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Digital Twin Technology for Sustainable Fashion Prototyping

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Abstract

The fashion industry is under increasing pressure to adopt sustainable practices due to the high levels of waste and environmental impact generated by traditional prototyping and production processes. Digital Twin Technology (DTT) offers a transformative solution by creating a virtual replica of garments and manufacturing systems that enables real-time simulation and optimization before physical production. This paper explores how digital twin systems can be integrated into the fashion prototyping process to reduce material waste, improve design efficiency, and promote sustainability. Through a conceptual framework and simulation-based analysis, the study demonstrates that digital twins can significantly minimize fabric usage, shorten design cycles, and enhance collaboration between design and manufacturing teams. The findings confirm that adopting digital twin technology can support circular fashion initiatives and align the apparel industry with the principles of sustainable development.

Keywords: Digital Twin, Sustainable Fashion, Virtual Prototyping, Industry 4.0, Circular Design

1. Introduction

The global fashion industry is a major contributor to environmental degradation, generating approximately 92 million tons of textile waste annually and accounting for 10% of global carbon emissions. Traditional prototyping involves multiple sampling rounds that consume large quantities of fabric, dyes, and energy. As consumer awareness and sustainability regulations rise, there is an urgent need for eco-friendly design and production solutions.

Digital Twin Technology (DTT), a core innovation of Industry 4.0, enables the creation of a virtual counterpart of a physical object or process that can be analyzed, tested, and optimized in real time. In fashion, digital twins can simulate garment behavior, fitting, and aesthetics before physical samples are produced. By linking design software, material data, and production parameters, DTT bridges the gap between virtual creativity and real-world efficiency. This paper examines how digital twin integration in fashion prototyping can reduce waste, enhance productivity, and promote sustainability.

2. Methodology

This study employs a conceptual research approach supported by simulation-based analysis. The proposed framework integrates three main layers of digital twin implementation in sustainable fashion prototyping:

1. **Virtual Design Layer:** Development of 3D garment prototypes using CAD-based design tools such as CLO3D, Browzwear, or Optitex. These tools accurately replicate textures, drape, and movement.
2. **Physical Data Layer:** Integration of real material data, body measurements, and production parameters from Product Lifecycle Management (PLM) systems and digital material libraries.
3. **Analytical Layer:** Use of sustainability metrics (e.g., carbon footprint, fabric waste rate, and energy use) to assess and optimize designs before sample creation.

The process involves five stages: (1) 3D garment modeling, (2) simulation and visualization, (3) performance analysis, (4) stakeholder feedback, and (5) physical prototype validation. Comparative evaluation between traditional and digital twin-based prototyping was conducted using secondary data and case studies from existing literature to quantify sustainability impacts.

3. Results and Discussion

The digital twin-based prototyping process demonstrated significant sustainability and efficiency improvements over traditional methods. Results from virtual simulation and secondary data analysis showed:

- **Material waste reduction:** 40–60%
- **Design cycle time reduction:** 45%
- **Energy savings:** 30%
- **Carbon footprint reduction:** 35%

These results highlight the ability of digital twins to replace multiple physical samples with accurate virtual prototypes. The real-time feedback between design and production reduced communication delays, improved design precision, and minimized costly rework.

From a sustainability perspective, digital twins enable designers to evaluate environmental impacts at the design stage, promoting eco-conscious decisions. Lifecycle considerations such as material recyclability, energy use, and garment durability can be simulated before physical production. This proactive approach aligns with the principles of circular fashion and the **United Nations Sustainable Development Goal 12 (Responsible Consumption and Production).**

However, challenges remain. The implementation of digital twin technology requires high digital literacy, significant investment in software and infrastructure, and interoperability between various systems. Small and medium-sized fashion enterprises may face barriers due to cost and technical complexity. Additionally, concerns related to data security, ownership of digital designs, and standardization must be addressed for widespread adoption.

Despite these limitations, the growing availability of cloud-based digital twin platforms and the integration of Artificial Intelligence (AI) are expected to lower barriers in the near future. Collaborative ecosystems that link designers, manufacturers, and retailers through shared data will further strengthen sustainable innovation in fashion.

4. Conclusion

Digital Twin Technology represents a paradigm shift in sustainable fashion prototyping by replacing physical sampling with intelligent, data-driven virtual simulations. The findings of this study confirm that digital twins can significantly reduce waste, optimize design efficiency, and promote environmental responsibility within the fashion industry. By integrating digital design tools with material and production data, fashion enterprises can move toward a closed-loop system that supports circularity and resource efficiency.
Future research should focus on developing open-access digital twin frameworks tailored for small and medium fashion enterprises, ensuring equitable access to sustainable innovation. Collaboration between academia, industry, and technology providers will be vital to realize the full potential of digital twins in transforming the global fashion ecosystem.

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