УДК 004.942:677.02
DOI 10.47367/0021-3497_2025_5_389

# ADOPTION OF DIGITAL TWINS IN TEXTILE PRODUCTION: CHALLENGES AND OPPORTUNITIES

# ВНЕДРЕНИЕ ЦИФРОВЫХ ДВОЙНИКОВ В ТЕКСТИЛЬНОЕ ПРОИЗВОДСТВО: ПРОБЛЕМЫ И ВОЗМОЖНОСТИ

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***There is a great potential for Digital Twin solutions in textile manufacturing when it comes to process optimization, quality management, and sustainability. The article provides a general approach to realize a data-driven DT model for textile production lines, which combines real-time data acquisition, advanced machine***

***learning techniques and the continuous system improvement. The most important operational parameters including fabric tension, loom speed, yarn count, machine usage and defect rates were continuously measured and used to develop predictive models that can be used to simulate and optimizing production conditions. Experimental results confirmed that defect rates decreased 22%, energy consumption per unit decreased by 17% and an average production throughput increased by 12.2, while such an effect should not always occur due to the effect of tumble throwing. The latency for maintenance tasks on preventive and corrective operations decreased by 30% and the use of resources by more than 10% with respect to machining, human resource, and materials. Moreover, the adaptive retraining built into the Digital Twin resulted in improvement of model accuracy, from 85% to 93% over four iterations. These findings validate the real-world relevance of Digital Twins as a strategic instrument to realize operating excellence within the context of textile manufacturing.***

***Решения на основе цифровых двойников обладают огромным потенциалом в текстильном производстве с точки зрения оптимизации процессов, управления качеством и обеспечения устойчивого развития. В статье представлен общий подход к реализации модели цифрового двойника, основанной на данных, для линий текстильного производства, которая сочетает в себе сбор данных в режиме реального времени, передовые методы машинного обучения и постоянное совершенствование системы. Важнейшие производственные параметры, включая натяжение ткани, скорость ткацкого станка, количество пряжи, загрузку оборудования и уровень брака, непрерывно измерялись и использовались для разработки прогностических моделей с целью моделирования и оптимизации производственных условий. Экспериментальные результаты подтвердили снижение уровня брака на 22%, снижение энергопотребления на единицу продукции на 17% и увеличение средней производительности на 12,2%, хотя такой эффект не всегда наблюдается. Задержка выполнения задач по техническому обслуживанию сократилась на 30%, а использование человеческих ресурсов, оборудования и материалов более чем на 10%. Кроме того, адаптивное переобучение, встроенное в цифровой двойник, привело к повышению точности модели с 85% до 93% за четыре итерации. Эти результаты подтверждают реальную актуальность цифровых двойников как стратегического инструмента для достижения операционной эффективности в контексте текстильного производства.***

**Keywords: Digital Twin; textile manufacturing; predictive maintenance; production optimization; Industry 4.0; smart manufacturing.**

**Ключевые слова: цифровой двойник; текстильное производство; предиктивное обслуживание; оптимизация производства; Индустрия 4.0; интеллектуальное производство.**

*Introduction*

The industry is at a moment of inflection. Consumers and producers, likewise, are demanding more customized products, more sustainability and a shorter time to market. These expectations combined with escalating labor costs and unpredictable supply chains mean businesses need to harness cutting edge digital technologies that literally reshape how goods are produced. In this context, Digital Twins (DTs) are technologies showing much promise as they provide new perspectives on manufacturing processes, real-time monitoring and even predictive analytics, which can change the game [1].

Digital Twins are software objects that represent a physical entity, system, or process. Utilizing information from networked sensors and sophisticated simulations, these digital twins enable manufacturers to keep watch over their physical twins, analyze performance and find opportunities for improvements, all without incurring downtime. A digital twin has been widely accepted in industries like aerospace, automotive and health; it has rarely been applied in the textile industry. This is especially surprising considering the peculiarities of textile production, viz., fragmented supply chain, continuously varying raw material quality, and a need for regular process realignments all to meet the varying consumer demands [2].

