Modernizing Apparel Design within Intangible Cultural Heritage through Digital Innovation

Qingyi Zhang[1], Haze Ng[2*]

[1]*The Hong Kong Polytechnic University, Yuk Choi Road, 000000, Hong Kong SAR, China*
[*]Corresponding author's email: hazekh.ng@polyu.edu.hk
Presenting author's email address:
1st author's email address: kimleigh.zhang@connect.polyu.hk

Abstract

This paper investigates how digital innovation revolutionizes apparel design, specifically addressing the modernization and inheritance of Intangible Cultural Heritage (ICH) craftsmanship amidst growing sustainability demands. We analyse the transformative capabilities of Computer-Aided Design (CAD) and advanced Digital Manufacturing technologies, including 3D printing, across design processes. The study demonstrates these integrated tools enhance efficiency, enable personalized production, and fundamentally reshape workflows through process integration and data-driven methodologies. Findings reveal significant strategic value in ICH preservation, promoting sustainable development, and fostering novel business models within the fashion industry.

Keywords: Digital Innovation; Apparel Design; Intangible Cultural Heritage; Sustainable Fashion; Personalization

1. Introduction

The global fashion industry is undergoing a significant transformation, driven by an increasing imperative for sustainable development and evolving production and consumption models. Concurrently, ICH apparel craftsmanship faces multifaceted challenges, including effective inheritance, adaptation to modern demands, and innovative revitalization. Preserving these traditional techniques is crucial for cultural identity and fostering unique, sustainable, diversified fashion ecosystems. Digital innovation presents a powerful avenue for addressing these complexities, offering opportunities to enhance traditional craftsmanship, optimize design processes, and facilitate a more sustainable and personalized future for the industry.

Despite the recognized value of digital transformation and cultural heritage, the specific mechanisms through which advanced digital technologies can systematically empower and innovate ICH apparel design processes warrant further investigation. Existing research often addresses digital tools in a general fashion, design, or isolated aspects of heritage preservation. This paper aims to bridge this gap by comprehensively exploring the application of digital innovation in apparel design, specifically examining its impact on the modernization and inheritance of ICH craftsmanship. By detailing the evolution and capabilities of CAD systems and various Digital Manufacturing technologies (including 3D printing, laser cutting, CNC embroidery, and digital printing), this study demonstrates how these tools revolutionize the design workflow, fostering process integration, data-driven approaches, and multi-stakeholder collaboration. This analysis provides a multi-layered understanding of digital technology's transformative value in ensuring the vitality and relevance of traditional apparel heritage within the contemporary, sustainable fashion landscape.

2. Digital Manufacturing for Personalized Design

The contemporary concept of cultural heritage has particularly evolved, extending beyond static monuments and tangible artifacts to encompass living traditional expressions inherited from ancestors, namely ICH. Within the ICH

framework, traditional craftsmanship, characterized by its unique material manifestations, constitutes a core category. The intrinsic value of ICH lies in the knowledge and sophisticated skills transmitted through its living vehicles, rather than its outward cultural manifestations; the intergenerational transmission of such knowledge and skills holds equivalent socio-economic value for populations across nations.

This section explores the application of digital technologies in apparel design and their impact on the innovation of design processes for ICH apparel craftsmanship, which currently faces challenges in inheritance and modernization. In contrast, digital tools and methodologies provide crucial impetus for transforming the apparel industry. Consequently, investigating the application of digital technologies in this domain holds significant importance for exploring pathways to the protection, revitalization, and innovation of ICH apparel techniques.

Multiple factors drive the application of digital technologies in ICH apparel design. The challenges to the continued existence of traditional techniques necessitate digital documentation and dissemination to preserve their knowledge systems. Growing demand for personalized customization and rapid response requires technological empowerment to meet consumer needs for uniqueness. Digital technologies offer crucial impetus for transforming the apparel industry, particularly in the inheritance and modernization of ICH apparel craftsmanship. These tools enhance design efficiency and precision, enabling personalized customization and sustainable production.

2.1 Computer-Aided Design

Computer-Aided Design (CAD) utilizes computers to assist in product development, encompassing model creation, modification, analysis, and optimization. CAD software integrates drafting, modeling, and analysis functionalities, significantly enhancing design efficiency, precision, and data management. In fashion and textile design, CAD has evolved from a 2D drafting tool into a comprehensive platform integrating 3D modeling, simulation, and automation [1].

The development of apparel CAD systems began in the early 1990s, with initial research focusing on integrating computer technology into garment design. Early efforts demonstrated 3D CAD garment design systems that used virtual mannequins for visualization and explored "2D to 3D" and "3D to 2D" design methodologies, alongside tools for simulating fabric drape [2]. By the mid-to-late 1990s and early 2000s, CAD technology saw closer integration with artificial intelligence and 3D human body data. This led to design assistance systems and methods for deforming 2D fabric patterns on 3D objects. This period also saw the development of more comprehensive 3D garment CAD systems, including flat pattern drafting, resizable virtual mannequins, fabric simulation engines, and computer-driven pattern modification for customization.

