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INDUSTRY 5.0 AND DIGITAL TRANSFORMATION FOR SUSTAINABLE TEXTILE AND MANUFACTURING SYSTEMS

Scientific paper
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ABSTRACT: *The rapid evolution of digital technologies has significantly transformed modern manufacturing systems, creating new opportunities for improving productivity, sustainability, and industrial resilience. In this context, Industry 5.0 has emerged as a new industrial paradigm that extends the technological achievements of Industry 4.0 by emphasizing human-centric manufacturing, sustainable production, and resilient industrial systems. Simultaneously, digital transformation has become a key enabler for integrating intelligent technologies into both textile and manufacturing industries, supporting resource-efficient production, process optimization, and environmentally responsible manufacturing practices. This paper presents a comprehensive review of the relationship between Industry 5.0, digital transformation, and sustainable textile and manufacturing systems. The study examines the fundamental principles of Industry 5.0 and discusses the role of enabling technologies, including Artificial Intelligence (AI), the Internet of Things (IoT), Digital Twins, Big Data analytics, Cloud Computing, and Cyber-Physical Systems (CPS), in supporting intelligent manufacturing environments. Particular attention is devoted to the application of these technologies in textile manufacturing, where digitalization contributes to automated quality control, smart textile production, resource efficiency, digital product traceability, and circular production strategies. Based on the findings of the literature review, the authors propose a conceptual model of Industry 5.0-driven digital transformation that integrates three complementary dimensions: Digital Technologies, Human-Centred Manufacturing, and Sustainable Manufacturing. The proposed model illustrates how the interaction among these dimensions contributes to improved manufacturing performance through enhanced productivity, flexibility, product quality, environmental responsibility, and industrial resilience. Furthermore, the model demonstrates the importance of integrating technological innovation with human expertise and sustainability principles to support the future development of both textile and manufacturing systems. The proposed conceptual model may serve as a foundation for future research focused on intelligent manufacturing, smart textile production, Artificial*

Intelligence, Digital Twins, sustainable industrial development, and Industry 5.0 implementation strategies.

Keywords: *Industry 5.0; Digital transformation; Sustainable manufacturing; Textile industry; Smart manufacturing; Human-centred manufacturing.*

INDUSTRIJA 5.0 I DIGITALNA TRANSFORMACIJA ZA ODRŽIVE TEKSTILNE I PROIZVODNE SISTEME

APSTRAKT: *Brz razvoj digitalnih tehnologija značajno je transformisao savremene proizvodne sisteme, stvarajući nove mogućnosti za unapređenje produktivnosti, održivosti i otpornosti industrije. U tom kontekstu, Industrija 5.0 pojavljuje se kao nova industrijska paradigma koja proširuje tehnološka dostignuća Industrije 4.0 stavljajući poseban akcenat na proizvodnju usmerenu ka čoveku, održivu proizvodnju i otporne industrijske sisteme. Istovremeno, digitalna transformacija postala je ključni pokretač integracije inteligentnih tehnologija u tekstilnu industriju i proizvodne sisteme, omogućavajući efikasnije korišćenje resursa, optimizaciju procesa i ekološki odgovornu proizvodnju. U ovom radu dat je pregled odnosa između Industrije 5.0, digitalne transformacije i održivih tekstilnih i proizvodnih sistema. Analizirani su osnovni principi Industrije 5.0, kao i uloga ključnih digitalnih tehnologija, uključujući veštačku inteligenciju (Artificial Intelligence – AI), Internet stvari (Internet of Things – IoT), digitalne blizance (Digital Twins), analitiku velikih podataka (Big Data Analytics), računarstvo u oblaku (Cloud Computing) i sajber-fizičke sisteme (Cyber-Physical Systems – CPS), u razvoju inteligentnih proizvodnih okruženja. Posebna pažnja posvećena je primeni ovih tehnologija u tekstilnoj industriji, gde digitalizacija doprinosi automatizovanoj kontroli kvaliteta, pametnoj tekstilnoj proizvodnji, efikasnijem korišćenju resursa, digitalnoj sledljivosti proizvoda i primeni principa cirkularne proizvodnje. Na osnovu sprovedenog pregleda literature, autori predlažu konceptualni model digitalne transformacije zasnovan na Industriji 5.0, koji integriše tri komplementarne dimenzije: digitalne tehnologije, proizvodnju usmerenu ka čoveku i održivu proizvodnju. Predloženi model ilustruje kako međusobna interakcija ovih dimenzija doprinosi unapređenju proizvodnih performansi kroz povećanje produktivnosti, fleksibilnosti, kvaliteta proizvoda, zaštite životne sredine i otpornosti industrijskih sistema. Pored toga, model naglašava značaj integracije tehnoloških inovacija, ljudskog znanja i principa održivosti kao osnove budućeg razvoja tekstilne industrije i savremenih proizvodnih sistema. Predloženi konceptualni model može predstavljati osnovu za buduća istraživanja usmerena na inteligentnu proizvodnju, pametnu tekstilnu proizvodnju, veštačku inteligenciju, digitalne blizance, održivi industrijski razvoj i strategije implementacije Industrije 5.0.*