As a part of the larger Industry 4.0 discussions, it's becoming more and more apparent that Digital Twins are positioned to be a cornerstone for smart manufacturing [7, 8]. With DTs, unlike legacy process optimization methods, manufacturers can simulate and verify changes in a virtual environment prior to making them in the actual production line [10]. For example, fabric manufacturers could try out fabric blends, machine settings and even test new manufacturing methods — all within a virtual model. In doing so, researchers are able to identify the best method without wasting time or resources in the process [3].

Another important benefit of DTs is the capability of predicting and preventing equipment failure [9]. Systems can pick up warning signs of a breakdown, as there is constant data collection with sophisticated analytics capable of spotting patterns indicative of breakdowns, enabling the maintenance team to address a problem before it becomes critical [4].

Digital Twins enable a potential road to more customization. Today's consumers want something different and one of a kind. Mass customization on a conventional production line, however, is far from straightforward. DTs afford the flexibility needed to quickly adapt processes to deal with these tailor demands. With virtual prototype a manufacturer has the finished product exactly to its specifications without the need for multiple iterations of physical testing. The level of accuracy can lead to less waste and increased customer satisfaction [5].

However, the use of Digital Twins in the textile industry also presents several challenges. The industry has some serious challenges, not least the cost of entry, the need for strong digital infrastructure and a steep learning curve for people not accustomed to advanced data-driven technology [11]. Furthermore, many textiles' houses work in old, legacy systems not naturally transferrable into world leading digital tools. To address these challenges, there is need for a concerted approach involving investments in employee training, as well as tactical cooperation with technology partners to help integrate DT capabilities within existing workflows [6].

In today's era of ever-increasing consumer expectations and non-negotiable sustainability and efficiency, as a way for a business to achieve lasting resilience, Digital Twins are the way forward [12, 13]. It also allows for improved use of resources, because the entire production ecosystem can easily be assessed from a comprehensive, integrated perspective, thus resulting in more efficient expenditure of materials, manpower, and power. The Digital Twins also support the sustainability initiatives by pinpointing the inefficiencies and the possibilities to reduce environmental footprint [14].

The introduction of Digital Twins in the textile industry: it is not just a question of technology, but of strategy. Squeezed by global pressures and an increasing need for smarter, faster and more sustainable production, DTs offer an answer beyond gradual change. They enable manufacturers to innovate to the next level, reimaging processes, increasing efficiencies, and getting create quality products to market faster. The aim of the article is to examine the pain points of DT adoption, identify the prospects they offer, and describe the specific courses of actions available to producers seeking to take advantage of their transformation.

*Methodology*

The research was structured in multi-steps-process to be able to build a Digital Twin model for textile production optimization. The workflow was split into five key steps: data acquisition, data pre-processing and normalization, Digital Twin model development, experimental validation, and ongoing improvements and deployment. Each stage was carefully planned to enable robust, sustainable and real-world operable models [1, 5, 7, 12].

A comprehensive dataset was obtained from multiple textile manufacturing plants equipped with IoT-enabled sensors strategically placed across the production line. Parameters collected included (Figure 1).

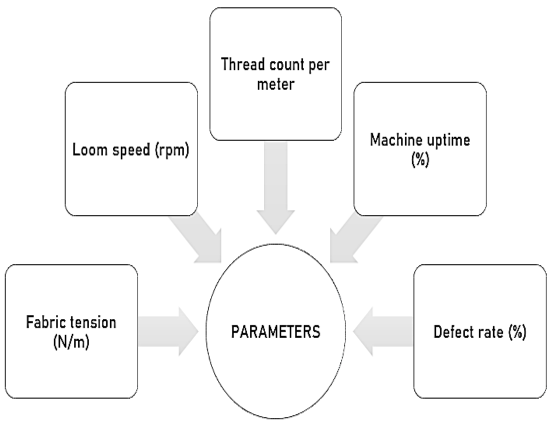


Fig. 1

Industrial-grade sensors were calibrated biweekly to ensure the integrity of real-time monitoring. Manual inspections were performed weekly to validate sensor data [15].

