experimental integration of historical heritage and technological innovation. This was exemplified by the development of a digitally modelled shoulder pad through reverse engineering (Vandi, Bertola & Suh 2024), derived from photogrammetric survey data and reinterpreted through advanced 3D modelling techniques. The resulting component functions as both a structural and symbolic element (Almond, 2019) within the collection, embodying a synthesis of artisanal tradition and computational design. Through this approach, the project highlights the potential of digital technologies to reactivate and recontextualise cultural heritage within contemporary fashion practice.

The development of a shoulder pad inspired by historical armour preserved at the Stibbert Museum represents a crucial stage in integrating digital design processes into the construction of a contemporary fashion collection. Central to this phase was the creation of a three-dimensional digital model, designed to be materialised through 3D printing. The process began with the

Fig. 03

acquisition of the original artefact using photogrammetric techniques, resulting in a dense point cloud and a high-resolution mesh. This data was subsequently imported into Rhinoceros 3D, optimisation for additive manufacturing. However, several critical challenges emerged \ a modelling environment chosen for its support of NURBS surfaces and its precision in managing complex geometries, particularly in the context of additive manufacturing.

The reinterpretation of the shoulder element aimed to preserve the proportions and curvature of the original armour piece while translating it into a contemporary design language. The morphological analysis of the reference object informed the generation of construction lines, initially traced as 2D curves in orthogonal projections. These profiles served as the foundation for building continuous 3D surfaces, resulting in a structurally coherent solid capable of expressing the formal identity of the historical source.

Throughout the modelling process, special attention was paid to surface cleanliness, edge continuity, and volume optimisation to ensure a closed geometry suitable for 3D printing. Care was devoted to the distribution of material thicknesses and the orientation of surfaces to guarantee both structural integrity and printability, while optimising the aesthetic and tactile qualities of the final object with respect to the chosen printing material. The resulting shoulder pad retains a strong symbolic and visual connection to the museum piece while establishing itself as an original design object that bridges historical memory and contemporary innovation.

Upon completion of the digital modelling, the file was exported as an STL file, compatible with slicing software for additive manufacturing. The 3D-printed model was subsequently integrated into a bespoke garment, entirely handmade using traditional tailoring techniques. This juxtaposition between textile craftsmanship and digital precision gave rise to a hybrid object, capable of weaving together two distant domains: that of manual tradition and that of technological experimentation.

The shoulder pad, in this context, is not conceived as a mere decorative element, but as an active structural component of the garment – a conceptual hinge between body, memory, and design. Its placement on the garment is both functional and symbolic: it serves as a form of visible protection, a contemporary reinterpretation of armour that does not conceal but rather exposes and emphasises. The hosting garment was designed with an ergonomic interface that supports the printed element while maintaining the perceptible contrast between the fabric's softness and the rigidity of the 3D component. This formal and material dissonance becomes a central expressive device of the project. Within the overall collection, the shoulder pad has been designed as a modular, scalable element, adaptable to different outfits. The digital model can be replicated, modified, or personalised, promoting a design approach based on functional modularity and transformable aesthetics, aligned with the principles of a versatile and dynamic wardrobe.

DISCUSSION

For professional practice, the research outlines a transferable methodology applicable to fashion design, costume design, and fashion technology contexts, particularly in collaboration with museums and cultural institutions. The use of digitised heritage artefacts as direct inputs for design development opens new possibilities for sustainable innovation, modularity, and personalisation. Moreover, the integration of digital fabrication into traditional garment construction suggests alternative modes of production and storytelling, in which historical memory becomes an active component of contemporary fashion narratives.

From a didactic perspective, the proposed workflow offers a replicable model for teaching fashion design as a research-driven practice (Fig. 04). By integrating historical analysis, digital surveying, computational modelling, and prototyping, the project demonstrates how cultural heritage can be actively engaged within design education. This approach encourages students to critically reinterpret archival materials rather than passively reference them, fostering an understanding of fashion as a site where theory, technology, and embodied experimentation converge.

CONCLUSIONS

This research has examined the enduring dialogue between fashion, material culture, and digital innovation through the conceptual and structural lens of historical armour. Drawing from a critical semiotic analysis of selected European armours housed in the Stibbert Museum, the study has highlighted the historical convergence of function and ornament – of protection and self-representation – as a foundational aspect of wearable design.

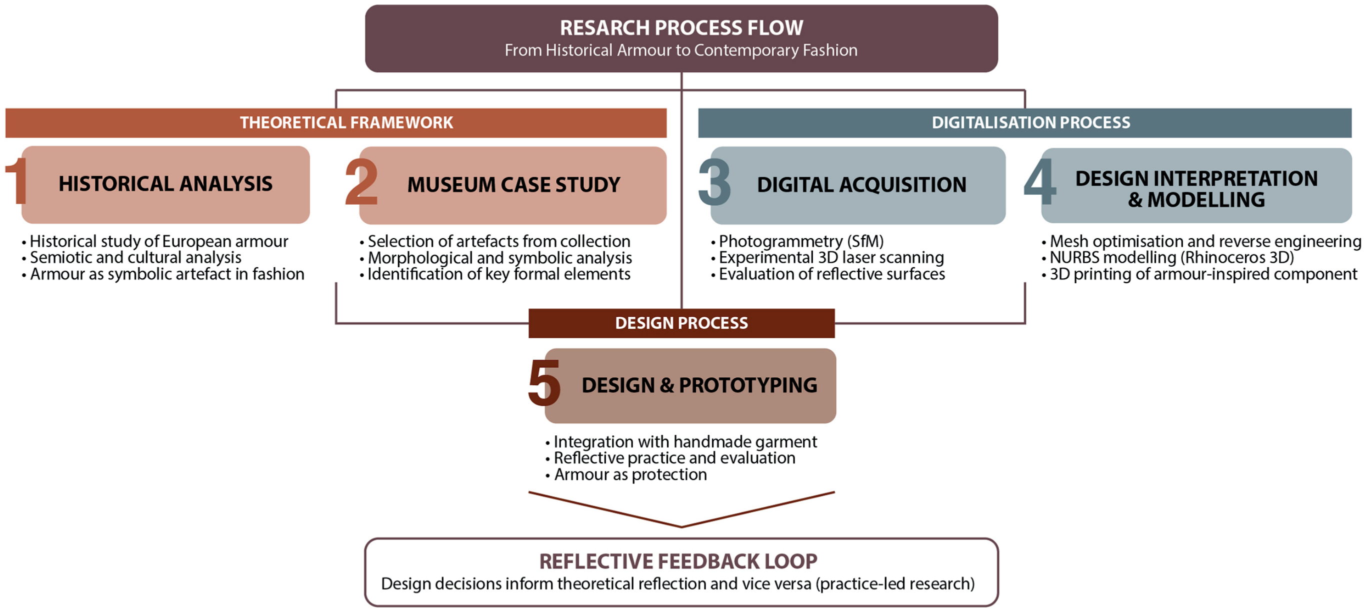

Fig. 04

By engaging with these artefacts not solely as relics of the past but as active cultural texts, the project reconceptualises armour as a powerful precursor to the communicative systems of contemporary fashion.

Through advanced digitisation techniques, the research has further explored how heritage objects can be reinterpreted within design-led practices. These technologies enable a material and symbolic translation of historical data into new formal expressions that engage the body and its identity in ways that transcend temporal boundaries. The resulting fashion collection, centred on the notion of "inner armour", situates garments as adaptive, emotionally attuned interfaces – offering not static protection, but flexible responses to the psychological and social conditions of contemporary life.

By reversing the traditional hierarchy between form and function, the project proposes a new methodology in which historical signifiers such as armour serve not only as aesthetic references but also as structural and conceptual anchors for future-forward design. Fashion, in this framework, emerges as a language that is both reflective and projective: capable of preserving memory while enabling transformation. The shoulder pad prototype – designed through a synthesis of digital craftsmanship and traditional tailoring – exemplifies this hybrid approach, serving as a visible hinge between past and present, body and object, technology and emotion.

Ultimately, this interdisciplinary investigation highlights fashion's ability to serve as a cultural interface: simultaneously protective, expressive, and transformative. By reclaiming the visual and symbolic codes of armour, the project emphasises the importance of historical design practices in shaping new narratives of identity, resilience, and embodied meaning in the digital age.

Future research could expand the methodology through broader collaborations with museums, the exploration of additional armour typologies, or the integration of immersive technologies. Further investigations might also address the application of this framework within industrial production contexts, examining how digitally reinterpreted heritage can inform sustainable and adaptive fashion systems at scale.

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CAPTIONS

[Fig. 01] Timeline illustrating the main influences of armour on contemporary fashion. Elaborated by the authors.

[Fig. 02] Above: the Sala della Cavalcata at Stibbert Museum and the selected armour with the shoulder pad. Below: digitalisation process of a metal helmet using the 3DeVOK MT 3D scanning device. Elaborated by the authors.

[Fig. 03] Above: the nine outfits of the collection, inspired by historical armours from the Stibbert Museum. Below: development of the 3D model of the shoulder pad and the corresponding 3D-printed prototype. Elaborated by the authors. On the right: Flagship piece of the collection, designed and created by Giulia Gattuso. Elaborated by the authors.

[Fig. 04] Research process flow illustrating the hybrid methodology adopted in this study, integrating historical and semiotic analysis, digital heritage acquisition, design interpretation, and practice-led prototyping. Elaborated by the authors.

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CONTROLLABLE COLOUR CHANGING MODULAR TEXTILES USING 3D PRINTING AND SCREEN PRINTING FOR ALTERNATIVE SUSTAINABLE FASHION

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Abstract

The role of technology in fashion no longer remains a gimmick limited to high fashion, eccentricities or fiction. With the advent of wearables and integratable electronics, innovations are shifting the digital fashion paradigm from visual to functional. Meanwhile, the fact that the fashion industry contributes significantly to global emissions and textile waste is irrefutable (Igini, 2023; Quantis, 2018; United Nations Environment Programme, 2018).
Some researchers (Koo et al., 2013; Lang & Wei, 2019; Niinimäki & Hassi, 2011) suggest modular, reusable garments can help counteract the effects of fast fashion. Transformable garments are a potential alternative, but the aesthetics, affordability and functionality limit them from being adaptable to fast-moving trends. (Peter, 2018). A truly transformable garment still lies within the realm of speculations, considering its complexity and limitations of current technology. Cromaflux, is a prototype capable of changing colours as the user wishes, which takes the form of a modular system with varying applications, enhancing both functionality and aesthetics. It utilises 3D printing, traditional screen-printed textiles, and thermochromic elements, allowing for colour changes with smartphone apps. This research aspires to create affordable, adaptable, tech-integrated clothing that defies traditional textile norms, negates the socio-cultural harm of fast fashion, without compromising personal expression.

Keywords: *Digital Fashion; Cromaflux; Thermochromic Textiles; Smart Textiles; Sustainable Fashion*

INTRODUCTION

How many pieces of clothing did you buy this year? Do you remember the exact number? The exact reason for buying what you bought? I believe that as you're reading this, you're trying to rack your brains as to the precise number, and you can't get it right. The pervasiveness and addictiveness of fast fashion are also prompting you to seek justifications for every purchase. According to a report by Uniform Market, adults in the UK have 118 pairs of clothing on average and 60.2 apparel per capita sales volume. (UniformMarket, 2024) Keep in mind that the number is an average, and there are a significant number of people with financial constraints who do not buy anywhere near this number of apparel in a year. The purpose of apparel and textiles in the current global scenario has shifted far beyond the status of a basic human need and has significantly impacted the global stage of resource depletion, waste and climate change (Quantis, 2018). Global emissions from the textile industry will likely increase by 50% by 2030 (Igini, 2023).

The psychology behind fast fashion is explained in an article on the *Sustainable Fashion Forum* from February 2025. Emotional, social, and cognitive factors all play a role in its popularity despite the widespread knowledge of its devastating effects. It is deeply connected to self-identity and expression, and a sense of instant gratification. There certainly is awareness of sustainable practices and their importance;

however, any such conversations usually end up imparting guilt to an average consumer. (Sierra, 2025) Guilt is not a very pleasurable expression to say the least, and serves only to steer the conversation away, or makes people dig their heels in to defend themselves. Something you probably did too when you read the first few lines of my article. So the question arises, how do you change global behaviour without causing a metaphorical withdrawal syndrome of sorts?

HYPOTHESIS AND RATIONALE

The answer I came up with was change. What if we could come up with a textile that could change everything about it every time its owner so desired. What if a garment could change all three, i.e. form, pattern, and colour on demand, without needing to buy anything new? My research is built around this question.

However, does a modifiable colour-changing garment address the problem and is the ability to change a garment enough for the consumer to abandon fast fashion and be satisfied? The short answer might just be "No, not entirely. However, it is a valid alternative."

There is definite interest in sustainable clothing. An article published in the *Journal of Cleaner Production* in 2011 found that 74% of men and 87% of women surveyed were interested in ethical consumption. The study stated that innovative designs that fight against planned obsolescence and also allow personal gratification and self-expression are needed to turn the tables on the trend of overconsumption. Specific strategies they express include modular garments as well. (Niinimäki & Hassi, 2011).

In another research, Koo, Dunne, and Bye in 2013 investigated the feasibility of transformable garments as a strategy to promote sustainable clothing by investigating customer preferences. With the research question "What kind of changeable design functions do people desire in transformable garments?"- the results showed that the most frequently preferred change was changes in colour/pattern and sleeve length (100%), followed by neckline shape and collar type (86%), and silhouette (70%) (Koo et al., 2013). In another study by Chunmin Lang and Bingyue Wei, published in the *International Journal of Interdisciplinary Research*, a quantitative study with 306 female college students in the U.S. was done to examine the predictors of intention to purchase transformable apparel. Fashion consciousness and the tendency for creative choice were two such characteristics that strongly predicted the purchase intention. So, creative, ethical and fashion-forward consumers would very likely take a transformable design positively(Lang & Wei, 2019).

LITERATURE REVIEW

COLOUR CHANGING GARMENTS

I know colour-changing garments are not a novelty. There have been multiple iterations over time. While exploring colour-changing clothing, I saw that the industry was moving in two different technological directions: LED-based and yarn/material-based. Although they had rather different ramifications in terms of sustainability, aesthetics, and practicality, both presented intriguing possibilities.

On the LED/electronic display side, Philips Research Labs created soft interactive displays on the garments by developing soft and flexible LED arrays under the textile surfaces. (Harold, 2006)**,** Joanna Berzowska's Karma Chameleon project produced colours and patterns by weaving photonic bandgap fibres in a lighted jacquard loom (Berzowska & Skorobogatiy, 2009), and an E-ink flexible display on a jacket was developed by E-ink in collaboration with 878co, a Hungarian sportswear producer (Vikarius, 2021).

Although this direction was undoubtedly creative, the very idea of walking around illuminated like a billboard didn't feel rooted in the complex, tactile world of fashion, which is my experience as a textile designer. More significantly, as electronic components may degrade more quickly than conventional textiles, such methods run the risk of leading to planned obsolescence.

So, I decided to look into a natural route instead, using textiles as the colour-changing substance, which I feel can be modified into wearable clothing in daily life and is more aligned with textile craftsmanship.

My interest in this area was sparked by Margaret Ann Orth's PhD research, which questioned the dominant approach of integrating computing technology into everyday objects to produce smart objects, which she found to be ugly, physically ill-suited to their tasks, and lacking the aesthetic and practical goals of designers. She came up with a solution to use textile itself as a computational material, being cuttable, bendable and shapeable and ushered in the era of smart fabrics. She went on to create aesthetically pleasing functional pieces, such as the fabric keypad or musical jackets (Orth, 2001). She also created an art display called the "100 *Electronic Art Years"* that used steel fibres and thermochromic dyed yarns to create a mesmerising display (Orth, 2009). Much of my experimentation is influenced by her work.

In 2013, Lynsey Calder and Sarah Robertson used thermochromic ink and copper heat sinks to create a colour-changing tutu skirt with an origami theme. (Calder et al., 2013). Electrochromic yarns were used to create Ebb fibres for a working textile screen prototype in the Google Jacquard project in collaboration with the Berkeley School of Information (Devendorf et al., 2016). In 2022, a textile capable of changing colour with the help of smartphone apps was patented. Made with thermochromic yarns and heating fibres, it was capable of a certain degree of pattern change (Abouraddy F et al., 2022).

However, none of these innovative creations have really found a large market, as evidenced by their lack in everyday life.

WHY HAVE THEY FAILED?

Despite the apparent interest in sustainable fashion, most modifiable and colour-changing clothing has failed to make it to the mainstream. The reason behind this contradictory statement is multifaceted. An article in *The Fashion Studies Journal* in 2018 argues that, in spite of significant consumer interest, the actual results falter as these designs lack either aesthetic appeal or practicality (Peter, 2018). The complexity in creating these garments presents technical challenges, especially when scaled for industrial production, leading to increased costs and a reluctance for manufacturers to accept these designs. (Varshney & Swami, 2023; Zhang et al., 2025). The washability of any modular textile is always a concern, and especially so for ones with electronic components, as it can impair the functionality and oftentimes special laundering methods have to be used, making it cumbersome or impractical. (Islam et al., 2025; S. Lee & Park, 2024). The durability of various components also adds to the issue pertinent to e-textiles, along with their consistency and stability during use. (Meena et al., 2023). In conclusion, all these designs are plagued by issues of aesthetics, practicality, washability, affordability and challenges in reproducibility. These factors have invariably led to their unacceptance in mainstream fashion.

RESEARCH QUESTION

The research question after all of these reviews was "Can we create controllable colour-changing modular textiles for sustainable fashion and explore their real-world applications?"

OUTCOMES

Considering the previous iterations have lacked practicality, affordability and reproducibility and aesthetics, four major outcomes were expected from the research.

Functionality- The textiles would have to be functional. By functional, I refer to the definition provided by The Britannica Dictionary, which describes it as "designed to have a practical use" (Encyclopædia Britannica, n.d.). That means the textiles should have appreciable functioning outcomes, like being modular or capable of changing colour.

Reproducibility- The textiles would incorporate very basic technologies, making them easily reproducible at the lowest possible costs and needing very little technical expertise

Controllability- Fashion is intimately associated with self-expression. The ability to control that expression is paramount to creating a sustainable garment. The possibility of accurately controlling the look that is created would be the main feature that I believe would attract attention to the textile.

