

## An Integrated Framework for High-Performance Rapier Loom Weaving: Mechanics, Automation, and Quality Analytics

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### Abstract

The increasing digitalization and automation and decreasing mechanization and human controlled operation of textile manufacturing shows need for weaving systems that synthesize mechanical precision with advanced monitoring and analytical capabilities. Among contemporary weaving technologies, rapier looms, especially Dornier models exhibit distinctive advantages in weft insertion accuracy, shedding stability, and compatibility with high performance technical yarns. Furthermore, sustaining fabric quality at elevated production velocities requires a holistic optimization paradigm that accounts for the interdependence of loom mechanics, operational data, and constructional parameters.

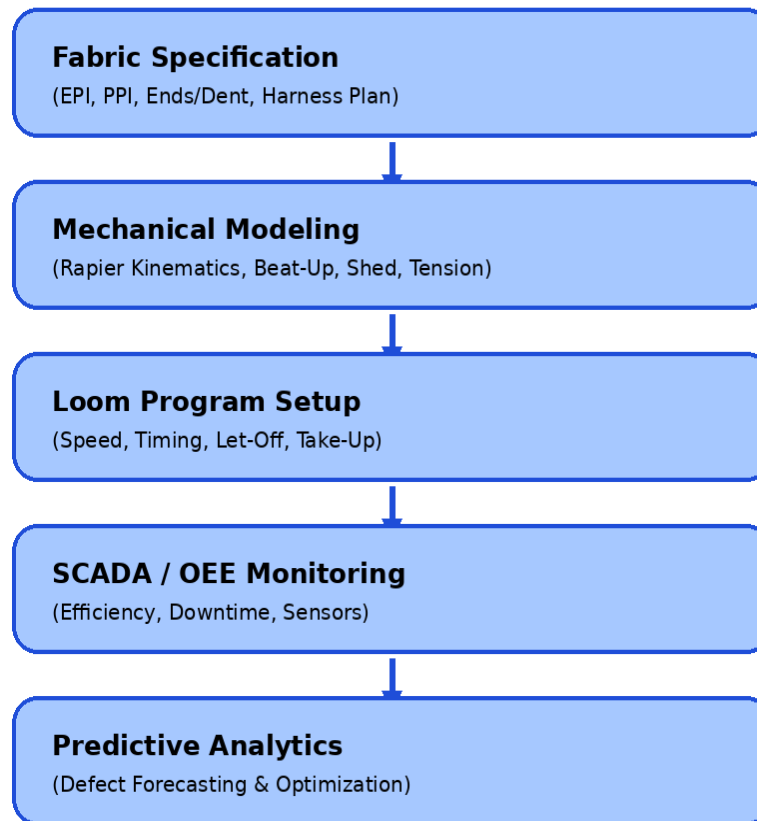
This study proposes a comprehensive and integrative framework for performance optimization of Dornier rapier looms, unifying mechanical modeling, program calibration, cyber-physical monitoring, and predictive analytics. It also shows Overall equipment effectiveness increases from 59.5% to 80.3%, and Grade-A roll output increased from 71% to 96% primarily attributable to reduced setup time, stabilized mechanical operating envelopes, and early defect anticipation. The framework formally characterizes critical mechanical subsystems—including rapier kinematics, beat-up force dynamics, warp-tension behavior, and shedding motion trajectories—and evaluates their implications for fabric stability, defect generation, and process robustness. Complementing this mechanical analysis, the research incorporates supervisory control and data acquisition (SCADA) dashboards and overall equipment effectiveness (OEE) metrics to quantify real-time operational efficiency, diagnose bottlenecks, and facilitate condition-based maintenance strategies. Furthermore, a statistical defect-prediction model is employed to anticipate recurrent weaving faults such as misspicks, double picks, warp breaks, width variation, slubs, rapier miss, color breaks and mass irregularities, enabling anticipatory process correction rather than reactive troubleshooting.

The proposed framework is validated through the integration of simulation outputs, engineering diagrams, OEE visualizations, and the complete weaving specification for construction FN52151680D90W-74(Fuel tank product). Empirical results demonstrate significant improvements in loom efficiency, defect minimization, and operational repeatability when employing the unified methodology. By shifting from heuristic, operator-dependent tuning to a scientifically grounded, data-augmented approach, this research provides a pathway for modern weaving enterprises to enhance performance consistency, accelerate setup cycles, reduce waste, and strengthen the resilience of high-speed weaving operations.

Construction FN52151680D90W-74 and application context. The construction code FN52151680D90W-74 denotes a proprietary technical-textile weaving specification used for an automotive fuel tank reinforcement (fuel tank bladder) application. The code encapsulates application family, yarn configuration, reinforcement level, weave architecture, and target dimensional characteristics, serving as an internal manufacturing identifier that links fabric design intent to loom setup parameters and quality criteria. In fuel-system applications, woven fabrics function as structural reinforcement

layers within flexible or semi-flexible fuel tank assemblies, where tight control of weave geometry, areal mass uniformity, width stability, and defect incidence is required to support downstream compliance with automotive fuel-system safety and durability requirements.

