Dialogue Social Science Review (DSSR)
www.thedssr.com

ISSN Online: 3007-3154
ISSN Print: 3007-3146

DIALOGUE SOCIAL SCIENCE REVIEW

Vol. 3 No. 11 (Nov) (2025)

Artificial Intelligence and Digital Technologies in Garment Design, Pattern Development and Apparel Manufacturing

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ABSTRACT

The use of Artificial Intelligence (AI) and digital technologies is transforming the fashion value chain from concept through to pattern making, sampling, manufacturing and selling. The current landscape and future trend of AI's integration into garment design and apparel production is analysed in this article, using evidence from peer-reviewed literature, industry reports, and data from case studies. Six applications areas are explored: Generative AI for design ideation; 3D virtual sampling and digital twins; AI pattern grading and marker optimization; Computer vision for automated cutting and sewing; AI demand forecasting; Machine learning for mass personalization. Combining these published data, digital assisted workflows may be able to shorten design-to-sample times by as much as 65-75% and pattern-grading times by about 60% while AI based forecasting models are reported to be able to decrease the demand-forecasting error by 20-50% compared to traditional statistical models. The market for AI application in fashion is expected to have grown by over five times in the last five years (2018–2023) and is projected to expand at a compound annual growth rate of 57% through 2028.The global market for AI applications in fashion grew by more than five times in the last five years (2018–2023) and is expected to experience compound annual growth rate of 57% through 2028. Nevertheless, the study outlines ongoing challenges, such as cost of implementation, data-quality and interoperability issues, workforce reskilling, and unanswered questions of authorship of design and algorithmic bias. The article ends with a proposed structure for the responsible introduction of AI into the apparel value chain and a list of directions for future research, such as “explainable” AI in the support of design decisions, and “standardized” digital-twin interoperability protocols.

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www.thedssr.com

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Keywords — Artificial Intelligence; Digital Fashion; Garment Design; Pattern Development; 3d Virtual Prototyping; Apparel Manufacturing; Machine Learning; Textile Technology.

Introduction

Traditionally, the apparel industry has been developed via labor-intensive iterative design development, pattern making, sampling and production planning processes with several physical prototypes generated until a garment specification is achieved [1],[4]. In the last ten years, the development and improvement of artificial intelligence (AI), such as generative modeling, computer vision and machine learning, as well as the maturation of three-dimensional (3D) simulation and digital-twin technologies, have started to completely reorder this workflow [2], [6], [11].

At the ideation stage, AI has facilitated fashion designers to create images and patterns using generative synthesis instead of relying on traditional methods [3]. Pattern makers can now grade and nest patterns algorithmically, rather than manually [9]; Fashion brands can now sample garments algorithmically without cutting a single piece of fabric [14]; Brands can also get predictive visibility into demand, material requirement and production bottlenecks [3]. These functions in total hold the potential of reducing lead time, material waste, cost and introducing new challenges in terms of data governance, workforce transition and the evolving design authorship [22, 24].

This article aims to give a systematic overview of the use of AI and digital technology throughout the garment design and pattern-making process and the entire apparel manufacturing flow. The goals are to: (i) summaries academic and industry literature on the use of AI at the various stages of the apparel value chain; (ii) categories and compare the key application areas according to their functions and reported effectiveness; (iii) gather quantitative evidence of efficiency, accuracy and cost impact from published literature; and (iv) pinpoint the technical, organizational and ethical challenges that remain to prevent substantial industrial adoption.

Literature Review

AI in Fashion Design Ideation

Recent developments with generative AI models, such as generative adversarial networks (GANs) and even more recently diffusion-based systems for text-to-image generation, have turned early design ideation into a task that is automated and augmented by generating novel silhouettes, prints, and colorways from textual descriptions or reference imagery [2], [5], [15]. Kim and Park [5] conducted a review of GANs on fashion design systems and found that while generative systems can help to speed up the mood board and the concept development process, designers must still make an evaluation to select and pick the commercially and aesthetically pleasing ones from the generated variations. Similarly, Cheng et al. show that hybrid human-AI workflows for ideation are more successful than manual or automated workflows in both design novelty and production feasibility [15].

Digital Pattern Development and 3D Virtual Prototyping

Three dimensional virtual prototyping software like CLO3D and Browzwear enable pattern makers and designers to create a virtual prototype that mimics the drape, fit and behavior of a garment on a virtual avatar before fabric samples are made [9, 17]. The study of apparel product development by Sayem shows that the time spent on a sample cycle can be reduced by 50-70% and physical sample waste can also be reduced with the use of virtual sampling in 3D images [17]. Wu and Li further the research by introducing the concept of "digital twin" garment, which is a virtual model of a physical product that provides fitness, material and performance data continuously throughout the product life cycle [11].