Aesthetics- A significant hurdle in most of the previous projects has also been a lack of aesthetics when it comes to current fashion trends. A part of my project would consider the real-world applications and showcase the various ways they could be used.

MATERIALS AND METHODS

In this research, I developed a modular colour-changing textile prototype through material experimentations, electronic prototyping and digital designing techniques. The system can be divided into 5 interconnected elements, i.e. the fabrication of colour-changing textile surfaces, the integration of resistive heating elements, the electronic control hardware, the development of a user-facing mobile application, and the creation of digital garment visualisations to communicate potential use scenarios.

COLOUR-CHANGING TEXTILE FABRICATION

In recent times, there has been some research regarding creating clothing with 3D printing. (Ge et al., 2023; J. Lee & Lee, 2024; Takahashi & Kim, 2019). I wanted to experiment with 3D printing techniques and use thermochromic filaments and conductive filaments for the material base. However, such techniques and materials come at a high cost, and their availability is limited. So regular 3D printing was used. The chainmail structure was chosen for its flowy nature, which is akin to textiles and the freedom it provides for designing various elements of the chainmail. The small elements of the chainmail could not be printed using PLA printing methods, so instead, SLS nylon printing was used.

For the colour-changing attribute, I used thermochromic pigments. Thermochromic screen printing paste was used based on availability. All methods of dyeing the chainmail with the thermochromic paste failed, so instead, each component of the chainmail was hand-painted. The colours were chosen after mixing and testing on a polycotton swatch. The change of colour was tested using a hairdryer to generate heat. According to the label, the paste would change colour at 45 degrees Celsius; however, in practice, it would change colour at lower temperatures than that. The approximate temperature was around 35 degrees Celsius, which was a good thing considering the human skin perceives temperatures above 45 degrees as hot (Craig, 2009).

I also decided to create another piece using polycotton cloth and screen printing techniques. At heart, I am still a textile designer and working with textiles is just as important to me as researching. A geometric but asymmetrical design on the textile was screen printed. Other components were added by hand embroidery techniques, including the conductive threads. The colour swatches, challenges of dyeing, and initial concepts of 3D printing can be seen in (Fig. 01).

INTEGRATION OF RESISTIVE HEATING ELEMENTS

The functional qualities that the prototype was supposed to have were modularity and controlled colour change. The controlled colour change experimentations were the most difficult to conduct

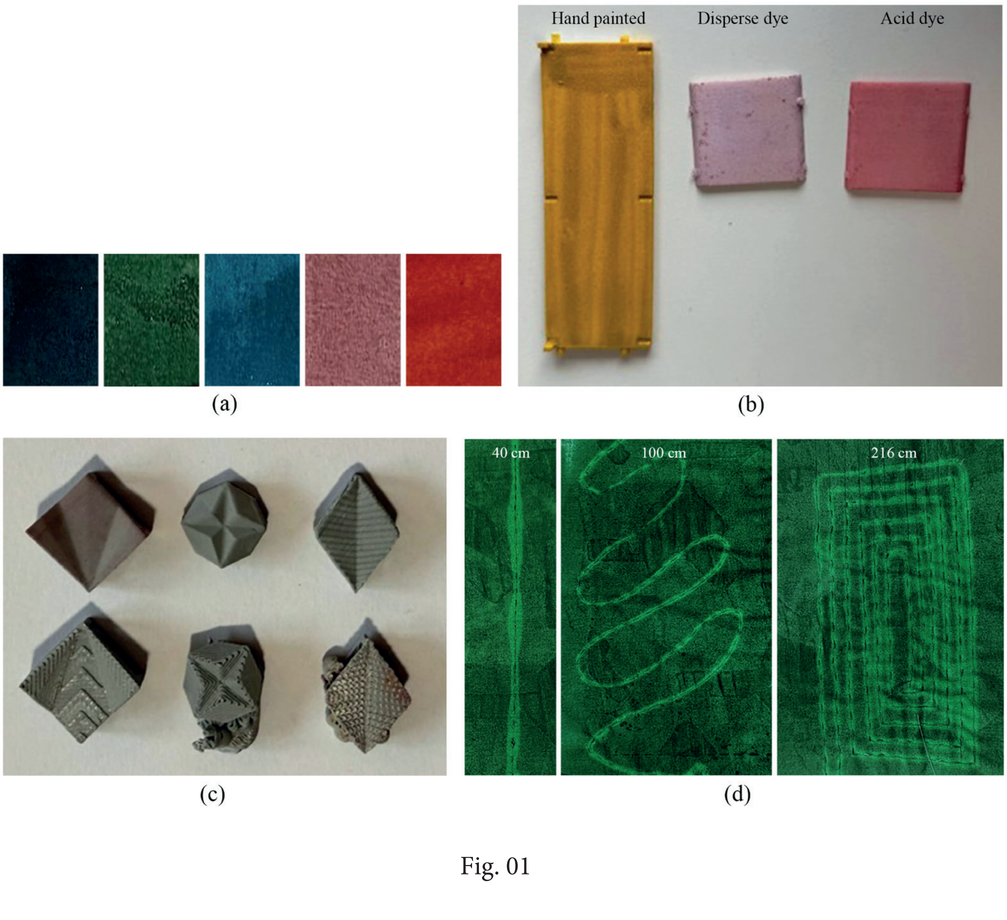


Fig. 01

and obtain. As the heating element, I chose to use steel conductive threads, which are more flexible than other materials and can easily be bought on the internet, and tested them. With the help of the people at the Bournemouth University laboratory, we experimented with the conductive thread stitched onto a piece of cloth coated in thermochromic paste. Stitching was done in 3 different forms, linear, zigzag and spiral, and we subjected them to various voltages and amperages to determine the highest intensity and spread of colour change. It was evident that the most spread was seen in the spiral stitch; however, it also required a significant voltage, as you can see in Figure 01.

The conductive threads were attached behind the chainmail and stitched linearly on the screen-printed fabric, but as predicted, the spread was unsatisfactory. Assuming inadequate heat dissipation and insulation, I added cork-sheets for insulation behind the conductive thread and thermal conductive paste for heat spreading between the thread and the colour-changing surface, which increased the spread of heat, and by extension, the spread of the colour change to satisfactory levels. A 3D rendering of the final schematics can be seen in Figure 02.

CONTROL ELECTRONICS

The control mechanism would enable heating specific pieces of conductive thread as commanded by the user interface app, dictating a change in colour and creating patterns. I used basic, cheap commercial microcontrollers and used two different types to explore various methods of control: one with a Bluetooth unit, and another with built-in Wi-Fi. The power supply was three 3.7-volt rechargeable Li-ion batteries for reusability. The circuit design used MOSFETs for gateways. There were 3 sets of outputs that could be independently controlled to create 7 unique patterns. This number was determined by the output capabilities of the microcontrollers.

USER INTERFACE APP

For the user interface, I created a Bluetooth app for one microcontroller and a web-based app for the Wi-Fi-based microcontroller. Both apps were minimalistic button-based apps with options for various patterns. The buttons function to switch on heating for individual conductive threads at half or

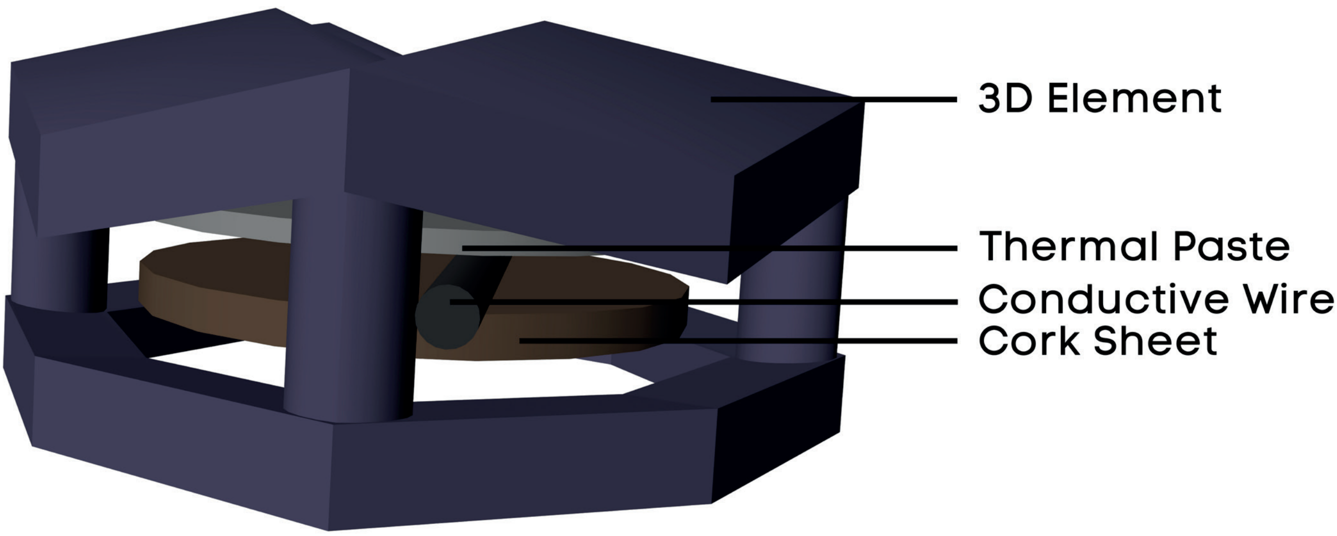


Fig. 02

full strength for testing and control purposes.

DIGITAL GARMENT VISUALISATION

Past forays into colour-changing attire, as previously mentioned, had a lack of aesthetics and practicality. To be able to create complete, intricate pieces of attire was out of scope for this research owing to time constraints. I decided to create virtual depictions of the concept using 3D and virtual reality software. Virtual garments, ads and video depictions of what the final results could be imagined as were created. This enables me to showcase possibilities for this technology and generate an interest in both investors and consumers.

DESIGN CHOICES

There are various design decisions I made at every step that hold some value of expression. The entire research is built to oppose fast fashion and overconsumption while preserving personal expression and design choices. Every part of the design thought process is based on opposing elements. The repeated, sharp morphic motifs in the 3D printed chainmail were meant to reflect the fast fashion cycle. A geometric but asymmetrical design screen printed was meant to symbolise the imbalance between glamour and overproduction in the current fashion landscape. The other components added to the screen-printed textile were to give a definite feminine look. The sharp edges clashing with the shiny pearls and beads were intended to evoke a response from the viewer and represent the clash of glamour and overabundance in fashion. Also, I wanted to incorporate hand embroidery techniques to marry my cultural knowledge to my experiments.

The virtual rendition included bleak, dystopian desert-like future backgrounds to address the grim extreme end result of modern consumerism and greed, while the bright technology-driven actual garment was a classic flowy gown fitted with the futuristic 3D colour changing chainmail as collars and belts, once again conforming with the opposing elements theme.

RESULTS AND DISCUSSION

The major outcomes expected from the research, as previously stated, were functionality, reproducibility, controllability and aesthetics. The prototypes were created after multiple rounds of experimentation and challenges. Despite that, they are still works in progress. 2 prototypes were created in the duration of this research. A prototype made of 3D printed chainmail and another by screen printing techniques on polycotton capable of changing colour with the help of Wi-Fi or Bluetooth connections and an app for control.

FUNCTIONALITY

Both prototypes fulfil their intended functions. The structure of the chainmail provided an aspect of modularity. It was rectangular in shape with dimensions of 30cm by 20cm. It is fluid in structure and malleable, conforming to the body's curvatures. It could be used independently as a sleeve, a belt, or a collar or attached to any other garment structure the designer sees fit. Figure 03 shows the chainmail being used as a halter top on a mannequin.

The screen-printed prototype has geometric but asymmetrical patterns. The patch of textile created could be used as a belt or as a decorative patch on any normal piece of clothing, keeping in line with the modular concept. Figure 03 also shows the belt form and the pattern changes of this prototype.

There was a visible and reversible colour change with 8 unique patterns (with 1 pattern that is its neutral/off state). The colour changes take about 5-7 seconds, depending on the ambient temperature and return to the off state in similar times.

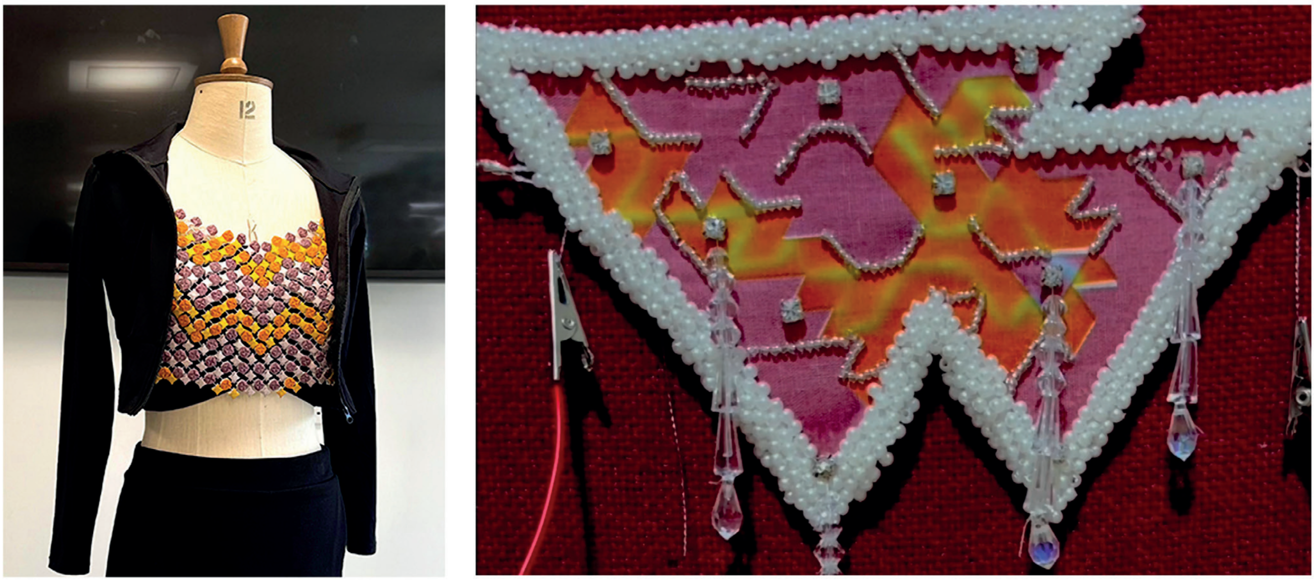
The electronic component, except for the heating threads, can be separated from the actual textile as well, creating a modular controlling unit.

CONTROLLABILITY

The prototypes are controlled using apps, with the 3D printed prototype being controlled by a web-based app and the screen printed prototype by a Bluetooth app. The easiest method to allow users to interact with their device is to connect to it with the help of a smartphone. The Bluetooth app currently has to be downloaded and installed on the user's smartphone, while the web app is accessible by connecting to the microcontroller’s wifi and visiting its IP address, which opens the web-based app. The interface itself is minimalistic and intuitive.

AESTHETICS

Aesthetics in itself is a very subjective concept. As I mentioned before, a complete garment using these prototypes was not feasible, so I used 3D and VR software, and AI-generated images to better express



(a) (b)

Fig. 03

their application. I created virtual belts and collars made from the prototype fitted on a flowy gown to showcase its modular use. A fashion ad video of the 3D model with animated colour changes of the collar and belt was also created to further simulate its use in fashion. (Fig. 04) shows the various virtual outcomes of this research.

REPRODUCIBILITY

This entire project was self-funded, except for the thermochromic paste, which the Innovation Studio at Art University Bournemouth provided. It was created using basic 3D printing techniques, screen printing techniques, readily available online materials, and the most basic electronic technology that is readily reproducible and modified as needed. The entire cost of each prototype was under 100 pounds. The prototypes were made from scratch in a university and, quite frankly, in home settings. If mass-produced and automated, the price per unit would be less by a significant fraction. I did require the help of experts in electronics and technology, considering my background in textile design; however, if scaled to manufacturing levels, this should not be a problem.

SUSTAINABILITY

Apart from the proposed outcomes, this technology was created with sustainability in mind. The modular nature of the textile itself is a sustainable alternative (Zhang et al., 2025); however, the carbon footprint is also a significant indicator of sustainability. The textile developed here has an estimated operational carbon footprint of approximately 7 g CO_2 per square foot per wear, based on the energy consumed by pulsed heating (~33 % duty cycle) from a 3-cell Li-ion battery and amortising battery manufacturing emissions over ~300 cycles. This is, however, by no means an accurate number and further research is needed to assess its actual carbon footprint. In contrast, the estimated average carbon footprint for the life cycle of a pure cotton shirt can be up to many kilograms (Wang et al., 2015).

CONCLUSION

Previous iterations of modular or colour-changing garments suffered from a number of faults, including lack of functionality, practicality, aesthetics, reproducibility and affordability (Peter, 2018; Varshney & Swami, 2023; Zhang et al.,

(a)

(b)

Fig. 04

2025). My prototype has tried to address these specific issues in creating a new direction for sustainable clothing.

"*Chroma"* is a Greek-origin English word which stands for colour, and "*flux*" means change. I decided to name the technology Cromaflux as it is a 3D-printed modular textile capable of controlled colour change, the first of its type in the world. Despite its prototype phase, it is sure to herald a change in the future of textiles. It is capable of changing according to fashion trends and allows self-expression by the consumer while being user-friendly, affordable and most importantly, it looks and feels good.

LIMITATIONS

I tried to challenge many of the weaknesses of modular clothing in my research; however, there are still many limitations to my work.

The washability factor is one of the most important factors, especially in e-textiles. I tried to incorporate washable components and made the electronic circuit detachable from the actual textile; however, no laundering experiments were done to confirm the washability and durability of the textiles.

Similarly, dedicated user acceptance studies could not be done to confirm that the final aesthetics would be liked.

The issue of degradation of electronic components, discarding of batteries, and the total average carbon footprint are also yet to be determined, making the question of its sustainability still a topic for further debate.

FUTURE RESEARCH

Further research with experimentation is needed to test durability, safety certifications, and washability. Although the virtual designs allow for the exploration of aesthetic possibilities, more research is needed to investigate user perception and acceptance of both the virtual and the real-world garments created using this technology.