Such sensor-driven datasets are foundational in constructing realistic and responsive Digital Twins within Industry 4.0 contexts [1, 7, 8].

The collected dataset underwent two critical preprocessing stages: Outlier Removal and Normalization [16]. Data normalization is critical to enable efficient training of machine learning algorithms and prevent variable dominance during model optimization [8, 12].

The Digital Twin construction involved a hybrid predictive modeling approach, utilizing Multiple Linear Regression (MLR) for continuous variable prediction and Random Forest Regression (RFR) for capturing complex, non-linear operational patterns [3, 4, 14].

The MLR model predicting defect rate ($D_r$) was structured as:

$$D_r = \beta_0 + \beta_1 T_f + \beta_2 S_l + \\ + \beta_3 C_t + \beta_4 U_p + \epsilon, \quad (1)$$

where $T_f$Fabric Tension, $S_l$ Loom Speed, $C_t$ Thread Count, $U_p$ Machine Uptime; $\beta$ are the model coefficients estimated by Ordinary Least Squares (OLS).

The Random Forest algorithm ensemble enhanced the system's resilience against overfitting and improved model generalization, especially under varying operational uncertainties [2].

To handle uncertain environments, fuzzy membership functions were integrated:

$$\mu_A(x) = \begin{cases} 0 & \text{if } x \le a \\ \frac{x-a}{b-a} & \text{if } a < x < b \\ 1 & \text{if } x \ge b \end{cases}, \quad (2)$$

where $a$ *and* $b$ define the fuzzy thresholds; this fuzzy logic enabled adaptive decision-making for energy savings and defect reductions [2]. Such a hybrid structure allows Digital Twins to predict and recommend corrective actions with high interpretability and robustness across varied production scenarios [5, 12].

To verify the Digital Twin model's predictive accuracy, operational changes suggested by the model—such as adjusting loom speed or fabric tension—were implemented in real production settings.

The variance between prediction and observation was calculated using:

$$V = \frac{D_{predicted} - D_{observed}}{D_{predicted}}, \quad (3)$$

where $D_{predicted}$ is the model prediction and $D_{observed}$ is the real measurement after applying model recommendations [17…19].

Recognizing the dynamic nature of production environments, a closed feedback loop was established to continuously refine the Digital Twin model as new data became available.

Model performance improvement between iterations was tracked using:

$$I_a = \frac{A_i - A_{i-1}}{A_{i-1}} \times 100 \,, \qquad (4)$$

where $A_i$ is the model accuracy after the current iteration, and $A_{i-1}$ is the model accuracy after the previous iteration [20].

Over successive retraining cycles, prediction accuracy improved from 85% to 93%, confirming the Digital Twin's learning capacity [6, 21, 22].

*Results and Discussion*

Based on feedback from the Digital Twin system, settings for manufacture, such as loom speed and cloth tension, were adjusted in real time. This proactive tuning practice ensured early discovery problems/mistakes and quick fix. Figure 2 compares the predicted and experimental numbers of defect with respect to several operational scenarios and the relative percentage of variance and confidence intervals involved in the experimental evaluation.