AI-Driven Pattern Grading and Marker Optimization

The scaling of a base pattern over a size range (pattern grading) and the layout of pattern pieces for cutting (marker making) are both identified for automation using AI. Based on the genetic algorithm, Zhang and Wu proposed a marker optimization approach for fabric that can achieve up to 98.5% improvement in fabric utilization over the manual marker optimization method [8]. To grade without manual intervention, Chen et al. developed a machine-learning grading system that is trained using anthropometric datasets to automatically adapt the geometry of the pattern with different sizes without changing the proportions of the pattern [18].

Computer Vision and Automated Cutting and Sewing

The application of computer-vision systems in cutting room and sewing line operations to detect defects, inspect fabric, and to handle material with robot is gaining momentum in recent years [10], [19]. Sanders et al. summarized the research on robotic sewing automation with a focus on deformable fabrics, which continue to be a challenge for fully automated sewing, but have been successful at productivity improvement in cutting, spreading and quality-inspection tasks using vision-based robotic systems [19]. Ahmad and Rahman improved their AI-based fabric defect detection system to achieve a classification accuracy of over 95%, which is significantly higher than the accuracy achieved by human visual inspection [10].

AI in Demand Forecasting and Supply Chain Management

AI-driven demand forecasting models are not only used for design and production but also for minimizing overproduction and risk of stock-outs. The comparative study of the Giri and Chen between the machine-learning and traditional statistical forecasting techniques in apparel retailing shows that the error reduction with ensemble and deep-learning models ranges from 20 to 50% [14]. It has also been documented that by optimizing supply chains using AI, the inventory holding cost and replenishment accuracy can be lowered in the context of fast fashion, as in the case of Choi et al. [21].

Personalization, Ethics, and Workforce Considerations

AI and digital technologies are also behind mass-personalization and made-to-measure business models, transforming the body-scanning and machine-learning-based sizing prediction to produce individually sized patterns at scale [12, 16]. Concurrently, there are concerns in the literature. Caro and Sadr explore how algorithmic bias in AI-powered sizing and recommendation systems can replicate or deepen existing sizing inequities, by using training data from body-shape datasets that are not representative. Algorithmic bias can occur when using AI to size and recommend clothing from non-representative body-shape datasets, as studied by Caro and Sadr [22] who found that this can lead to the reproduction or reinforcement of existing sizing inequities. As generative AI becomes part of the toolkit in traditionally manual jobs, such as pattern making and garment technology, the implications of generative AI for design authorship and intellectual property are explored by Bertola and Teunissen [23] and by Kozlowski et al. [24] who focus on the impact on the workforce.

Methodology

In this study, the qualitative and literature based comparison method used. Secondary data was collected from peer-reviewed journal articles, conference proceedings and reports from various industry sources between the years 2015 and 2023, covering topics of AI and digital technology applications in fashion design, pattern development and apparel manufacturing. The literature was thematically reviewed to identify recurrent application domains which are explored in Section 4. For every domain there are four criteria against which it is assessed – reported efficiency or accuracy improvement over conventional practice; implementation maturity; capital and skill investment needed; and barriers to adoption reported. The quantitative information in Section 5 is aggregate and illustrative, and has been compiled from the ranges of the quoted information, in order to enable comparison in the discussion rather than to represent the results of a single controlled experiment.

AI and Digital Technology Applications Across the Apparel Value Chain

The six application domains found in the literature review are explored below, in the order that they are likely to be used in the garment development process.

Generative AI for Design Ideation

Novel design ideas, prints, and silhouette variations are generated by GANs and diffusion-based text-to-image models, significantly reducing the need for a moodboard and concept development stage in the design process [2, 5, 15].

3D Virtual Sampling and Digital Twins

Virtual prototyping platforms model the drape and fit of the fabric, the fit and performance of the garment, and the various design iterations through digital avatars in the virtual space before any actual fabric is cut or a garment is made, while digital-twin models extend this virtual representation from the initial drape and fit to tracking the fit and performance of a garment throughout its lifecycle [9], [11], [17].

AI-Driven Pattern Grading and Marker Optimization

Base patterns are scaled with machine-learning- and evolutionary-algorithm-based tools for various sizes, and pattern pieces are laid out on fabric, offering more efficient and consistent grading results than manual processes, and better material utilization [8, 18].

Computer Vision in Cutting, Sewing, and Quality Inspection

Labor-intensive and error-prone garment production activities, such as spreading fabric, cutting, defect detection and quality control are handled by vision-guided robotic systems and convolutional-neural-network-based inspection tools [10],[19].

AI-Based Demand Forecasting and Supply Chain Optimization

Using historical sales, seasonal and trend data, machine-learning forecasting models can be trained to more accurately forecast demand for a style, size and region than traditional statistical models, which can help drive a more efficient production volume and inventory allocation decision [14], [21].