Ključne reči: *Industrija 5.0; Digitalna transformacija; Održiva proizvodnja; Tekstilna industrija; Pametna proizvodnja; Proizvodnja usmerena ka čoveku.*

1. INTRODUCTION

The manufacturing sector is currently undergoing a profound transformation driven by rapid technological advancements, increasing sustainability requirements, and the growing integration of digital technologies. Following the widespread implementation of Industry 4.0 concepts, the emergence of Industry 5.0 represents a new industrial paradigm that emphasizes human-centric production, resilience, and sustainability while maintaining the advantages of digital transformation and smart manufacturing technologies [3,10].

Digital transformation has become one of the primary drivers of competitiveness in modern manufacturing systems. Technologies such as Artificial Intelligence (AI), the Internet of Things (IoT), Big Data analytics, cloud computing, Digital Twins, and Cyber-Physical Systems (CPS) enable manufacturers to optimize production processes, improve product quality, increase flexibility, and reduce operational costs. These technologies simultaneously support data-driven decision-making and facilitate the transition toward more intelligent and sustainable manufacturing environments [4,6].

The textile industry is also experiencing significant changes resulting from digitalization, environmental regulations, and increasing customer demands for sustainable products. Traditional textile manufacturing is gradually evolving toward smart production systems characterized by automated processes, digital monitoring, resource-efficient production, and environmentally responsible manufacturing practices. Consequently, Industry 5.0 principles provide new opportunities for integrating advanced digital technologies with sustainable textile production while maintaining a strong focus on human creativity and industrial resilience [3,8].

Unlike Industry 4.0, which primarily focused on automation, connectivity, and productivity, Industry 5.0 places greater emphasis on collaboration between humans and intelligent technologies. Human expertise, creativity, and decision-making are considered essential components of future manufacturing systems, where digital technologies function as supporting tools rather than complete replacements for human operators. This transition reflects broader societal objectives related to sustainable development, circular economy principles, workforce well-being, and resilient industrial production [1,7]. Although numerous studies investigate Industry 5.0, digital transformation, or sustainable manufacturing independently, relatively few review papers systematically integrate these concepts within both textile and manufacturing systems. Establishing such an integrated perspective is increasingly important for supporting future industrial development and interdisciplinary research.

Therefore, the aim of this paper is to review the relationship between Industry 5.0, digital transformation, and sustainable manufacturing with particular emphasis on textile and manufacturing systems. The study analyses the key enabling technologies, current industrial applications, sustainability aspects, and future research directions while providing a comprehensive overview of the ongoing transition toward next-generation manufacturing.

