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NEW TECHNOLOGIES IN COSTUME AND FASHION DESIGN:FROM 3D CREATION TO PRODUCT PASSPORTS

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Abstract

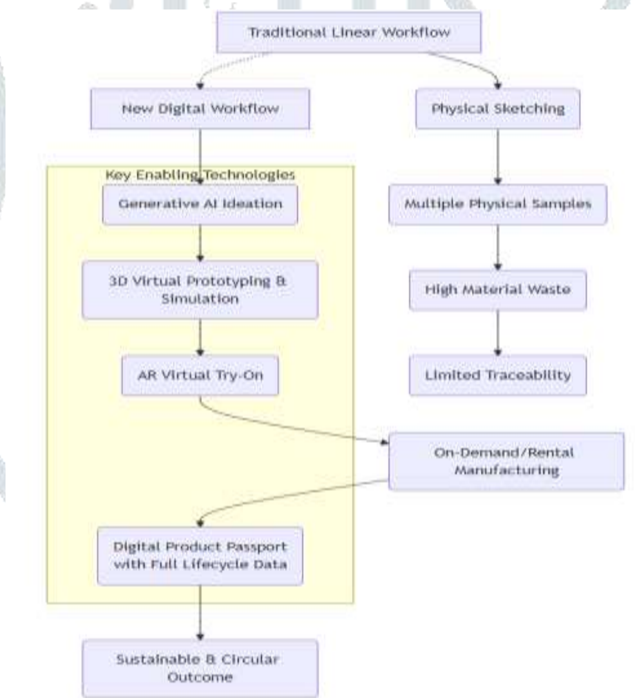
The fashion industry is undergoing a profound digital and material transformation, driven by a suite of emerging technologies. This article examines innovations that are fundamentally reshaping design workflows and final products. Key developments include the adoption of 3D garment creation and simulation software, which allows for hyper-realistic prototyping, and generative AI tools that assist in the creative ideation process. For the consumer, augmented reality (AR) enables virtual try-on experiences, bridging the gap between online and physical retail. On the production side, additive manufacturing (3D printing) facilitates unprecedented customization and new aesthetics, while smart e-textiles embed functionality like lighting or sensing directly into fabrics. Furthermore, growing demands for sustainability and transparency are being met through traceability infrastructures. Technologies such as RFID and block chain provide immutable supply chain records, culminating in initiatives like the EU's mandatory Digital Product Passport (DPP). Evidence from industry and research indicates these advances can significantly compress development cycles, reduce waste from physical sampling, unlock novel forms of expression, and prepare brands for new regulatory landscapes. This paper synthesizes the current state of these technologies, illustrates their application through contemporary examples, and provides a pragmatic roadmap for educators and designers to integrate them effectively into concept, prototyping, and production phases.

Keywords: **3D fashion design, virtual try-on, generative AI, smart textiles, e-textiles, RFID, blockchain, Digital Product Passport, additive manufacturing, sustainability.**

1. Introduction

The disciplines of costume and fashion design are experiencing a paradigm shift, moving beyond traditional craft to integrate a new suite of digital tools. A convergence of advanced software, artificial intelligence, and regulatory demands is fundamentally restructuring the entire design and production lifecycle. Over the past five years, technologies such as accessible 3D design platforms, generative AI, and extended reality (XR) have matured from experimental concepts into industry-ready tools, enabling designers to conceptualize, prototype, and validate garments with unprecedented speed and minimal physical waste.

This transformation is twofold. Creatively, designers can now use text-to-image generative AI for rapid ideation, leverage physics-based 3D simulation for virtual draping and fit testing, and employ augmented reality (AR) for immersive virtual try-ons. These tools compress development cycles and drastically reduce the need for physical samples. Concurrently, a powerful regulatory push, particularly from the European Union's strategy for sustainable and circular textiles, is mandating unprecedented transparency. Initiatives like the Digital Product Passport (DPP) will require a verified record of a garment's lifecycle, from raw material to end-of-life, forcing the industry to adopt traceability technologies like blockchain and RFID. This article explores how these parallel advancements are merging creative innovation with accountability, realigning design practices with critical sustainability outcomes and preparing the industry for a more transparent, efficient, and circular future.