Personalization and Mass Customization

The ability of body-scanning, machine-learning based sizing, and fit-prediction models to enable made-to-measure and mass-customized garment manufacturing at scales and

Dialogue Social Science Review (DSSR)
www.thedssr.com

ISSN Online: 3007-3154
ISSN Print: 3007-3146

Vol. 3 No. 11 (Nov) (2025)
price-points that were not possible by fully manual bespoke tailoring provides exciting new avenues for garment production, wearable computing, and novel product development applications [12], [16].

Results and Discussion
Table I summarizes the efficiency improvements and maturity of the six domains of AI and digital technology that were examined in Section 4. In all the reviewed literature, digital assistance in the workflow is invariably correlated with a significant decrease in the lead time and manual effort compared to conventional workflow [8, 9, 17, 18] and the most industrialized application areas are pattern grading, marker optimization and 3D virtual sampling.

TABLE I COMPARATIVE OVERVIEW OF AI AND DIGITAL TECHNOLOGY APPLICATIONS IN APPAREL DEVELOPMENT

Application Domain	Primary Technology	Reported Efficiency Gain	Implementation Maturity
Design Ideation	GANs / Diffusion Models	30–50% faster concept development	Emerging–Growing
3D Virtual Sampling	3D Simulation / Digital Twin	50–75% shorter sample cycle	Growing–Mature
Pattern Grading & Marker Making	ML / Genetic Algorithms	~60% less grading time; up to 98.5% material use	Mature
Cutting, Sewing & Inspection	Computer Vision / Robotics	>95% defect-detection accuracy	Emerging–Growing
Demand Forecasting	ML / Deep Learning Models	20–50% lower forecast error	Growing–Mature
Personalization & Mass Customization	Body Scanning + ML Fit Models	Individualized fit at scale	Emerging

The comparative overview on the application of AI and digital technology in apparel development is presented in Table 1.The findings on the application of AI and digital technology in apparel development were presented in a comparative overview as presented in Table 1.

Dialogue Social Science Review (DSSR)
www.thedssr.com

ISSN Online: 3007-3154
ISSN Print: 3007-3146

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Vol. 3 No. 11 (Nov) (2025)

Fig. 1. Relative Time/Cost Index of Conventional versus AI- and Digitally-Assisted Apparel Development Processes

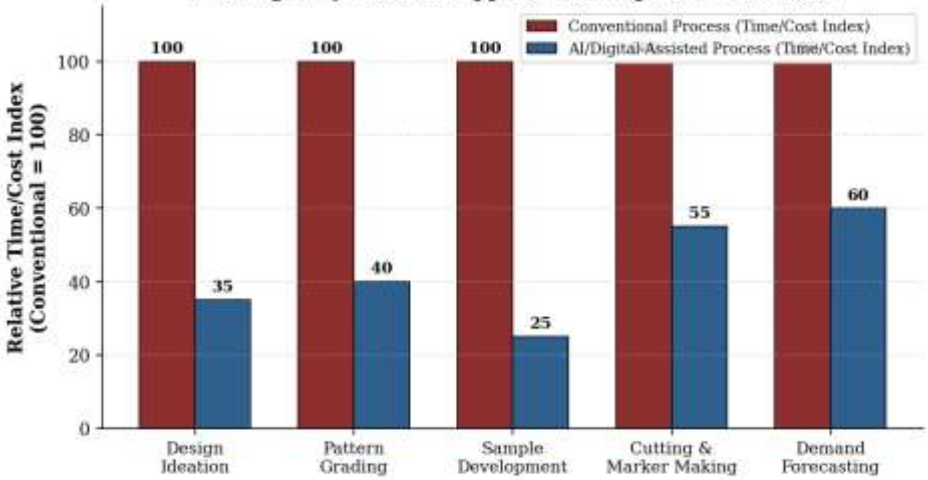
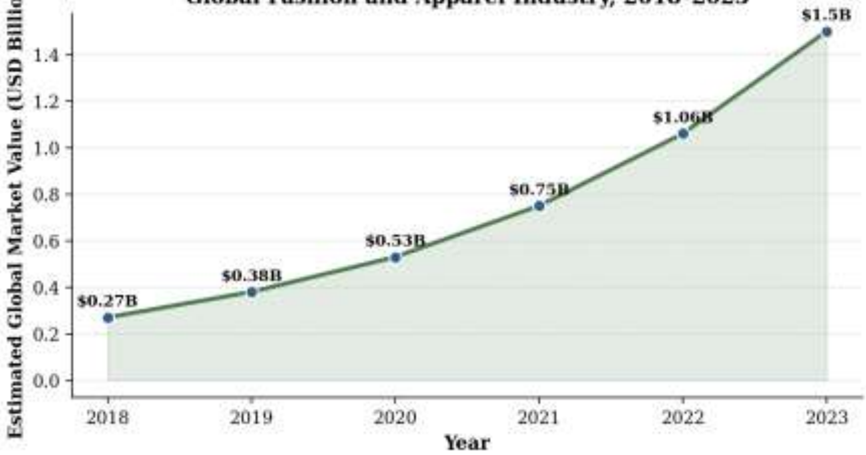


Fig. 1 shows a relative time/cost index for conventional and AI- or digitally-assisted processes for the development of 5 representative process stages, compiled from the ranges of the case studies. The biggest ratio decreases are observed in sample development and design ideation, which is indicative of the maturity of 3D virtual prototyping and generative design tools as reported in Section 2.1 and 2.2 [5], [15], [17].