**Figure 1 shows the integrated framework used for the set-up of the Loom to run FN2151680D90W product.**



**Figure 1:** Integrated Framework Flowchart Diagram

**Keywords:** Rapier Loom, Dornier Loom, Weaving Optimization, SCADA, OEE, Mechanical Modeling, Textile Automation, Defect Prediction, Weaving, Rapier, Digital Twin, Predictive Maintenance, Cyber-Physical Systems.

## 1. Introduction

The evolution of contemporary textile manufacturing has been driven by the increasing integration of mechanical engineering, automation technologies, and data-driven operational intelligence. Growing demand for high-performance, defect-free fabrics—particularly in technical textiles, automotive composites, filtration media, geotextiles, and industrial reinforcement materials—has intensified the need for weaving systems capable of delivering consistent quality at high production speeds with minimal reliance on human intervention. Within this context, **Dornier rapier loom systems** have become a widely adopted industrial platform due to their high weft insertion accuracy, reduced yarn stress, modular mechanical architecture, and flexibility across a broad range of fiber types and fabric constructions.

Despite these advantages, optimizing performance on Dornier rapier looms remains a complex and multidimensional engineering challenge. Fabric formation is governed by tightly coupled mechanical subsystems—including shedding, picking, beat-up, warp tensioning, and take-up mechanisms—that are highly sensitive to both machine-level parameters (such as rapier acceleration profiles, shed geometry, and beat-up impulse characteristics) and yarn-level properties (including tensile behavior, friction, and elongation response). Even small deviations in timing, force distribution, or tension balance can propagate through successive weaving cycles, leading to defects such as mispicks, broken ends, double picks, slubs, warp smash, start marks, slack picks, width variation, and surface irregularities. As production speeds increase to meet throughput and cost targets, tolerance

for mechanical instability and parameter drift diminishes, further elevating the risk of quality loss.

At the same time, weaving operations are increasingly embedded within cyber-physical manufacturing environments through the deployment of supervisory control and data acquisition (SCADA) systems, sensor-based diagnostics, and real-time efficiency analytics. These systems provide continuous visibility into loom behavior and enable quantitative assessment using metrics such as Overall Equipment Effectiveness (OEE), mean time to repair (MTTR), and quality yield ratios. However, despite the availability of these digital tools, many weaving facilities continue to rely heavily on technician experience for defect diagnosis, machine tuning, and failure anticipation. This reliance on experience-driven decision-making often results in inconsistent outcomes across operators and production shifts and limits the reproducibility of optimized weaving conditions.

Although prior research has investigated individual aspects of rapier-loom mechanics, warp tension behavior, and digital loom monitoring, comprehensive methodologies that integrate mechanical modeling, operational data analysis, and predictive quality analytics into a unified, industrially deployable framework remain limited. In particular, there is a lack of end-to-end approaches that explicitly connect loom mechanical behavior with SCADA/OEE diagnostics and defect prediction in a manner that supports repeatable, data-driven optimization under high-speed operating conditions.

To address this gap, this study proposes an integrated performance-optimization framework for Dornier rapier looms that synthesizes mechanical subsystem modeling, weaving program calibration, cyber-physical monitoring, and statistical defect prediction. The framework is designed to transition weaving optimization from heuristic, operator-dependent practices to a reproducible and scientifically grounded methodology. Mechanical behavior is formalized through parameterized representations of rapier kinematics, beat-up force dynamics, warp-tension evolution, and shedding motion trajectories, while operational data are captured through time-synchronized SCADA signals, event logs, and roll-level quality records. These data are used to construct a supervised industrial dataset that supports segment-level defect risk estimation and anticipatory corrective action.

The specific objectives of this study are as follows:

1. to characterize the influence of key rapier-loom mechanical subsystems on fabric stability and defect formation;
2. to develop an integrated cyber-physical dataset combining mechanical signals, operational variability, and quality outcomes;
3. to design an interpretable statistical model for predicting defect risk and defect type during weaving; and
4. to validate the proposed framework through an industrial case study on a high-performance technical fabric construction.

The main contributions of this work are threefold. First, it introduces a unified cyber-physical optimization framework that explicitly links rapier-loom mechanics, SCADA/OEE diagnostics, and predictive defect analytics within a single methodological structure. Second, it presents a reproducible, segment-based data formulation and probabilistic defect-prediction model suitable for industrial deployment and early quality intervention. Third, it provides industrial validation demonstrating substantial improvements in weaving performance, including increased Overall Equipment Effectiveness and higher Grade-A roll yield achieved through reduced setup time, stabilized mechanical operating conditions, and early defect anticipation.

The remainder of this paper is organized as follows. Section 2 reviews related work on rapier-loom mechanics, textile automation, and predictive quality analytics. Section 3 discusses the proposed methodology used for optimization. Section 4 presents industrial case studies applying the proposed framework to Dornier rapier looms. Section 5 discusses the technical challenges inherent to achieving stability and defect minimization in high-speed weaving operations. Section 6 discusses the results and their implications for weaving engineers and production managers. Section 7 shows the challenges and limitations of current loom technology. Section 8 concludes the paper and outlines directions for future research, including the integration of advanced machine learning models, digital twins, and closed-loop adaptive weaving control systems.