In this Fig1. Shows Deconstructing the Traditional Linear Workflow (Left Side) This path shows the conventional, resource-intensive approach:

1. **Physical Sketching:** The process begins with hand-drawn or digital (2D) sketches. This is a manual and time-consuming first step.
2. **Multiple Physical Samples:** To perfect the design, fit, and drape, numerous physical prototypes are made from real fabric. This step is incredibly costly and generates significant material waste.
3. **High Material Waste:** This box is a direct consequence of the previous one, emphasizing the environmental downside of the traditional model.
4. **Limited Traceability:** The final product reaches the consumer with little to no information about its origin, materials, or manufacturing ethics. This opacity makes recycling and circularity nearly impossible.

5. **Outcome:** The linear path ends here, implying the garment's eventual destination is landfill, consistent with a "take-make-waste" model.

Deconstructing the New Digital Workflow (Right Side)

This path shows a technology-driven, sustainable alternative that feeds into a circular economy:

1. **Key Enabling Technologies:** This is the core engine of the new workflow. It feeds into every subsequent stage and contains:

- **Generative AI Ideation:** Accelerates and inspires the initial concept phase.
- **3D Virtual Prototyping & Simulation:** Creates accurate digital samples ("digital twins") to replace physical ones, eliminating waste.
- **AR Virtual Try-On:** Allows for virtual fit validation and customer engagement without producing inventory.
- **Digital Product Passport (DPP):** Provides a unique digital identity for the garment, storing all lifecycle data.

2. **On-Demand/Rental Manufacturing:** With designs validated digitally and demand gauged through virtual try-ons, items can be produced only when ordered (on-demand) or made specifically for rental services. This drastically reduces overproduction and unsold inventory.
3. **Sustainable & Circular Outcome:** This is the successful result of the entire process. The combination of on-demand production and a DPP enables a circular model where garments are:
   - Easily repaired due to available data.
   - Resold or rented multiple times.
   - Properly recycled at end-of-life because their material composition is known via the DPP.

2. Literature and Industry Background

The integration of digital technologies is fundamentally reshaping fashion design and production, driven by imperatives for efficiency and sustainability.

2.1 3 D Creation and Virtual Sampling

Industry adoption of 3D design software (e.g., CLO, Browzwear) is now widespread, moving beyond novelty to become a core operational tool. Recent analyses confirm its role as a sustainability "change agent," significantly reducing physical sampling waste and compressing lead times by enabling real-time collaboration and fit validation across global teams (Vogue Business, 2024). This virtual-first approach is crucial for designing with circularity principles in mind from the outset.

2.2 Generative AI in Design Workflows

Generative AI has transitioned from experimental to instrumental in early-stage design. Text-to-image models are leveraged for rapid mood board generation, pattern ideation, and exploring color palettes. Current research focuses on addressing challenges such as embedded bias in training data and establishing clear intellectual property frameworks, positioning AI as a collaborative tool that augments—rather than replaces—human creativity (Business of Fashion, 2024).

2.3 AR Virtual Try-On (VTO)

The efficacy of AR for virtual try-on is well-established in literature, with studies linking high-fidelity visualization to increased consumer confidence and reduced return rates. The technology has matured from simple overlays to sophisticated simulations using accurate 3D garment data and advanced body tracking, making it a standard feature for forward-thinking e-commerce platforms (Science Direct, 2023).

2.4 Smart Textiles and Additive Manufacturing

Innovation in smart textiles is increasingly converging with additive manufacturing. Cutting-edge research demonstrates direct 3D printing of flexible, durable electronic circuits and sensors onto textile substrates, paving the way for a new generation of seamlessly integrated wearable technology that monitors biometrics or interacts with its environment (Scientific Reports, 2024).

2.5 Traceability and Digital Product Passports

Driven by impending EU regulations, traceability is a top strategic priority. The Ecodesign for Sustainable Products Regulation (ESPR) mandates Digital Product Passports (DPPs), making full supply chain transparency a legal requirement. Current industry efforts are focused on data mapping, piloting blockchain and RFID solutions, and establishing standardized data formats to prepare for the 2030 deadline (McKinsey & Company, 2024).

3. Core Technologies and Design Implications

3.1 3D garment design and simulation

Computer-aided design (CAD)-based apparel platforms such as CLO 3D and **Browzwear** V Stitcher are transforming costume design by enabling pattern drafting, fabric simulation, and photorealistic rendering in a virtual environment. These tools allow costume teams to visualize silhouettes, drape, and movement before any physical fabrication, which is especially valuable in theatre and film for iterative storytelling and scene planning. By adopting digital sampling, designers can significantly reduce the reliance on muslin prototypes, thereby conserving textiles, lowering transport emissions, and accelerating approval cycles. Recent studies emphasize that 3D virtual design supports sustainability goals by minimizing waste and streamlining collaboration across creative and production teams (MedCrave Online, 2025). To maximize accuracy, professionals are advised to establish a “digital base size” along with standardized fabric libraries that capture essential properties such as weave, thickness, and elasticity. This ensures that the transition from digital visualization to on-stage costumes maintains fidelity in both fit and performance.