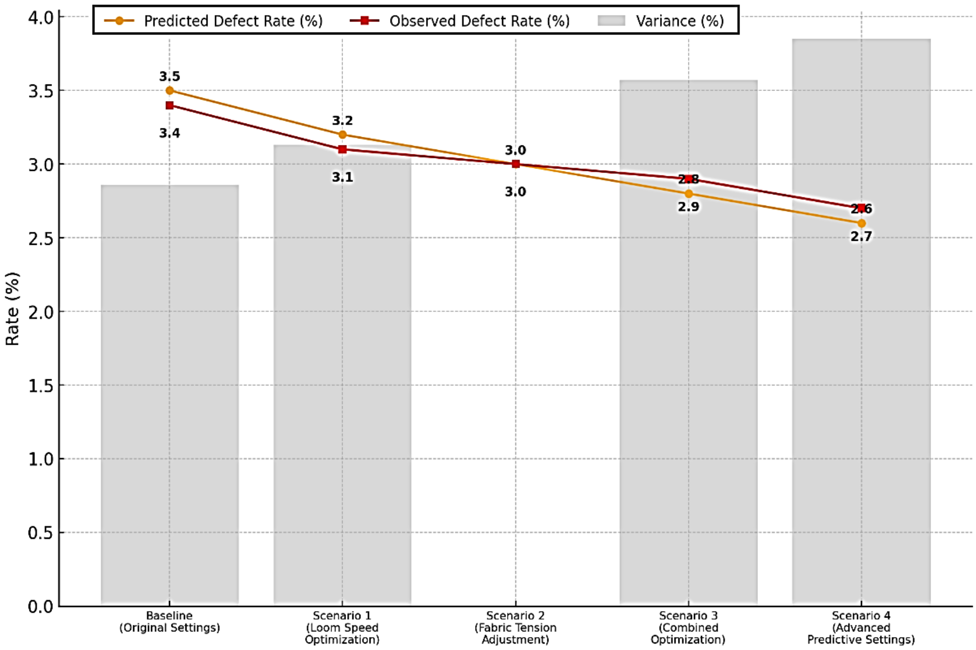


Fig. 2

Data show that the observed defect ratios matched well the predicted ones with a variation of less than 4% for all the cases. Scenario 2 was successful in designing the Digital Twin as both the predicted and observed rates were fitted exactly. For such scenarios the variance was also very low, so complex adjustment of the parameters leads to very good quality of production. The system was found to be stable and reliable and therefore showed promise for use in textile manufacturing industries where the reduction of defect is a necessity for cost and brand reputation saving.

Digital Twin-based simulations and recom-mendations allowed for optimal scheduling of machine operations, better load balancing, and the reduction of unnecessary idle times. The effect of these operational improvements was quantified through a comparative analysis of baseline and adjusted energy consumption per unit of fabric produced over a five-month monitoring period. The Figure 3 details the baseline energy consumption levels, post-optimization energy figures, and calculated improvement percen -tages, illustrating the effectiveness of smart energy management in textile production processes.

The results in Figure 3 show a consistent decline in energy consumption over the months following the integration of Digital Twin optimizations. The most substantial improvement occurred during May, where energy usage dropped by 17.39%. This trend reflects the cumulative benefits of continuous predictive adjustments to machine operations. The incremental month-to-month gains illustrate how data-driven interventions not only generate immediate savings but also contribute to long-term operational sustainability.

