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Advanced Digitization and CAD Simulation: Technological Convergence, Skills, and Innovation for a Circular Fashion Industry

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ABSTRACT

The digital transformation in the textile and apparel industry has reinforced the role of advanced CAD systems to supporting more sustainable and circular practices. Technologies such as CAD/CAM, 3D garment simulation, material digitization, and digital twins are increasingly integrated into product development, enabling waste reduction, improved efficiency, more sustainable use of materials and less reliance on physical prototyping. This study is based on a systematic literature review with focusing on CAD systems, digital representation of fabrics, and textile circularity. The obtained results highlight that the reliability of simulation is strongly dependent on the accuracy of digital models of the materials and their parameterization. The literature analysis identifies two main approaches in simulation systems. While fashion-oriented platforms prioritize the visual realism and rapid design iteration, the technically oriented systems are focus on the accurate representation of the structure the materials and their physical properties. The integration of these two approaches is a key challenge and opportunity for improving simulation reliability. The findings also show that the integration of CAD systems with artificial intelligence and digital twin technologies is emerging as a key driver of innovation, enabling for more efficient digital workflows and the reducing reliance of physical prototyping. The adoption of these technologies can support sustainability through the reduction of materials and improved decision-making, although challenges remain in modelling recycled materials, ensuring data consistency, and integrating digital workflows.

Keywords: CAD systems, Digitalisation, 3D simulation, Digital twin, Circular fashion, Sustainability

INTRODUCTION

The textile and apparel (T&A) industry is undergoing a period of technological transformation driven by digitalization, the growth of sustainability demands and changes in the expectations of the consumer. This transformation results

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from the need to reduce environmental impacts, associated with the traditional linear production models, and from the evolution of digital technologies that can support product development and decision-making throughout the value chain (Parnell et al., 2025; Rahaman & Pranta, 2025; Glogar et al., 2025; Angelova, 2025).

The traditional development of products relies on physical prototypes, multiple samples, and poor communication, leading to wasted materials and operational inefficiencies (Baria et al., 2025; Wang, 2024). Virtual prototyping and digital sampling have emerged as alternatives to the traditional model, allowing the reduction of the development cycles and improving efficiency in the design process (Glogar et al., 2025; Papachristou et al., 2023a).

The advanced CAD systems enable the development of digital workflows that support digital product modeling, simulation, and validation. The use of 3D virtual prototyping during product development, has demonstrated the potential to significantly reduce consumption of materials and the number of physical prototypes (Shcherbak, 2026), while supporting design decisions oriented towards the product lifecycle (Sharma et al., 2025). Additionally, the integration of physical simulation and material parameters reinforces the role of these systems as tools to support decision-making (Petrak et al., 2021; Sabantina, 2024).

In the context of fashion design, 3D simulation platforms emphasize visual realism and rapid iteration, while approaches more oriented to textile engineering focus on the structural modeling and the physical behavior of materials. This difference between the visual realism and the accuracy of physical properties limits the applicability of these tools in different contexts (Youn & Mathur, 2023; Aychilie et al., 2022).

The CAD systems for the fashion and textile sectors are part of a broader evolution toward integrated digital ecosystems. Emerging technologies such as digital twins, artificial intelligence, and advanced material digitization reinforce this integration (Angelova, 2025; Petrak et al., 2025). More informed decision-making during product and fabric development is driven by these technologies as they allow for improved material representation and simulation reliability.

Sustainability issues have become growing concerns in the fashion and textile industries, being directly linked to traceability and transparency strategies. The Digital Product Passport (DPP) has emerged as a relevant instrument to support circularity by allowing the integration and sharing of data across the entire product value chain (Carvalho et al., 2025; Legardeur & Ospital, 2024). Despite advances in CAD systems used in garment development, they still have limitations, namely in modeling recycled materials and in ensuring simulation accuracy due to variability in material properties (Petrak et al., 2025; Aychilie et al., 2022). These limitations highlight the importance of the quality of material digitization and parameterization.

In this work was analyzed the role of advanced CAD systems and digital simulation technologies in the transition of the textile and fashion industries to a circularity model. It aims to: (1) evaluate the convergence among CAD systems, digitalization, and sustainability; (2) compare digital simulation platforms and material digitization implementation; and (3) discuss the role of hybrid skill needed for the adoption of these technologies.

METHODOLOGY

The methodology used in this work is based on a systematic review of scientific literature and institutional documents and was focused around five topics: (i) digitization of textile materials; (ii) CAD platforms applications and 3D simulation in fashion and textiles; (iii) virtual prototyping deployment and its impact on sustainability; (iv) digital twins and data integration throughout the value chain; and (v) circular economy framework, with focus on the Digital Product Passport (DPP).