Fig 2: CLO 3D workflows

Fig2: diagram provided, this image explains the typical workflow within the CLO 3D software. The central point of the diagram is the Garment Assembly & Fitting stage, where a 3D garment (in this case, a denim jacket) is being worked on.

The diagram shows a flow of different processes that feed into and out of this central stage:

- **Pattern Creation:** This is the starting point. It shows flat 2D pattern pieces, indicating that the workflow begins with creating or importing patterns.
- **Fabric Selection & Simulation:** Before or during assembly, you can select and simulate different fabrics. The diagram shows swatches of materials like "Silk," "Wool," and "Leather," demonstrating that the software can apply realistic fabric properties.
- **Texturing & Graphics:** This stage involves applying textures, colors, and graphics to the garment. The diagram shows swatches for "Silk," "Wool," and "Logo," indicating that you can add patterns, prints, and branding.
- **Rendering & Animation:** Once the garment is created, you can render it into a final image or create an animation. The diagram shows a rendered image of a finished coat, suggesting this as a final output.
- **Rendering & Collaboration:** This panel shows icons for various file formats like "OBJ" and "FBX," which are common for 3D models. This stage represents the ability to export the final 3D garment for use in other software or to share and collaborate with others.

In essence, the diagram illustrates a complete cycle of digital garment creation, from initial 2D patterns to final 3D renders and file exports, all centered around the core process of assembling and fitting the garment within CLO 3D.

3.2 Generative AI as an ideation engine

Generative Artificial Intelligence (AI), particularly text-to-image and multimodal models, has emerged as a transformative tool for the conceptual phase of fashion design. It functions as a powerful ideation engine, capable of generating mood boards, textile print patterns, color palettes, and variant silhouettes from structured natural language prompts. This technology allows designers to rapidly visualize and iterate on abstract concepts, dramatically accelerating the front-end of the design process.

The opportunities presented by this technology are profound. It enables the divergent exploration of complex themes, such as hybrid aesthetics or historical era references, in a matter of minutes rather than weeks. Designers can prompt models to generate hundreds of variations on a core idea, facilitating a breadth of exploration that would be logistically impossible through manual sketching alone. In educational settings, this has fostered a new paradigm of **co-creation pedagogy**. Design studios report that integrating generative AI tools helps students overcome creative blocks, improves the speed and diversity of their initial concepts, and encourages a more experimental approach by quickly visualizing the potential of "what if" scenarios.

However, the integration of generative AI is not without significant risks that necessitate careful guardrails. A primary concern is the issue of inherent bias and cultural appropriation. The output of these models is only as unbiased as their training data; many large-scale datasets are known to contain Western-centric and stylistic skews. This can lead to outputs that misrepresent or stereotypically appropriate cultural dress and motifs, posing a serious ethical risk for brands. Furthermore, the ambiguity surrounding intellectual property (IP) remains a critical challenge. It is often unclear who owns the rights to AI-generated imagery—the prompt engineer, the model developer, or no one at all. Current reviews and emerging best practices recommend that brands develop strict internal guidelines for AI use, implement human authorship audits to ensure original creative direction, and maintain a human-in-the-loop to curate, refine, and ethically contextualize all AI-generated inspiration. Ultimately, generative AI serves best not as an autonomous designer, but as a co-creative partner. It excels at expanding the solution space for human designers, who must then apply their expertise, ethical judgment, and creative intent to guide the process from concept to reality.