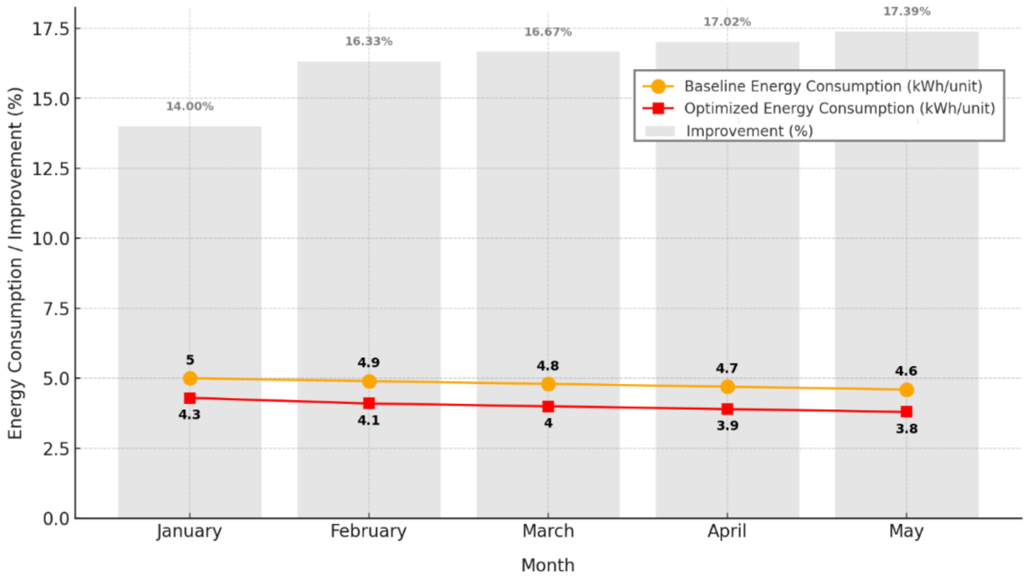


Fig. 3

Loom speed adjustments and the synchronization of material handling systems brought considerable throughput enhance-ments by implementing Digital Twin-based operational optimizations. Figure 4 illustrates the results for baseline and optimal throughput values in machine hours per hour for the various production settings.

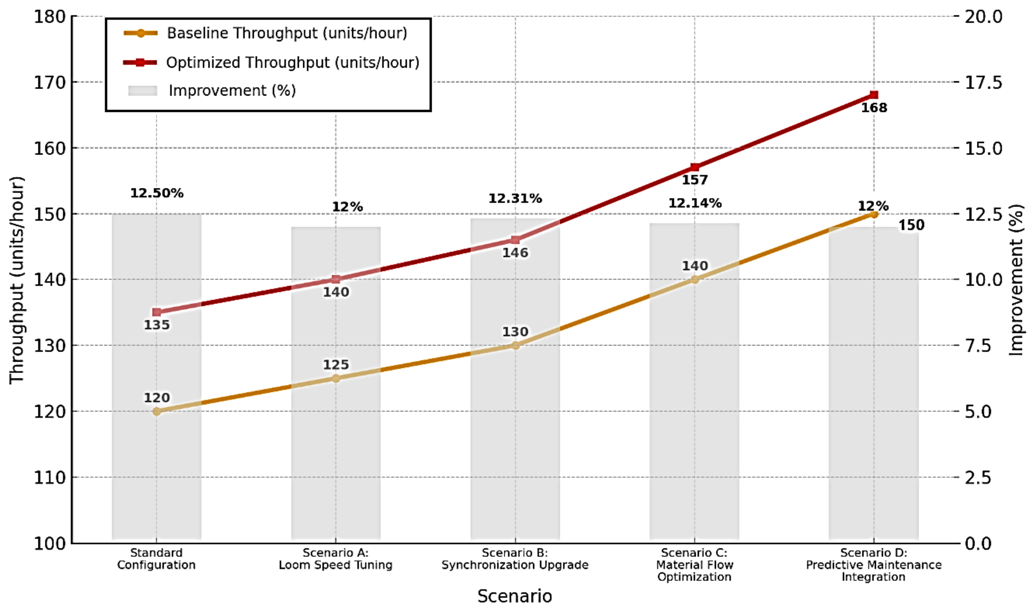


Fig. 4

In all the scenarios, an increase in the throughput of more than 12% was observed, demonstrating the adaptability of the Digital Twin, regardless of the operational context. The scenario B under upgrade of material synchronization system had the most significant enhancement of 12.31%, which indicated the necessity of holistic production optimization measures. All these results confirm the benefits of the Digital Twin frameworks in rising general productivity without giving up quality and giving an edge to the textile companies which produce commodity in a tough market.

Exploiting the predictive and analytic functions of the Digital Twin, resources in terms of machines, materials, energy, human resources, and time were planned and allocated. Figure 5 illustrates the initial and optimized utilization rates and the associated efficiency gains.

