



TRANSFORMATION OF TEXTILE PRODUCTION THROUGH INDUSTRY 4.0 IMPLEMENTATION: THE ROLE OF NEXT - GENERATION ROBOTICS

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ABSTRACT: Industry 4.0 represents a new chapter in the development of manufacturing systems, where digitalization, automation, and the application of advanced technologies become key drivers of competitiveness. The textile industry, traditionally characterized by manual processes, is undergoing a profound transformation through the integration of next-generation robotics. This paper analyzes the significance and impact of robotic implementation within the Industry 4.0 framework on process efficiency, flexibility, and sustainability in textile production. Special attention is given to the application of collaborative and autonomous robots, which enable smart work organization, optimized transport and storage, and adaptive production flow management. The study highlights both the benefits brought by the adoption of advanced robotic systems and the challenges encountered during their implementation, such as the need for digital competencies among the workforce and high investment costs. Through the analysis of current trends and examples of good practice, the paper points to key development directions aimed at enhancing innovation, sustainability, and global competitiveness of the textile sector. The conclusion emphasizes the necessity of a strategic approach and continuous investment in new technologies to ensure a successful transition toward the smart factory of the future.

Keywords: Industry 4.0, textile production, next-generation robotics, automation, smart factory, innovation.

TRANSFORMACIJA TEKSTILNE PROIZVODNJE KROZ IMPLEMENTACIJU INDUSTRIJE 4.0: ULOGA ROBOTIKE SLJEDEĆE GENERACIJE

APSTRAKT: Implementacija industrijskih i servisnih robota u tekstilnoj industriji

Savez inženjera i tehničara tekstilaca Srbije



predstavlja ključni korak ka modernizaciji proizvodnje u skladu s principima Industrije 4.0. Analizom koristi i izazova, jasno je da primjena robotske tehnologije doprinosi većoj produktivnosti, standardizaciji kvaliteta, smanjenju grešaka te poboljšanju sigurnosti na radu. Iako su izazovi prisutni, posebno u vidu visokih početnih ulaganja, potrebe za obukom kadrova i tehničke integracije sa postojećim sistemima, dugoročne koristi opravdavaju ove napore. Posebno je važno istaknuti rastući značaj servisnih robota u logistici i inspekciji, kao i pojavu robotike nove generacije koja omogućava saradnju s ljudima, autonomno donošenje odluka i fleksibilnu reakciju na promjene u proizvodnom procesu. Uspješne implementacije u praksi pokazuju da tekstilne kompanije koje ulažu u automatizaciju postaju konkurentnije, brže se prilagođavaju tržišnim promjenama i bolje odgovaraju zahtjevima kupaca. Za dalji razvoj sektora, preporučuje se veće strateško ulaganje u integraciju robotike sa vještačkom inteligencijom i IoT tehnologijama, kao i poticaji za obrazovanje i prekvalifikaciju radne snage. Na taj način, tekstilna industrija može postići veću održivost, prilagodljivost i tehnološki napredak u godinama koje dolaze.

Ključne reči: Industrija 4.0, proizvodnja tekstila, robotika sljedeće generacije, automatizacija, pametna tvornica, inovacija.

1. INTRODUCTION

The textile industry, one of the oldest and most significant industrial sectors, is increasingly facing challenges in today's global environment. Traditional production models, largely based on manual labor and limited automation, are struggling to meet market demands that emphasize rapid adaptability, product customization, and sustainable operations [1-3]. Moreover, stricter requirements concerning environmental sustainability and energy efficiency further intensify the pressure on textile companies to redefine their manufacturing processes. In this context, the concept of Industry 4.0 represents a revolutionary trajectory for the transformation of manufacturing systems. Industry 4.0 encompasses the integration of digital technologies such as the Internet of Things (IoT), Artificial Intelligence (AI), robotics, Virtual and Augmented Reality (VR/AR), and Big Data analytics into all aspects of production [4]. This transformation seeks to create intelligent production environments where humans and machines interact in real time to support flexible operations, efficient resource use, and tailored product output. Within this framework, *next-generation robotics* plays a crucial role. Unlike traditional industrial robots, typically confined to safety cages performing repetitive tasks, modern robotic systems are characterized by high autonomy, cognitive capabilities, and the ability to collaborate safely with human workers. Cobots and mobile autonomous robots contribute to enhanced flexibility and safety in manufacturing workflows, aligning well with the changing requirements of textile production. Beyond physical automation, next-generation robotics also introduces digital connectivity, providing the capability to collect, process, and analyze data in real time, which facilitates enhanced decision-making and predictive maintenance. These features position robotics as an indispensable element of Industry 4.0 implementation in the textile sector, where rapid adjustments to changing production