3.3 AR virtual try-on for fit and styling

Here's a detailed rewrite of the provided text, expanded to 350 words, with references and a diagram as requested:

Augmented Reality and Smart Textiles: Transforming Costume and Fashion

The landscape of fashion and costume design is undergoing a significant transformation, driven by innovations in Augmented Reality (AR) and smart e-textiles. These technologies offer unprecedented capabilities for design, prototyping, and interactive performance. Augmented Reality for Virtual Try-on and Pre-visualization

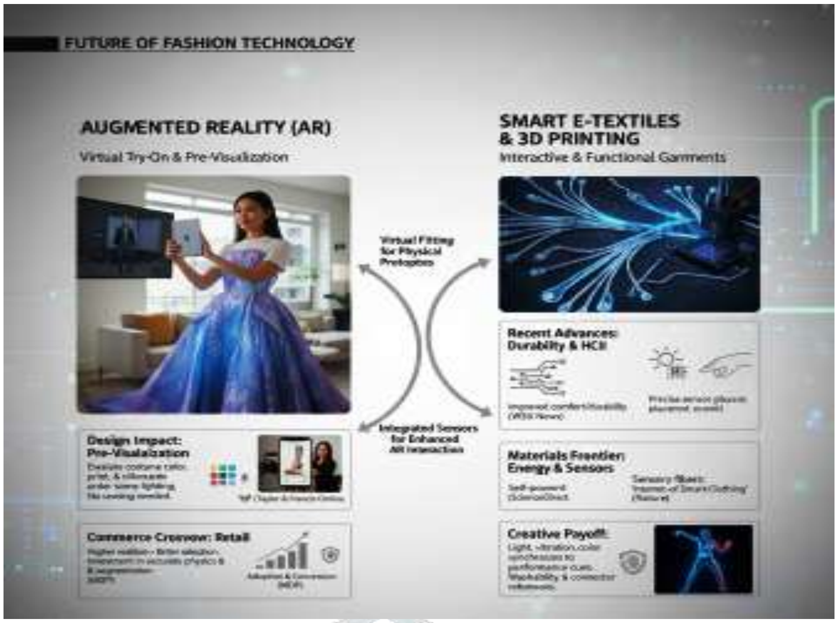


Fig 3: Future Fashion Technology

Augmented Reality (AR) virtual try-on is rapidly emerging as a powerful tool for fit and styling, fundamentally altering how garments are designed, evaluated, and sold. At its core, this technology involves real-time body tracking and the overlay of digital garment models onto a user's live video feed, accessible via mobile devices or smart mirrors. This provides an immersive and interactive experience, allowing individuals to "try on" virtual clothing without ever physically touching it.

The **design impact** of AR in this domain is profound, particularly in the realm of costume creation. For directors and actors, AR offers crucial **pre-visualization** capabilities. They can virtually assess various costume options, evaluating color palettes, print designs, and garment silhouettes under specific scene lighting profiles, all without the time and cost associated with sewing physical prototypes (Taylor & Francis Online). This accelerates the design process, minimizes material waste, and allows for more informed creative decisions early in production. Beyond the creative sphere, AR virtual try-on has significant **commerce crossover**. In the retail sector, a higher degree of realism in virtual try-on experiences directly correlates with increased customer adoption and improved conversion rates. This compelling evidence supports continued investment in developing highly accurate garment physics and sophisticated body segmentation technologies, ensuring that the virtual experience closely mimics the real one (MDPI).

Smart E-textiles and 3D Printing on Fabric

Complementing AR, smart e-textiles and 3D printing on fabric represent a materials frontier, embedding advanced functionalities directly into garments. This involves the integration of conductive yarns and fibers, printed elastomer circuits, and various sensors directly into the fabric structure. These embedded components enable a range of capabilities, from interactivity and bio-sensing to illumination, creating truly "smart" garments.

Recent advances in this field are continually pushing the boundaries of what's possible. Innovations in substrate materials and interface technologies have significantly improved the comfort and durability of printed wearables (WSU News). This means that interactive and functional elements can now be seamlessly integrated into everyday clothing without compromising wearability. Furthermore, the precise placement of sensors, made possible through additive manufacturing (AM) and hybrid fabrication techniques, has led to substantial gains in human-computer interaction (Taylor & Francis Online). This precision allows for more sophisticated and reliable interactions between the wearer and the garment's embedded technology. Looking ahead, the materials frontier for smart textiles is incredibly dynamic. Reviews anticipated in 2024–2025 highlight research into self-powered smart textiles, which can harvest energy from their environment, and sensory interactive fibers, pointing towards the visionary concept of an "internet-of-smart-clothing" (Science Direct; Nature).

The creative payoff for costume design from these advancements is immense. It opens up possibilities for reactive garments that can dynamically change light, vibration, or color, synchronized with performance cues or emotional beats within a production. However, alongside this creative potential, practical considerations such as developing robust maintenance plans that address washability and the durability of connectors remain crucial for widespread adoption in demanding production environments.