2. FUNDAMENTALS OF INDUSTRY 5.0 AND DIGITAL TRANSFORMATION

Industry 5.0 represents the next stage in the evolution of industrial development, extending the technological achievements of Industry 4.0 by placing greater emphasis on human-centricity, sustainability, and resilience. While Industry 4.0 primarily focused on automation, connectivity, and intelligent production systems, Industry 5.0 promotes a balanced collaboration between advanced digital technologies and human expertise. This paradigm recognizes that future manufacturing should not only pursue productivity and efficiency but also create social, environmental, and economic value [1,3].

The concept of digital transformation forms the technological foundation of Industry 5.0. Digital transformation refers to the integration of digital technologies into manufacturing processes, organizational structures, and business models to improve operational performance, flexibility, and innovation. Rather than representing a single technological solution, digital transformation combines multiple enabling technologies, including Artificial Intelligence (AI), the Internet of Things (IoT), Big Data analytics, Cloud Computing, Cyber-Physical Systems (CPS), Digital Twins, robotics, and advanced data communication networks [4,6].

One of the distinguishing characteristics of Industry 5.0 is its human-centric approach. Instead of replacing human workers with automation, Industry 5.0 promotes collaboration between people and intelligent machines. Advanced robotics, collaborative robots (cobots), and artificial intelligence assist human operators by performing repetitive, hazardous, or computationally intensive tasks, allowing employees to focus on creativity, decision-making, problem-solving, and innovation. This collaborative environment contributes to higher productivity while simultaneously improving workplace safety and employee well-being [3,7].

Another key pillar of Industry 5.0 is sustainability. Modern manufacturing systems are increasingly expected to minimize environmental impacts through efficient resource utilization, energy optimization, waste reduction, circular economy principles, and environmentally responsible production strategies. Digital technologies provide valuable support for monitoring resource consumption, optimizing production parameters, predicting equipment failures, and reducing unnecessary material losses throughout the manufacturing lifecycle [3,8]. Resilience has also become a fundamental objective of Industry 5.0. Recent global disruptions, including supply chain instability and rapidly changing market conditions, have demonstrated the necessity of flexible manufacturing systems capable of adapting to unexpected challenges. Digital transformation enhances industrial resilience through real-time monitoring, predictive analytics, intelligent decision support, and adaptive manufacturing systems that enable rapid responses to changing production requirements [6,10].

Overall, Industry 5.0 should be viewed as a comprehensive industrial strategy that integrates digital technologies with human knowledge, sustainability principles, and resilient manufacturing systems. This integrated perspective provides the foundation for the future development of textile production and advanced manufacturing industries.

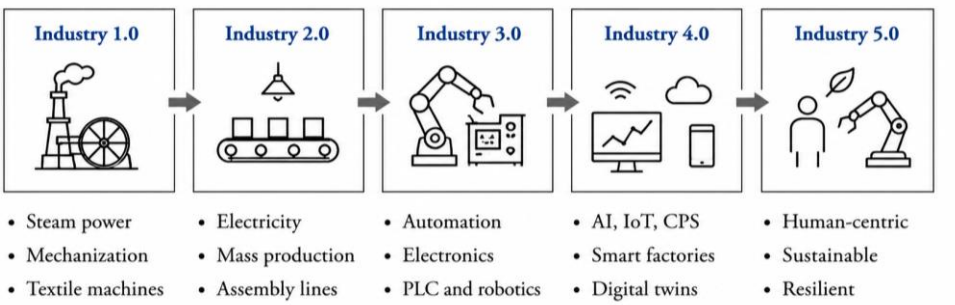

Figure 1: Evolution of industrial revolutions from Industry 1.0 to Industry 5.0

3. DIGITAL TRANSFORMATION IN TEXTILE AND MANUFACTURING SYSTEMS

Digital transformation has become one of the most significant driving forces behind the evolution of modern manufacturing systems. By integrating advanced digital technologies into industrial environments, manufacturers are able to improve operational efficiency, increase production flexibility, enhance product quality, and support sustainable manufacturing practices. Rather than representing the adoption of individual technologies, digital transformation involves the comprehensive integration of intelligent systems throughout the entire product lifecycle [4,6].