The systematic review of scientific literature was conducted using scientific databases, namely Scopus and Web of Science. In addition, institutional documents were used to address relevant regulatory frameworks. From these publications, the capabilities of 3D simulation systems, the digitization of textile materials, and the implications of their use in the development of products for sustainability and circularity were evaluated.

The methodology used has several limitations. The research works that were analyzed exhibit high heterogeneity and were applied across distinct contexts, which difficult the comparison of the results. As is common in reviews based exclusively on literature review, there is also the possibility of bias in the results. The absence of physical testing restricts the extrapolation of these results beyond the scope of the reviewed literature.

DIGITALISATION, CAD AND SIMULATION: ANALYSIS

Digitization of Materials and Simulation Reliability

The fidelity of textile product simulations depends on the quality of the digital representation of the materials. It must include not only the visual attributes of the materials such as texture and color, but also the physical properties of fabrics, including weight and thickness, and the mechanical behavior (Špelic, 2020; Dai & Hong, 2024). Integrating the visual and physical-mechanical properties is a critical requirement for aligning the digital model with the physical behavior of fabrics (Petrak et al., 2021; Volino et al., 2005).

The validity of virtual prototypes is compromising as the errors in capturing or parameterizing material properties are propagated throughout the simulation process. The reliability of digital material representation emerges as a critical bottleneck which high model complexity cannot compensate for inaccurate material characterization (Glogar et al., 2025; Sabantina, 2024). Therefore, it is crucial to experimentally validate the digital material models used in 3D simulation systems. The robustness and reliability of the digital material models are enhanced through comparative methods using physical and digital samples that enable the assessment of correspondence between physical and simulated performance (Petrak et al., 2021). The digitization of non-conventional materials, particularly recycled textiles and biomaterials, presents additional challenges due to their non-uniform mechanical properties. This hinders the creation of accurate digital models, resulting in differences between the behavior of physical materials and simulation outcomes (Sandin & Peters, 2018; Aychilie et al., 2022; Carvalho et al., 2025). This problem can be addressed by using approaches based on high-resolution digitization and advanced data processing methods, including artificial intelligence techniques, to standardize material characterization and thereby reduce errors associated with fabric parameterization (Alfaro Viquez et al., 2025; Tao et al., 2019).

The digital material models, derived from precise digitization, once validated, serve as the foundation for product-level digital twins, enabling lifecycle data integration (Jones et al., 2020; Fuller et al., 2020). Accurate material characterization is essential for simulation reliability, supporting design decisions and directly enhancing product development efficiency and driving sustainability within the textile and apparel (T&A) sector.

CAD Systems, Simulation Platforms and Integration

The CAD systems applied to the textile and apparel industry have evolved from two-dimensional visualization tools to integrated product development platforms, enabling the modeling, simulation, and the analysis of the behavior of materials and garments in digital environments (Volino et al., 2005; Sabantina, 2024; Wang et al., 2019). While the commercially dominant garment design systems prioritize visual realism, fit analysis, and rapid iteration, contributing to reduced physical sampling cycles and improved efficiency in the creative process (Papachristou et al., 2023b; Glogar et al., 2025), the ones oriented for textile engineering prioritize the structural modeling of materials, including yarns, fibers, and fabric architectures, enabling a more detailed and physically consistent representation of textile behaviour (Aychilie et al., 2022; Long & Brown, 2011). These two different approaches to product simulation may limit the reliability of simulations in more demanding applications, particularly in the development of technical textile products (Liu et al., 2023; Pizana et al., 2025).

The integration of material digitization, and structural modeling of materials within an unified systems is regarded as essential for increasing the simulation reliability and supporting more informed design decisions during product development (Sabantina, 2024; Glogar et al., 2025). At the same time, drive the integration of workflows and data throughout the textile and apparel value chain. The interoperability between product development platforms and consistency of digital information are essential conditions for the effective digital transformation in the textile and apparel industry (Jones et al., 2020; Tao et al., 2019). This integration relies on the ability to consistently represent the properties of materials across different systems, including CAD, simulation, and product lifecycle management (PLM) platforms. This continuity of information, often referred to as the digital thread, enables the reduction of redundancies and improves the efficiency in the product development processes (Fuller et al., 2020; Zhang et al., 2021).

Material digitization can provide the foundation for creating consistent digital representations to be used throughout the product lifecycle. Structured data sharing among the different stakeholders will enhance coherence, support decision-making, and improve traceability (Tao et al., 2019; Petrak et al., 2021; ISO, 2021). The literature also highlights the importance of data governance, including the definition of the responsibilities for the creation, validation, and updating of digital information. Issues such as data inconsistency or obsolescence may compromise simulation reliability and the quality of the decision-making, particularly in complex value chains (Jones et al., 2020; Fuller et al., 2020).