From 2003 to the present, CAD systems have achieved significant advancements in 3D modeling algorithms, interactivity, and automation, enabling more realistic simulations and efficient design workflows [3]. Current systems support advanced "2D to 3D" design modeling, automatic component modeling, and intelligent dressing of virtual human models. The application of artificial intelligence in parametric design, for tasks such as predicting pattern parameters and assisting design decisions, has also become more widespread. Modern comprehensive CAD systems now integrate 3D modelers, 2D CAD units, and 3D simulators, achieving complete workflows from 3D design to 2D pattern generation and simulation evaluation. Significant progress has also been made in responsive 2D/3D apparel pattern design, allowing for automatic synchronization between 2D and 3D modifications, alongside the maturation of virtual fashion shows and dynamic simulation tools. More recently, the focus has shifted towards the deepened application of automation, parameterization, and mass customization, enabling automatic generation of basic garment patterns from 3D measurement data and tailored programs for customized production. This trajectory reflects the apparel industry's continuous pursuit of efficiency, precision, and personalization, supporting virtual prototyping and customized production.

2.2 Digital Manufacturing for Personalized Design

Digital manufacturing technologies utilize computer-controlled equipment to produce physical products directly from digital models, encompassing 3D printing (additive manufacturing), laser cutting, computer numerical control (CNC) embroidery, and digital printing [4]. While CAD is an upstream design process, digital manufacturing directly employs the digital models for fabrication. These technologies show significant potential in traditional apparel

customization and innovation, overcoming conventional craftsmanship limitations and enabling highly personalized production.

Digital manufacturing provides an efficient pathway for personalized and customized design, supporting small-batch, multi-variety production, thereby reducing inventory and resource waste. Consumers can engage deeply in apparel design through online platforms, achieving individualized customization. Furthermore, digital manufacturing can realize complex geometric shapes and intricate structures that are challenging for traditional processes. Mass Customization, integrating mass production efficiencies with individual needs, has emerged as a key competitive strategy [5]. Parametric Computer-Aided Design (P-CAD) systems for apparel patterns enhance flexibility and efficiency in personalized pattern drafting by enabling parameter substitution and flexible design adjustments.

Digital manufacturing technologies offer diverse specific applications in apparel customization. For instance, 3D printing enables the layer-by-layer production of complex, high-precision objects, mitigating traditional manufacturing inefficiencies and supporting mass customization and rapid prototyping. In fashion, 3D printing creates flexible, functional apparel and accessories. Examples include Danit Peleg's "Bomber jacket" and Maria Alejandra Mora-Sanchez's 3D-printed dress "Loom," and printing Braille onto natural fabrics [6]. Laser cutting facilitates precise cutting and pattern engraving, enhancing production precision. CNC embroidery precisely controls traditional embroidery patterns for automated production. Digital printing, particularly Inkjet Digital Textile Printing (IJDTP), is recognized as an innovative and environmentally friendly technique [7], offering low cost, high precision, and speed. It provides flexibility and process improvements and, combined with CAD, can achieve photorealistic, large-format prints with hundreds of colors. Digital manufacturing technologies empower traditional craftsmanship by providing precise templates and pre-fabricated complex components. However, limitations exist in cost-effectiveness, efficiency, and the range of applicable materials for digital manufacturing, particularly for 3D printing to achieve desired textile flexibility and comfort[8]. Certain cutting-edge digital manufacturing technologies remain in developmental stages, and their deep integration with apparel production remains a significant research direction. Challenges in digital printing include color reproduction accuracy, dot gain, and the lack of comprehensive fabric defect detection datasets [9].

3. Impact on Design Process Innovation

Digital technologies have revolutionized traditional apparel design processes, particularly in the preservation, inheritance, and innovation of ICH apparel techniques. This transformation diverges from conventional paradigms, with digital technology as a core driving force progressively empowering and synergistically promoting innovation throughout the design workflow, yielding strategic outcomes. A multi-layered, interconnected systemic view can summarize its potential impacts, as illustrated in Figure 1 below.

Foundational technologies underpin digital technology innovation, collectively facilitating design process reform and laying the groundwork for the digital transformation of traditional apparel techniques. Specifically, CAD and CAM systems can establish a digital chain from concept to production. Product Lifecycle Management (PLM) systems enable comprehensive data integration and management across the product lifecycle. Furthermore, Artificial Intelligence (AI) and Big Data technologies hold promise for providing intelligent analysis and prediction for design decisions; Virtual Reality (VR) and Augmented Reality (AR) technologies can open avenues for design validation and immersive experiences; and Blockchain technology can ensure data traceability and intellectual property protection [10].