Multiple enhancements and tweaks can be done in the future for marketability as well as diversifying its applications. The product currently exists as a basic prototype. Various, if not all of the components, can be replaced by industrial-grade materials, including commercial-grade insulation and heat spreading materials for more energy-efficient colour change. Miniaturising the controller unit with microprocessors and insulating exposed heating threads would prevent heat loss and maximise safety. Replacing the conductive threads with nichrome or other wires for more efficient heating, covering the chainmail with transparent silicon coating to prevent degradation, and mini solar cells could be integrated in the chainmail to further reduce the carbon footprint. All these changes need further research to finally assess the marketability and practicality of this product.

OTHER APPLICATIONS

Other applications of this research could be in the military or health sectors. It could be used to make dynamic camouflage for both soldiers and their equipment, while it could be used in medicine as heating pads by switching the insulating material for a heat-conductive element to tackle difficult-to-access areas for heating.

The ultimate goal of my research is to create a completely new form of textile that can weather the changes in fashion trends while allowing the users to feel a sense of novelty and change whenever the whim hits. My belief, backed by my extensive literature review on this topic, is that this technology can help curb fast fashion to a certain degree, even if it still needs more research. It is a glimpse into the future of textiles. There is no one answer to sustainability, but I hope my research will be fundamental for its future. I will continue experimenting and refining my product to make it accessible to all.

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CAPTIONS

[Fig. 01] Early experimentations: a) Early thermochromic ink swatch experiments exploring colour mixing techniques, b) Challenges encountered during the initial dyeing process, c) Conceptual development of 3D-printed textile structures, d) Heating trials testing varied stitch lengths and patterns for thermal responsiveness; (Author holds the right to images)

[Fig. 02] 3D rendering of the final schematics; (Author holds the right to images)

[Fig. 03] Final Prototypes: a) 3D-printed prototype top demonstrating modular construction, b) Screen-printed belt showcasing thermochromic colour transitions; (Author holds the right to images)

[Fig. 04] Digital explorations: a) VR visualisation of the 3D-printed prototype (left) and its AI-enhanced rendering (right), b) 3D model illustrating potential applications of the prototype (left) alongside AI-enhanced visual outputs (right); (Author holds the right to images)

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ENTANGLED THREADS

RE-IMAGINING CANTON SILK HERITAGE THROUGH DIGITAL PRACTICE AT LOOM LOOP

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Abstract

The convergence of heritage craftsmanship and digital fabrication presents a complex paradox for the contemporary fashion practitioner: how to preserve material authenticity while embracing computational innovation. This paper addresses this tension through a practice-based inquiry into the operations of Loom Loop, a Hong Kong-based designer label specialising in the revitalisation of traditional Canton silk ("mud silk"). Substantiated by semi-structured interviews with the specialist washing teams in the Pearl River Delta, the study analyses the specific technical and aesthetic frictions encountered when hybridising fragile heritage textiles with modern digital intervention. The research is structured around three critical intersections: the application of digital fabrication tools to reinterpret traditional artisanal motifs within a "zero-error" production environment; the integration of circular design principles in response to the geopolitical pressures of land displacement and climate instability; and the translation of tactile material qualities into the realm of virtual fashion and NFTs. The findings suggest that the role of the artisan is evolving into that of a "hybrid practitioner" who possesses a form of "Systemic Intelligence"—an ability to mediate between the tacit knowledge of historical craft, the precision of digital systems, and the protocols of the virtual economy. Ultimately, this paper proposes that the future of heritage luxury lies not in preservationism, but in an "entangled" methodology where digital tools serve to amplify, rather than replace, the cultural narratives embedded in traditional materiality.

Keywords: *Practice-based research; Canton silk; Digital craftsmanship; Circular fashion; Virtual materiality; Loom Loop*

INTRODUCTION

The contemporary fashion landscape undergoes a profound transformation, increasingly shaped by the convergence of digital innovation, advanced material science, and the pressing demand for sustainability. These forces prompt a fundamental rethinking of traditional craftsmanship, challenging long-standing assumptions about how fashion is conceived, produced, and experienced. While historical craftsmanship has been defined by manual expertise and the preservation of heritage techniques, twenty-first-century production demands a "new craftsmanship" grounded in the seamless integration of computational tools and circular economic principles (Braddock Clarke & Harris, 2012; Oxman, 2016).

Current literature often addresses digital design and heritage preservation as distinct subjects. To bridge this conceptual gap, this paper presents a practice-based inquiry into Loom Loop, a Hong Kong-based designer label that operationalises the fusion of traditional Canton silk (Gambiered Guangdong silk) with contemporary digital fabrication. To substantiate this inquiry, the research methodology draws upon semi-structured interviews conducted with the specialist washing teams situated in the Pearl River Delta. These on-site dialogues provided critical insight into the tacit knowledge required to produce the silk, allowing this study to examine how the role of the artisan evolves into that of a "hybrid practitioner" who navigates the tension between the tactile unpredictability of natural materials and the precision of digital systems.

The distinctiveness of this inquiry lies in the material contrasts inherent to Loom Loop's production cycle. The practice roots itself in the preservation of Canton silk, or "mud silk." This textile production remains intensely manual, relying on a localised, agrarian cycle that resists automation. The process begins with greige silk soaked in yam root juice, then laid out on grassy fields to dry under the sun—a cycle repeated approximately 30 times to ensure vegetable tannins fully penetrate the fibre. In the final stage, the fabric receives a coating of mineral-rich mud dredged from the Pearl River Delta. This iron-rich mud reacts with the tannins to create a unique, dark, lustrous coating. As emphasized by the washing teams, the process concludes with a massive communal effort, requiring up to ten people to wash the mud from the fabric back into the river. This labor-intensive methodology yields a fabric with a "living" texture, deeply connected to the specific terroir of the river delta.

In stark contrast to this ancient methodology, Loom Loop intervenes with a high-fidelity digital workflow. This study examines how motifs are conceptualised on tablets using Procreate, vectorised and refined in Adobe Illustrator, and finally translated into stitch data using Brother embroidery software. This digital data is then executed on in-house digital embroidery machines or is sent for digital printing on delicate substrates such as Canton silk, crepe de chine, and chiffon. The challenge explored here involves reconciling these two worlds: the farmer-like patience required for mud silk and the pixel-perfect immediacy of digital placement prints and embroidery.

Detailing this collision of "high-touch" and "high-tech" processes, the paper posits that digital fabrication—such as 3D printing and laser cutting—does not displace the artisan but rather extends their creative agency (Diez, 2017) (Gao et al., 2023). Furthermore, the paper analyses how these hybrid practices align with emerging regulatory frameworks, such as the European Union's Ecodesign for Sustainable Products Regulation (ESPR) (European Commission, 2022), and the rise of virtual fashion, including Non-Fungible Tokens (NFTs) and augmented reality (AR) (The Fabricant, 2021).

The following sections are organised to mirror this material-digital journey: The subsequent section, 'Digital Meets Craft', analyses the technical workflow of translating hand-drawn art into digital embroidery on heritage textiles. The third section, 'Material Futures', examines the ecological implications of using Canton silk and biomaterials within a circular economy. The fourth section, 'Virtual Fashion', explores the translation of tactile material qualities into the metaverse. Ultimately, this paper posits that the future of luxury craftsmanship lies in the entangled ability to weave code as proficiently as silk.

DIGITAL MEETS CRAFT: THE FRICTION OF HYBRID FABRICATION

While theorists such as Braddock Clarke and Harris argue that twenty-first-century craftsmanship integrates code and cloth (Braddock Clarke & Harris, 2012), the operational reality within the Loom Loop atelier reveals a more complex dynamic. This involves a constant negotiation between the infinite possibilities of digital design and the finite constraints of physical machinery and heritage materials. This section analyses the specific technical challenges encountered when imposing digital logic onto traditional Canton silk.

The first point of friction arises at the interface of digital embroidery. In the Loom Loop workflow, motifs often design to mimic the grandeur of traditional Chinese imperial artwork—elaborate, symmetrical, and expansive (Wang & Sun, 2023) (Barron, 2021). However, while the digital canvas in software like Procreate or Adobe Illustrator offers limitless space, the physical embroidery hardware imposes strict boundaries. The in-house embroidery machines restrict designs to a maximum frame size of 30x30cm. To achieve large-scale, continuous imperial patterns, the "digital artisan" must deconstruct the virtual image into modular segments. This reintroduces a high degree of manual skill; the practitioner must employ precise physical marking techniques to align these 30cm blocks perfectly. The challenge becomes particularly acute when attempting to achieve the perfect bilateral symmetry characteristic of heritage Chinese aesthetics (Gu & Rusli, 2024). A misalignment of a single millimetre during the hoop-change process disrupts visual continuity, revealing the seam between the digital and the manual (Diez, 2017).

Furthermore, the material properties of the substrate dictate the parameters of the digital file.

When embroidering on lightweight, translucent fabrics typical of the Loom Loop aesthetic—such as chiffon or fine Canton silk—standard digitisation settings often result in puckering or tearing. The density of the needle penetration requires rigorous calibration through iterative testing. The "finest stroke" of a digital drawing does not always translate to a stable stitch; if the stitch density proves too high, it effectively cuts the delicate silk; if too low, the luxury aesthetic faces compromise. This demands that the practitioner possess a tacit understanding of the fabric's tensile strength, adjusting the digital thread count to match the "grain" of the analog material (Oxman, 2016).

The most significant technical constraint, however, emerges from the Canton silk ("mud silk") itself. Unlike modern synthetic weaves, which exhibit forgiveness and elasticity, mud silk presents as structurally brittle and retains a permanent "memory" of intervention. In the Loom Loop studio, this characteristic creates a "zero-error" production environment. If a digital embroidery file contains a mistake, or if a stitch is misplaced, it cannot simply be unpicked. The removal of a thread leaves behind visible needle holes—permanent scars on the mud-coated surface—rendering the panel unusable. This irreversibility contrasts sharply with the "undo" culture prevalent in digital design, necessitating a disciplined, high-stakes approach to fabrication that mirrors traditional calligraphy, where a stroke cannot retract.

Finally, the materiality of mud silk exerts agency over the garment's silhouette, challenging the capabilities of modern digital pattern cutting. The mud coating reduces the fabric's elasticity, making it susceptible to tearing under tension. Consequently, contemporary "body-con" or fitted trousers are structurally incompatible with the heritage material. This material limitation necessitates a design philosophy that aligns with historical precedent; just as ancient wearers utilized loose robes to accommodate the fabric's lack of stretch, Loom Loop must engineer silhouettes that rely on drape rather than tension. The digital design process, therefore, functions not as a tool of domination over the material, but as a tool of accommodation—calculating the precise volume and fold required to protect the integrity of the heritage silk (Gao et al., 2023).

Through these specific production challenges, a new definition of the "hybrid practitioner" emerges. Such an individual does not merely use new tools, but masters the calibration between the unforgiving permanence of heritage materials and the precision of digital systems (Hu et al., 2023; Shim et al., 2024; Dumitrescu & Motta, 2024).

MATERIAL FUTURES: THE GEOPOLITICS OF MUD AND SILK

While the global discourse on sustainable fashion frequently centres on material innovation—such as lab-grown leathers or closed-loop recycling—the experience of Loom Loop highlights a different reality: the fragility of heritage supply chains amidst rapid urbanization and climate instability. This section examines the specific material and economic vulnerabilities inherent in the production of Canton silk, asserting that genuine sustainability requires preserving the entire ecosystem of the craft, not solely the fibre itself.

A primary challenge in integrating traditional Canton silk into a contemporary fashion system involves chromatic consistency. The industrial fashion model relies on standardization, where every garment in a stock-keeping unit (SKU) must appear identical. However, the Loom Loop dyeing process remains radically non-standard. Because the yam juice and river mud interact organically with the protein fibres (Croyle Johnson, 2024), no two bolts of silk emerge with identical shading. The resultant colour depends on the chemical composition of the mud and the duration of sun exposure. In the Loom Loop practice, this chromatic heterogeneity is reframed not as a manufacturing defect, but as a critical signifier of authenticity. This approach challenges the homogenized aesthetic of fast fashion, proposing a value system where variation serves as a "fingerprint" of the natural process (Fletcher & Tham, 2019). However, this refusal to standardize introduces friction when interfacing with modern retail expectations and digital cataloguing, necessitating an educational narrative to shift consumer perception from "flaw" to "character."

Beyond aesthetics, the future of this material is threatened by the socio-economic transformation of the Pearl River Delta. The production of mud silk is spatially dependent; it requires vast tracts of grassy land for the drying process (where the silk absorbs the sun) and proximity to the specific mineral-rich riverbed. Nevertheless, the rapid economic development of the region has caused land values to escalate. Practice-based research reveals a trend of "displacement by development": suppliers increasingly sell their drying fields to property developers, as real estate yields immediate financial returns compared to the arduous, low-margin nature of textile agriculture. This creates a crisis of space for heritage craftsmanship (Rafae, 2024). The "Material Future" of Canton silk thus intertwines with regional land politics; without the physical land to dry the silk, the craft cannot exist, irrespective of market demand.

Furthermore, the process is uniquely vulnerable to environmental determinism. The production cycle mimics agriculture in its reliance on specific weather conditions. The yam juice impregnation and mud coating require precise solar levels; excessive ultraviolet exposure renders the silk fibres brittle and fragile, while insufficient sun or excessive rain prevents the necessary oxidation and drying. The process cannot be mechanised indoors without losing the unique chemical reaction provided by the terroir. Consequently, production capacity is dictated by the climate. In an era of increasing climate unpredictability, Loom Loop's supply chain faces disruption from unseasonal rains or extreme heatwaves.

This case study indicates that a "circular future" for fashion must account for labour and land (Virta & Räisänen, 2021). The laborious nature of the process—requiring workers to stand waist-deep in river water and manually manipulate heavy, wet fabric—becomes less appealing to a younger workforce. As the older generation of artisans retires, the tacit knowledge of "reading the weather" risks being lost (Wan Isa et al., 2018). Genuine sustainability, therefore, transcends merely utilising a biodegradable material; it involves sustaining the delicate balance between labour, land use, and weather patterns that enables such a material to exist (Earley & Goldsworthy, 2019).

VIRTUAL FASHION: THE PARADOX OF INTANGIBLE HERITAGE

The emergence of virtual fashion—encompassing digital couture, Non-Fungible Tokens (NFTs), and Augmented Reality (AR)—forces a radical re-evaluation of craftsmanship. Traditionally, the value of a luxury garment has been inextricably linked to its sensory properties: the weight of the weave, the cool touch of silk, and the manual labour evident in the finish. However, as fashion migrates into the Metaverse, the "hybrid practitioner" confronts an ontological challenge: how to translate the aura of heritage materiality into a medium composed entirely of pixels and light (Choi & Kim, 2021) (The Fabricant, 2021). This section analyses Loom Loop's digital interventions to comprehend the friction between tangible heritage and virtual representation.

The primary conflict encountered in the Loom Loop digital atelier involves the simulation of "authenticity." In a recent collaboration funded by PMQ (a creative hub supported by the Hong Kong Government), the label aimed to launch a collection of digital-only garments. The project, which resulted in NFT assets retailed via the platform DressX, highlighted a distinct material barrier. Standard digital fabric rendering engines are optimised for uniform textures—shiny satin, matte cotton, or rigid denim. They struggle, however, to capture the nuanced, organic lustre of Canton silk ("mud silk"). The mud silk's surface is characterised by a subtle, matte-finish darkness that refracts light unevenly due to the mineral coating and hand-washing process. Translating this "imperfection" into a digital asset necessitated collaboration with specialised digital artists to manually map the texture, ensuring the virtual garment did not appear merely as generic black silk, but retained the specific visual signifiers of its river-based origin. This process reveals that digital craftsmanship requires not just coding skills, but a deep, ethnographic understanding of the physical material to prevent the erasure of cultural identity in the virtual realm (Wu et al., 202; Masciotta et al., 2019; Nofal, 2023).

Despite these textural limitations, the integration of digital ownership models offers a new avenue for brand equity and cultural dissemination (Hammou et al., 2020). As noted by Murtas et al., NFTs can decouple the value of a fashion item from its physical production, enabling a form of "liquid consumption" (Murtas et al., 2023). For Loom Loop, the partnership with DressX allowed heritage aesthetics to be consumed globally without the carbon footprint associated with logistics or textile manufacturing. This democratisation of access suggests that virtual fashion can serve as a vehicle for cultural storytelling, allowing international audiences to engage with Cantonese motifs without the barrier of physical scarcity (Desai, 2021).

Furthermore, Loom Loop's investigation into virtual technologies extends beyond the aesthetic into the functional, specifically regarding sustainability. While the label bypassed the "Metaverse hype cycle" of 2020–2022 due to resource constraints and the prioritisation of physical survival during the COVID-19 pandemic, current research focuses on the utility of Augmented Reality (AR) and body-scanning technology. Developing protocols where users capture biometric data via smartphone (e.g., photo-to-measurement algorithms), the label aims to implement a made-to-measure system precisely. This digital intervention directly addresses the "Material Future" concerns outlined previously (Jiang & Zhang, 2024). By securing accurate measurements digitally before physical cutting occurs, the atelier can significantly reduce deadstock and inventory waste. This aligns with findings by Jiang et al., who argue that AR enhances engagement while mitigating the returns culture that affects e-commerce (Jiang et al., 2023).

Consequently, the move toward the virtual does not represent a rejection of physical craft, but a preservation strategy. By utilising AR to solve sizing issues and NFTs to handle cultural dissemination, Loom Loop's physical production can remain small-scale, slow, and focused on preserving the labour-intensive mud silk, protected from the pressures of mass overproduction (Yaşar & Yayla, 2023).

CONCLUSION: TOWARDS AN ENTANGLED METHODOLOGY OF CARE

This research interrogated the evolving role of craftsmanship within a fashion system increasingly shaped by digital acceleration and ecological instability. By anchoring the analysis in the specific operational realities of Loom Loop, the study challenges the prevailing binary that positions "heritage" and "technology" as opposing forces. Instead, the findings indicate that the survival of traditional material culture—specifically the endangered practice of Canton silk—depends entirely on its successful, albeit frictional, entanglement with digital systems.

The core insight emerging from this practice-based inquiry is that the contemporary artisan must evolve into a "hybrid practitioner" possessing a dual literacy. As demonstrated in the second section, the application of digital embroidery to fragile mud silk is not a simple act of automation; it constitutes a negotiation. The digital machine, with its rigid coordinate systems and "undo" logic, was compelled to accommodate the irregular, brittle, and irreversible nature of the organic substrate. This reverses the typical narrative of industrialisation: here, the material exerts agency over the machine. The findings reveal that "new craftsmanship" (Oxman, 2016) defines itself not by the dominance of technology, but by the sensitivity with which a designer calibrates digital tools to respect material limits—downgrading precision to preserve integrity.