The need for systems capable of integrating structured information on materials, processes, and impacts throughout the product lifecycle has been further reinforced by initiatives such as the Digital Product Passport (DPP) (European Commission, 2024; Carvalho et al., 2025). Despite the progress made, there are still challenges to overcome related to the lack of data standardization, limited interoperability between systems, and difficulties in the representation of heterogeneous materials such as recycled materials (Aychilie et al., 2022).

IMPLICATIONS FOR CIRCULARITY AND MATERIALS

Recycled Materials and Simulation Challenges

The digitization and simulation of recycled materials on CAD platforms presents several challenges related to variations in the properties of these materials, both mechanical and structural, which reduces the reliability of their digital models and decreases the fidelity of the simulation (Aychilie et al., 2022; Shen et al., 2020).

In more conventional CAD systems, a limited set and constant of physical parameters is generally used for a given material. Although this approach is adequate for homogeneous materials, for recycled materials the structural irregularities are not adequately represented by this method, leading to discrepancies between the physical behavior and simulation outcomes (Petrak et al., 2021; De Carvalho et al., 2022). The literature states the need for more advanced modeling approaches, including using data-driven methods, predictive models, and representations that incorporate the variability of material properties, parameter ranges or "behavior envelopes." The integration of this type of solutions tends to produce more flexible and more reliable models in supporting the design process (Zhang et al., 2021; Liu et al., 2021).

An accurate digital representation of recycled materials facilitates its adoption in the early stages of product design, which is particularly relevant in the current context of transition to more sustainable and circular models. The adoption of recycled materials during design stages depends on their technical suitability and compatibility with the production processes (Shen et al., 2020; Carvalho et al., 2025). The simulation and material digitization technologies can help reduce barriers to their adoption by enabling virtual testing of material behavior and reducing the need for physical prototypes

(Glogar et al., 2025; Papachristou et al., 2023b). The variability of recycled materials is a challenge for digital simulation, requiring the development of more robust modeling approaches.

Lifecycle Assessment and Digital Product Passport

Digitalization and simulation play an important role in integrating sustainability practices into product development in the textile and apparel industry. The use of digital tools, particularly virtual prototyping, helps to reduce the number of physical samples and improves efficiency in material use (Glogar et al., 2025; Papachristou et al., 2023b).

Integration with Life Cycle Assessment (LCA) methodologies enables the incorporation of environmental criteria in the early stages of design. The combination of digital simulation and LCA allows the evaluation of alternative materials and processes prior to physical production, functioning as a decision-support mechanism oriented toward sustainability (Hauschild et al., 2018; ISO, 2006a; ISO, 2006b). The effectiveness of this approach depends on data quality and consistency and inaccurate representation of materials in the digital environment may compromise both technical performance and the validity of environmental decisions (Tao et al., 2019; Jones et al., 2020).

In this context, the Digital Product Passport (DPP) plays a central role by supporting traceability, transparency, and circularity across the value chain. Its implementation depends on the ability to integrate structured information on materials and processes from the early stages of product development (European Commission, 2024; Carvalho et al., 2025).

The integration of CAD systems, material digitization, and product lifecycle management platforms enables the association of the technical and environmental information of the products across its lifecycle, in line with the concept of digital thread (Fuller et al., 2020; Zhang et al., 2021). This integration facilitates the incorporation of circularity criteria into design decisions. The lack of standardization, system integration, and the quality of data, still limit the effective implementation of solutions that combine digital simulation, LCA, and DPP (Jones et al., 2020; Carvalho et al., 2025).

HUMAN FACTORS, SKILLS AND ADOPTION

Hybrid Skills and Interdisciplinary Knowledge

When introduce digital systems at the level of companies in the textile and apparel industry, it will be all the more efficient the better the digital literacy, particularly in the areas of hybrid skills that integrate fashion design, textile engineering and digital technologies.

There is increasing complexity in CAD systems, in the various phases of the development and production process, at the level of simulation platforms and material digitization processes. Therefore, technical knowledge is required, but also an understanding of the underlying physical and material principles (Petrak et al., 2021; Sabantina, 2024). It is necessary that professionals, in addition to knowing how to use the software, interpret the properties of materials, select the appropriate parameters and validate the results to ensure the reliability of the digital models used in each situation (Aychilie et al., 2022; Volino et al., 2005).