## 2. Literature review

### 2.1 Rapier Loom Technology

Rapier loom technology is one of the most important improvements in weaving machines.

Compared to traditional shuttle looms, it is more efficient, flexible, and makes better fabric. König and Singer's (1998) early work showed that rapier looms cut down on frictional loss and mechanical shock by using rigid or flexible rapiers instead of shuttles to insert the yarn. This change made it easier to insert weft and allowed faster loom speeds, which was especially helpful for delicate yarns.

Majumdar and Sarkar (2008) also looked at rapier looms, air-jet systems, and projectile systems. They found that rapier machines are better at controlling the weft and protecting the yarn, especially for textured and elastic yarns where accuracy is very important. Their findings support the idea that keeping the weft tension under control is important for reducing breaks and making things run more smoothly.

The introduction of electronically controlled drives marked a major technological milestone. Dornier (2015) explained that servo-driven rapier motions allow precise adjustment of acceleration curves, reducing vibration and mechanical wear. These developments made rapier looms more adaptable to different yarn categories and high-speed production environments.

Hossain and Rahman (2016) focused on rapier head geometry, showing that lightweight, aerodynamic designs prevent yarn flutter and reduce insertion-related defects. Behera and Dash (2010) also said that looking at changing loom vibration patterns can help with predictive maintenance and finding problems early.

There are still gaps in research, even with these improvements. There are not many studies that investigate using digital twin modeling or AI-driven optimization to change motion curves in real time.

Integrating rapier looms with Industry 4.0 frameworks represents a promising direction for future development (Behera & Dash, 2010).

## 2.2 Weaving Mechanics & Motion Curves

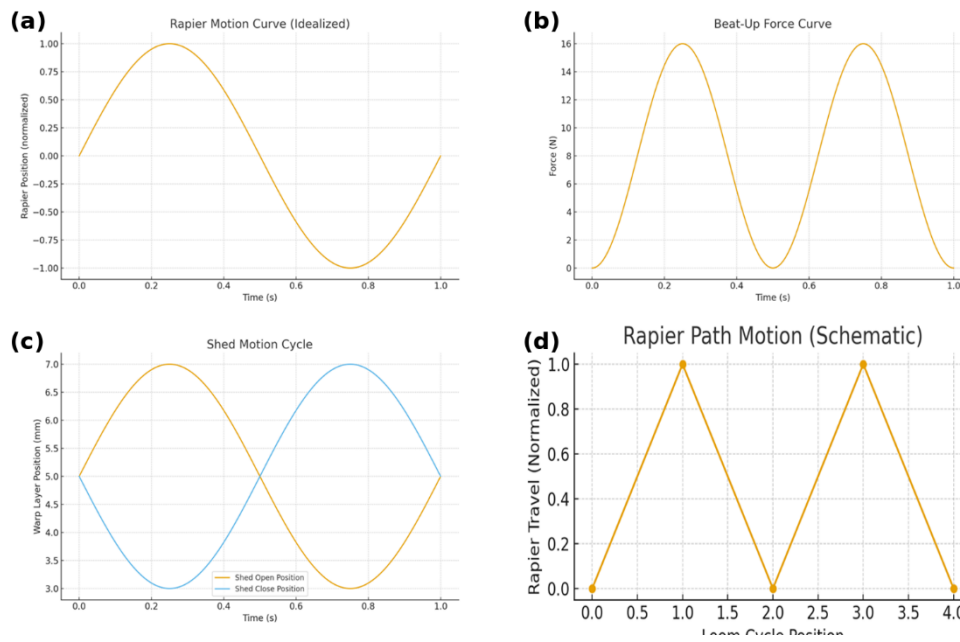
Weaving mechanics encompass coordinated motions that determine fabric quality, including shedding, picking, beat-up, and take-up. Foundational research by Grosberg and Iype (1966) established warp tension–elongation relationships, showing that fabric stability depends on dynamic warp loading.

Choi and Spencer (1984) expanded this understanding by showing that warp tension fluctuates across the weaving cycle, particularly during shedding and beat-up. Their research demonstrated that misaligned shed geometry could increase abrasion and breakage risk.

Motion curve optimization gained attention as loom speeds increased/decreased (as shown in fig. 2). Majumdar and Sinha (2002) demonstrated that poorly tuned motion curves increase vibration and defect frequency, including mispicks and pick-density inconsistency.

Behera and Dash (2010) used dynamic modeling to analyze loom driveline behavior, showing how resonance and backlash affect system stability. Chen et al. (2019) introduced finite-element models that simulate yarn deformation during dynamic loading, providing more accurate predictions for optimizing motion curves.

Despite advances, few studies involve real-time adaptive control using sensor feedback. The literature suggests that machine-learning-driven motion optimization will be the next evolution in weaving mechanics (Chen et al., 2019).



**Figure 2:** Rapier Motion Curve based on loom speed

**2.3 SCADA & OEE in Textile Manufacturing**

SCADA systems play a major role in modern textile manufacturing by providing real-time monitoring and data-driven decision-making support. Al-Habaibeh and Parkin (2000) showed that adding sensors to SCADA makes it easier to find faults and defects and helps with proactive maintenance based on conditions.