Within textile manufacturing, digital transformation enables substantial improvements in production planning, process monitoring, quality control, inventory management, and supply chain coordination. Smart sensors, automated inspection systems, and real-time data acquisition allow manufacturers to continuously monitor production parameters and rapidly identify process deviations. These technologies contribute to reduced material waste, improved resource utilization, and greater manufacturing flexibility while supporting increasingly customized textile production [3,8].

Artificial Intelligence (AI) has emerged as one of the most influential technologies supporting digital transformation. Machine learning algorithms enable predictive maintenance, quality prediction, defect detection, production scheduling, and intelligent decision-making based on large volumes of manufacturing data. AI-assisted optimization reduces production downtime, improves equipment utilization, and supports adaptive manufacturing strategies capable of responding to changing customer requirements [6,10].

Beyond conventional manufacturing, Artificial Intelligence is increasingly applied in textile production for automated fabric inspection, defect detection, colour consistency evaluation, production scheduling, and demand forecasting. Machine learning algorithms enable the identification of weaving and knitting defects, optimize dyeing parameters, and improve production planning, thereby reducing material waste and enhancing product quality. These intelligent systems support mass customization while simultaneously contributing to more sustainable textile manufacturing [6,8].

The Internet of Things (IoT) further strengthens digital manufacturing through interconnected sensors, machines, and production equipment capable of continuously exchanging operational information. Combined with cloud computing and Big Data analytics, IoT enables real-time monitoring of manufacturing systems, facilitating data-driven decision-making and improved process transparency. These technologies are particularly valuable for textile manufacturing, where continuous monitoring of temperature, humidity, machine performance, and production quality contributes to more stable and efficient manufacturing operations [4,5].

The Internet of Things also plays a significant role in modern textile manufacturing by enabling continuous monitoring of weaving, knitting, dyeing, and finishing operations. Smart sensors provide real-time information on machine conditions, temperature, humidity, energy consumption, and production quality, allowing manufacturers to rapidly respond to process deviations while improving resource efficiency and reducing production losses [4,5].

Digital Twins have also become increasingly important in Industry 5.0 environments. A Digital Twin represents a virtual replica of a physical manufacturing system that continuously receives operational data from the real production process. This technology enables virtual testing, process simulation, predictive maintenance, and optimization before implementing changes within industrial environments. Consequently, Digital Twins reduce development time, minimize production risks, and improve overall manufacturing performance [3,9].

In the textile industry, digital transformation supports intelligent weaving, knitting, dyeing, finishing, and garment manufacturing through automated production control, machine vision systems, RFID-based traceability, and AI-assisted quality inspection. These technologies improve production efficiency, reduce defects, optimize material utilization, and enable mass customization while supporting sustainable textile production [6,8].

Overall, digital transformation provides the technological foundation for Industry 5.0 by connecting intelligent digital technologies with human expertise and sustainable manufacturing principles. The successful integration of AI, IoT, Digital Twins, and advanced analytics enables manufacturing organizations to achieve higher productivity while simultaneously improving sustainability, resilience, and customer-oriented production.

Table 1: Digital technologies supporting Industry 5.0 in textile and manufacturing systems

Digital technology	Main application	Industrial benefit
Artificial Intelligence (AI)	Predictive maintenance and quality prediction	Improved productivity
Internet of Things (IoT)	Real-time monitoring	Process optimization
Digital Twins	Virtual simulation	Reduced development time
Big Data Analytics	Data-driven decision-making	Improved efficiency
Cloud Computing	Data storage and communication	Enhanced collaboration
Cyber-Physical Systems	Smart production integration	Flexible manufacturing

4. SUSTAINABLE TEXTILE AND MANUFACTURING SYSTEMS

Sustainability has become one of the defining principles of modern industrial development and represents a central pillar of Industry 5.0. Contemporary manufacturing systems are increasingly expected to achieve high levels of productivity while simultaneously reducing environmental impacts, improving resource efficiency, and ensuring long-term economic and social sustainability. Unlike previous industrial paradigms, Industry 5.0 places sustainability at the core of manufacturing strategies, promoting environmentally responsible production supported by advanced digital technologies [1,3].