The increasing integration of digital systems also entails requirements related to data management, including the organization of digital material libraries, traceability, and information processing throughout the product development cycle (Jones et al., 2020). The convergence of CAD systems, simulation, and product lifecycle management (PLM) reinforces the need for skills related to the use, but also to knowing how to interpret structured data. The adoption of these technologies allows clothing/accessory simulation to be a decision support tool, especially in the selection of materials and the evaluation of design solutions (Glogar et al., 2025; Fuller et al., 2020). Concomitantly, digitization promotes new forms of collaborative work, requiring communication and coordination skills among different professional profiles (Carvalho et al., 2025; Shen et al., 2020).

Usability and Decision Support

Usability is one of the key factors for the simple implementation of CAD systems and simulation itself, in terms of digital platforms. The literature indicates that these technologies assist in visualization, comparison, and iterative evaluation between solutions, exponentially increasing the design and development process throughout the entire value chain (Volino et al., 2005; Petrak et al., 2021).

In simulation, visualization tools allow for the analysis of material behavior and the anticipation of potential problems before production, reducing processes based on trial-and-error approaches (Liu et al., 2023; Sabantina, 2024).

The effectiveness of these systems depends mainly on the usability of the interface and the reliability of the results. Complex interfaces, unitary flows, and lack of transparency in the models can obscure the interpretation of the results and limit their use in decision-making processes (Fuller et al., 2020; Jones et al., 2020). The integration of these platforms into organizational processes also represents a significant challenge, associated with factors such as alignment with existing practices, interoperability, and resistance to change (Glogar et al., 2025; Shen et al., 2020). Usability is also related to the ability to integrate the information relevant to strategic decision-making, including data on textile materials and accessories, environmental impact, and traceability. This integration remains limited, particularly in the representation and management of complex information (European Commission, 2021; Carvalho et al., 2025; Hauschild et al., 2018).

LIMITATIONS AND CHALLENGES

The digital transition in the textile and apparel industry faces technical, organizational, and methodological limitations that affect the adoption and effectiveness of CAD simulation, and materials digitization.

From a technological point of view, there are still major challenges related to the lack of standardization and interoperability of data, hindering the integration between the CAD systems, simulation platforms, and product lifecycle management (PLM) solutions, and compromising the consistency of information throughout the value chain (Jones et al., 2020; Tao et al., 2019; Fuller et al., 2020).

Dependence on technological infrastructures also represents a significant limitation. The 3D simulation, high-resolution digitization, and data management systems require large computational resources, which can hinder the adoption of these solutions, particularly among small and medium-sized enterprises (Glogar et al., 2025; Shen et al., 2020). In organizational terms, the implementation of these technologies requires transformations at the level of work processes and team skills. The need for continuous training, the technical complexity of the tools, and resistance to change can limit their effective use (Carvalho et al., 2025).

It is also worth noting that in terms of garment simulation, there are still limitations in representing the physical behavior of materials, particularly in complex or even recycled materials, whose variability cannot be simulated by conventional parameter-based approaches (Petrak et al., 2021; Liu et al., 2023; Pizana et al., 2025). Highlighted the need for more robust and flexible models capable of incorporating variability and uncertainty in material properties (Aychilie et al., 2022; Liu et al., 2021). The data integration of simulation, Life Cycle Assessment (LCA), and Digital Product Passport (DPP) imposes additional requirements in terms of data quality and governance. Ensuring data consistency and interoperability throughout the product lifecycle is a key factor for the reliability of simulations and design decisions (Jones et al., 2020; Fuller et al., 2020; European Commission, 2024).

CONCLUSION

This study investigated the role of advanced CAD systems and digitalization in the transition of the textile and fashion industry to a more sustainable a circular model, based on a systematic literature review. The findings indicate that the integration of material digitization, and CAD/3D simulation represents a key driver of innovation, with direct implications for product development efficiency and waste reduction.

Virtual prototyping allows for the reduction of physical prototypes, optimization of material use, and early identification of technical problems, minimizing trial-and-error processes throughout product development. This advantage depends on the quality of material digitization and model validation, with the correspondence between the physical behaviour of the materials and the simulation output being a critical factor.

Significant limitations still exist, mainly in the digitizing and simulation of complex fabrics, especially recycled materials, whose mechanical and structural variability makes accurate simulation difficult.

The data integration between Life Cycle Assessment (LCA) and the Digital Product Passport (DPP) reinforces the role of digitization and simulation technologies in incorporating sustainability practices and improving transparency throughout the product lifecycle.

The adoption of these technologies depends on human and organizational factors, including the development of hybrid skills and the usability of digital platforms. Advanced digitization of textile materials and CAD-based simulation offer great potential to support the transition of the fashion and textile industry to more sustainable practices and a circular model. However, its effectiveness depends on the reliability of the models used, the quality of the data, and the capabilities of the professionals.

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