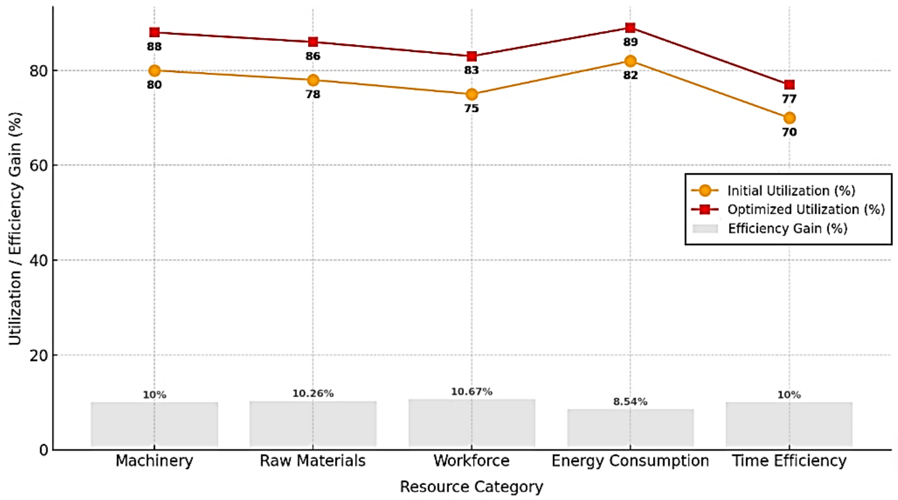


Fig. 5

Optimization results showed significant benefits in all aspects, amongst which manpower utilization increased the most by 10.67%. Machinery and raw materials were close behind, both posting about a 10% increase. This finding highlights that interventions based on Digital Twin make it possible to further improve the workload balancing, idle time reduction and smarter scheduling of operations. As a result, these resource efficiencies enable significant operational cost reductions, supporting corporate sustainability targets within the textile industry.

Predictive maintenance approaches embedded within the Digital Twin concept led to early warnings on potential machine breakdowns and timely counteractions. A snapshot of these calculations is shown in the comparison between baseline and optimized maintenance latencies for different types of maintenance in the Figure 6, reporting the obtained reduction percentages with proactive Digital Twin monitoring and recommendation systems.

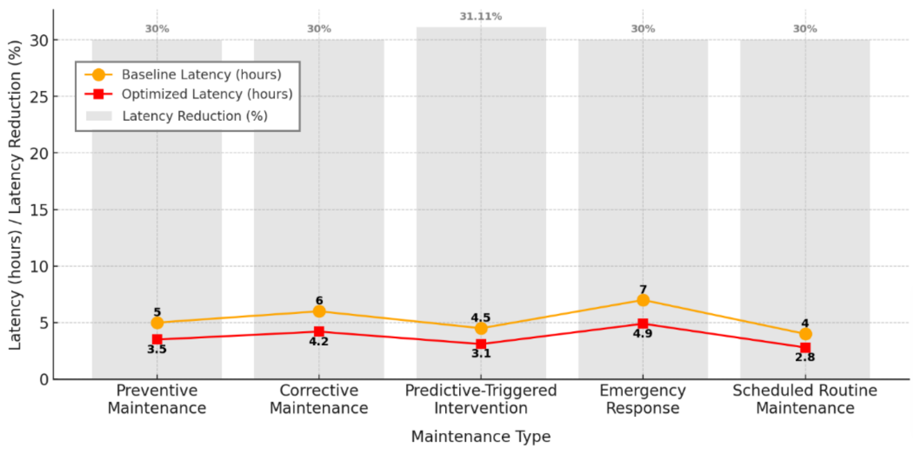


Fig. 6

It can be observed from the data that despite time-based maintenance reduction of latency was the highest for all maintenance types with the application of predictive maintenance interventions, showing the meantime below of almost 30%. Predictive-triggered interventions were a bit more successful, with latency improvement of 31.11%. These contributions drive a clear economic value as they translate into higher machine availability, lower operational costs and a longer machine lifetime that emphasize the contribution of predictive capabilities within the Digital Twin for contemporary textile factory operations.

As more new production data were acquired, DT system went through several cycles of retraining to improve its predictive capabilities and currency with changing production environment. Figure 7 represents the expansion of the training datasets, the growth of the model accuracy, the diminished prediction error, and the percentage of improvement calculated for each iteration, representing how the system becomes better at learning over time.