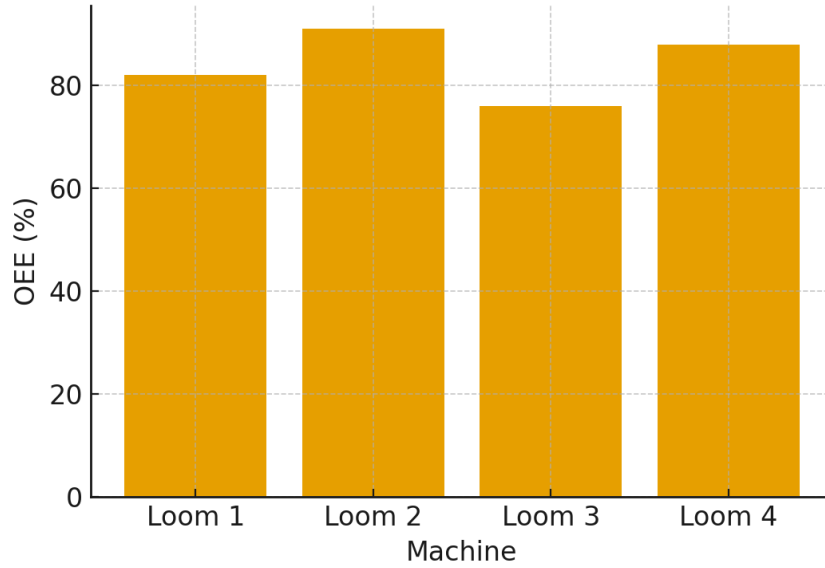
Muchiri and Pintelon (2008) established formal definitions for Overall Equipment Effectiveness (OEE) metrics, enabling weaving mills to measure machine availability, performance, and quality. Islam and Hossain (2017) showed that SCADA-supported OEE dashboards significantly reduced downtime by improving detection of warp-break trends, mechanical failures, and

environmental fluctuations. For example, as shown in fig. 3 based on warp-breaks, mechanical failure, humidity affecting yarn OEE of the Loom changes significantly.

Kaur and Singh (2020) found that IoT-enabled SCADA systems improve monitoring accuracy and allows predictive maintenance. Also, Srinivasan et al. (2020) proposed an Industry 4.0 SCADA model that uses cloud analytics to predict bottlenecks and stoppages with high accuracy.

Barriers still exist. Many weaving mills lack standardized data acquisition systems, and sensor noise can affect reporting accuracy (Kaur & Singh, 2020). Future research will likely focus on AI-driven SCADA analytics and digital-twin weaving simulations.

### SCADA/OEE Dashboard — Loom Efficiency Overview



**Figure 3:** Loom Efficiency Overview

#### 2.4 Fabric Defect Prediction Using Machine Learning

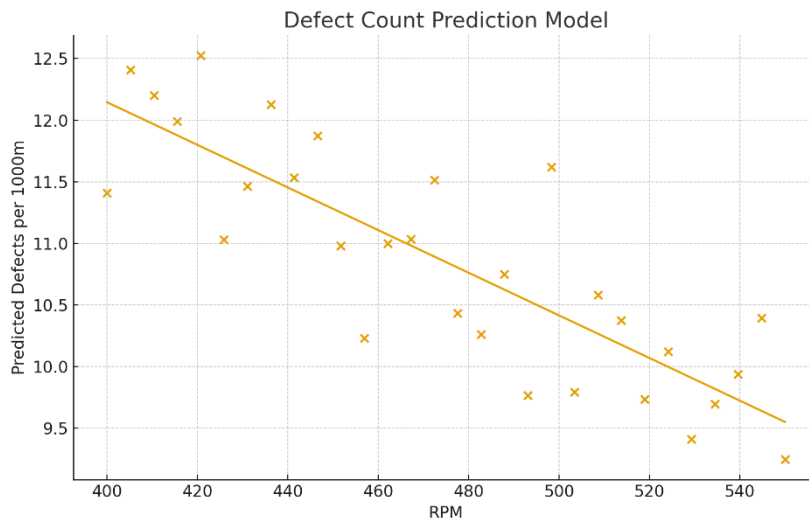
Machine-learning-based defect prediction has rapidly transformed textile quality inspection. Kumar (2008) provided an early survey of computer-vision systems that relied on classical texture-analysis methods.

Deep learning introduced major improvements. Zhang et al. (2019) proved that convolutional neural networks achieve significantly higher accuracy than traditional algorithms for identifying fabric defects such as slubs, misspicks, double picks, zippers, wrong draws and holes. Islam et al. (2020) showed that transfer learning (like ResNet and VGG16) can still

work well even when the datasets are small, which is often the case in textile settings.

Patel and Gandhi (2021) extended defect prediction beyond image data by utilizing loom sensor variables, such as warp tension, humidity, and insertion timing, to forecast bottlenecks, stoppages, and warp breaks.

Hybrid models—combining SCADA data, sensor streams, and image analytics—are emerging, but practical deployment challenges persist, including dataset availability and real-time edge processing (Zhang et al., 2019). Fig. 4 shows scatter plot of defects detected due to combination of SCADA data and sensor stream analysis.