Furthermore, the investigation into material futures in the third section reveals that "sustainability" for heritage brands cannot decouple from geopolitics and land use. The precarious nature of the Pearl River Delta's supply chain—threatened by real estate development and climate volatility—demonstrates that preserving a craft requires more than just training weavers; it requires preserving the ecosystem that enables the craft to exist. In this context, the role of the designer expands from creator to custodian.

Finally, the exploration of virtuality in the fourth section offers a resolution to the tension between preservation and consumption. While the metaverse struggles to replicate the tactile "aura" of mud silk, technologies such as Augmented Reality (AR) and NFTs offer a strategic pathway to decouple cultural storytelling from physical resource extraction. By using AR for precise sizing and NFTs for cultural dissemination, Loom Loop illustrates how virtual tools can be deployed to protect physical scarcity, reducing deadstock and allowing the labour-intensive production of mud silk to remain slow and dignified.

Ultimately, this paper proposes a reconceptualization of the fashion designer. We move away from the romanticized image of the solitary genius sketching in isolation, towards a model of "Systemic Intelligence." The future-facing couturier must demonstrate capability in reading the weather patterns of the Pearl River Delta, manipulating the vector nodes of a digital file, and navigating the blockchain protocols of the digital marketplace. It is in this complex, entangled space—between the mud of the river and the code of the cloud—that the future of authentic luxury resides (Mazzetto, 2024).

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SATELLITE-BASED REMOTE SENSING FOR ASSESSING FASHION INDUSTRY ENVIRONMENTAL FOOTPRINT AND URBAN DEGRADATION

A FEASIBILITY STUDY FOR DIGITAL PRODUCT PASSPORT

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Abstract

This study investigates the pivotal role of geospatial technologies, including Geographic Information Systems, remote sensing, and satellite imagery within the fashion industry. Motivated by regulatory advancements like the EU's Digital Product Passport, the study addresses the existing gap in integrating spatial environmental data into product-level transparency frameworks.
The core methodology of this research employs secondary data; this study aims to foresee the integration of remotely tracking both the direct and indirect (latent) environmental impacts of intensive fashion and textile production. Direct impacts assessed for their detectability include water pollution (e.g., color and thermal anomalies), air pollution (e.g., particulate matter and trace gas concentrations), and solid waste accumulation (e.g., landfill expansion and spectral signatures of textile waste). Latent urban degradation elements, such as signs of overcrowding, infrastructural deficiencies, and resource depletion, are also explored for their spatial detectability within surrounding urban environments. The compilation of existing research, impacts, and detection methodologies into a structured matrix is intended to serve as a foundation for subsequent applied investigations within the domain of fashion production. Ultimately, this study assesses the suitability and potential of these technologies to enhance environmental monitoring and systemic accountability within the fashion sector. It seeks to lay the groundwork for integrating verifiable geospatial intelligence into sustainability frameworks, including Digital Product Passports, thereby fostering more accountable and data-informed practices at the intersection of industry, environment, and urban systems.

Keywords: *Textile; Supply chains; Remote sensing; Geospatial; Environment*

INTRODUCTION

In recent years, the fashion industry has undergone increasing scrutiny for its environmental and social impacts across global supply chains. In response to this, the European Union has introduced the Digital Product Passport (DPP) as part of its broader strategy toward a circular and sustainable economy. The DPP aims to collect and disseminate structured data about products - including their composition, production origins, and environmental footprint - with the goal of enhancing transparency, traceability, and consumer awareness. As this policy framework takes shape, the fashion sector is being pushed toward more data-intensive practices that require new forms of documentation and accountability. The expected increase of data driven decisions and evaluations in this context calls for a robust method for measuring anthropogenic impacts.

Concurrently, geospatial technologies - including Geographic Information Systems (GIS) and remote sensing - have become increasingly sophisticated and accessible, enabling new methods for tracking environmental change, industrial activity, and urban development (Yang & Liu, 2025). These technologies are already widely used in agriculture, mining, forestry, and infrastructure monitoring, yet remain underutilized in the fashion industry. Their potential to offer continuous, large-scale, and spatially precise data represents a significant opportunity to extend the reach and granularity of DPP systems, particular ly when it comes to tracing environmental impacts and mapping production networks.

Anthropogenic impacts, including land degradation, water pollution, and urban expansion, are currently measured through a variety of environmental indicators (Singh et al., 2024). However, these assessments are often fragmented, industry-agnostic, and lack of integration with product-level data systems such as DPPs. Furthermore, there is limited understanding of how the fashion industry contributes to or correlates with urban degradation in the vicinity of production hubs, especially in developing countries where regulatory oversight may be weak.

Despite these developments, significant knowledge gaps remain. Specifically, there is a lack of research on how GIS and remote sensing technologies can be applied to the fashion industry to support environmental monitoring and compliance. The spatial dimension of Scope 1, 2, and 3 emissions — as well as indicators of industrial misconduct or urban distress — remains poorly mapped. Similarly, the ways in which fashion-intensive industrial zones contribute to the degradation of surrounding urban environments are rarely examined through spatial data.

his study proposes to address these gaps by assessing the feasibility of applying GIS and satellite-based remote sensing to the fashion sector. By the creation of a matrix of impacts and their indicators for possible detection, the study explores how remote sensing can enhance the environmental granularity of DPPs data, monitor urban stress, and serve as a future basis for empirical research. Ultimately, this study aims to test whether these tools can detect spatial markers of intensive textile production and associated urban degradation. It seeks to lay the groundwork for the integration of geospatial intelligence into fashion sustainability frameworks, fostering more accountable and data-informed practices at the intersection of industry, environment, and urban systems.

GEOSPATIAL TECHNOLOGIES FOR ENVIRONMENTAL MONITORING IN THE FASHION SECTOR

As previously stated, the fashion industry, a significant global economic force, is increasingly under scrutiny for its substantial environmental and social impacts across its complex supply chains (Battisti & Spennato, 2024). This pressing concern necessitates a shift towards greater transparency, traceability, and accountability within the sector. Policy initiatives, such as the European Union's Digital Product Passport regulation, are driving this demand for enhanced data visibility. Concurrently, advancements in geospatial technologies offer promising avenues for monitoring and mitigating these impacts, yet their full potential within the fashion industry remains largely untapped.

The Digital Product Passport is emerging as a critical innovation designed to foster traceability, sustainability, and regulatory compliance across various industries, including textiles. As a central element of the EU's Circular Economy Action Plan, DPPs aim to collect and disseminate structured data about products, encompassing aspects like material composition, production origins, and environmental footprint. This digital record serves as a repository of information throughout a product's lifecycle, from its creation to disposal, with the goal of enhancing transparency, promoting sustainability, and facilitating a circular economy (Psarommatis & May, 2024). The mandatory implementation of DPPs aspires to improve resource circularity, reduce emissions, and strengthen supply chain governance by enhancing product traceability and supply chain transparency (Zhang & Seuring, 2024). Beyond just material data, DPPs are envisioned to include information on carbon footprint, repairability, and recycling pathways.

The concept of digital product passports is part of a broader trend towards using digital technologies to improve supply chain systems and ensure sustainability. Blockchain technology, for instance, offers robust solutions for monitoring details such as time and place of elaboration, raw material origins, and material quality throughout the manufacturing process, thereby improving transparency and traceability in the fashion and textile supply chain (Badhwar et al., 2023; Pérez et al., 2020). These technologies enable control and monitoring of textile articles from production to consumer acquisition, addressing concerns about environmental impact and labor rights by enhancing accountability (Amin et al., 2025).

Geospatial technologies, including Geographic Information Systems, remote sensing, and satellite imagery, provide powerful tools for analyzing and monitoring environmental concerns on a large scale. Most importantly, this technology can track latent effects that are not accounted for intensive industrial production in standard reporting. Also, it provides a great tool for overseeing agencies and certificating bodies. While widely used in sectors like agriculture, mining, and forestry, their application within the fashion industry for environmental monitoring is still developing (Moran et al., 2020). However, these technologies offer significant potential to identify and map the environmental footprint of fashion production and waste.

Remote sensing and GIS can be leveraged to:

- **Identify and analyze textile waste** accumulation: Studies have demonstrated the effectiveness of remote sensing and GIS in mapping fast fashion landfills, identifying their spatial extent, and tracking their growth over time. Spectral analysis techniques can differentiate textile waste from natural land cover based on their distinct spectral signatures (Stoyanova & Vitov, 2025).

- **Monitor environmental degradation:** Satellite data can be used for "before-and-after" temporal analysis to detect changes related to land degradation, water pollution, and urban expansion caused by industrial activities (Ruppen et al., 2023; Yuan et al., 2020). This can be particularly valuable in assessing the environmental impacts of production hubs where regulatory oversight might be weak (Velástegui-Montoya et al., 2023).

- **Assess pollution and emissions: Earth** observation systems can monitor various environmental parameters, including water pollution (Karakuş, 2022) and waste detection (Magyar et al., 2023). These tools can provide continuous, large-scale, and spatially precise data, which is crucial for understanding the fashion industry's contribution to environmental issues, including Scope 1, 2, and 3 emissions.

- **Latent urban degradation: GIS markers** of textile industrial activity, when considered alongside environmental stressors, can reveal unforeseen degradation in urban environments. The adverse effects of large-scale production sites may extend beyond immediate cause-and-effect relationships; these applications can track subtle spatial trends like overpopulation, infrastructural deficiencies, and resource depletion. These factors serve as key indicators of potential unsustainability, environmental strain, and under-examined forms of violence against resident populations.

The integration of remote sensing and GIS allows for spatiotemporal analysis, enabling the tracking of changes in textile waste accumulation and the progression of illegal dumping activities. This provides critical insights into landfill expansion trends and supports data-driven decision-making in environmental management. The use of open-source tools and freely accessible data for such analyses further promotes transparency and reproducibility in environmental monitoring efforts (Stoyanova & Vitov, 2025).

Despite the advancements in both DPPs and geospatial technologies, a critical gap exists in integrating spatial data and environmental indicators within the frameworks of product-level data systems like DPPs. Assessments of anthropogenic impacts such as land degradation and water pollution are often fragmented and lack integration with product-specific data. This limits the ability to trace the environmental footprint of products with spatial precision and granularity.

The feasibility of applying GIS and satellite-based remote sensing to the fashion sector lies in its potential to enhance the environmental granularity of DPPs. By detecting spatial markers of intensive textile production and associated urban degradation, these technologies can provide real-world, verifiable data that complements the information contained within a DPP. This integration can lead to more accountable and data-informed practices at the intersection of industry, environment, and urban systems, moving beyond current limitations where the spatial dimension of emissions and indicators of industrial misconduct are poorly mapped. Such an approach would enable a more comprehensive understanding of the entire supply chain's environmental impact, from raw material sourcing to production facilities and waste disposal sites. This application has the potential of bridging the gap of intersectional realities.

THE MATRIX OF INDICATORS OF DIRECT AND LATENT IMPACTS

To achieve its goal, the study systematically identifies and details a “matrix” of impacts, where each type of impact is linked to unique geospatial indicators and the specific remote sensing or GIS techniques capable of tracking them. This isn't a simple list; it's a conceptual framework that maps out how distinct environmental changes translate previously conducted studies, both in the satellite detection field and fashion industry pollution analysis. Widely researched and more straightforward is how to detect direct effects as visible in Table 01, a deeper focus has been done on latent effects visible in Table 02.

For instance, when considering water pollution, the study looks for changes in the water's spectral properties (how it reflects light, which can indicate the presence of dyes or suspended solids) or thermal anomalies (warm spots from discharged heated water), both of which are detectable using multispectral or thermal infrared satellite sensors. For air pollution, the presence of particulate matter can be inferred from changes in Aerosol Optical Depth values, while specialized sensors can map concentrations of trace gases. Solid waste accumulation is assessed by monitoring the spatial expansion of waste sites over time using high-resolution optical imagery and by identifying the unique spectral signatures of textile materials.

Moving to the more subtle latent urban degradation elements, the study proposes that overcrowding could be tracked by analyzing urban sprawl, changes in building density, or the growth of informal settlements through multi-temporal optical imagery and advanced GIS techniques. Infrastructural deficiencies might manifest as land subsidence, detectable with millimeter precision using Interferometric Synthetic Aperture Radar, or the presence of unmanaged waste sites. Lastly, resource depletion can be inferred from changes in surface water body extent (monitored by multispectral imagery or altimetry) or vegetation stress, as revealed by declining vegetation indices like NDVI (Normalized Difference Vegetation Index).

By meticulously detailing these connections between specific impacts and their geospatial indicators, this feasibility study constructs a robust framework. This framework is crucial for laying the groundwork for future integration of this verifiable geospatial intelligence into fashion sustainability frameworks, such as the Digital Product Passport, ultimately fostering more accountable and data-informed practices that bridge the complex realities of industry, environment, and urban systems. (Tab. 01)

TRACKING LATENT URBAN DEGRADATION ELEMENTS

Beyond direct polluting effects, textile production may also contribute to broader urban degradation. Remote sensing and GIS techniques can be harnessed to discern the physical manifestations of these intricate socio-environmental challenges. The far-reaching consequences of extensive production facilities may extend beyond readily apparent cause-and-effect dynamics; consequently, these approaches can be employed to monitor subtle spatial trends, including overpopulation, infrastructural shortcomings, and resource depletion.

OVERCROWDING AND POPULATION DENSITY

Intensive industrial activity, such as large textile production hubs, can act as a magnet for labor, leading to rapid and often unplanned urban growth in surrounding areas. This rapid influx can quickly outpace the development of adequate housing, infrastructure, and services, resulting in overcrowding.

- **How Remote Sensing and GIS Detect It:**
  - Urban Sprawl and Density Changes: Remote sensing excels at mapping land use and land cover changes over time. By analyzing multi-temporal satellite imagery, we can observe the physical expansion of built-up areas (urban sprawl). GIS then allows for the quantification of this expansion and the assessment of changes in building density within these areas (Singh et al., 2024). For instance, an increase in the number of residential structures or the vertical growth of buildings within a defined area, coupled with a lack of new infrastructure, can indicate rising population density (Láng-Ritter et al., 2025; Szarka & Biljecki, 2022). Studies show that remote sensing can identify urban areas based on population density, land cover, and night-time lights, and can assess urban environmental sustainability indicators (Uchiyama & Mori, 2017). Various geospatial and statistical methods are used to estimate population distribution at fine spatial scales, which is essential for urban studies and planning (Láng-Ritter et al., 2025; Szarka & Biljecki, 2022; Zhou et al., 2020). Deep learning approaches coupled with remote sensing images also provide capabilities for estimating

Matrix of Direct Textile Production Pollutants and Remote Sensing Indicators/GIS Detectable Indicators

Pollutant Category	Pollutants/Alterations	Remote Sensing/GIS Detectable Indicators & Mechanisms
Water Pollution	Dyes and Colorants, High Suspended/ Dissolved Solids, Chemical Residues, pH Imbalance, Thermal Discharge.	**- Spectral Analysis of Water Bodies**: Changes in water color and spectral reflectance (e.g., increased reflectance in certain bands for turbidity or specific absorption/reflection patterns for dyes). Multispectral and hyperspectral sensors detect these altered optical properties (Halepoto et al., 2022). **- Thermal Anomaly Detection**: Localized increases in water temperature and the presence of thermal plumes, detectable by thermal infrared sensors (Ferrara et al., 2017; Naimaee et al., 2024). **- Effluent Plume Mapping**: Visible plumes on the water surface due to color, turbidity, or thermal differences, identifiable through optical, thermal, and sometimes radar imagery (Gancheva et al., 2021; Trinh et al., 2017).
Air Pollution	Particulate Matter (PM2.5, PM10), Volatile Organic Compounds, Sulfur Dioxide, Nitrogen Dioxide, Smoke Plumes	**- Aerosol Optical Depth Measurement**: Elevated AOD values over industrial areas and downwind regions, indicating increased concentrations of airborne particulates (Rowley & Karakuş, 2023; Scheibenreif et al., 2021). **- Trace Gas Concentration Mapping**: Spatially resolved maps showing elevated concentrations of specific pollutant gases (e.g., SO2, NO2), detected by specialized atmospheric chemistry sensors (Potts et al., 2021; Wang et al., 2021). **- Smoke Plume Detection**: Visible smoke plumes in high-resolution optical satellite imagery, and thermal anomalies associated with industrial facilities (Xia et al., 2018).
Solid Waste	Textile Waste (clothing dumps), Textile Dyeing Wasted Sludge	**- Spatial Extent and Growth Monitoring**: Mapping and temporal analysis of landfill expansion and textile waste accumulation using high-resolution optical satellite imagery (Magyar et al., 2023; Papale et al., 2023). **- Spectral Signature Analysis and Indexing**: Distinct spectral reflectance patterns from textile materials (both synthetic and organic) that differentiate them from natural land covers. Specialized spectral indices (e.g., Normalized Difference Enhanced Sand Index) enhance detection and classification (Stoyanova & Vitov, 2025).

Tab. 01

population distribution (Huang et al., 2021).

- Informal Settlement Expansion: High-resolution satellite imagery can visually detect the emergence and growth of informal settlements, characterized by irregular patterns, dense construction, and often a lack of formal planning or infrastructure (Cutini et al., 2019). The rapid expansion of such settlements is a strong indicator of unmanaged population growth and potential overcrowding, particularly in areas attracting migrant labor for industrial work (Abebe et al., 2019). Remote sensing data, particularly very high spatial resolution satellite imagery, has proven useful for identifying these informal settlements and monitoring their evolution (Bhangale et al., 2016; Mudau & Mhangara, 2021; Samper & Liao, 2023).

- Population Estimation Proxies: Advanced techniques combine remote sensing data with statistical models or deep learning to estimate population distribution at a finer scale (Huang et al., 2021). By analyzing features like building footprints, road networks, and even night-time lights, these models can infer population density, highlighting areas experiencing significant increases (Bektemyssova et al., 2025; Kii et al., 2023; Zhou et al., 2020).