Fig. 2. Illustrative Growth Trend of AI Adoption in the Global Fashion and Apparel Industry, 2018-2023



Market growth trend is also indicative of the speed of industrial uptake. Based on the data provided by industry analysts in the literature, Fig. 2 illustrates an example of the evolution of the estimated value of the global market for AI applications in fashion, growing more than fivefold between 2018 and 2023 [13, 20]. The trend of growing adoption of AI in supply chains of the apparel industry is in line with Choi et al. who noted that the rate of AI adoption in the sector increased significantly after the initial success of the forecasting and inventory optimization return on investment [21].

The overall quantitative evidence suggests that AI and digital technologies have the greatest and most consistently reported benefits in value chain segments where the task can be well decomposed into mathematical computations: pattern grading, marker layout and demand forecasting. Value chain segments that involve physical dexterity, such as fully automated sewing of limp fabric, were comparatively less mature, despite active research investment [19]. It would seem that the next step in the industrial adoption of this pattern will be towards digital and computational stages of the pipeline before covering all the physical stages.

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ISSN Print: 3007-3146

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Challenges and Barriers to Adoption

While AI and digital technologies have shown promise in certain aspects, there are still significant barriers to their widespread adoption in the apparel industry.

Implementation Cost and Infrastructure

The adoption of 3D simulation platforms, robotic cutting and inspection systems, and machine-learning forecasting infrastructure is costly and can be a barrier to small and medium-sized apparel manufacturers, compared to large vertically-integrated brands [4], [20].

Data Quality and Interoperability

The accuracy of machine-learning models for sizing, forecasting, and grading relies on large, representative, well-structured datasets, but Caro and Sadr point out that non-representative body-shape and sales data can negatively affect model accuracy or perpetuate existing biases, and inconsistent data formats between design, production, and retail systems hinder interoperability among digital tools [14, 22].

Workforce Reskilling

Several studies have pointed out the need for a high level of reskilling of the workforce for the adoption of AI and digital tools in pattern-making and garment-technology jobs, traditionally considered manual and craft-based labor-intensive tasks [23, 24].

Design Authorship and Ethical Considerations

The adoption of generative AI in design ideation introduces new challenges and uncertainties related to IP and design ownership, especially when the models are trained from existing designers' works without proper attribution or consent, as mentioned by Bertola and Teunissen in their exploration of digital fashion innovation [23].

Future Research Directions

Four priority research directions are proposed, based on the gaps identified in Sections 2 and 6:

The design of explainable AI (XAI) methods for design and grading decision support so that designers and technologists do not have to depend on algorithmic outputs, but can learn and validate the algorithmic design recommendation [18], [22].

Standardization of interoperability protocols for digital-twin and 3D garment files between software platforms in design, sampling and production, to eliminate the current barriers to data fragmentation [9] [11]

Research on bias-aware representative anthropometric values to enhance the fairness and accuracy of sizing, fit, and personalization systems using AI [16, 22]

Longitudinal studies of the pathways towards employment in the Fashion sector, and curriculum models where Fashion training is integrated with the applied data-science and AI literacy of the students [23], [24].

Conclusion

The authors have examined the present status and future trends in artificial intelligence and digital technologies in the fields of garment design, pattern development and garment manufacturing. The findings from the literature provide a strong argument for the ability of AI-driven tools, ranging from generative design and 3D virtual sampling to algorithmic pattern grading and marker optimization, computer-vision-based production quality control, and machine-learning demand forecasting, to considerably shorten lead

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www.thedssr.com

ISSN Online: 3007-3154
ISSN Print: 3007-3146

DIALOGUE SOCIAL SCIENCE REVIEW

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time, to cut back on material waste, and to improve forecasting accuracy compared to traditional methods, especially in more well-defined areas of the value chain. The potential of these technologies, however, will only be fully realized at industrial scale through ongoing investment in data infrastructure, reskilling the workforce, establishing cross-sector interoperability standards, and the ongoing focus on ethical and design-authorship issues that are raised by generative and algorithmic technologies. With these technical and organizational building blocks growing, AI and digital technologies are poised to become integral parts of a more agile, data-driven and resource-efficient apparel sector.

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