Digital transformation also supports the development of smart textile manufacturing through digital textile printing, automated cutting systems, intelligent material handling, and real-time production traceability. These technologies facilitate customized production, improve process flexibility, and contribute to more efficient utilization of textile materials while supporting circular production strategies. Furthermore, digital product passports and traceability systems are expected to play an increasingly important role in textile recycling and sustainable supply chain management [2,8].

Within the textile industry, sustainability has become particularly important due to high energy consumption, intensive water usage, chemical processing, and significant waste generation throughout the production lifecycle. Digital transformation enables textile manufacturers to optimize resource utilization, monitor environmental performance, improve process efficiency, and reduce emissions through intelligent production management. Technologies such as AI, IoT, and Digital Twins contribute to more efficient control of textile manufacturing processes while supporting sustainable production practices [6,8].

Energy efficiency represents another major objective of sustainable manufacturing systems. Real-time monitoring, predictive analytics, and intelligent process optimization enable manufacturers to reduce unnecessary energy consumption while maintaining production quality and operational stability. Smart manufacturing technologies further contribute to minimizing equipment downtime, optimizing machine utilization, and extending equipment lifetime through predictive maintenance strategies [4,5].

Resource efficiency and circular production principles have also become fundamental components of sustainable manufacturing. Industry 5.0 encourages manufacturers to optimize raw material utilization, reduce production waste, improve recycling practices, and implement closed-loop manufacturing systems whenever possible. Digital technologies facilitate these objectives by enabling continuous monitoring of material flows, production efficiency, and environmental performance throughout the product lifecycle [2,3].

The transition toward circular textile manufacturing additionally requires the integration of digital technologies capable of tracking material flows throughout the entire product lifecycle. Advanced information systems support textile collection, sorting, recycling, and remanufacturing processes, thereby improving material recovery and enabling more efficient implementation of circular economy principles within the textile sector [1,2].

Furthermore, sustainability within Industry 5.0 extends beyond environmental considerations by incorporating social responsibility and human well-being. Human-centred manufacturing emphasizes safe working environments, employee development, collaborative robotics, and improved interaction between workers and intelligent manufacturing systems. Consequently, sustainable manufacturing should be understood as the balanced integration of technological innovation, environmental responsibility, economic competitiveness, and human welfare [1,7].

Overall, sustainable textile and manufacturing systems demonstrate that digital transformation and Industry 5.0 are mutually reinforcing concepts. Digital technologies provide the technological capabilities necessary for sustainable production, while Industry 5.0 establishes the strategic vision for integrating technological innovation with environmental stewardship and human-centred industrial development.

Table 2: Sustainability dimensions supported by Industry 5.0 technologies

Sustainability dimension	Industry 5.0 contribution	Example
Environmental	Resource efficiency	Reduced energy and material consumption
Economic	Intelligent process optimization	Lower production costs
Social	Human-centred manufacturing	Improved workplace safety
Technological	Digital transformation	AI, IoT and Digital Twins
Circular	Closed-loop production	Recycling and material recovery

5. CONCEPTUAL MODEL FOR INDUSTRY 5.0 - DRIVEN DIGITAL TRANSFORMATION

The literature reviewed throughout this study demonstrates that Industry 5.0 extends beyond the technological focus of Industry 4.0 by integrating digital innovation with sustainability, resilience, and human-centred manufacturing. Although numerous studies investigate individual enabling technologies or sustainability strategies, relatively limited attention has been devoted to presenting a unified conceptual model that illustrates how these elements collectively support the digital transformation of textile and manufacturing systems [1,3].