INFRASTRUCTURAL DEFICIENCIES

Rapid and unplanned urbanization driven by industrial growth often strains existing infrastructure, leading to deficiencies in critical services like water, sanitation, roads, and waste management

- **How Remote Sensing and GIS Detect It:**

- Land Subsidence: Over-extraction of groundwater to support growing industrial and urban populations can lead to ground subsidence (Medici et al., 2024). This subtle sinking of the land surface can damage buildings and infrastructure (Ciampalini et al., 2021; Miano et al., 2022). Interferometric Synthetic Aperture Radar technology uses radar signals from satellites to precisely measure ground deformation over large areas with millimeter-level accuracy (Bischoff et al., 2020; Deng et al., 2019; Fan et al., 2021; Lee et al., 2025; J. Zhang et al., 2023; Z. Zhang et al., 2023). By tracking subsidence patterns, particularly around industrial zones or densely populated areas, InSAR can indicate stress on groundwater resources and potential damage to underlying infrastructure (Hu et al., 2019; Miano et al., 2022

- Unmanaged Waste Sites: The presence of informal or unmanaged general waste sites within or near urban areas is a clear sign of inadequate municipal waste management infrastructure (Papale et al., 2023). Remote sensing can identify these sites through their distinct spectral properties, irregular shapes, and often lack of vegetation. Time-series analysis can also track their expansion, reflecting increasing pressure on waste disposal systems (Stoyanova & Vitov, 2025). The integration of GIS helps to spatially assess waste accumulation and identify areas prone to illegal dumping, pointing to systemic infrastructural weaknesses (Ragazzo et al., 2025)

- Road/Pavement Degradation: While detailed road condition assessment often requires very high-resolution imagery or ground surveys, satellite imagery and remote sensing techniques can identify major disruptions or significant deterioration in road networks (Yu et al., 2024). Changes in road patterns or the development of informal access routes in response to inadequate formal infrastructure can also be observed through multi-temporal analysis of satellite images, as these changes manifest as detectable alterations in the urban fabric.

RESOURCE DEPLETION

The intense demands of both industrial processes and an expanding urban population can lead to the depletion of natural resources, most notably water.

- **How Remote Sensing and GIS Detect It:**

- Water Scarcity Indicators: Changes in Surface Water Bodies: Satellite imagery is crucial for monitoring the spatial extent and volume of surface water bodies such as rivers, lakes, and reservoirs (Albizua et al., 2012). Decreases in water body size or changes in water levels, quantifiable through multi-temporal analysis, can indicate high water withdrawal rates for industrial processes (e.g., textile dyeing) or urban consumption (Kalhor & Emaminejad, 2019; Palazzoli et al., 2022). Satellite altimetry provides precise measure-

ments of water levels in inland water bodies for effective water resource management (Thakur et al., 2020). Urban areas are a main driver of surface water loss (Palazzoli et al., 2022).
◦ Vegetation Stress: Water scarcity impacts vegetation health. Satellite-derived vegetation indices like NDVI can monitor the greenness and vigor of vegetation (Bondarenko et al., 2021). A decline in NDVI values in areas surrounding industrial or urban centers, particularly during dry seasons, can signal water stress, soil degradation, or changes in local ecosystems due to water diversion or pollution (Kabiraj et al., 2022; Peng et al., 2024). Remote sensing can also monitor plant and soil conditions and provide decision-making support related to drought stress in agriculture (Jindo et al., 2021).
◦ Groundwater Depletion Proxies: While groundwater is not directly visible from space, its depletion can lead to observable surface changes. As mentioned with land subsidence, excessive groundwater extraction can cause the ground to sink. Moreover, the impact of decreased groundwater on vegetation health or the drying up of shallow surface water bodies can be detected, providing indirect evidence of groundwater stress (Vasco et al., 2019; Zhou & Hao, 2025). Remote sensing technologies, including gravimetric measurements and changes in Earth surface height, are increasingly used for monitoring and assessing groundwater at various scales (Chawla et al., 2020; Ibrahim et al., 2024).

- **Land Degradation:**
  Industrial activities and associated urbanization can lead to land degradation, impacting soil quality and ecosystem health (Prokop, 2020; Yuan et al., 2020). Remote sensing can track indicators such as:
  ◦ Changes in Land Surface Temperature: Urbanization and industrialization often lead to an increase in Land Surface Temperature (LST) and Urban Heat Island (UHI) effect, which can be monitored by thermal infrared sensors (Singh et al., 2024).
  ◦ Soil Moisture Index: Some satellite products can infer soil moisture, and a decline can indicate degradation (Kabiraj et al., 2022). Albedo and Vegetation Indices: Changes in surface albedo (reflectivity) and vegetation cover can signify soil exposure and a decline in land productivity (Prokop, 2020). Monitoring these changes provides insights into the extent and severity of land degradation in and around industrial areas (Bondarenko et al., 2021; Sun et al., 2019).

By integrating these geospatial observations, we can build a comprehensive picture of the complex and interconnected environmental and social challenges arising from concentrated industrial development. This spatially explicit understanding is vital for creating effective policies and interventions aimed at sustainable urban and industrial development (Tab. 02).

TESTING: THE CASE EXAMPLE OF VIETNAM SHOES PRODUCTION

Vietnam’s transformation into a global footwear and fashion manufacturing hub began in the early 1990s, when market- oriented reforms initiated under Đổi Mới opened the country to foreign investment and spurred the relocation of production from economies facing rising labor costs, particularly Taiwan and China. These reforms enabled Vietnam to develop a competitive industrial base powered by an abundant workforce, improving infrastructure, and increasingly sophisticated manufacturing capabilities, attracting a wave of foreign- invested enterprises that established the foundations of its export- oriented footwear sector. As production capacity expanded through the 1990s and 2000s, the European Union rapidly emerged as a central economic partner, becoming one of Vietnam’s largest importers of footwear and accounting for more than 30% of the country’s footwear export value by the mid- 2010s. The EU’s importance grew further as Vietnam evolved into the EU’s largest trading partner in goods within ASEAN, with footwear consistently ranked among the EU’s primary imports from Vietnam. This long- term economic integration reached a pivotal milestone with the entry into force of the EU–Vietnam Free Trade Agreement (EVFTA) in August 2020, which eliminated tariffs on a wide range of Vietnamese footwear exports and reinforced Vietnam’s role as a strategic production base for the European fashion industry. Together, Vietnam’s openness to foreign investment, the inflow of global manufacturers seeking competitive production conditions, and the consolidation of preferential trade relations with the EU have shaped a production landscape whose environmental and urban impacts now demand rigorous geospatial scrutiny.

Matrix of Latent Urban Degradation Elements and Remote Sensing/GIS Detectable Indicators

Latent Element	Geospatial Indicator(s)	Remote Sensing/GIS Techniques & Argumentation
Overcrowding & Population Density	Urban expansion and changes in building density.	**- Urban Sprawl and Density Changes**: Multi-temporal satellite imagery allows for mapping the physical expansion of built-up areas (urban sprawl) and quantifying the rate and pattern of urban growth. GIS facilitates the assessment of changes in building density within these areas, where rapid, unplanned expansion or increased vertical construction can indicate growing population pressure. Remote sensing can identify urban areas based on population density, land cover, and night-time lights, while advanced techniques like deep learning can infer population distribution at fine spatial scales. **- Informal Settlement Expansion**: High-resolution satellite imagery directly reveals the emergence and growth of informal settlements, characterized by irregular patterns and dense construction without formal planning. Their rapid expansion indicates unmanaged population influx and potential overcrowding, particularly around industrial zones attracting labor.
Infrastructural Deficiencies	Land subsidence, unmanaged waste sites, road/pavement degradation.	**- Land Subsidence**: Interferometric Synthetic Aperture Radar precisely measures ground deformation (sinking of land). Subsidence patterns around industrial areas can indicate over-extraction of groundwater, straining water supply infrastructure, or structural stress on other underground utilities and buildings due to overburden. **- Unmanaged Waste Sites**: High-resolution satellite imagery, combined with spectral and textural analysis, identifies and maps unofficial or poorly managed waste accumulation areas. Their presence and growth signify inadequate municipal waste management infrastructure, reflecting a deficiency in public services. **- Road/Pavement Degradation**: While detailed assessment often requires very high-resolution imagery, significant deterioration in road networks or the development of informal access routes in response to inadequate formal infrastructure can be inferred from satellite images through changes in urban texture and connectivity.
Resource Depletion	Changes in surface water bodies, vegetation stress, and proxies for groundwater depletion.	**- Surface Water Body Monitoring**: Multispectral satellite imagery monitors the spatial extent and volume of rivers, lakes, and reservoirs. Decreases in water body size or levels indicate high water withdrawal for industrial processes or urban consumption. Satellite altimetry provides precise measurements of water levels, signifying overall water resource availability. **- Vegetation Stress**: Satellite-derived vegetation indices (e.g., NDVI) assess vegetation health. A decline in these indices in areas near industrial or urban centers can signal water stress, soil degradation, or ecosystem changes due to water diversion or pollution. This reflects the strain on natural resources from industrial and urban demands. - Groundwater Depletion Proxies: While not directly observable, sustained land subsidence detected by InSAR can be a strong proxy for excessive groundwater extraction. Similarly, observable impacts on surface vegetation or water bodies can indirectly point to a depleted groundwater table, as these resources are often interconnected.

Tab. 02

as access to Sentinel- 5 products was not granted within the temporal window considered.

The initial phase of the analysis involved identifying the main footwear production sites in Vietnam, as reported in (Tijdens & Van Klaveren, 2018). It is important to note that these sites correspond to officially declared manufacturing facilities and are therefore presumed to be subject to heightened public and institutional scrutiny. For each site, a surface reference point—defined as a Geographical Reference Point (GRP)—was selected to monitor, over time, the variation of spectral signals and environmental parameters in the immediate surroundings. GRPs were identified exclusively in areas classified as paved surface in 2023, a condition verified through targeted spectroscopic analysis to ensure homogeneous sampling of surface materials.

Once the GRP was established, an Area of Interest (AOI) of identical dimensions was delineated for each site to ensure comparability of results. Satellite image analysis for all AOIs was set to 23 June 2023, a date on which cloud cover over the area was below 30%, the threshold necessary to guarantee radiometric reading quality. Discrepancies in the acquisition dates of certain scenes are attributable to orbital constraints and meteorological conditions, which occasionally hinder the availability of usable imagery.

The first analytical operation concerned the interpretation of natural colour images, aimed at identifying the principal anthropogenic and natural modifications within each AOI. Subsequently, using Landsat data, surface temperature values for the years 2002 and 2023 were examined, as no more recent acquisitions with comparable characteristics were available. The same Landsat datasets were also used to conduct a spectroscopic analysis of each GRP (Fig. 01; Fig. 02), alongside the reconstruction of temporal profiles for temperature, vegetation cover, and soil moisture.

Finally, the AOIs were analysed for land- use change using the global LULC (Land Use/ Land Cover) map derived from ESA Sentinel- 2 imagery at 10- m resolution and compared with regional- scale change data. The combined analyses are visible in Table 03. Variations in moisture, vegetation, temperature, land use, and

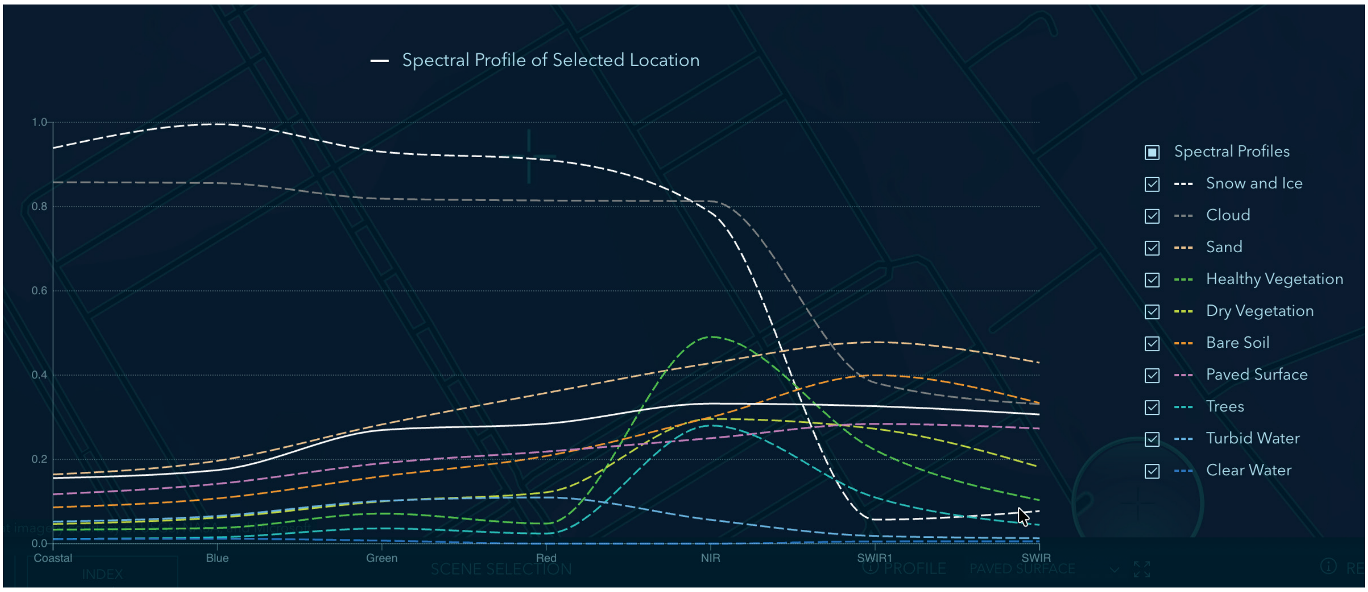


Fig. 01

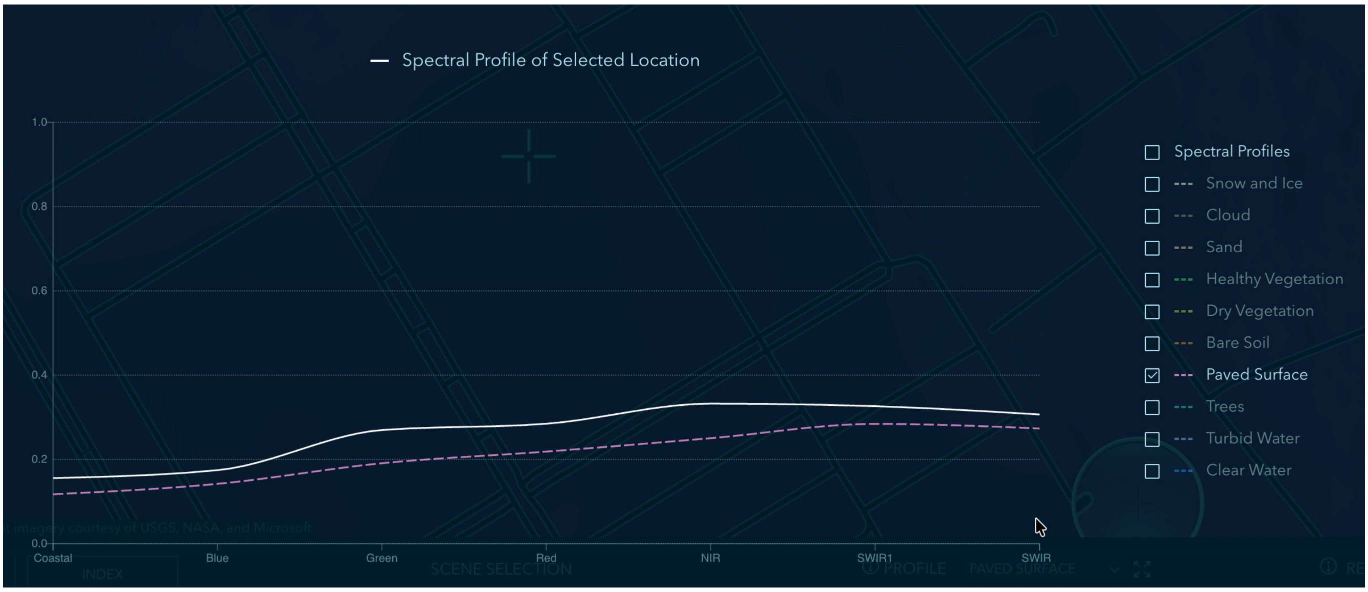


Fig. 02

METHODOLOGY USED, LANDSAT AND COPERNICUS DATA ANALYSIS

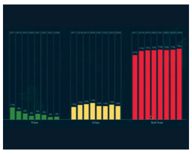
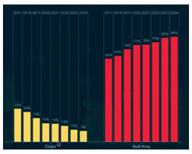
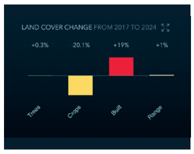
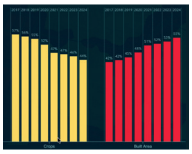
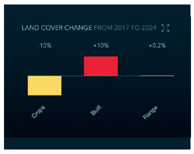
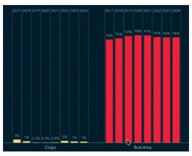
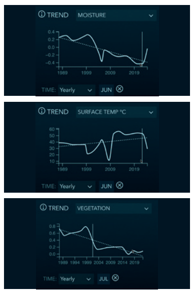
For the purposes of this study, data provided by the Landsat and Copernicus programmes were employed, supplemented and by access to the high- frequency satellite imagery databases. The methodological approach adopted relies exclusively on the datasets currently accessible and analyzable, with the aim of offering a preliminary technical demonstration of the potential of geospatial indicators. It does not therefore aspire to exhaustiveness; rather, it intends to outline a descriptive and operational framework that may be further expanded in future research. Conversely, it was not possible to include data on air quality and atmospheric greenhouse gas concentrations, the ratio between built- up and green or agricultural surfaces constitute sensitive indicators of potential environmental stress and degenerative phenomena, such as the emergence of urban or industrial heat- island effects. These effects can be linked to environmental changes in the area and, thanks to the availability of historical satellite data, to the establishment of the intensive production facility under analysis.

ANALYSIS OF A SAMPLED SITE

To deepen the analysis, one of the facilities listed in Tab. 03—specifically, the Vietnam Chingluh Shoes Ltd site—was selected as a representative case study. Historical satellite observations reveal that in the earliest usable acquisition from 2006, the manufacturing complex appeared recently established, with primary urbanization works still underway. Although the 2000 image could not be included due to insufficient radiometric quality, it nevertheless indicates that the area consisted predominantly of uncultivated green land, confirming the absence of significant industrialization prior to the installation of the plant.