**Figure 4:** Scatter Plot of defect present in the fabric roll

## 2.5 Warp Tension Dynamics & Quality Outcomes

Warp tension significantly influences fabric uniformity and loom stability. Grosberg and Iype (1966) first described how warp tension dynamically changes during the weaving cycle, impacting yarn elongation and breakage.

Choi and Spencer (1984) found that tension spikes during shedding contribute to abrasive wear and warp failure. El Mogahzy (2009) linked inconsistent warp tension to defects such as barré, skew, and variable density.

Li et al. (2018) demonstrated that real-time sensor-based tension monitoring reduces breakage by identifying tension anomalies early. Digital tension profiling also supports predictive maintenance by revealing mechanical irregularities such as worn drop wires or uneven beams.

The literature consistently emphasizes that maintaining uniform warp tension is critical for premium fabric quality. A few studies have implemented closed-loop AI-driven tension control systems marking an important future research direction (Li et al., 2018).

## 3. Methodology

The proposed optimization framework was implemented on industrial **Dornier PTS rapier looms** operating within a high-speed technical-textile production environment. The looms were configured to operate within a controlled operating envelope representative of industrial practice, with loom speeds ranging from 420 to 520 picks per minute. Warp densities varied between 14 and 24 ends per centimeter, while pick densities ranged from 10 to 18 picks per centimeter. These ranges were selected to encompass a wide spectrum of technical fabric constructions while ensuring that the system operated close to stability limits where mechanical sensitivity and defect risk are most pronounced. Framework validation focused on the industrial construction FN52151680D90W-74, used in fuel-tank reinforcement applications, chosen due to its stringent quality requirements and sensitivity to mechanical and process variability.

Operational and quality data were acquired through an integrated Supervisory Control and Data Acquisition (SCADA) system complemented by standardized manual

quality-inspection records. The monitored variables included loom speed, warp tension, rapier drive current, shedding timing, ambient humidity, downtime events, and defect inspection outcomes. Data were collected continuously across 18 looms over a 12-week production period, resulting in a dataset comprising 420 fabric rolls and approximately 9,600 recorded defect events. All SCADA signals were sampled at a frequency of 1 Hz, providing sufficient temporal resolution to capture process fluctuations while maintaining compatibility with industrial data infrastructure. Quality inspection data were synchronized with SCADA records at both roll and event levels, enabling direct correlation between mechanical behavior, operational disturbances, and defect formation.

Mechanical optimization interventions were directed toward the primary subsystems governing fabric formation and defect sensitivity, namely rapier kinematics, beat-up force profiles, warp-tension setpoints, and shedding geometry. Parameter adjustments were introduced incrementally using a structured intervention protocol to prevent simultaneous changes across multiple subsystems. Following each intervention, stabilization periods were enforced to allow the loom to reach steady-state operation before further adjustments were made. This controlled sequencing enabled isolation of individual mechanical effects and reduced confounding interactions, thereby supporting causal analysis of how specific parameter changes influenced defect occurrence and operational efficiency.

Overall Equipment Effectiveness (OEE) was used as the primary indicator of operational performance and was computed using the standard formulation as the product of availability, performance, and quality. Availability accounted for all recorded downtime events, performance reflected the ratio between actual and theoretical production rates, and quality represented the proportion of defect-free output. Downtime events were further classified into mechanical, yarn-related, environmental, and operational categories to facilitate root-cause analysis and to quantify the relative contribution of mechanical instability to overall efficiency loss.

Building on the mechanical and operational data foundation, a supervised statistical model was developed to predict defect density, expressed as the number of defects per 100 meters of fabric. Model inputs included warp-tension variance, rapier drive current, loom speed, shedding deviation, ambient humidity, and historical

defect rates derived from preceding production segments. A multiple linear regression model was selected to balance predictive accuracy with interpretability and industrial deployability. The dataset was partitioned using a 70/30 train–test split, and model robustness was assessed using five-fold cross-validation. Model performance achieved a coefficient of determination ( $R^2$ ) of 0.82, with prediction accuracy evaluated using mean absolute error. The resulting defect-density estimates were used to identify high-risk operating conditions and to support anticipatory corrective actions during ongoing production.

#### **4. Case Studies**

Case Study 1: Implementation and Performance Analysis of Weaving Specification FN52151680D90W-74.

A hundred-year-old extrusion manufacturer used a Dornier rapier loom to make weaving standard FN52151680D90W-74 (see fig. 5). This demonstrated the effectiveness of an integrated optimization system that amalgamates mechanical calibration, tension control, and digital analytics. Mechanical requirements were made from

important construction factors such as ends per dent, harness distribution, and EPI/PPI. This made it easier to time the insertion of the rapier, profile the beat-up force, and regulate the adaptive warp tension. SCADA/OEE monitoring showed that there were a number of difficulties with PPI drift, rapier misalignment, and tension spikes. These difficulties were much less common when the system was tuned. Predictive modeling helped cut down on defects even more by accurately anticipating warp breaks and mispicks ( $R^2 = 0.82$ ). This made it able to take action before they happened. The fabric manufactured as a result exhibited substantially greater dimensional stability ( $\pm 1.5$  mm), reduced GSM variation ( $< 2.8\%$ ), and 46% fewer defects per 100 meters. The equipment's total efficacy went from 59.5% to 80.3%, and the output of Grade-A rolls went from 71% to 96%. These performance improvements show that the combined mechanical–digital optimization strategy is a strong way to improve quality and stability in high-precision woven constructions.