requirements and consumer expectations are increasingly critical. However, despite the evident benefits, the digital transformation of textile companies faces several challenges, including high initial investment costs, the need for comprehensive workforce training, and difficulties in integrating new systems with existing infrastructure [5, 6]. Moreover, adapting organizational culture and managing change are essential components for a successful transition. This study aims to examine the role of advanced robotic technologies in reshaping textile manufacturing within the framework of Industry 4.0. The focus is on analyzing the benefits and challenges associated with the deployment of collaborative and mobile robots in textile manufacturing processes, as well as identifying best practices for successful digital transition. Through a systematic review of the current literature and analysis of practical examples, this study aims to provide a comprehensive overview of emerging trends and development prospects in the digitalization of the textile industry. Previous research highlights that the adoption of Industry 4.0 not only boosts productivity in the textile sector but also supports sustainability and resilience in production systems [7]. The integration of robots with IoT devices and Big Data analytics enables dynamic production planning and monitoring, thereby increasing transparency and reducing resource consumption [8]. Additionally, the development of flexible robotic solutions is particularly critical for textile processes due to the diversity of materials and the complexity of fabric manipulation [9, 10]. Consequently, modern robotics is emerging as a core element of innovation strategies in the textile industry, laying the foundation for the creation of smart and sustainable production systems for the future.

2. INDUSTRY 4.0 AND THE TEXTILE INDUSTRY

Industry 4.0 represents a modern direction in industrial development, based on the integration of digital technologies, automation, and data management into manufacturing processes. By incorporating robotics, the Internet of Things, big data analytics, artificial intelligence, and advanced automation, this concept enables the development of 'smart factories' that operate with greater efficiency, adaptability, and responsiveness to market changes. The textile industry, traditionally known for its labor-intensive nature, is undergoing a rapid transformation through the implementation of Industry 4.0 principles, fundamentally redefining manufacturing, logistics, and market dynamics. Modern robotic systems enable precise, fast, and consistent execution of manufacturing tasks. In the context of the textile industry, robots are employed to automate processes such as fabric cutting, sewing, and product packaging, significantly reducing operational costs while increasing productivity [11, 12]. Internet of Things (IoT) technology connects physical devices via the internet, enabling continuous data collection and real-time processing. In textile production, IoT sensors monitor environmental conditions, machine status, and production flows, enabling rapid response to emerging issues and optimization of resource usage [13]. The figure illustrates the flow of smart manufacturing, starting with real-time data collection through sensors, followed by analysis using advanced algorithms and artificial intelligence. The gathered information enables process optimization through digital factories and cyber-physical systems, resulting in high flexibility and customized

production according to specific customer requirements. The integration of the Internet of Things (IoT), big data, and automated systems allows for rapid feedback and continuous improvement of manufacturing processes .