Based on the reviewed literature, a conceptual model is proposed to illustrate the relationship between Industry 5.0 principles, digital transformation technologies, and sustainable manufacturing objectives. Rather than representing a sequential implementation procedure, the proposed model emphasizes the interaction between technological innovation, organizational transformation, and sustainability-oriented manufacturing strategies.

At the core of the model is Industry 5.0, which provides the strategic vision for future manufacturing systems. Three complementary dimensions support this vision.

The first dimension, Digital Technologies, includes Artificial Intelligence (AI), the Internet of Things (IoT), Digital Twins, Big Data Analytics, Cloud Computing, and Cyber-Physical Systems. These technologies provide real-time data acquisition, intelligent decision-making, process automation, and predictive manufacturing capabilities [5,6].
The second dimension, Human-Centred Manufacturing, emphasizes collaboration between human expertise and intelligent technologies. Advanced automation and collaborative robots support workers by improving productivity, occupational safety, knowledge sharing, and innovation while maintaining human decision-making as a central component of manufacturing systems [3,7].
The third dimension, Sustainable Manufacturing, focuses on resource efficiency, energy optimization, circular production, waste reduction, environmental responsibility, and resilient industrial development. Digital technologies enable continuous monitoring and optimization of manufacturing processes, thereby supporting more sustainable and competitive production systems [2,8].
The interaction among these three dimensions leads to improved manufacturing performance through higher productivity, increased flexibility, enhanced product quality, reduced environmental impacts, and greater industrial resilience. Consequently, the proposed conceptual model demonstrates that successful digital transformation requires the simultaneous integration of technological innovation, human involvement, and sustainability principles rather than focusing exclusively on technological advancement.

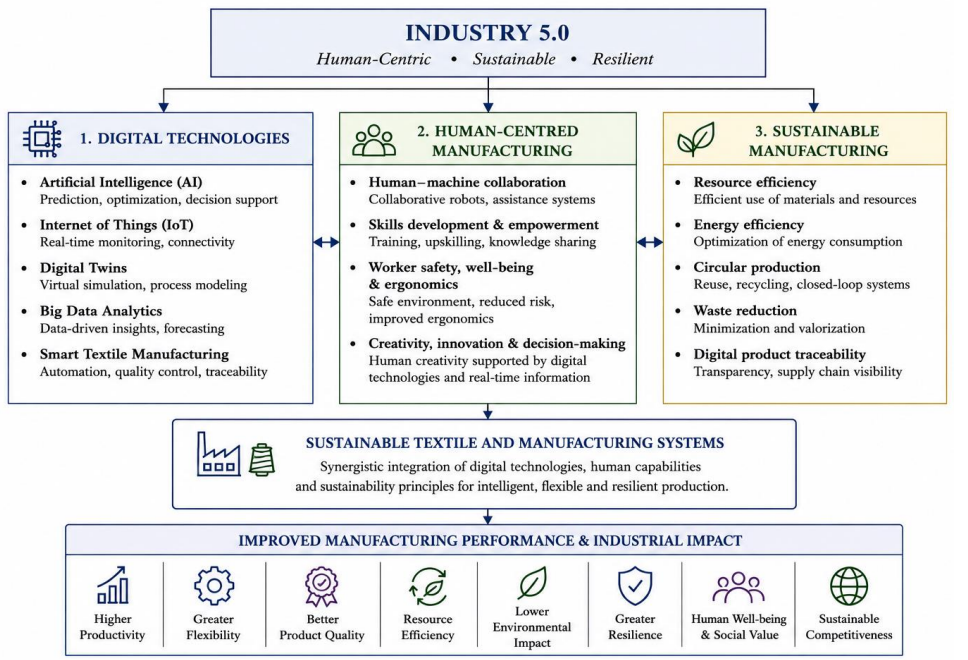

Figure 2: Conceptual model of Industry 5.0-driven digital transformation for sustainable textile and manufacturing systems

6. FUTURE RESEARCH DIRECTIONS

The transition toward Industry 5.0 is expected to accelerate the integration of advanced digital technologies with sustainable and human-centred manufacturing systems. Future research should focus on developing comprehensive methodologies capable of simultaneously integrating Artificial Intelligence (AI), Digital Twins, the Internet of Things (IoT), Big Data analytics, and Cyber-Physical Systems into unified manufacturing environments. Such integrated approaches may significantly improve manufacturing efficiency, flexibility, and sustainability while supporting more resilient industrial production systems [3,6].