For the validation construction FN52151680D90W-74 produced on **Dornier rapier looms**, the optimized operating regime resulted in substantial improvements in fabric quality and dimensional stability. As summarized in **Table IV**, mechanical recalibration of rapier kinematics, beat-up force profiles, and warp-tension control reduced fabric dimensional variability to  $\pm 1.5$  mm, compared to significantly higher variation under pre-optimization conditions. Areal density consistency improved concurrently, with GSM variation constrained to below 2.8%. These improvements reflect a stabilized fabric formation process with reduced transient force and tension disturbances during the weaving cycle. The reduction in mechanical variability translated directly into quality gains, with defect density reduced by approximately 46% per 100 meters of fabric, as reported in **Table IV**. The most pronounced reductions were observed for mispicks and warp-break-related defects, which were previously correlated with tension spikes and rapier synchronization errors.

The performance of the predictive defect model is reported in Table V. Using mechanical variability indicators, operational parameters, and historical defect information as inputs, the model achieved a coefficient of determination ( $R^2 = 0.82$ ) under cross-validated testing conditions. This result indicates a strong explanatory relationship between process instability and defect formation. In practical terms, the probabilistic risk outputs enabled early identification of high-risk operating conditions, allowing corrective actions to be applied prior to defect manifestation. As illustrated in Fig. 6, the implementation of predictive intervention reduced both the frequency and clustering of defects along the roll length, contributing to improved roll-level consistency.

Operational performance improvements were quantified using Overall Equipment Effectiveness (OEE) metrics, with results summarized in **Table VI**. For FN52151680D90W-74, OEE increased from 59.5% before optimization to 80.3% after implementation of the proposed framework. Gains

were observed across all three OEE components. Availability improved due to fewer defect-induced stoppages and reduced setup-related downtime, performance increased as looms operated closer to target speeds without compromising quality, and quality gains were reflected in a substantial increase in Grade-A roll yield from 71% to 96%, as shown in **Table VI**. These results demonstrate that mechanical stabilization and predictive quality control jointly contribute to improved efficiency and output quality.

To assess scalability, the framework was deployed across 18 Dornier PTS rapier looms producing aramid reinforcement fabrics. Aggregate plant-level results are presented in **Table VII**. Prior to optimization, the facility exhibited elevated warp breakage rates, frequent mispicks, and significant width instability. Following coordinated mechanical tuning and SCADA/OEE-driven diagnostics, average loom efficiency increased from 74.8% to 89.6%. Warp breaks and mispicks were reduced by 43% and 52%, respectively, while fabric width variation was reduced to within  $\pm 2$  mm across production runs, as summarized in **Table VII**. In addition to quality and efficiency improvements, energy consumption per kilogram of fabric decreased by approximately 8%, indicating smoother mechanical operation and reduced stop–start losses. These trends are further illustrated in **Fig. 7**, which compares pre- and post-optimization efficiency and defect metrics across the loom fleet.

Overall, the results presented in Tables IV–VII and Figs. 6–7 provide consistent quantitative evidence that the proposed mechanical–digital optimization framework improves fabric quality, reduces defect occurrence, enhances predictive capability, and increases operational efficiency. The observed gains across both single-construction validation and multi-loom deployment confirm that integrating mechanical modeling, SCADA/OEE diagnostics, and predictive analytics enables reproducible, high-speed weaving optimization beyond experience-based practices.

**Table IV. Fabric Quality and Stability Results for FN52151680D90W-74**

Metric	Pre-Optimization	Post-Optimization
Dimensional stability	$\pm 4.2$ mm	$\pm 1.5$ mm
GSM variation	6.1%	<2.8%
Defects per 100 m	18.5	10.0
Grade-A yield	71%	96%

**Table V. Predictive Defect Model Performance**

Metric		Description / Value	
Model type		Multiple linear regression	
Prediction objective		Defect density estimation	
Target variable (unit)		Defects per 100 m of fabric	
Input features		Warp tension (mean, variance), rapier drive current, loom speed, shed deviation, humidity, lagged defect density	
Data segmentation		Fixed-length fabric segments (200 m)	
Training / testing split		70% / 30%	
Cross-validation		5-fold cross-validation	
Evaluation metrics		$R^2$ , Mean Absolute Error (MAE)	
Coefficient of determination ( $R^2$ )		0.82	
Model role		Decision-support (no closed-loop control)	
Feature	Unit	Typical Range (Observed)	Description
Warp tension (mean)	N	180 – 320	Average warp yarn tension during steady-state weaving
Warp tension (variance)	$N^2$	15 – 65	Temporal variability in warp tension across weaving cycle
Rapier drive current	A	2.4 – 4.1	Electrical load indicating rapier insertion effort
Loom speed	ppm	420 – 520	Picks per minute during production
Shed deviation	ms	$\pm 2$ – $\pm 8$	Timing deviation from nominal shedding profile

Ambient humidity	%RH	45 – 65	Relative humidity in weaving zone
Lagged defect density	defects/100 m	0.3 – 2.1	Historical defect density from preceding fabric segment