Digital technologies drive the integration of design processes and multi-party collaboration, fundamentally reshaping traditional design collaboration models. The seamless integration of CAD, CAM, and PLM systems enables end-to-end data flow from garment design, pattern making, and virtual simulation to final manufacturing, effectively breaking down information silos and significantly enhancing overall efficiency. Digital platforms facilitate multi-stakeholder collaboration among designers, traditional artisans, pattern makers, manufacturers, and consumers [11]. These shared platforms promote real-time communication and joint decision-making, optimizing designs, accelerating development, and fostering the transmission of traditional craft knowledge. This transformation also impacts the roles and required competencies of designers and related practitioners: they must master new digital tools such as 3D modeling, parametric design software, and AI-assisted design platforms, while deeply understanding the essence of traditional craftsmanship. They are also required to actively engage in interdisciplinary collaboration

with experts from diverse fields, including traditional artisans, engineers, and data scientists, to integrate traditional and modern design philosophies and expand innovative possibilities. Additionally, virtual prototyping and testing are now achievable; designers can accurately simulate and test garments using virtual models before physical sample production, which shortens development cycles, reduces trial-and-error costs, and increases design success rates.

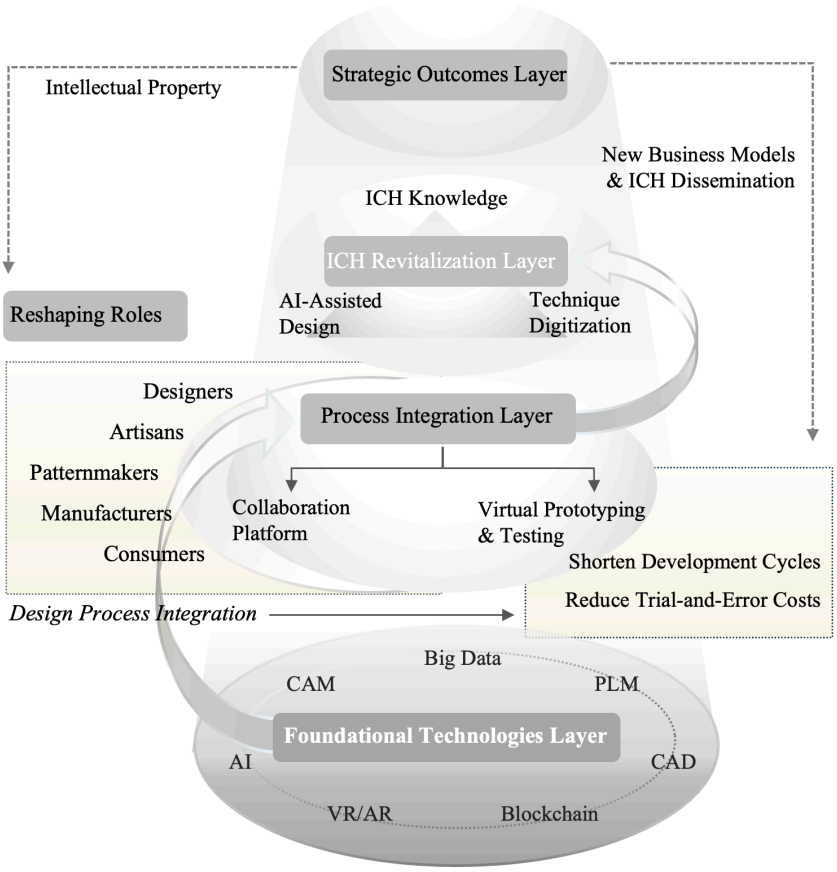

Fig. 1 Comprehensive View of Digital Technology's Impact
on ICH Apparel Design Process Innovation

The data streams generated by process integration and collaboration further propel the design process towards data-driven paradigms, thereby promoting the revitalization of ICH apparel techniques [12]. Big data analytics and AI technologies enable the systematic digitization of traditional garment patterns, craftsmanship details, and motif designs. In-depth analysis of vast datasets can reveal traditional techniques' inherent principles and aesthetic characteristics, providing scientific guidance for contemporary design decisions and innovations. The application of AI in design is becoming increasingly widespread; for instance, AI-assisted garment design, intelligent generation of traditional patterns, and market trend prediction all inspire the modernization of traditional apparel. Furthermore, digital technologies facilitate the construction of ICH knowledge bases by systematically recording and managing the tacit knowledge of traditional artisans, transforming it into searchable and learnable digital assets, which ensures the inheritance and dissemination of ICH techniques [13].