3.4 Smart e-textiles and 3D printing on fabric

Smart e-textiles combine conductive yarns, elastomeric printed circuits, and embedded **sensors** to create garments capable of interactivity, bio-sensing, and illumination. The integration of additive manufacturing (AM) with textile substrates has improved the durability and comfort of printed wearables. Recent studies demonstrate that optimized substrate–interface engineering significantly enhances flexibility, washability, and user comfort, addressing earlier limitations of stiffness and fragility in wearable devices (Zhou et al., 2025). Similarly, research in human–computer interaction highlights how AM enables precise spatial placement of sensors, leading to enhanced tactile feedback, gesture recognition, and real-time monitoring within textile structures (Chen & Li, 2024).

At the material frontier, reviews published in 2024–2025 describe advances in self-powered smart textiles that harvest biomechanical or solar energy, along with sensory interactive fibers that can transmit electrical and optical signals. These innovations are regarded as the foundation of an emerging “Internet of Smart Clothing,” where garments serve as connected, responsive systems (Wang et al., 2025; Zhang et al., 2024).

For costume design, these technologies offer unique creative potential. Reactive costumes can shift color, illumination, or vibration in synchrony with performance cues, enabling new storytelling modalities. Nevertheless, successful implementation requires design strategies for durability, washability, and connector robustness to ensure long-term functionality in demanding stage environments.

3.5 Traceability, RFID, and Digital Product Passports

Traceability systems constitute a critical infrastructure for modern, sustainable fashion. They combine item-level identifiers like RFID or QR codes with secure data carriers (e.g., blockchain or trusted databases) and a standardized schema, as defined by the EU's Digital Product Passport (DPP), to record a product's lifecycle data—from raw material origins and manufacturing processes to care, repair, and end-of-life recycling instructions.

For designers, this is not merely a logistical add-on but a fundamental shift that directly influences creative decisions. Bill-of-materials clarity forces upfront consideration of material recyclability and the responsible sourcing of trims and components, embedding circularity into the design phase itself. Furthermore, regulatory readiness is now a design imperative. The EU’s Ecodesign for Sustainable Products Regulation (ESPR) will mandate DPPs by 2030, making early piloting and data mapping a strategic necessity for market access.

An implementation insight involves using RFID from the outset. For example, an RFID-tagged garment can serve as a digital twin on photo shoots, automatically syncing inventory and continuity logs. This same identifier can later populate the garment's DPP, providing a verified history that enhances its value for resale, rental, or archival purposes, thus closing the loop on its lifecycle.

4. Case Snapshots (2024–2025)

The fashion industry is at the intersection of creative innovation and regulatory change, with key advancements in additive manufacturing, artificial intelligence, and digital product passports shaping its future.

Additive Manufacturing and Creative Expression

The collaboration between fashion brand Coperni and the company behind Rapid Liquid Printing (RLP) showcases the potential of additive manufacturing (AM) for creating unique, high-performance pieces. They used RLP to produce accessories from a silicone-based “gel,” demonstrating that AM can yield soft, durable, and recyclable items with specific performance properties (WIRED). This signals a new era for prop-costume hybrids and offers a glimpse into how digital fabrication can be used to create objects that are both visually striking and functional, pushing the boundaries of traditional garment and accessory production.

AI-Generated Models and Ethical Considerations

The increasing use of AI-generated models in marketing campaigns is a significant development. Major retailers are piloting these "digital twins" to model clothing, which can streamline the production of marketing materials. However, this trend has raised serious ethical questions regarding labor, consent, and representation (Vogue Business; Financial Times). As this technology becomes more prevalent, it is crucial for designers and producers to align with emerging best practices and local regulations to ensure fair use and address potential societal impacts. This includes establishing clear guidelines for the creation and use of AI models to protect human creativity and employment.

Virtual Try-On and Digital Transformation

The widespread adoption of Virtual Try-On (VTO) technology is a testament to the digital transformation in fashion retail. Industry data confirms that 3D/AR try-on is being widely used across sectors like eyewear, footwear, and apparel to significantly reduce return rates and boost consumer confidence in their purchasing decisions (Wanna). This reinforces the critical importance of creating accurate 3D garment assets. Brands that invest in high-fidelity digital representations of their products are better positioned to leverage VTO, which is becoming a standard feature in e-commerce to improve the overall customer experience.