A comparison with the 2025 satellite imagery illustrates a marked and extensive transformation of the surrounding environment (Fig. 03; Fig.04). The expansion of anthropogenic land use is both pronounced and spatially intrusive, with multiple industrial facilities of differing types emerging around the original manufacturing site. This pattern suggests a progressive and largely uncoordinated densification of industrial activities. Concomitantly, no adequate transporta-

Summary of workflow testing across three development phases

Factory*	**no. empl.**	**Location**	**Geografical Reference Point Selection** (GRP)	**Surface temerature** (Landsat Explorer)	**Land Cover Change 2017-2024** (Copernicus Sentinel-2 Land Cover/Land Use LCLU)	**Overall land cover change 2017-2024** (Copernicus Sentinel-2 Land Cover/Land Use LCLU)	**Index change 1989-2025** (Landsat)
Chang Shin Vietnam Co Ltd	24300	Ấp 1, Tổ 14, Thanh Phú, Vĩnh Cửu, Đồng Nai, Vietnam	Spectral Analysis: 2002: Dry vegetation 2023: Paved surface x: 106.84814 y: 11.00764 NDVI: 0.454 MNDWI: -0.379	2002 (August 01*): Surface Temp: 85°F / 29°C 2023 (June 23): Surface Temp: 138°F / 59°C			
Vietnam Chingluh Shoes Ltd	22400	JFCR+59X Thuan Dao Industri-al Park, TT. Bến Lức, Bến Lức, Long An, Vietnam	Spectral Analysis: 2002: Trees 2023: Paved surface x 106.494 y 10.623 NDVI: 0.077 MNDWI: -0.095	2002 (June 23): Surface Temp: 98°F / 37°C 2023 (June 23): Surface Temp: 119°F / 48°C			
Vinh Long Footwear Co Ltd	22300	5W9M+ XCW, Hoà Phú, Long Hồ, Vĩnh Long, Vietnam	Spectral Analysis: 2002: Trees 2023: Paved surface x: 105.93484 y: 10.16968 NDVI: 0.177 MNDWI: -0.330	2002 (July 23*): Surface Temp: 96°F / 36°C 2023 (June 23): Surface Temp: 117°F / 47°C			
Freetrend VN Industrial Co Ltd	21600	VPRC+G64, Đường số 3, KCX, Thủ Đức, Thành phố Hồ Chí Minh, Vietnam	Spectral Analysis: 2002: Dry vegetation 2023: Paved surface x: 106.72034 y: 10.88884 NDVI: 0.081 MNDWI: -0.488	2002 (August 24*): Surface Temp: 104°F / 40°C 2023 (June 23): Surface Temp: 128°F / 54°C			

***Tijdens & Van Klaveren, 2018**

Tab. 03

Fig. 03

Fig. 04

tion network appears to have developed to support the substantial workforce commuting daily to the area, indicating that industrial expansion occurred without proportional infrastructural planning. The immediate vicinity also shows a high residential density, often characterized by fragile or informal settlement structures, further demonstrating the urban pressures generated by the intensification of production activities.

Spectroscopic analyses reinforce these findings. Beginning in the early 2000s—coinciding with Vietnam's broader opening to foreign investment and the establishment of this manufacturing facility—a sharp decline in vegetation cover and surface moisture is detected at the GRP, paired with a notable rise in average surface temperatures (Fig. 07; Fig. 08). These changes align with multi-temporal patterns observed across the broader Area of Interest (AOI): starting in 2017, the AOI experienced a substantial reduction in cultivated green areas (−20.1%) and a corresponding increase in built-up land cover (+19%). This reconfiguration of the landscape is associated with a generalized increase in surface temperatures (+9 °C), a trend indicative of vegetation stress and symptomatic of localized microclimatic alteration,

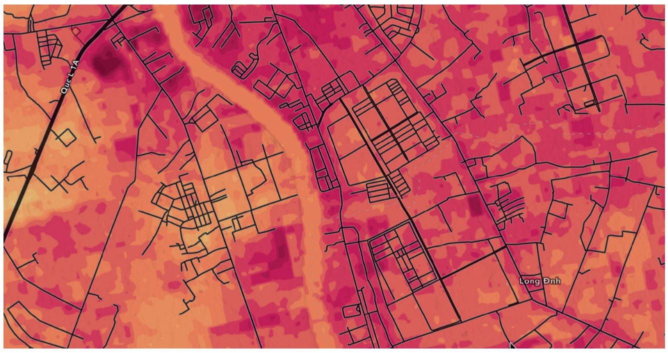


Fig. 05

Fig. 06

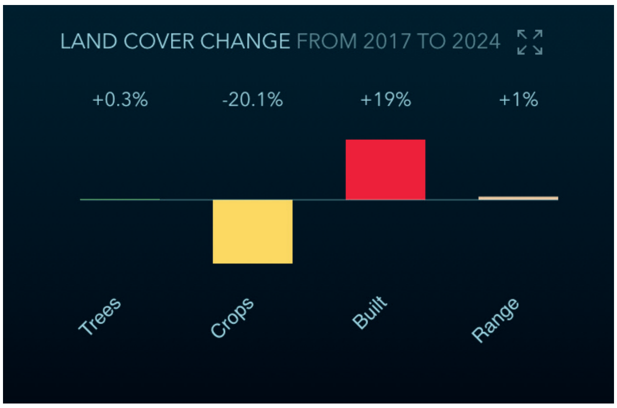


Fig. 07

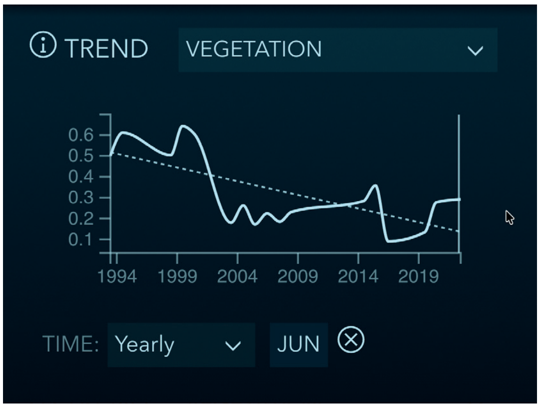


Fig. 08

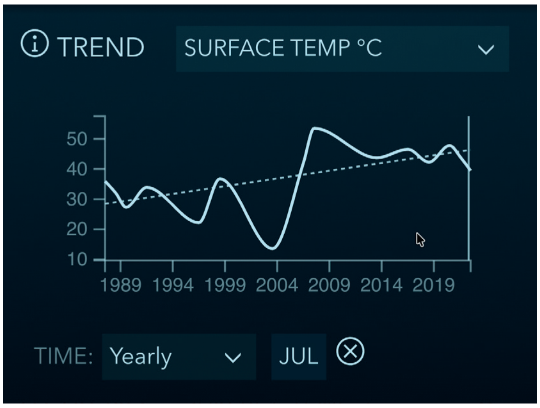


Fig. 09

CONCLUSION

This study illustrates the capacity of satellite based remote sensing and geographic information systems to document and interpret both direct and latent environmental impacts generated by fashion and textile production. Through the analysis of spectral, thermal and land surface indicators, the research demonstrates how industrial expansion can produce rapid and spatially uneven transformations that conventional reporting systems often fail to capture. The Vietnam case study highlights the extent to which concentrated manufacturing activity can alter local ecological conditions in ways that diverge from regional environmental baselines, revealing localized pressures on land use, vegetation cover, surface temperatures and urban systems.

The results also clarify how geospatial indicators can be incorporated within a Digital Product Passport data architecture. Each indicator obtained from remote sensing sources can be expressed as a structured environmental attribute associated with the production site of a given product. These attributes can include spatial coordinates, reference to the area of interest, the date of image acquisition, the sensor or data source employed, the type of environmental indicator observed and the quantitative value derived from satellite analysis. Such information can be stored within the Digital Product Passport as verifiable and machine readable records, ensuring that environmental assessments are informed by externally generated evidence rather than solely by producer declarations.

Operational integration can be achieved through a sequence of data flows that link Earth observation platforms with Digital Product Passport registries. In the first stage, satellite derived indicators are processed at the facility level and organized into a standardized environmental dataset. In the second stage, these datasets are incorporated into the existing data model of the Digital Product Passport, allowing alignment with established environmental reporting categories and facilitating automated updates. In the third stage, an interoperability layer enables continuous exchange of information between remote sensing data services and Digital Product Passport systems, allowing ongoing verification of environmental conditions associated with each production site throughout the life cycle of a product.

The integration of geospatial intelligence with the Digital Product Passport framework suggests a pathway toward more transparent and reliable environmental accountability in global fashion supply chains. The ability to monitor land transformation, stress on natural resources and changes in urban conditions through satellite data provides an independent and scalable method for assessing the environmental footprint of production sites. Future work should focus on developing standardized taxonomies for geospatial indicators, defining protocols for the validation of satellite derived measurements and designing operational models that support the systematic incorporation of Earth observation data into regulatory and market based sustainability instruments. Such advances would help strengthen the evidentiary foundation of the Digital Product Passport and contribute to more robust environmental governance in the fashion industry.

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Landsat Level-2 Imagery:

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CAPTIONS

[Fig. 01] Spectral profiles of multiple materials, data courtesy of the U.S. Geological Survey via ESRI

[Fig. 02] spectral profiles of paved surface (purple) and sampled point (white), data courtesy of the U.S. Geological Survey via ESRI

[Fig. 03] Satellite image 19/04/2006 Google Earth.

[Fig. 04] Satellite image 21/03/2025 Google Earth.

[Fig. 05] Landsat surface temperature 23/07/2002, data courtesy of the U.S. Geological Survey via ESR (via ESRI).

[Fig. 06] Landsat surface temperature 23/06/2023, data courtesy of the U.S. Geological Survey (via ESRI).

[Fig. 07-08-09] Differences in land cover change between 2017 and 2024 (Data via ESRI).

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SYMPOIETIC ASSEMBLAGE

FROM BIOMIMETICS TOWARD A MORE-THAN-HUMAN ECOLOGY OF FASHION

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Abstract

Fashion has long engaged nature as both a formal and material field, a reservoir of forms through which the discipline negotiates its relationship with matter and time. This contribution investigates the progressive transformation of this condition, tracing a shift from an initial conception of nature as a formal referent to be imitated, toward the operationalisation of biological principles and behavioural logics, until nature itself emerges no longer as a passive referent, but as an active co-agent within contemporary design processes. Through the analysis of selected fashion practices, the contribution traces a trajectory from digitally mediated forms of computational biomorphism to functional biomimesis, and toward post-anthropocentric forms of ontological design in which non-human agencies increasingly participate in the constitution of the project itself.. The concept of *Sympoietic Assemblages* serves as a critical lens through which these developments are interpreted. Drawing on Deleuze and Guattari's notion of assemblage and Donna Haraway's theory of sympoiesis, the contribution outlines the emergence of a relational ecology of design in which form, meaning, and agency emerge through processes of co-constitution.

Keywords: Fashion ecologies; Sympoietic design; Material Agency; Biomimicry; More-than-human practices

INTRODUCTION

Design has always been a way of thinking with the world, a practice of attuning to its forms, rhythms, and vital forces. Within this relational field, nature has historically operated as a source of formal inspiration and as a dispositive through which the human imagination interrogates its own limits and possibilities. This dynamic is particularly resonant with fashion design, where the encounter between living matter and material-aesthetic configurations destabilises distinctions between biological processes, cultural imaginaries, and technical systems.

While the impulse to imitate nature is as old as human creativity itself, it was not always approached equally. Primarily positioned as an external referent, nature was valued for its morphological richness and expressive potential, with particular emphasis placed on stylised, often surreal organic forms that translated the vitality of the living into new visual and material expressions. This practice is associated with *biomorphism*, understood here as a modelling system through which design elements are generated from natural morphologies and formal configurations. From the second half of the twentieth century, with the rise of *biomimicry* as an autonomous scientific and design field capable of translating biological processes into operative strategies, a new trajectory of inquiry based on functional transposition is inaugurated (Schmitt, 1969). The publication of Janine Benyus' *Biomimicry: Innovation Inspired by Nature* gives this field a more articulated epistemological status, positing nature as "Model, measure, and mentor" (Benyus, 1997, p.6). The focus thus shifts to adaptive strategies, ecological principles, and optimisation processes embedded within ecosystems. From the early

2000s onward, biomimicry gradually intersects with computational design, algorithmic morphogenesis, digital fabrication, and material engineering, contributing to the emergence of hybrid fashion paradigms (Hensel, Menges & Weinstock, 2014). The ability to extract, encode, and systematize data from nature has contributed to the transformation of fashion design into a situated computational environment, in which generative software, machine learning tools, and digital platforms redefine modes of interaction. Within a broader epistemic shift, critical reflections emerging from post-anthropocentric design discourse begin to challenge the separation between human and non-human, destabilising conventional understandings of nature as a passive external entity. (Escobar, 2018; Haraway, 2016; Akama et al., 2020). The act of designing is conceived as a relational outcome of heterogeneous interactions between technologies and environments. In this transition, the epistemological evolution that, originating in biomorphism and traversing biomimicry, culminates in an ecological and relational vision of design, wherein nature actively participates in the act of producing forms.

The present contribution critically examines this shift within the field of fashion, framing sympoietic design practices as a paradigmatic reorientation in which agency is articulated across biological and computational assemblages.

EPISTEMOLOGICAL AND INTERPRETATIVE FRAMEWORK

This study adopts a qualitative and theoretical methodology situated within critical fashion studies, design research, and posthuman theory. The contribution is conceived as a conceptual and epistemological inquiry aimed at clarifying how the role of nature in fashion design has shifted from biomorphic representation to biomimetic optimisation and, ultimately, to sympoietic co-agency. The method is grounded in the critical reading of theories and practices inherent to fashion design, selected through a purposive logic for their capacity to materialise distinct ontological approaches to the nature-design relationship. The analysis is conducted through secondary sources, including designer statements, exhibitions, and academic literature; the selected cases study are treated as situated instances that render visible the material-discursive articulations that manifest the relations between data, matter, and living systems. The analysis of these fashion practices offers a comparative perspective on how nature is variously enacted across contemporary design practices. The proposed methodological framework is intended as a transferable interpretative tool for analysing fashion practices in which design emerges from its multi-level entanglement with planetary ecosystems.

GENEALOGIES OF NATURE IN FASHION DESIGN

As previously mentioned, an initial approach to the relation between nature and fashion design is undoubtedly tied to *biomorphism*: nature functions as a symbolic catalogue and morphological archive, materialising in ornamental and stylised motifs that are inspired by floral and zoomorphic morphologies. Alfred H. Barr Jr. was the first to articulate the term *biomorphism* in 1936. The preference for indeterminate, organic forms suggestive of dynamism, often evoking the amorphous and quasi-spherical configurations of germs, amoebae, and embryonic life, can be understood as rooted in the vegetal imaginary of the late nineteenth-century Art Nouveau. Within the architectural and aesthetic and aesthetic milieu, the extensive production of of Henry van de Velde, Victor Horta, and Hector Guimard stands as one of the most significant expressions of the Art Nouveau giving rise to fluid spatial and decorative systems informed by vegetal morphologies. In fashion design, biomorphism has historically operated less as a functional strategy than as a formal and symbolic language through which the vitality of nature was transposed into silhouette, surface, and movement, privileging organic continuity over structural rationalisation. Its early stands as one of the most significant expressions of the Art Nouveau giving rise to fluid spatial and decorative systems informed by vegetal morphologies, designers such as Paul Poiret and Mariano Fortuny experimented with forms inspired by marine and floral motifs through soft geometries, pleats, and draping (Evans, 2003). Over the course of the twentieth century, biomorphism developed into increasingly complex sartorial articulations, exemplified by the sculptural volumes of Balenciaga's garments and the pleated architectures of Fortuny's *Delphos* dress. In these works, a plastic and organic sensibility aligned with modernist formal experimentation gives rise to early biomorphic translations of natural growth and fluidity into sartorial form, wherein nature operates as a morphological archive. The advent of parametric modelling has enabled biomorphism to expand into three-dimensional space, allowing for the materialization of homothetic structures inspired by natural systems. Software environments capable of generating forms through algorithms, mathematical functions, or an iterative set iterative set of rules, have significantly extended the morphogenetic repertoire of design, making it possible not only to emulate existing patterns but to create entirely new, plausible formations. This shift marks the transition from geometrical design systems to algorithmic and systemic modes of form generation, in which form emerges through procedural logics. Data extracted from the observation of nature, now accessible across microscopic scales, acquire a new epistemic status, operating as computable parameters that activate generative matrices and recursive units within open-ended design systems. This transformation resonates with the digital turn identified by Mario Carpo, whereby natural natural forms are translated into algorithmic logic and variable-driven processes (Carpo, 2011). This convergence of nature and algorithms marks the beginning of biologically informed design, where form and function co-emerge as the outcomes of dynamic systemic processes.

BIOMIMESIS: NATURE AS OPERATIVE AND PERFORMATIVE SYSTEM

The formalist conception was gradually accompanied by the idea of nature as an operative and optimised system, giving rise to the concept of *biomimesis* (or *biomimetics*), a design strategy oriented toward replicating the functional and systemic principles of the living world. This trajectory has been fostered by the refinement of methods for observing nature across scales ranging from the nanometric to the macroscopic, enabling the dynamics and organizational logics of living systems to be rendered legible and translated into design data (Vincent et al., 2006).

The term *biomimesis*, introduced by biophysicist Otto Schmitt, derived from the words βίος (life) and μίμησις (imitation) and consists in observing and reproducing mechanisms found in nature to develop projects that incorporate their functional, systemic or behavioural characteristics (Vincent et al., 2006). Janine Benyus (1997) formalised this approach in her seminal work *Biomimicry: Innovation Inspired by Nature*, where she argued that nature should be observed in its engineering perfection.

Within the textile sector, biomimetic strategies enable designers to integrate functional properties such as self-cleaning, self-repair, energy efficiency, friction reduction, dry adhesion, and superhydrophobicity (Bar-Cohen, 2006). These innovations have led to the development of bio-inspired fabrics with functional surfaces, structural colouration, self-healing capacities, and thermal insulation properties. The development of biomimesis was further consolidated with the advent of computational and generative design, which enabled the algorithmic simulation and modelling of complex biological behaviours (Weinstock, 2010; Hensel, Menges & Weinstock, 2014). Nature is approached as a dynamic reservoir of performative and systemic data that can be empirically extracted. Through the use of biosensing technologies, high-resolution microscopy, finite element analysis (FEA), and AI-driven material simulations, such data are interpreted computationally and consequently translated into design strategies. Nature is rendered intelligible and operative through a logic of extraction and transposition where biological processes are emulated by algorithmic models. As Neri Oxman observes: "Computational design enables us to think like nature, rather than about nature" (Oxman, 2010, p. 12), encapsulating the shift from a mimetic conception of nature to a design paradigm that embraces its systemic and generative logics.