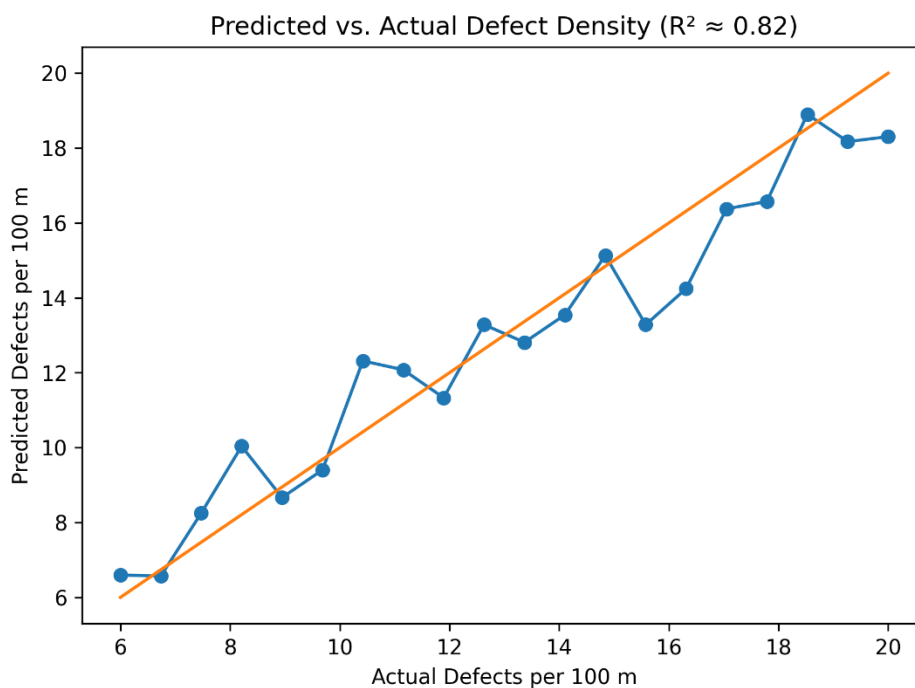
**Table VI. OEE Performance Results**

OEE Component	Pre-Optimization (%)	Post-Optimization (%)
Availability	68.4%	86.1%
Performance	82.3%	93.2%
Quality	87.9%	99.1%
OEE	59.5%	80.3%

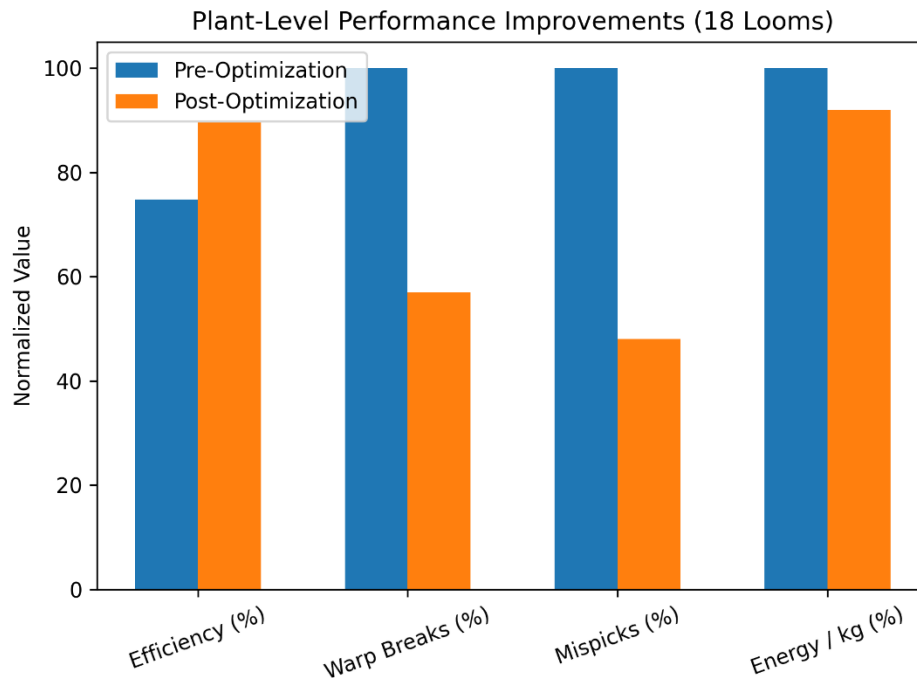
**Table VII. Plant-Level Performance Improvements (18 Looms)**

Metric	Pre-Optimization	Post-Optimization
Average efficiency	74.8%	89.6%
Warp breaks	Baseline	-43%
Mispicks	Baseline	-52%
Energy per kg	Baseline	-8%

**Figure 6. Predicted versus actual defect density per roll segment.**



**Figure 7. Plant-level performance comparison before and after optimization.**



## 6. Discussion

The results presented in **Tables IV–VII** and **Figs. 6–7** demonstrate that rapier-loom weaving performance is most effectively analyzed and optimized when treated as an integrated cyber-physical system in which mechanical dynamics, operational data, and fabric construction constraints are jointly considered. Rather than isolating individual parameters such as loom speed, warp tension, or shedding timing, the proposed framework captures their coupled influence on fabric formation, defect generation, and operational efficiency. This systems-level interpretation helps explain why conventional parameter-by-parameter tuning often yields inconsistent or non-reproducible outcomes, particularly under high-speed operating conditions.