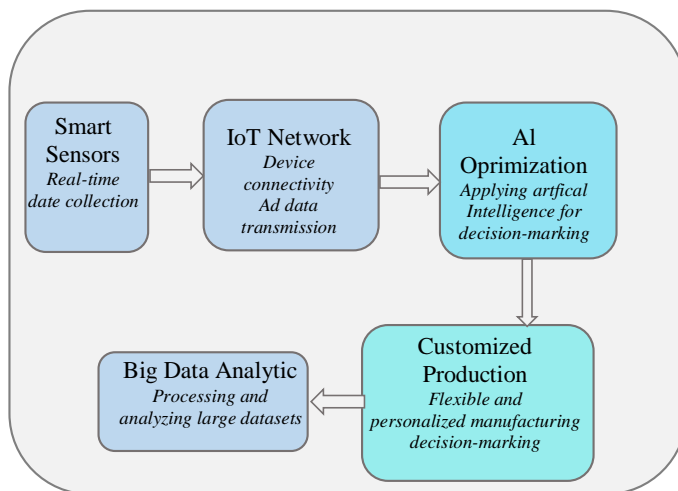


Figure 1: Flow of Smart Manufacturing: From Sensors to Customized Production

This structure supports more efficient, sustainable, and market-driven production. Smart sensors are crucial elements in the digitalization of manufacturing. They enable precise monitoring of parameters such as temperature, humidity, yarn tension, and machine conditions in real-time. Integrated with IoT networks, smart sensors provide vast amounts of data for advanced analytics, supporting predictive maintenance and production process optimization [14,15]. The importance of smart sensors in facilitating data-driven operations in the textile sector can be illustrated in the following Table 1. Table 1 highlights the critical role of smart sensors in enabling data-driven operations within the textile industry. It presents key functionalities such as real-time monitoring, quality control, and predictive maintenance, all of which contribute to increased efficiency and reduced downtime.

The table emphasizes how sensor integration supports automated decision-making and adaptive process management . These capabilities are essential for transitioning traditional textile production into a more intelligent and responsive manufacturing environment. Big data technologies enable the processing and analysis of massive volumes of data generated throughout the manufacturing process. In the textile industry, big data analytics is employed for demand forecasting, supply chain optimization, and product customization based on market trends [16]. The table emphasizes how sensor integration supports automated decision-making and adaptive process management . These capabilities are essential for transitioning traditional textile production into a more intelligent and responsive manufacturing environment. Big data technologies enable the processing and analysis of massive volumes of data generated throughout the manufacturing process. In

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Table 1: The importance of smart sensors in data collection in the textile industry

Component	Function	Benefits for the Textile Industry
Smart Sensors	Monitoring temperature, humidity, yarn tension	Reduction of defects, predictive maintenance
Internet of Things (IoT)	Network connection of sensors	Real-time monitoring, automatic responses
Big Data	Analysis of sensor-generated data	Production optimization, failure prediction
Artificial Intelligence	Automated decision-making and data analytics	Product personalization, efficient management

AI facilitates autonomous decision-making, predictive analytics, and process optimization without the need for constant human oversight. In the textile industry, AI is applied in quality inspection, product design, and predictive machine maintenance [17]. Advanced automation involves the use of software and hardware systems to perform production processes with minimal human intervention. Automated production lines accelerate manufacturing, minimize errors, and increase operational capacity in textile factories [18,19]. Smart factories in the textile sector are characterized by interconnected machines capable of self-diagnosis and autonomous corrective actions. Through the integration of IoT systems, predictive analytics, and adaptive automation, smart textile factories achieve high levels of flexibility and significantly reduce downtime [20]. The implementation of flexible automation and AI technologies allows textile companies to tailor products to individual customer preferences without significant increases in production costs. The mass customization concept enables rapid switching between different models, designs, and sizes [21]. Digitalization of supply chains enables full real-time visibility over inventory, manufacturing, and distribution activities. Through the use of technologies such as blockchain, IoT, and cloud computing, textile companies optimize logistics, reduce delivery times, and increase transparency [22].

3. INDUSTRIAL AND SERVICE ROBOTS IN THE TEXTILE INDUSTRY

3.1 Implementation of Robots and Service Robots in the Textile Industry

The textile industry, which has historically relied on manual labor, is undergoing a fundamental transformation driven by digitalization and automation. This evolution is driven by the need to address global competition, rising labor costs, and increasing demands for faster and higher-quality production. Central to this transformation are industrial and service robots [22, 24].