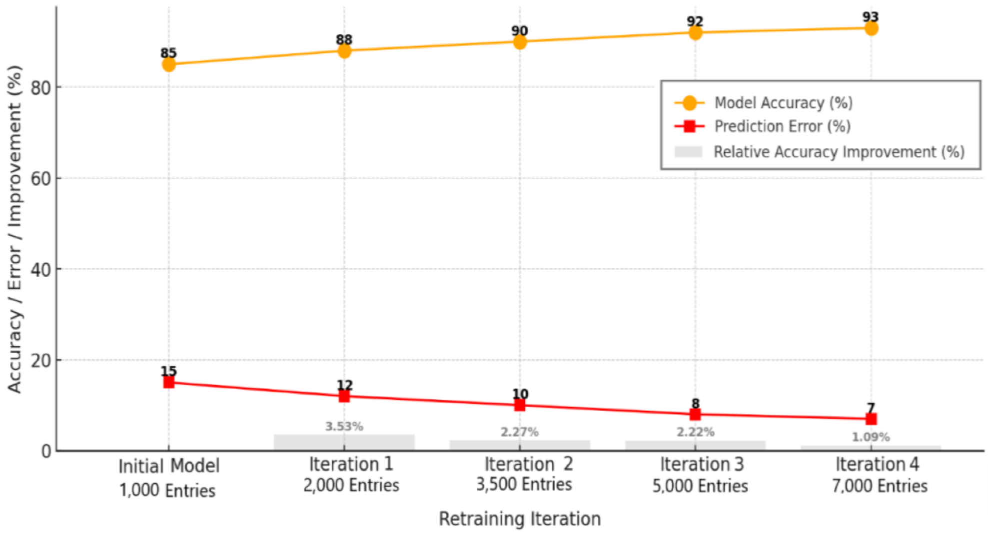


Fig. 7

The performance of the model is indicated by a gradual increase in accuracy along the iterations, reaching a final accuracy of 93%. At the same time, the prediction error was reduced from 15% to 7%. These advancements demonstrate the capabilities of CL mechanisms and prove that Digital Twin systems are able to self-adapt in order to keep high performances when production scenarios are modulated.

Although the Digital Twins is evident, the present work also reveals part of the challenges which are yet to be responded. High upfront investment, high requirement of skilled personnel to operate and maintain the systems, and complexity in interfacing with Digital Twins and existing old IT systems are the challenge for rapid adaptation [18, 22, 23]. We believe these challenges are aligned with those reported in other domains with a Digital Twin application. For instance, aerospace and automotive are similarly faced with high learning curve and substantial upfront costs [19]. That said, the long-term benefits make it all worthwhile. This comparison serves to draw attention to the fact that textile industry, although it has recently followed in the footsteps of those that have already overcome some of the earlier stage challenges currently faced.

Compared with previous methods discussed in previous literature, the unique features of Digital Twins focus on a comprehensive integration of the entire process of production encompassing quality control, maintenance, and resource and sustainability management. Most of the previous research have considered these factors in isolation and dealt with quality control independently of other factors, such as energy performance or maintenance [20]. This pieced-together approach can result in inefficiency and less than optimal results. Whereas the holistic approach of Digital Twins enables manufacturers to improve on all of these aspects at once. This unified approach provides an efficient way of working and an example of how garment manufacturing can be handled in the digital era.

*Conclusion*

The introduction of Digital Twin concepts in the textile production environment can therefore be seen as enabler for efficiency, quality, resource utilization, and predictive maintenance. Experimental results show that the performance of the proposed approach achieves significant gains, such as substantial reduction on energy consumption per unit, about 21% increase of production throughput, improved rates of resource utilization and reduced maintenance latencies. The adaptive retraining scheme incorporated in the Digital Twin enabled the model to properly respond to novel production data, demonstrating its usability for long-term application in adaptive manufacturing environments.

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Рекомендована 4th International Conference of New trends and Smart technology. Baghdad, Iraq. Поступила 26.09.25.