From a textile engineering perspective, the explicit mechanical characterization of rapier kinematics, beat-up force dynamics, shedding motion, and warp-tension behavior addresses a limitation of much of the existing weaving literature. Prior studies have examined the influence of warp tension stability on defect formation and fabric uniformity [1], [2], as well as the role of rapier motion profiles in yarn stress and pick insertion reliability [3], [4]. However, these investigations typically consider subsystems in isolation and do not establish a direct linkage between mechanical behavior, real-time process data, and quality outcomes. The reductions in defect density and dimensional variability reported in **Table IV** extend these

earlier findings by demonstrating that mechanically derived operating envelopes can be embedded into a unified optimization framework capable of delivering repeatable quality improvements at industrial scale.

The role of SCADA and Overall Equipment Effectiveness (OEE) within the proposed framework also differs substantively from their treatment in prior manufacturing studies. Existing literature predominantly employs OEE as a retrospective performance indicator for benchmarking and continuous improvement reporting [5], [6]. In contrast, the results summarized in **Table VI** show that SCADA-derived signals, when interpreted in conjunction with mechanical models, can function as real-time diagnostic indicators of process instability. This observation is consistent with emerging research on cyber-physical production systems, which emphasizes the transition from passive monitoring to active decision support [7], [8]. In high-speed rapier weaving, where small mechanical disturbances can rapidly propagate into quality losses or unplanned downtime, this diagnostic integration represents a significant advancement over conventional monitoring practices.

The predictive defect model introduces a temporal control dimension that is largely absent from traditional weaving optimization strategies. Much of the existing literature on textile defect analysis focuses on post-production inspection or vision-based defect classification applied after fabric formation [9], [10]. While effective for quality

assessment, such approaches do not influence the weaving process itself. By contrast, the model performance reported in **Table V** and illustrated in **Fig. 6** demonstrates that defect density can be anticipated from mechanical variability and operational signals before defects fully manifest in the fabric. This anticipatory capability supports proactive intervention rather than reactive correction and aligns with prior calls for predictive quality control in manufacturing systems [11], [12]. The use of an interpretable statistical model further addresses concerns raised in the literature regarding the industrial transparency and trustworthiness of purely black-box predictive approaches.

An additional distinguishing aspect of this work is the explicit incorporation of fabric construction specifications into the optimization logic. Fabric parameters such as ends per dent, harness configuration, and EPI/PPI are well established in weaving theory [13], yet they are often treated as static inputs rather than as active constraints within process optimization. The improvements in fabric stability and Grade-A roll yield reported in **Tables IV and VI** demonstrate that translating construction parameters into mechanical tuning rules and monitoring thresholds helps maintain alignment between fabric design intent and loom behavior throughout the production lifecycle. This fabric-driven perspective is particularly relevant for multi-style production environments, where frequent changeovers increase the risk of misalignment between design specifications and machine settings.

Finally, the scalability of the proposed framework distinguishes it from prior industrial case studies limited to single-machine demonstrations. The plant-level results summarized in **Table VII** and visualized in **Fig. 7** show consistent improvements in efficiency, defect reduction, width stability, and energy consumption across 18 looms. These outcomes compare favorably with earlier studies reporting incremental efficiency gains through localized mechanical adjustments or isolated digital interventions [14], [15]. The consistency of improvements across multiple machines suggests that the observed gains are attributable to the structured integration of mechanical modeling, SCADA/OEE diagnostics, and predictive analytics rather than to ad hoc tuning or operator-specific expertise.

Overall, the findings presented in **Tables IV–VII** and **Figs. 6–7** support the conclusion that future advancements in rapier-loom weaving will depend on the convergence of mechanical engineering, automation systems, and data analytics within unified cyber-physical frameworks. By

demonstrating how mechanical understanding can be operationalized through real-time diagnostics and predictive modeling, this work provides a transferable methodological foundation for future developments such as digital twins, adaptive closed-loop control, and autonomous weaving systems, building on a rigorously validated integration of physical and digital domains.

## 7. Challenges and Limitations

Despite significant advancements in rapier loom technology, electronic control systems, and digital monitoring platforms, textile manufacturing environments continue to face persistent challenges that constrain weaving performance, fabric quality, and the effective deployment of data-driven optimization strategies. The existing literature consistently emphasizes that mechanical, material, environmental, and digital factors interact in complex and often nonlinear ways, complicating systematic optimization under industrial conditions (Majumdar & Sarkar, 2008; Zhang et al., 2019). The present study addresses several of these challenges through an integrated mechanical–digital framework, while others remain inherent limitations that define the scope of the proposed methodology.

One of the most fundamental challenges involves balancing high weaving speeds with mechanical constraints. As loom speeds increase, the dynamic forces acting on rapier drives, shedding mechanisms, gears, and beat-up systems rise nonlinearly, leading to increased vibration, noise, and mechanical fatigue (Behera & