Title:
Artificial Intelligence and Generative Design in the Footwear Industry: Implications for Design, Manufacturing, and Sustainability.

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Introduction:
Over the last decade, artificial intelligence (AI) and generative design (GD) have gained momentum and are increasingly discussed as promising directions for product development. However, footwear production remains largely rooted in traditional craft-based and industrial practices, where established workflows are often prioritised and the adoption of new technologies can be slower or met with resistance. At the same time, growing sustainability pressures are pushing the sector to rethink material flows, reduce waste, and improve resource efficiency across the design-to-production chain. Against this background, AI and GD offer tools that can gradually support idea exploration, digital modelling, and production optimisation. In this context, AI refers broadly to data-driven computational methods, while GD refers to computational design approaches that generate and evaluate multiple design alternatives based on predefined constraints and performance goals, helping teams move from concept development to feasible solutions more efficiently [22]. Studies have shown that generative models do not simply automate ideation; they can encourage unexpected design directions that a designer might not have considered on their own [20], [24]. However, fewer studies have critically examined how these systems reshape design practice itself, particularly in terms of how design knowledge is produced, evaluated, and negotiated. In practical terms, generative systems allow designers to input parameters such as intended use, movement patterns, foot morphology, cushioning needs, or stylistic cues. The generative system then generates multiple plausible variations that can be adjusted iteratively. This process aligns well with the way many designers already work: moving between free exploration and evaluation. Research in fashion design workflows suggests that when AI systems reflect real studio routines rather than rigid optimization, designers treat them as creative partners rather than threats [22]. In footwear, this partnership is strengthened through 3D modelling tools and increasingly accessible 3D printing methods, which make it easier to prototype and test individualized forms [39].

This review explores the integration of AI and generative design techniques in the footwear industry, examining their implications for design creativity, manufacturing efficiency, and sustainability. Specifically, the paper focuses on the research questions: **RQ1:** How are AI and GD technologies being applied in footwear design and manufacturing, and what areas do they influence most? **RQ2:** What key opportunities and challenges emerge when integrating AI and GD into existing footwear manufacturing processes? **RQ3:** How can these technologies support sustainability in footwear production, particularly in reducing material waste and improving material utilisation? By exploring these questions, the review aims to demonstrate how computational design approaches-such as generative design and artificial intelligence -enable the creation of innovative footwear designs, while enhancing production workflows and minimizing environmental impacts for sustainable development in the industry. The review is based on a structured literature search that was limited to English-language publications in the Scopus database using the query TITLE-ABS-KEY ((footwear OR shoe) AND (AI OR "artificial intelligence" OR "generative"), which initially returned 435 documents. The selection was refined in two stages - first by screening titles/abstracts and then by analyzing full texts. By excluding medical-only studies and focusing on industrial footwear design, we focused on 50 key papers for the final review.

Main Results:

The body of work reviewed points to a growing interest in using AI and GD within footwear design and manufacturing, particularly around creativity, efficiency, customisation, and sustainability. Rather than treating AI as a standalone solution, most approaches position it as a supportive element within existing design and production practices. In fact, in product design, AI can be applied both to the product itself and to the design process [13]. Regarding RQ1, it's clear that AI and GD make the biggest impact during the early stages of design. For instance, advanced generative tools help turn a creative concept into a high-quality 3D model that is actually ready for production.

A common thread across the reviewed work is the emphasis on collaboration between designers and AI systems. The integration of AI in creative design aims to overcome human limitations, optimize resource allocation, and enhance creativity. In human–machine collaboration, AI increasingly functions as a near-equal partner, enabling iterative exchanges of input and output data until a satisfactory outcome is achieved (Fig. 1) [22].

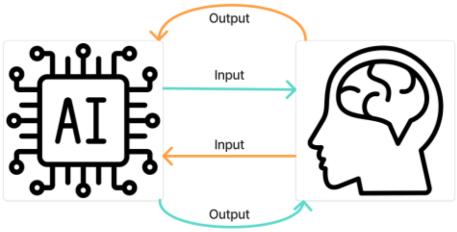

Fig. 1: The back-and-forth cycle established in a human-AI collaboration.

Moreover, studies demonstrate that combining AI with additive manufacturing for prototyping improves final products, reduces work time and design costs, and supports frameworks that merge AI digital tools with designer expertise [22], [18]. AI employs inductive and deductive reasoning to inspire, suggest, and evaluate design alternatives, while designers iteratively influence AI outputs. Several studies focus on early design stages, where visual exploration and concept generation play a key role. In these cases, generative AI models—most often GAN-based—are used to generate and refine design imagery [9], [13], [20], [24]. The findings suggest that clearer stylistic guidance in prompts tends to lead to more coherent results, while highly complex outputs can raise concerns around feasibility and downstream development.

In the footwear industry, combining AI and 3D modeling software enables designers to create realistic shoe models, visualize and modify designs before physical prototyping, and simulate human movement [18]. AI supports concept generation from basic prompts and integrates with functional detailing to transform concepts into manufacturable 3D designs, promoting innovation while maintaining feasibility [31]. As projects move closer to manufacturing, AI becomes critical for 3D modeling, feasibility evaluation, and manufacturing preparation. Studies in this area often report that it accelerates production workflows, improves quality control, and simplifies evaluation processes [37], substituting traditional evaluation teams [29]. Generative AI tools allow rapid exploration of hundreds of variations, streamlining the concept-to-prototype workflow and reducing manual effort

[36], [17], [33]. AI-driven creativity support tools like ShoeGenAI improve design intent communication, enhance manufacturing feasibility, and support rapid prototyping [18], [42].

A substantial portion of the reviewed literature addresses customisation and performance-oriented design. In these studies, platforms analyzing customer foot scans generate bespoke footwear with precise fit, transforming traditional production models [17], [32]. Generative AI allows companies to customize running shoes by analyzing athlete foot data, running style, gait dynamics, and consumer preferences [32]. Predictive analytics and AI-supported trend forecasting enhance design flexibility, inventory management, and operational efficiency [27], [34]. Optimized machine learning models have demonstrated measurable improvements, including increased throughput, reduced downtime, and lower energy consumption [34]. GD algorithms can produce multiple optimized solutions based on predefined constraints, surpassing traditional methods in speed and efficiency while expanding creative possibilities. Figure 2 shows the Benefits of GD. Such systems have been applied to high-performance running shoes at lower costs, and brands like Nike and Adidas utilize AI and GD to optimize midsoles, materials, and performance features [18], [32], [4]. Advanced AI platforms like NextGen-AI accelerate design pipelines, reduce late-stage changes, and empower less-skilled workers [3].

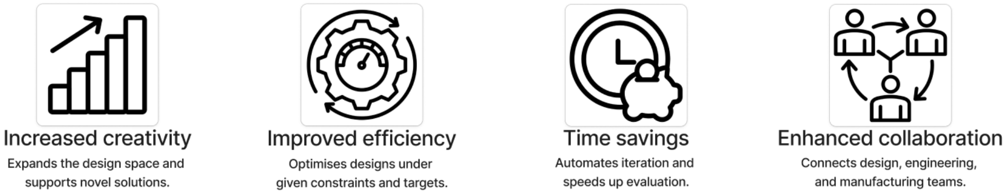

Fig. 2: Benefits of GD.

Leading brands leverage AI in GD and additive manufacturing. New Balance developed midsoles optimized with runner performance data and 3D printing materials with superior properties [15], [26] while Adidas implemented AI Archive, a diffusion-model-based tool trained on its sneaker archive, enabling designers to explore hundreds of variations while preserving brand identity [35], [36], [4]. AI-driven systems can generate images, extend creative outputs, and respond to market trends, enhancing creativity while reducing design time and costs [39].

Finally, according to the studies reviewed, sustainability and waste reduction appear to be central to AI adoption. Generative AI and design optimization allow companies like Nike to produce superior-performing shoes at lower costs while minimizing production waste [33]. AI-based quality control and image recognition reduce defects and improve product yield [26], [35]. AI algorithms optimize leather tanning, chemical use, and water consumption [26], while digital simulation tools facilitate environmentally informed design decisions [18], [29]. Designers can input sustainability criteria directly into generative AI, producing lightweight, structurally optimized products and eco-friendly packaging [32], [7]. Parametric design, 3D knitting, and topological optimization reduce material usage, production time, and waste without compromising performance or aesthetics [14]. Automated nesting and hybrid algorithms maximize material utilization and minimize waste [1]. AI-driven supply chain optimization improves inventory prediction, prevents overproduction, and enhances operational efficiency [24], [36]. In response to RQ3, sustainability is driven by highly optimized material use. For instance, using advanced algorithmic optimization for midsoles is far more than a technical tweak, as it optimizes stress distribution much more effectively than traditional methods. Similarly, predictive modeling in 3D printing ensures consistent performance, leading to a significant decrease in material waste.

Despite these opportunities, challenges persist: feasibility of generated designs, learning curves, technology costs, data quality, and integration with existing workflows [10], [19], [2], [18], [4]. Ethical considerations, including job displacement and data security, must be addressed before full-scale AI adoption [33], [5], [2]. Earlier AI applications focused on manufacturing efficiency, such as material nesting [11] and assembly line optimization [18], while later studies targeted performance optimization through evolutionary computation and finite element analysis [33]. AI-assisted trend forecasting shows promise, but individual variability, such as color preferences, complicates prediction [41]. In addressing RQ2, the review identifies the gap between digital simulations and physical reality as a major hurdle. Even though AI reaches high precision in controlled settings, moving these systems to unpredictable factory floors is a complex task. Without making AI processes more transparent to build worker trust, shifting from a lab environment to real-world production remains a significant challenge.

Taken together, the reviewed studies suggest that AI and generative design are currently applied in selective and uneven ways across the footwear sector. Their impact appears strongest in early design exploration, targeted manufacturing tasks, and sustainability-related optimisation, while full integration across workflows remains limited. This uneven adoption highlights both the potential of these technologies and the need for further validation in real production contexts. [30], [25], [23], [36], [34]

Conclusions:

Although footwear production remains largely rooted in traditional craft-based and industrial practices, the literature reviewed suggests that AI and generative design can gradually support meaningful improvements across the design-to-production workflow. Rather than replacing established expertise, these technologies appear most valuable when they extend the designer's ability to explore alternatives, evaluate feasibility earlier, and connect design intent with manufacturable outcomes.

Across the studies discussed, three topics stand out addressing the proposed research questions. First, addressing RQ1, by facilitating quicker iteration and providing variations that might not arise through traditional workflows, generative and AI-assisted approaches can broaden design exploration through advanced 3D modelling techniques. Secondly, responding to RQ2, they can enhance manufacturing efficiency by reducing late-stage changes through digital modelling, prototyping, and better-informed decision-making using high-accuracy automated systems Third, regarding RQ3, when combined with optimization techniques and additive manufacturing options, they can help achieve sustainability goals by highlighting material flows, waste reduction, and resource efficiency through high-precision predictive models.

At the same time, the review highlights persistent barriers that limit wider adoption in footwear, including the fragmentation of digital workflows, limited access to domain-specific data, the gap between digital simulations and physical production, integration challenges with existing CAD and production systems, and the need for clear evaluation criteria that go beyond novelty and aesthetics. The lack of transparency in AI decision-making also remains a challenge for industrial trust. Future research should focus on validated footwear-specific case studies and datasets, measurable sustainability outcomes, and design practices that balance creative exploration with manufacturability and real-world constraints.

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