Although robotics has traditionally been primarily applied in the automotive and electronics industries, it has recently been making increasing inroads into the textile sector. The main motivations include efficiency improvement, quality standardization, and reduced dependence on manual labor [25]. Industrial robots are automated systems designed to perform tasks such as cutting, sewing, material handling, and product assembly with precision and repeatability. Their effectiveness is particularly notable in repetitive and high-precision operations, such as automated fabric cutting with robotically controlled blades or laser systems [26].

Robots are also used in textile finishing and the application of decorative elements, contributing to greater uniformity and reduced waste. In some Asian factories, fully automated production lines for manufacturing t-shirts and underwear already exist, operating with minimal human supervision [23].

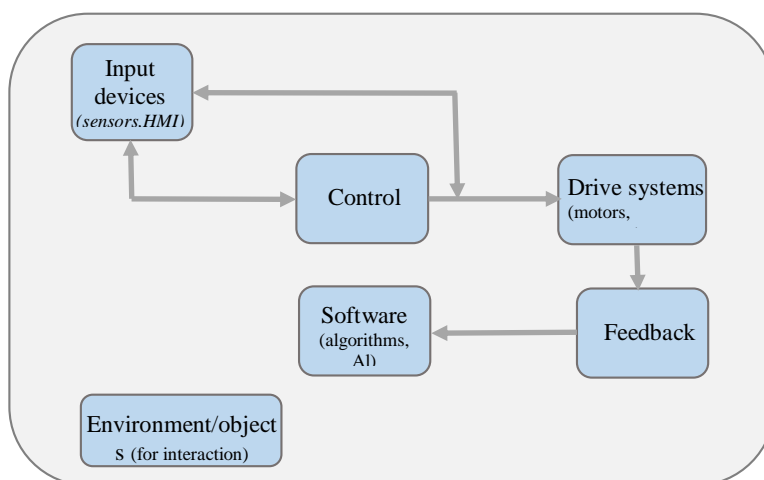


Figure 2: Diagram of Industrial and Service Robot Implementation

As shown in Figure 2, input devices include sensors (e.g., cameras, LIDAR, ultrasound, temperature sensors) and user interfaces (e.g., touchscreens or remote controls). The control unit—typically a central computer or microcontroller—manages system logic. Software includes path-planning algorithms, signal processing, and artificial intelligence (e.g., object recognition, navigation). The drive system consists of servomotors, actuators, and pneumatic components. Feedback loops provide sensor signals on command execution and system status (closed-loop control). The environment encompasses the physical space where robots operate, including objects being manipulated and users being served.

On the other hand, service robots in the textile industry perform supportive functions related to logistics, quality inspection, and material handling. Mobile logistics robots equipped with LIDAR sensors and cameras automate the transport of materials from warehouses to production lines, reducing downtime and increasing transfer efficiency [27].

Visual inspection robots use advanced sensors and AI to detect defects in weaving, dyeing, or printing processes, eliminating human error and improving final product quality [24,28]. According to available data, the number of installed robots in the textile industry has shown a steady upward trend over the past decade. Although precise yearly data are not always available, estimates based on industrial reports and automation trends indicate a consistent growth pattern [29].