EXAPTATION AND THE RECONFIGURATION OF NATURAL AGENCY

Such a framework introduces a teleological and optimisation-oriented rationality into the reading of nature, a perspective that tends to marginalise the contingent and emergent dynamics constitutive of living systems (Vincent, 2009). Within this horizon, the evolutionary concept of *exaptation* provides a critical lens for rethinking the assumptions underpinning biomimetic approaches. As emphasised by architect and theorist Alessandro Melis, and articulated through his curatorial direction of the 2021 Venice Architecture Biennale *Resilient Communities*, exaptation foregrounds processes of adaptive reuse, redundancy, and improvisation as intrinsic dimensions of natural evolution. Originally introduced by Stephen J. Gould and Elisabeth S. Vrba, exaptation designates evolutionary processes through which traits developed within one functional context are subsequently redeployed within different and unforeseen domains (Gould & Vrba, 1982). Canonical examples, such as feathers initially associated with thermoregulation and later implicated in flight, illustrate how innovation emerges through the reconfiguration of existing structures and latent capacities. From this post-Darwinian perspective, nature appears as an entropic and open-ended system, characterised by the capacity to activate alternative pathways of transformation (Melis & Pievani, 2022). When translated into the field of fashion, exaptation supports an epistemic orientation attentive to contingency and emergent function. Design practices informed by this approach engage processual configurations, in which unintended outcomes and performative reinterpretations acquire generative value. This methodology fosters a speculative design culture that accommodates complexity and uncertainty while cultivating aesthetic and material practices aligned with open-ended modes of becoming (Pigliucci & Müller, 2010; Arthur, 2009).

RELATIONAL AND SYMPOIETIC ECOLOGIES OF DESIGN

Beyond the dialectic between form and function, a new ontological stance emerges in which nature becomes a co-agent in design processes. The focus shifts from *representation* to *intra-action*, a key concept introduced by Karen Barad, who states: "Relata do not pre-exist relations; rather, relata-within-phenomena emerge through specific intra-actions" (Barad, 2007, p. 140).

Aligned with this orientation, fashion design is intended as a relational and performative practice, where nature and technology co-emerge. Donna Haraway, with her notion of *sympoiesis*, insists on the need to *make-with*: "Nothing makes itself; nothing is really autopoietic or self-organizing. The smallest unit of analysis is always a relation" (Haraway, 2016, p. 58). Within this sympoietic paradigm, data mutually constitute through the continuous interaction between environmental and computational systems. Such data are situated, dynamic, and multispecies and encompass environmental inputs (light, CO_2, humidity), biological signals (growth, cellular stress), and relational parameters (use, care, temporality). Their acquisition relies on environmental sensors, bio-digital interfaces, machine learning algorithms, and real-time feedback loops that enable the project to unfold as an interactive system, where data are the actors of operative events: the contingent expressions of an ongoing co-existence. The entangled design practices proposed by Keune substantiate an epistemic shift wherein material and living systems are brought into relation according to logics of "aesthetics of interdependence and vulnerability" (Keune, 2017, p. 65). In fashion design, these instances take form in projects such as Neri Oxman's *Wanderers* (2014), where generative materials and biologically inspired forms are co-created through additive technologies and environmental data. Fashion liberates itself from its role as representational surface and becomes a reactive onto-political dispositive (Foucault, 1980)[1] capable of activating multispecies worlding processes in which design is configured as a gesture of care and openness to non-human alterity (Puig de la Bellacasa, 2017).

MATERIAL PRACTICES AT THE INTERSECTION OF BIOMORPHISM AND BIOMIMETICS

This section examines contemporary fashion practices that engage nature as both a formal and morphological archive and a source of functional and performative principles. The selected case studies reconstruct a trajectory from formal experimentation toward co-emergent design conditions, foregrounding different ontological configurations of the relationship between nature and design. Particular attention is given to projects in which natural morphologies, biological processes, and environmental dynamics assume an operative role within the design process. Attention was also given to the use of computational, material or bio-digital infrastructures that enable relational and processual modes of making, as well as to practices in which agency is redistributed across human and more-than-human actors.

Historically, and within the analytical framework of this study, biomorphism emerges as an early form of design engagement with nature. In contemporary fashion, this practice moved beyond the representational role of nature it toward the generation of hybrid sartorial morphologies suspended between reality and imaginary worlds. This posture is evident in Alexander McQueen's *Plato's Atlantis* (Spring/Summer 2010), where digitally generated reptilian and aquatic morphologies informed prints and material transformations, translating evolutionary and biological imaginaries into computationally mediated form. A similar approach can be observed in Hussein Chalayan's *One Hundred and Eleven* (Spring/Summer 2007), in which garments mechanically and morphologically transform on the runway, evoking processes of organic growth, adaptation, and temporal mutation through technological orchestration. The Dutch designer Iris van Herpen is recognised worldwide for her collections inspired by nervous systems, corals, neural tissues, and cellular formations. In the *Voltage* collection (2013), where she references bioelectric patterns and magnetic fields, while in *Sensory Seas* (2020), she reproduces marine coral structures and synaptic tissues (Fig. 01). These collections are developed through the use of computational simulation tools, in particular, the use of tools such as Grasshopper, Houdini, and fluid dynamic simulations that enables the translation of biological information into complex visual structures, reinforcing the bond between natural data and aesthetic composition. In this sense, it is possible to speak of *computational biomorphism*: an aesthetic that celebrates mutation, morphological fluidity, and the hybridisation of nature and artifice. These algorithmic simulations are subsequently materialised through digital fabrication processes, which enable the translation of computational geometries into physical garments via additive manufacturing, laser cutting, and hybrid craft–technological techniques. The use of hybrid materials and the application of fluid-dynamic textures generate a visual effect that evokes cellular porosity and plasticity (Quinn, 2002; Bolton, 2016). These approaches do not take nature as a systemic model: nature is not imitated in its function but transformed into visual and volumetric patterns that chart a path toward an aesthetics of organic becoming (Quinn, 2002).

Design strategies associated with biomimicry, by contrast, do not directly affect the aesthetic aspects of design; rather, they are guided by biological structures with the goal of transferring the functional properties of biological "mechanisms" into the artificial world. As Vincent et al. clarify: "Biomimetic design is not about copying appearances, but about extracting principles that make biological systems work" (Vincent et al., 2006, p. 471). A paradigmatic example of this approach is the adoption of the microstructure of

1 A thoroughly heterogeneous ensemble consisting of discourses, institutions, architectural forms, regulatory decisions, laws, administrative measures, scientific statements" (Foucault, 1980, p. 194).

Fig. 01

shark skin in the development of technical fabrics, as in the case of Speedo's *Fastskin™* swimsuit: here, the micro-ribbing inspired by shark dermal denticles was replicated to reduce water resistance, without any intention of evoking the animal's aesthetic (Vincent et al., 2006) (Fig. 02). Moussavi's reconceptualisation of form as a product of performance rather than predefined function enables a reading of biomimicry that foregrounds behavioural and operational logics over static functional equivalence (Moussavi, 2014). Yet, while form may follow function, it does not always render it visible. Similarly, Dawson et al. developed a textile prototype inspired by the mechanism of pinecone opening and closing, capable of increasing its air permeability in response to rising relative humidity in the local microclimate (Dawson et al., 1997). A similar concept was recently implemented by Nike in a clothing system commercialised under the name *Macro React™*. This technology was integrated into a tennis dress worn by Maria Sharapova during the 2006 US Open. The garment featured a back panel composed of a fish-scale pattern, which opened as the athlete perspired, thereby increasing localised ventilation and enhancing wearer comfort.

These applications are based on the analysis of biological data obtained through electron microscopy techniques and physio-behavioural simulations, which are translated into textile configurations via algorithmic modelling software. The use of parametric technologies and smart materials thus enables the transfer of functional properties observed in nature into responsive ecologies of fashion.

Fig. 02

MORE-THAN-HUMAN ECOLOGIES OF FASHION

Beyond biomimicry, contemporary fashion increasingly engages with speculative and experimental practices that reconfigure the relations through which human and more-than-human actors coexist and co-evolve within design processes. The evolutionary trajectory of the nature-design symbiotic relationship in fashion finds its highest expression in the work of Paula Ulargui Escalona (Ulargui Escalona, n.d.). In collaboration with Loewe, the designer creates garments integrated with living plant systems in which nature is neither represented nor simulated: it just becomes an integral part of the garment's life cycle (Fig. 03).

The plants, germinated and cultivated within the fabrics, require constant care from the wearer, establishing an increasingly entangled relationship between the human and the vegetal realm. As Escalona herself states, "we have to care for our garments in order to care for our environment" (No Kill Mag, 2023), thereby subverting the throwaway logic and establishing an ethics of care, as theorised by Puig de la Bellacasa (2017). These performative practices reveal the possibility of a fashion that does not merely speak *about* nature, but *with* nature, in a shared process of worlding (Haraway, 2016).

ChromaPhy, a speculative project developed at the Textile Futures Research Centre at Central Saint Martins, brings this reflection into the field of synthetic biology. By integrating genetically modified bacteria capable of reacting to the skin's pH and changing colour, the garment becomes a living interface between biology, environment, and corporeal identity (Collet, 2012). At this stage, fashion configures itself as a bio-sensing medium, in which intelligence is distributed across living systems and genetic protocols. At the same time, innovations linked to self-growing materials such as *Mylo*™, a mycelium-based material developed by Bolt Threads and adopted by Stella McCartney, demonstrate how biofabrication may become a tool for the ethical reconfiguration of material use in fashion: these materials no longer imitate nature; they are nature.

A more speculative direction that redefines fashion design systems as entangled, is manifested in the projects of the London-based brand Auroboros. Their creation, *Biomimicry Dress*, represents a paradigmatic example of hybridisation between digital aesthetics and biological simulation (Zwieglinska, 2021) (Fig. 04). The dress, capable of changing colour and shape in real time, was worn by the artificial intelligence (AI) robot Ai-Da during the 2021 London Design Festival. The gown was designed using parametric drawing tools, its structure sculpted from

Fig. 03

Fig. 04

recycled plastic, while the garment's stratigraphy follows a performative logic: the outer surface is chemically programmed to react, evoking metabolic and morphogenetic dynamics typical of living systems. This approach aligns with Oxman's notion of material-based design computation, wherein biological and digital processes converge into a continuous design-technology paradigm (Oxman, 2010). The dress operates as a hybrid autonomous system, in which visual transformation is triggered by external environmental conditions (humidity, air, oxidation). *Biomimicry* thus presents itself as a post-digital artefact that integrates nonhuman generative systems, chemical synthesis, parametric modelling, AI, and responsive materials, transcending the dichotomy between nature and technology (Parisi, 2019).

SYMPOIETIC ASSEMBLAGES

The concept of sympoietic assemblage emerges as one of the most promising lenses to read these design approaches, offering a conceptual lexicon capable of accounting for multispecies alliances and distributed processes. It is from this notion that the following theoretical investigation unfolds.

Karen Barad's (2007) concept of *intra-action* deconstructs the distinction between subject and object, asserting that identities emerge from material and discursive entanglements. The concept of vibrant matter (Bennett, 2010), on the other hand, attributes agency to what has historically been considered passive, promoting an aesthetic of co-agency. Within this framework, design becomes an ontogenetic event in which it is necessary to "stay with the trouble" (Haraway, 2016), cultivating provisional alliances with nonhuman, material, and environmental entities. Tim Ingold (2011), in this regard, proposes understanding design as a continuous dialogue between materials and trajectories of growth, embracing the concept of relational ecology, a notion also central in the work of Anna Tsing (2015), who, through the lens of precarious assemblages, reveals how modes of coexistence between species, environments, and infrastructures challenge linear and modernist narratives of design. Complementary to these perspectives is the work of María Puig de la Bellacasa (2017), who argues that design must take the form of speculative care: a practice that attends to the interdependencies and vulnerabilities of the actors involved.

The concept of sympoietic assemblage proposed in this contribution is situated within the broader field of ontological design, as articulated by Arturo Escobar, who maintains that design configures modes of being, perceptions, affects, and worlds: "we design the world, and the world designs us back" (Escobar, 2018, p. 4). The term *assemblage* was introduced by Deleuze and Guattari in *A Thousand Plateaux* as a heterogeneous, dynamic, and contingent entity composed of both human and nonhuman elements: "An assemblage [...] is a multiplicity which is made up of heterogeneous terms and which establishes liaisons, relations between them" (Deleuze & Guattari, 1987, p. 22). While the idea of *assemblage* introduced by Deleuze and Guattari (1987) breaks with the logic of organic unity and linear causality, it is with Haraway (2016) that this multiplicity becomes radically co-productive. Drawing on and reworking this intuition through a posthuman lens, Haraway coins the notion of *sympoiesis*, literally, "*making-with*." Unlike autopoiesis, which presupposes a closed and self-producing system, sympoiesis is open, relational, and situated.

In the context of fashion design, speaking of sympoietic assemblages entails shifting away from a teleological and anthropocentric conception of design toward an ecological and interactive process, where matter itself, living organisms, responsive materials, algorithms, technologies, and environments partake in the formal and functional invention of the project. Data and technologies likewise become co-agentive and co-productive elements through the elaboration of environmental inputs involving sensors, bio-digital interfaces, and generative algorithms. Data functions as a living interface between matter and body: through the deployment of generative algorithms, bio-digital interfaces, and machine learning, design becomes a situated and relational event in which living matter, environmental stimuli, and corporeal behaviours co-emerge according to an intra-active logic. This approach is particularly evident in fashion tech projects that integrate responsive materials and biosensing textiles, where biometric information actively participates in the aesthetic and functional formation of the garment (Berzowska, 2005; Seymour, 2009). The idea of sympoietic design thus manifests itself in the dissolution of the subject-object divide, wherein data co-constructs the interaction between human and nonhuman actors.

CONCLUSION

The analysis developed in this contribution articulates a sequence of conceptual shifts through which the relationship between fashion design and nature is progressively reconfigured. From early biomorphic imaginaries, in which nature operated as a morphological and symbolic archive, to biomimetic approaches grounded in functional translation and systemic modelling, further informed by notions of exaptation and more-than-human relationality, the paper delineates a constellation of fashion design paradigms. Although these configurations have been discussed along a progressive and sequential trajectory, they persist within contemporary fashion practices as often coexisting modes of engagement with the living. Nature takes shape within this stratified horizon, as a plural and dynamic construct, articulated through shifting roles of form and relation. The concept of exaptation contributes to this articulation by foregrounding processes of latency through which existing structures acquire renewed significance, fostering a specific epistemic attunement (Gould & Vrba, 1982; Melis & Pievani, 2022). More-than-human perspectives further extend this sensibility, situating fashion within relational ecologies in which, biological, and technological agencies participate in shared processes of becoming (Haraway, 2016; Puig de la Bellacasa, 2017). The act of designing for fashion thus takes shape as a situated process unfolding through co-emergent materialities. Fashion, positioned at the intimate interface between body, technology, and nature, offers a sensitive site for observing how material, biological, and computational agencies are configured through practice (Barad, 2007).

It is within this domain of interactions that the contribution proposes a critical framework for understanding the ways in which the negotiation between contemporary vestimentary practices and ontological assumptions about nature takes form in design experiences. The reading advanced here highlights how the different configurations through which fashion design has thought and operated nature constitute a stratified ensemble of projectual postures. That continue to act simultaneously in the present. The originality of the contribution lies in assuming this coexistence as a critical object, rendering legible an epistemic transformation that traverses biomorphism, biomimetics, exaptation, and more-than-human perspectives as articulations of a shared field of inquiry. The fashion field thus emerges as a theoretically productive domain, capable of making visible ontological shifts in the relationship between design, technology, and the living through practices in which nature progressively enters the operative and relational conditions of the project. In dialogue with theories of ontological design and intra-action, fashion is situated today within a relational ontology shaping the very conditions of design and giving rise to systems in which living matter operates as material intelligence and generative force in the production of garments.

CAPTIONS

[Fig. 01] Iris van Herpen, Sensory Seas, Look 20 (2020).

In this sculptural ensemble from the Sensory Seas collection, Iris van Herpen choreographs a visual and material symbiosis between the neural intricacies of the human body and the fibrous architectures of marine ecologies. Drawing from the anatomical drawings of Spanish neuroscientist Ramón y Cajal, the garment materializes a computational biomimesis in which the aesthetics of the organic emerge through algorithmic layering, laser-cut membranes, and flowing textile stratifications.

[Fig. 02] Speedo Fastskin™ and biomimetic microstructure of shark skin. This diptych illustrates the translation of biological intelligence into high-performance sportswear through biomimetic design. On the left, the Speedo Fastskin™ swimsuit, originally developed for competitive swimming, emulates the drag-reducing microstructures found in shark skin. On the right, an electron microscope image reveals the dermal denticles of a shark: ribbed, overlapping scales that channel water efficiently to minimize turbulence. Rather than aesthetic mimicry, this is a paradigmatic case of functional biomimesis, where material innovation is driven by performance rather than form. In doing so, the garment becomes a technical interface that extends the body's hydrodynamic potential through a silent alliance with nature's evolved morphologies.

[Fig. 03] Auroboros, Biomimicry (2021).

This wearable sculpture by fashion-tech duo Auroboros exemplifies a sympoietic assemblage, where material science, couture craftsmanship, and speculative ecology converge. The garment is grown. Crystals develop organically across a prepared understructure through a self-directed crystallization process, much like plants forming over time on a nutrient-rich surface. This procedure resists full control, producing unpredictable yet materially specific formations. Supported by scientific collaboration with Queen Mary University of London and material partnerships with Swarovski and Tiranti, the process reflects a deep entanglement between biology and design. Rather than acting as a static shell, the garment co-evolves with its medium, embodying an ontological shift from fashion as form to fashion as emergent material ecology. In Auroboros' practice, the boundaries between physical and digital dissolve as both garments are shaped by iterative, collaborative, and non-linear systems of making.