One promising research direction involves the application of Artificial Intelligence for autonomous decision-making, predictive maintenance, intelligent quality control, and adaptive manufacturing. Combining AI with real-time production data may enable self-optimizing manufacturing systems capable of continuously improving production performance while reducing operational costs and environmental impacts [4,10].

Another important area concerns the wider implementation of Digital Twins throughout the entire product lifecycle. Future Digital Twin platforms are expected to integrate simulation, process monitoring, predictive analytics, and sustainability assessment within a single digital environment. Such integration would enable manufacturers to evaluate production scenarios before implementation, reduce material waste, improve equipment utilization, and support more sustainable industrial operations [9].

Future investigations should also explore the integration of Industry 5.0 technologies within smart textile manufacturing, including intelligent textile production systems, digital textile printing, automated fabric inspection, wearable technologies, digital product passports, and AI-assisted textile recycling. These emerging technologies may significantly improve sustainability, product traceability, and circular textile manufacturing while supporting more resilient textile supply chains [2,8].

Future research should additionally investigate human-machine collaboration in increasingly digital manufacturing environments. Developing collaborative production systems that combine advanced automation with human creativity, expertise, and decision-making will remain one of the defining characteristics of Industry 5.0. These systems should prioritize worker well-being, occupational safety, continuous learning, and technological adaptability while maintaining high manufacturing performance [1,7].

Overall, future developments should concentrate on establishing manufacturing ecosystems in which digital transformation, sustainability, resilience, and human-centred production operate as complementary components of a unified industrial strategy capable of supporting long-term technological and societal progress.

7. CONCLUSION

Industry 5.0 represents a significant evolution of modern manufacturing by extending the technological capabilities introduced in Industry 4.0 toward a more human-centred, sustainable, and resilient industrial paradigm. As demonstrated throughout this review,

digital transformation has become the primary enabler of this transition by integrating advanced technologies such as Artificial Intelligence (AI), the Internet of Things (IoT), Digital Twins, Big Data analytics, Cloud Computing, and Cyber-Physical Systems into manufacturing environments. These technologies contribute not only to improved operational efficiency but also to enhanced sustainability, flexibility, and industrial competitiveness [3,6].

The analysis presented in this paper demonstrates that digital transformation and Industry 5.0 provide significant opportunities for both advanced manufacturing and textile production by supporting intelligent process optimization, automated quality control, resource-efficient manufacturing, and sustainable industrial development. These concepts operate as complementary strategies that support sustainable textile and manufacturing systems. The integration of digital technologies enables manufacturers to improve productivity while simultaneously reducing energy consumption, material waste, and environmental impacts [4,8].

As the principal contribution of this study, a conceptual model of Industry 5.0-driven digital transformation was proposed to illustrate the interaction between three fundamental dimensions: Digital Technologies, Human-Centred Manufacturing, and Sustainable Manufacturing. The proposed model provides a systematic perspective for understanding how these complementary dimensions collectively contribute to improved manufacturing performance. Unlike conventional technology-oriented approaches, the model emphasizes the balanced integration of technological innovation, human expertise, and sustainability principles as the foundation for future industrial development.

The findings presented in this review may serve as a conceptual basis for future investigations focused on intelligent manufacturing, Digital Twins, Artificial Intelligence, smart textile production, and sustainable industrial systems. Furthermore, the proposed model may support researchers and industrial practitioners in developing integrated manufacturing strategies capable of addressing future technological, environmental, and societal challenges associated with Industry 5.0.

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