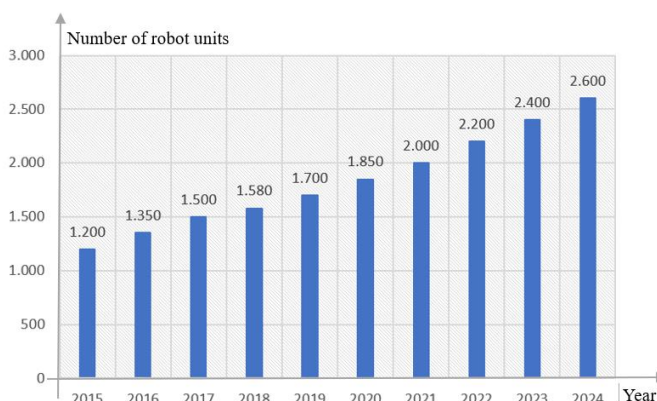


Figure 3: Annual Estimates of Robot Installations in the Textile Industry

This sustained growth reflects increasing acceptance of robotics in the textile industry, especially in Asian countries, where governments and industry leaders recognize automation as a strategic asset for maintaining global competitiveness. For example, China has significantly increased robot use in textile manufacturing as part of its "Made in China 2025" initiative aimed at modernizing industry through advanced technologies [33].

In addition to industrial robots, the textile industry increasingly relies on service robots to enhance both internal transport within production processes and logistics operations in storage facilities. These robots contribute significantly to streamlining material handling, ensuring greater operational efficiency, and reducing manual labor dependency in both manufacturing and warehousing environments [23, 25]. Global trends in the deployment of service robots for professional applications in 2023 are illustrated in Figure 4, which highlights seven key sectors of application [29,30]. As depicted in Figure 4, logistics and transport dominate the use of service robots, with approximately 113,000 units installed—accounting for nearly half of all professional service robot implementations. This prevalence reflects the growing demand for automation in warehousing, distribution, and delivery operations, which contributes to faster workflows and significant cost reductions [24,30]. The increasing integration of service robots into intralogistics systems aligns with broader trends in smart manufacturing and Industry 4.0 initiatives, where real-time data, mobility, and adaptive intelligence are essential [25, 32]. Integrating industrial and service robots enhances work organization and process scalability. Combined with Manufacturing

Execution Systems (MES) and the Internet of Things (IoT), robots become part of a broader smart factory ecosystem.



Figure 4: Deployment of service robots for professional use in seven leading sectors (2023)

For instance, when an automated inspection robot detects a defect, the system can adjust machine parameters in real time, forming a closed loop of control and self-adjustment [33]. In addition to technical benefits, robots also contribute to improved workplace safety by taking over hazardous tasks such as handling heavy loads, working with toxic materials (e.g., during dyeing), or operating in high-temperature environments. Despite high initial implementation costs, long-term benefits such as reduced labor needs, increased productivity, and higher precision justify the investment, particularly in countries with rising wages and stringent quality and sustainability regulations [30].

3.2 The Role of Next-Generation Robotics in Textile Manufacturing

Next-generation robotics represents an advanced form of automation that includes the ability to learn, make independent decisions, and collaborate safely with humans in real-world production environments. This concept encompasses three key categories:

- *Cognitive robots* that use machine learning and AI algorithms to adapt to complex tasks;
- *Collaborative robots (cobots)* that work alongside humans in shared workspaces;
- *Mobile robots* that navigate autonomously and optimize intralogistics.

Unlike traditional industrial robots, next-generation systems do not operate solely based on predefined tasks, but actively communicate with the environment and human operators [22,32]. In the textile industry—known for the complexity of handling flexible materials—such robotic systems offer numerous advantages. These robots enable adaptable production flows, as they can be quickly reconfigured to process different types of fabrics or clothing designs. They also exhibit high adaptability by responding to production changes without requiring hardware replacement. Collaboration between humans and robots contributes to



higher productivity and ergonomics, as robots take over strenuous, repetitive, or hazardous tasks, freeing workers for supervision and creative activities [34]. Moreover, these systems reduce labor costs and material waste through precise and predictive process control. Examples of successful application of this technology already exist. For instance, Sewbo Inc. has developed a robotic system for automatic sewing using fabrics that are temporarily secured, allowing for precise automation of previously difficult-to-automate production stages [32]. In Italy, collaborative robots assist in highly customized garment production, preparing components that human workers then finalize. Mobile robots in textile company logistics centers, such as those used in Zara and H&M warehouses, have improved internal distribution efficiency and reduced order processing time by more than 30% [30]. Finally, cognitive robotic systems can be applied for real-time defect detection during weaving or textile printing, analyzing visual data through deep learning algorithms. These systems not only improve product quality but also conserve resources by enabling early detection of flaws [28]. By implementing next-generation robotics, the textile industry is gradually shifting from a traditional mass-production model to a digitally oriented, adaptable, and sustainable production platform aligned with Industry 4.0 principles.