[Fig. 4] Paula Ulargui Escalona x Loewe, Spring/Summer 2023. In this collaboration with Loewe, designer Paula Ulargui Escalona cultivates garments as living systems, integrating germinating plants directly into the fabric structures. Rather than representing nature through symbolic or biomimetic motifs, the pieces enact a literal incorporation of the vegetal. The garments must be watered, tended to, and cared for by the wearer, thus establishing a symbiotic dependency between human and plant. In this sense, fashion becomes a temporal, metabolic, and co-evolving practice—no longer an object to be consumed, but a living assemblage that unfolds relationally over time. The collection offers a radical gesture toward more-than-human design, where dressing becomes a mode of cohabitation rather than adornment.

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FILM REVIEW AND PROJECT WORK

FROM THE WALL TO THE SCREEN

FASHION VICTIMS 2.0
AN ANIMATION SHORT FILM REVIEW

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Abstract

This article reviews an acclaimed Spanish animated short film created by María Lorenzo in 2023 as a tribute to urban artist Escif. Based on his mural painting Fashion Victims, controversial for its criticism towards an industrial model that is both massive and unsustainable, but which has eventually become a hallmark of the Valencian neighborhood where it is located, the short film Fashion Victims 2.0 brings the mural's characters to life based on photographs of it to denounce our passivity towards child labor and its questionable conditions in developing countries. The film was screened at the 2024 Cyprus Fashion Film Festival.

Keywords: *Fashion Victims; María Lorenzo; Escif, Street Art; Animation*

It all begins in January 2022. Valencian artist Escif is commissioned to create a mural, the production of which will be captured by the cameras of a documentary about Equipo Crónica, the paradigmatic artistic duet of the Spanish Transition that brought the social and political reality of the moment to the galleries through a pop aesthetic that channeled a profoundly revisionist perspective. Under the slogan "Can art be a weapon?", the documentary *Equipo Crónica. Trench Art*, directed by Rafa Sesa and Felipe Villaplana, would not be premiered until 2025. In this time span, Escif's mural, which was announced as temporary in the chosen location —a municipally owned wall, behind the Bullfighting Museum and strategically located in front of the busy store of a well-known multinational fashion company— continues to stand as an independent voice that has inherited the critical bias of the Valencian team composed at the time by Manolo Valdés and Rafa Solbes. And although the one-year deadline agreed between the production company Zootropo Studio and the city council has largely expired, the municipal ordinance that was supposed to activate its deletion has been suspended indefinitely (Devís, 2024, n/p).

This achievement has been a landmark for Escif —first nicknamed Escyf—, who began his career as a graffiti writer in 1996 and has since established himself as a consolidated artist at museums, galleries and completing major commissions such as the Valencian Fallas, though without losing the nonconformist and deeply uncomfortable vision he displayed in his early murals, now lost, which populated his hometown during the wave of protests during the Valencian Spring of 2012. Known as the Spanish Banksy, Escif has left his mark on walls around the world, including countries devastated by war and commercial exploitation, such as Lebanon, Syria, and Indonesia, experiences that underscore his sincere activism for a more just and egalitarian world. As Escif asserts, 'a painted wall ceases to be a boundary and becomes an open channel of communication [...] demonstrating that another world is possible, opening a rift in the heart of the city' (Escyf, 2010, p. 91).

The criticism in Escif's painting is all the more effective because it is devoid of artifice: his scenes present alienated characters, their expression absent in a strangely aseptic world dipped on gray and muted tones that is, however, distorted by some inexplicable presence: through visual irony, Escif reveals our inexplicable tolerance towards corruption or injustice, both towards problems in our society and towards otherness, the inhabitants of other countries to whom we are inevitably connected through our decisions, such as our consumption habits. In his own words, Escif always tries 'to erase (or at least blur) the boundaries between life and spectacle, between presentation and representation, between contemplation and experience, between landscape and territory, between the power of institutions and the power of people' (Escif, 2024, p. 285).[1]

Following this ideology, the painting *Fashion Victims* (Fig. 01) is deliberately designed to stir consciences, depicting a group of children working in a Southeast Asian textile workshop; surrounded by foremen and the piles of clothing they produce, hovering above them the catalog prices of the well-known affordable clothing brand whose headquarters are on the same corner. The heartbreaking presence of the mural in the square leaves no one indifferent since it invites the passersby see, as María Lorenzo notes, 'both sides of the same coin: buying affordable clothing from a multinational also means collaborating with that kind of unsustainable market.' (ZF Team, 2024, n/p).

This powerful image was the inspiration for María Lorenzo, an animator who began her journey in short-form cinema when she studied Fine Arts in the late 1990s. She is fond of incorporating the diverse languages of art into her productions, creating films from a more pictorial style that draw on the realism of Joaquín Sorolla and John Singer Sargent (*Portrait of D.*, 2003; *The Night Ocean*, 2015) to tributes to the world of pre-cinema (*Impromptu*, 2017) and fictions that draw on the aesthetics of *film noir* and Expressionist cinema (*The Carnivorous Flower*, 2009; *The Cat Dances with its Shadow*, 2012; *Felina*, 2024). Street Art, a movement with a strong presence in Valencia, has not been an exception to María Lorenzo, who created *Urban Sphinx* taking from more than 3,000 photographs showing various pieces of paste-up, stencil art and murals found on the street between 2018 and 2019. In this film, María Lorenzo also approached for the first time the idea of animation as an archive for Street Art: while graffiti and other manifestations are, by their nature, ephemeral works, animation records their memory forever.

When María Lorenzo made *Fashion Victims 2.0*, the challenge was to start from a single image: the mural by Escif, which in turn showed a multiplicity of characters (children, foremen), objects (sewing machines, clothing), and symbols (prices and names of garments). Each of these elements could then be divided into sub-elements: heads, feet, hands, the sewing machine wheel, the needle, etc. During two photo sessions, general images and details of all the elements were collected to play with the montage and create short films: hands moving the fabric, heads turning, the needle sewing, the piles of clothing growing... In the film's editing, these scenes were distributed, accompanied by the sound of sewing machines, creating a progression toward a climax, increasing the speed of the succession of scenes, until the sound of the machine abruptly stops when one girl looks at the camera. The film ends with the title 'Fashion Victims' painted on the mural, as drops of paint fall from it (Fig. 02).

In María Lorenzo's words, she has 'intended to transmit the exact message of ESCIF, without any alteration of the image, other than that which involves cutting up the frames and composing a hypothetical movement' (ZP Team, 2024, n/p), although following the same author, who wrote the essay 'The transforming power of animation on Street Art',

Animation's essential contribution to urban art is to make visible what is invisible to the eye: to bring to life an image, an object that, paradoxically,

1 Translated by Graham Bell


3 SUJETADORES
ALGODON 10€
CHAQUETA
SUPER LIGERA 17€
BLUSA 9€
JERSEY CUELLO
REDONDO 7€
CAMISETA
MANGA LARGA 4€
CAMISETA
CUELLO
REDONDO 3,5€
CAMISON 6€
CAMISETA 2,5€
3 SUJETADORES
ALGODON 10€
LEGGINS 13€
CARDIGAN
PUNTO FINO 12€

Fig. 01


FASHION VICTIMS

Fig. 02

remains static, but which in its animated form transforms into something impossible to perceive with the naked eye. Like the ancient art of Anamorphosis, animation *reanimates* Street Art because it brings it to life by showing it from a different, lateral, artificial, and unexpected angle. (Lorenzo, 2022, p. 92) [2]

In *Fashion Victims 2.0*, the transformation of the mural into animation (Fig. 03) occurs thanks to a completely experimental vision of the medium: if other murals by Escif had previously been animated by turning the painted images into animated characters in a traditional way, as Silvia Carpizo did in her 2013 short film, *Alienation*, creating a narrative dynamic, Lorenzo's strategy is more similar to that of animators who experiment with the limits of the animated medium, such as Paul Bush or, especially, Gil Alkabetz, 'whose game between the still, the inanimate and motion, animating the changing forms at hyper speed, establishes a privileged relationship between animation and the world of objects' (Lorenzo, 2020, p. 649). Parallels can be drawn between *Fashion Victims 2.0* and Gil Alkabetz's short film *The Da Vinci Time Code* (2009), created entirely from an image borrowed from Leonardo Da Vinci, none other than the mural *The Last Supper*, which becomes a lively gathering through the careful selection of frames and the combination of photographs that create visual rhythms.

Fashion Victims 2.0 was presented to the audience under a challenging tagline: 'An inconvenient truth: the Western fashion industry is sustained by forced child labor in the Third World. Will you continue to tolerate it?' Despite this, the short film's format, faithful in spirit to Escif's mural, maintains a subtle and distant tone. For Vassilis Kroustalis, '*Fashion Victims 2.0* looks almost like a procedural, business-as-usual film […]. The visual texture reinforces the taste of the garment to be worn, while the sound design makes it obvious that this is a repetitive, mundane procedure' (ZP Team, 2024, n/p). Also, by the time of its premiere at Annecy 2023, Ray Laguna stated that the most striking quality of *Fashion Victims 2.0* is that,despite working with such limited material, [María Lorenzo] squeezes it in such a creative way that, at a certain point,

2 Author's translation

Fig. 03

it seems as if the mural has come to life or, even more extraordinary, that they are paintings made expressly for an animated piece. The proposed exercise in minimalism is enormously suggestive. (Laguna, 2023, n/p)

[3]What becomes evident when seeing *Fashion Victims 2.0* is that the mural's transformation to animation doesn't change its message but rather amplifies it. Its short duration, with its rhythmic *crescendo* and the deliberate absence of dialogue and music, gives the viewer room to interpretations. To date, the film has been selected at 75 film and animation festivals from 20 countries, with particular mention for its inclusion in programs focusing on environmental, documentary, and social themes at festivals such as Rising of the Lusitania – Animadoc 2023, Festival de Cine de Málaga 2024, Stuttgart Animation Festival 2024, Palm Springs AmDocs 2024 or Cine-Court Animé de Roanne 2024, as well as its selection at the 2024 Cyprus Fashion Film Festival. It was also screened at Cannes Film Festival 2023 within the program *Revelations. New Spanish Animation Short Films* curated by Carolina López Caballero. Despite its fiercely experimental nature, and the fact that it is based on a painting rather than a filmed reality, *Fashion Victims 2.0*'s presence at numerous documentary film events allows us to understand the scope of the social critique expressed in Escif's work, which spreads a vision rarely represented in the media. It also demonstrates Lorenzo's desire for non-intervention in his urban art films (Fig. 04), which become veritable the archive of ephemeral yet unforgettable images.

3 Author's translation.

Fig. 04

CAPTIONS

[Fig. 01] Escif; *Fashion Victims* mural by Escif as it appears in the film *Fashion Victims 2.0*; María Lorenzo courtesy.

[Fig. 02] María Lorenzo; title of film *Fashion Victims 2.0*; María Lorenzo courtesy.

[Fig. 03] Escif; *Fashion Victims* detail of a working young girl by Escif as it appears in the film *Fashion Victims 2.0*; María Lorenzo courtesy.

[Fig. 04] María Lorenzo; affiche of film *Fashion Victims* 2.0; public domain.

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HER NAME WAS SIMULATION

HER BODY WAS NEVER REAL

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Abstract

In the age of hyperreality, fairy-tale aesthetics are no longer illusions, they constitute the aesthetic logic of the real. My MA graduation collection, Her name was Simulation; her body was never real, explores the image-body: a form detached from physical referents and endlessly reproduced through fashion and media. Drawing on Jean Baudrillard's theory of the simulacrum, particularly the "third order" of signs, the project investigates bodily dislocation, visual deception, and technological idealization. Through textile manipulation, 3D printing, and prosthetic-inspired construction, I created garments that simulate artificial structures while maintaining tactile softness. Key designs incorporate spherical forms and inflated volumes, inspired by Eva Fàbregas' Pumping, to evoke a hybrid of the organic and the synthetic. The concept of the grotesque body, open, incomplete, transformable, guides the visual language of fragmentation and porous boundaries, where the body becomes a mutable image-space. Pastel colors associated with girlhood are recontextualized to critique aesthetic norms shaped by digital culture. Ultimately, the project constructs a narrative grounded in simulation: a body in perpetual transformation, an identity sculpted by signs, and an ideal that never belongs to reality. It asks: Does the body still belong to us, or has it been fully absorbed by the regime of images, filters, and tags?

Keywords: *Simulacrum; Image-body; Hyperreality; Fashion and Technology; Grotesque body*

In the age of hyperreality, fairy-tale aesthetics are no longer illusions; they have become the very aesthetic logic of the real. My MA graduation collection project, Her name was Simulation; her body was never real, begins from this theoretical and visual premise. It develops a series of critical explorations concerning bodily dislocation, the deceit of images, the aesthetics of the simulacrum, and the way idealized images are constructed through fashion, technology, and media.

The conceptual foundation of this series derives from Jean Baudrillard's Simulacres et Simulation (1981). Here, the simulacrum is not merely a copy, but a sign that has liberated itself from any referent, circulating autonomously within the order of signs. I have translated the idea of the "third order of simulacra" (*Baudrillard*, 1981) into a visual language that no longer refers to any real body: an image-body eternally reproduced, yet never possessing physicality. I imagined a character named Simulation. Her body has never actually existed. She is not a human being, but a perfect image within the symbolic order, a projection of ideal beauty shaped by the filters of social media, a fragmented body, modeled, extended, dissected, and modified.

Her apparition poses a fundamental question: How can we perceive the body in an era governed entirely by images? And how can we move from seeing to reconstructing? To answer these questions, I adopted "simulation" as a design

Fig. 01

methodology. Starting from traditional techniques, I created a wool-felt skirt with an overtly artificial appearance (Fig. 01). Its surface is adorned with protruding elements resembling simulated belts, creating a plastic illusion while preserving a tactile softness. This contrast between “soft” and “hard,” between “real” and “replicated,” lies at the core of my research. The felt technique allowed me to build three-dimensional volumes from two-dimensional drawings. This method of constructing volume from surface led me to reconsider the language of prosthetics, transforming the body itself into an image space to be recoded. This handcrafted simulation of a “technological” aesthetic serves as my response to the image-body paradigm. In the era of new media, our bodies increasingly obey the logic of the visible rather than the perceptible. The angle of your selfie, the filter you select, the way you manage your facial expressions, all converge toward a perfectly rendered self that, in truth, has never existed. This reminds me of the eternally youthful portrait in The Picture of Dorian Gray (*Wilde*, 2003), and of the ever mutating beauty standards of pop culture: You never truly change, but you must constantly transform.

Mikhail Bakhtin proposed the concept of the grotesque body (*Bakhtin*, 1984): an incomplete, open, and symbiotic body. This concept deeply resonates with my work. I began investigating the body’s extendability and instability. Within this framework, I developed three pieces centered on spherical forms: a yellow top with embedded spherical elements, a long white skirt composed of ball-like volumes, and a tubular pink belt integrated into a knitted dress (Fig. 02). These pieces were inspired by Eva Fàbregas’ installation Pumping (2019), which features inflatable, floating, sensual structures somewhere between organs and machines. Fàbregas’ visualisation of symbiosis between body and technology encouraged me to integrate spherical volumes into my designs, using tactile materials that merge bodily contours and artifice, blurring the line between inside and outside.

In addition to these, I designed a 3D-printed baseball cap to accompany the pink knitted dress, intending to explore the mutability of materiality itself (Fig. 02). This piece acts as a tangible experiment in simulation and substitution, where

Fig. 02

digital fabrication challenges the boundaries between the organic and the artificial, questioning how materials can be manipulated and replaced while retaining symbolic resonance within the body's extended image.

For instance, in the yellow sleeveless top, the spheres are positioned at the waistline (Fig. 03); in the white skirt, they extend across the front and back, as if active genetic molecules were unfolding from within the body (Fig. 04). The pink spherical belt resembles the rhythmic motion of bubbles, winding around the waist. These elements are intended to evoke a dual association: the technological simulacrum and the tactile qualities of the human body. They also raise further questions: How can the body become unstable, heterogeneous, and incomplete? How can it extend from within, merging with others, with the environment, with time? And through what means can a subject be entirely replaced by its own simulacrum?

This obsession with bodily transformation is also reflected in other experiments in my collection. I used padded inserts to create unnatural shapes at the hips and waist, drawing inspiration from Georgina Godley's sculptural silhouettes and Rei Kawakubo's theatrical costumes for Scenario (1997). Hans Bellmer's disjointed, fragmented, mirrored, and reassembled dolls have profoundly influenced my understanding of dislocated structures, which is evident in the repetition of exaggerated shoulders and joint elements in my work.

Beyond bodily structure, I am also concerned with the instability of the face. I created a knitted balaclava that covers the mouth (Fig. 02), inspired by the textile masks of Louise Bourgeois, 40 Portraits by Gisèle Vienne, and the photographic series Poupée de Peau by Ninot. All these references speak to a shared obsession: How can we maintain a sense of self in a society dominated by images? Have we become dolls under "sweet" filters, concealing the void beneath a kawaii aesthetic? For this reason, I selected seemingly innocent colors: pastel pink, pale yellow, mint green, and white. These are shades traditionally associated with "girlhood imagery," but in my vision, they function as a critique of the dominant aesthetic. I use "visual pleasure" as a vehicle for a deeper sense of discomfort.

Ultimately, I constructed a narrative system based on the aesthetics of the simulacrum: a body in perpetual transformation, an identity sculpted by images, an ideal that never belongs to reality. This project has led me to ask repeatedly: Does the body still belong to us? Or has it become the property of images, filters, and tags? Through fashion, I strive to challenge the relationship between clothing and the body, to expand the limits of the "skin," and to simulate a double that can never be touched.

Fig. 03

Fig. 04

CAPTIONS

[Fig. 01] Handcrafted three-dimensional felted wool skirt. Designer: Yulin Zhang; From the MA graduation project Her name was Simulation; her body was never real; Photograph by Peishan Lee.

[Fig. 02] Pink spherical knitted dress with 3D-printed cap and knitted balaclava mask; Designer: Yulin Zhang; From the MA graduation project *Her name was Simulation*; her body was never real; Photograph by Peishan Lee.

[Fig. 03] Left: Pink spherical knitted dress paired with 3D-printed cap. Right: Yellow top with spherical belt detail, worn with padded inflated shorts and white knitted balaclava-cap. Designer: Yulin Zhang; From the MA graduation project *Her name was Simulation; her body was never real*; Photograph by Peishan Lee.

[Fig. 04] White tweed jacket with structured shoulder pads, paired with a white spherical midi skirt. Designer: Yulin Zhang; From the MA graduation project *Her name was Simulation; her body was never real;* Photograph by Peishan Lee.

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