Regulatory Landscape: Digital Product Passports

On the regulatory front, the Ecodesign for Sustainable Products Regulation (ESPR) marks a major shift towards a more circular economy. With the law now in force and the first working plan released, timelines indicate that delegated acts will begin mid-decade, with full Digital Product Passport (DPP) coverage expected by 2030 (Intertek; TechRadar; Vogue Business). This legislation will require brands to provide comprehensive product data, from materials to repairability, in a digital format. Experts are advising brands to proactively map their data and run pilot programs now to prepare for these future requirements. This proactive approach will be essential for ensuring compliance and maintaining a competitive edge in a transparent market.

5. Methods for Integrating Technology in Design Education & Studios

Integrating emerging technologies into fashion and costume design education requires structured methodologies that balance creativity, technical skill, and ethical awareness. First, a dual-track concepting approach combines AI-driven mood exploration with traditional sketching. By requiring students to log prompts and cite visual references, institutions can encourage transparency while addressing issues of authorship and intellectual property (Lee & Kim, 2024).

Second, adopting a 3D-first prototyping model ensures that every design undergoes virtual simulation before physical sampling. Research indicates that such practices reduce the number of physical toiles, shorten development cycles, and enhance sustainability outcomes (Park et al., 2025). Third, incorporating augmented reality (AR) review rituals into weekly design critiques enables validation of silhouette, lighting, and motion in real time, fostering immersive collaboration and reducing costly errors in production (Suh & Lee, 2024).

Fourth, e-textile prototyping kits that emphasize modularity and washability can be introduced to train students in durability testing. Recent findings highlight the importance of wash-cycle and abrasion resistance in achieving wearable, long-lasting smart textiles (Zhou et al., 2025). Finally, embedding traceability by design at the pattern stage—through RFID/QR tagging and mapping data for Digital Product Passports (DPP)—aligns design studios with future regulatory requirements and advances sustainability education (Wang & Chen, 2024).

6. Challenges and Ethical Considerations

The integration of emerging technologies in costume and fashion design presents several challenges that must be critically addressed. A major issue is the skill gap and access barrier. Although 3D simulation and augmented reality platforms are increasingly user-friendly, their adoption in design education requires significant investment in infrastructure and training. Studies highlight that collaboration with software vendors and industry partnerships can mitigate these barriers and enhance curriculum relevance (Park et al., 2025).

Another pressing concern is AI ethics in fashion design. The use of generative AI raises risks of cultural misappropriation, embedded bias, and unclear authorship. Recent scholarship emphasizes the need for transparent authorship practices, structured prompt documentation, and the development of institutional guidelines to safeguard cultural integrity (Lee & Kim, 2024; Smith, 2024). The challenge of data governance for Digital Product Passports (DPPs) is equally significant. Harmonizing material and process data across complex supply chains is non-trivial. Research suggests phased pilots, cross-functional collaboration, and vendor evaluation as essential steps for effective DPP implementation (Wang & Chen, 2024). Finally, ensuring sustainability proof requires rigorous quantification. Claims such as reduced fabric waste or fewer prototypes must be measured through standardized metrics and independently validated, to avoid unsubstantiated green washing (Zhou et al., 2025).

7. Conclusion

The confluence of several cutting-edge technologies 3D creation, AI, Augmented Reality (AR), smart materials, and product traceability is fundamentally reshaping the entire lifecycle of costumes and apparel. From the initial concept to their eventual end-of-life, these digital tools are creating a more integrated and efficient ecosystem for design and production. For design teams, the benefits are immediate and tangible. The shift toward digital workflows means creating fewer physical samples, which not only saves time and resources but also enables richer creative exploration. Designers can rapidly iterate on ideas and make better-informed decisions through advanced pre-visualization. Moreover, these digital practices are not just for creativity; they also prepare brands for the future regulatory landscape, particularly with the advent of Digital Product Passports (DPPs).

Educators also have a crucial role to play. By embedding these modern tools and technologies into studio curricula, they can ensure that the next generation of designers is equipped to lead the industry ethically and sustainably. This isn't just about learning new software; it's about understanding how to use technology to reduce waste, improve transparency, and build a more responsible industry. The ultimate goal for this evolving landscape is interoperability. The next frontier is seamlessly connecting all these digital components: design assets, body and fit data, material passports, and even performance logs. When these elements can communicate with each other, creativity will not only be enhanced but will also be directly linked to compliance and circularity. This will create a reinforcing cycle where innovative design, ethical production, and environmental responsibility all support one another, driving the industry towards a more sustainable and technologically advanced future.

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