4. KEY BENEFITS AND CHALLENGES OF IMPLEMENTING ROBOTIC TECHNOLOGY IN THE TEXTILE INDUSTRY

The implementation of robotic technology in the textile industry is increasingly recognized as a strategic response to global competition, rising labor costs, and the demand for more efficient and flexible production systems. Although robotics offers a wide range of advantages, it also presents several implementation challenges that need to be addressed for long-term success and sustainability.

❖ Key Benefits

One of the main advantages of using robots is increased productivity, as they can work continuously without the need for breaks or rest, ensuring high throughput and consistency across all production lines. This is particularly relevant in the textile sector, where high-speed and repetitive operations such as cutting, sewing, and material handling benefit significantly from automation [23].

Another major benefit is the reduction in production errors. Thanks to their precision and consistency, robots reduce the possibility of human error, thereby decreasing waste and improving product quality. Advanced vision systems and AI integration allow for real-time detection and correction of defects in fabric weaving, dyeing, or printing processes [24].

Robotics also improves workplace safety, as it is used in hazardous conditions where there is a risk to workers, such as working with toxic materials or high temperatures [32].

In addition, automation leads to shorter production cycles. The ability of robotic systems to quickly adapt to different tasks and types of materials enables a faster response to changes in market demand [22]. This flexibility aligns with the growing trend toward personalized and just-in-time manufacturing in the textile industry.

❖ Key Challenges



Despite the benefits, several challenges hinder the widespread adoption of robotics in textile manufacturing. The first and most obvious challenge is the high initial investment cost in robotic systems. Acquiring and integrating robotic systems tailored to textile applications involves substantial capital expenditures, which may not be feasible for small and medium-sized enterprises [21]. A second significant challenge lies in the training and reskilling of the workforce. As robotic systems require technical know-how for operation, programming, and maintenance, companies must invest in continuous education and capacity building for their staff. The skills gap between traditional textile workers and modern automation needs is often substantial [31]. Another challenge lies in integrating modern robotic solutions into existing, often outdated, production systems. Many textile factories still rely on outdated equipment and infrastructure, making it technically and economically difficult to implement advanced robotics without extensive retrofitting or complete system overhauls [23]. Lastly, successful implementation also depends on organizational readiness and cultural transformation. The introduction of robotics requires a shift in managerial approach, as well as the organization's readiness to embrace innovation and technological change. Without these, even the most advanced systems may fail to deliver expected outcomes.

5. AN EXAMPLE OF A SUCCESSFUL IMPLEMENTATION OF ROBOTIC TECHNOLOGY IN A MEDIUM-SIZED TEXTILE COMPANY

The introduction of robotic technologies into textile production is not exclusively a privilege of large multinational companies. Medium-sized enterprises (SMEs) can also benefit significantly from automation when it is strategically planned and tailored to specific production needs. The following example illustrates a hypothetical yet realistic case of a medium-sized textile manufacturer that successfully implemented both an industrial and a service robot to modernize its operations.

❖ *Case Example: “TexPro Ltd.” – A Mid-Sized Apparel Manufacturer*

TexPro Ltd., a regional clothing manufacturer with around 250 employees, faced growing challenges caused by labor shortages, rising costs, and inconsistent product quality. To address these challenges, the management team initiated a phased robotic integration program focusing on automating high-precision tasks and improving intralogistics.