The application of digital technologies in the apparel design process, through the advancements across the aforementioned layers, yields multiple strategic outcomes. Regarding sustainable development, measures such as digital prototyping, on-demand production, and optimized cutting solutions contribute to reducing material waste and promoting circular design principles. Regarding intellectual property protection and product traceability, blockchain and similar technologies can provide reliable traceability mechanisms for customized products, thereby safeguarding the intellectual property of traditional techniques [14]. In business models and ICH dissemination, digital

technologies can foster the emergence of personalized and made-to-measure services, fulfilling consumer demand for uniqueness. Emerging models like virtual apparel and digital fashion shows offer new channels for the global dissemination of ICH apparel techniques. Concurrently, the on-demand production model enables brands to respond rapidly to market demands while preserving the living heritage of traditional craftsmanship.

4. Conclusion

This study investigated the transformative role of digital technologies, specifically CAD and advanced Digital Manufacturing techniques, in modernizing apparel design, focusing on preserving and innovating ICH craftsmanship. The core findings demonstrate that CAD systems have evolved into sophisticated platforms that enhance design efficiency, precision, and the transition from 2D to 3D virtual prototyping. Concurrently, digital manufacturing, encompassing 3D printing, laser cutting, CNC embroidery, and digital printing, enables personalized customization and sustainable production by supporting small-batch, multi-variety models and realizing complex designs. These integrated digital tools significantly empower traditional craftsmanship, fostering innovation within the apparel industry.

The research highlights the profound significance of digital innovation in driving process integration and multi-party collaboration within apparel design. It emphasizes how data-driven paradigms, fueled by big data analytics and AI, facilitate the systematic digitization and intelligent analysis of traditional patterns and craftsmanship, ensuring knowledge preservation and inspiring contemporary designs. Furthermore, applying these technologies yields strategic outcomes that contribute to sustainable development through reduced material waste and on-demand production, enhance intellectual property protection via traceability, and open new avenues for business models and global dissemination of ICH apparel techniques. These findings demonstrate a valuable contribution to bridging technological advancement with cultural heritage, fostering a more sustainable and innovative future for the fashion industry.

Despite these advancements, specific limitations exist within current digital manufacturing technologies, such as challenges in cost-effectiveness, the range of applicable materials (e.g., achieving traditional textile flexibility with 3D printing), and the complexities of deeply integrating these technologies with the manual expertise critical to apparel production. Future research should therefore focus on overcoming these material and integration bottlenecks, enhancing the accuracy of digital printing technologies, and exploring novel methods for human-AI collaboration that further blend traditional artistry with cutting-edge computational capabilities. Continued efforts are needed to fully harness digital potential in preserving and evolving ICH, ensuring its vibrant presence in a technologically advanced and sustainable fashion landscape.

5. Acknowledgement

The work described in this paper was fully supported by a grant from the Research Grants Council of the Hong Kong Special Administrative Region, China (Project No. PolyU15610922).

References

[1] Glogar M, Petrak S, Mahnić Naglić M. Digital technologies in the sustainable design and development of textiles and clothing—a literature review. Sustainability. 2025;17(4):1371.
[2] Fozzard G, Rawling D. A computer-aided design system for garment patterns: part 2. Comput Aided Des. 1992;24(4):216-21.
[3] Kim YJ, Kang JH, Lee JY. Automatic pattern generation for customized trousers. Int J Cloth Sci Technol. 2013;25(1):1-12.
[4] Dong B, Jia H, Li Z, Dong K. Implementing mass customization in garment industry. Systems Eng Procedia. 2012;3:372-80.
[5] Watcharapanyawong K, Sirisoponsilp S, Sophatsathit P. A model of mass customization for engineering production system development in textile and apparel industries in Thailand. Systems Eng Procedia. 2011;2:382-97.

[6] Istook CL. Enabling mass customization: computer-driven alteration methods. Int J Cloth Sci Technol. 2002;14(1):61-76.
[7] Xiu Y, Wan ZK, Cao W. A constructive approach toward a parametric pattern-making model. Text Res J. 2011;81(10):979-91.
[8] Meng Y, Wang CC, Jin X. Flexible shape control for automatic resizing of apparel products. Comput Aided Des. 2012;44(1):68-76.
[9] Kim S, Seong H, Her Y, Chun J. A study of the development and improvement of fashion products using a FDM type 3D printer. Fashion Text. 2019;6(1):9.
[10] Lim J, Chapman LP. Fabric surface characteristics and their impact on digital textile printing quality of PET fabrics. AATCC J Res. 2019;6(1):1-9.
[11] Koseoglu AU. Innovations and analysis of textile digital printing technology. Int J Sci Technol Soc. 2019;7(2):38-43.
[12] Khan MA. Challenges faced by digital printing industry. Pakistan Text J. 2018;67(11):48.
[13] Tyler DJ. Textile digital printing technologies. Text Prog. 2005;37(4):1-65.
[14] Nasim M, Mumtaz R, Ahmad M, Ali A. Fabric defect detection in real world manufacturing using deep learning. Information. 2024;15(8):476.