❖ *Implementation Phases*

- *Needs Assessment:* The first phase involved a detailed internal audit of production bottlenecks, error rates, and labor allocation. It was found that manual fabric cutting and internal material transport accounted for the majority of delays and inconsistencies.
- *Robot Selection:* Based on the analysis, TexPro selected:
 - An industrial robotic manipulator with an integrated laser cutter, designed for precise fabric cutting.
 - A mobile autonomous robot (AMR) for internal logistics, designed to transport fabric rolls from the warehouse to the sewing stations.
- *System Integration:* The industrial robot was integrated with a CAD/CAM system and programmed to cut up to 500 fabric pieces per hour with an error margin

below 0.5%. A mobile autonomous robot (AMR) was connected to the warehouse management system and used LiDAR technology and AI-based navigation to move safely through the production area.

- *Process Optimization* : After implementation, the production process was optimized through real-time data collection and machine learning algorithms. The material transfer time was reduced by 40% thanks to the AMR, while the robotic cutter increased processing capacity by 60% and almost completely eliminated cutting errors.

❖ ***Measurable Outcomes***

The integration of robotic technologies resulted in:

- A 25% overall increase in productivity.
- A 15% reduction in material waste.
- A 30% decrease in production cycle time.
- Improved worker safety by automating high-risk tasks.

These results demonstrate that even medium-sized companies can achieve significant benefits when robotic technologies are strategically and purposefully integrated into the production process[25].

❖ ***Supporting Industry Examples***

A comparable real-world example includes Sewbo Inc., which developed an automated sewing system using an industrial robot capable of handling chemically stiffened fabrics, previously considered too flexible for automation [32]. Similarly, H&M's logistics centers have implemented service robots for internal transport and order sorting, increasing delivery speed and reducing human error [31].

6. DISCUSSION

The application of robotic technologies in the textile industry brings numerous advantages that, in practice, often outweigh the existing challenges. Analysis of case studies and examples, including the case of a mid-sized company that successfully introduced automation, confirms that robotics contributes to increased efficiency, precision, and workplace safety, while simultaneously reducing operational costs and errors [23,25].

Practical outcomes demonstrate that the advantages of deploying both industrial and service robots are significant. Shortened production cycles, more consistent quality, and improved process control indicate that automation is becoming crucial for the competitiveness of modern textile manufacturing. Moreover, service robots used in warehouses and logistics improve delivery speed and reduce the need for manual labor in hazardous environments [31].

However, certain challenges still exist – primarily high initial costs, which are often beyond the capabilities of small and medium-sized enterprises and integrating new technologies with legacy systems requires technical expertise and time. Additionally, substantial investment in workforce training is necessary to fully realize the benefits of robotic technology [22].



Looking forward, there are numerous opportunities for further development. Notably, the integration of robotics with artificial intelligence (AI) enables robots to learn from data and make autonomous decisions in real time, moving beyond traditional automation toward *intelligent manufacturing systems* [22]. An additional perspective for development is the application of predictive analytics, which enables timely equipment maintenance and more precise production planning.

In conclusion, while implementation challenges remain, practical experiences show that a well-planned and phased introduction of robotic technologies significantly enhances performance in the textile sector. Given the rapid pace of technological advancement, it is expected that the integration of robotics, AI, and IoT will soon become standard practice rather than an exception.

7. CONCLUSION

The introduction of industrial and service robots represents a key step towards modernizing textile production in accordance with the principles of Industry 4.0. An analysis of the benefits and challenges clearly indicates that robotic technologies contribute significantly to increased productivity, standardized quality, error reduction, and improved workplace safety. Although there are still barriers such as high initial costs, the need for employee training, and technical integration with older systems, the long-term benefits outweigh these challenges. Notably, the growing importance of service robots in logistics and quality inspection, along with the emergence of next-generation robotics, enables human-robot collaboration, autonomous decision-making, and flexible adaptation to changing production conditions. Practical examples show that textile companies investing in automation gain a competitive edge, respond more quickly to market demands, and enhance customer satisfaction. For the continued advancement of the sector, strategic investment in integrating robotics with artificial intelligence and IoT technologies is strongly recommended, along with initiatives aimed at education and workforce reskilling. This will enable the textile industry to become more sustainable, adaptable, and technologically advanced in the future.

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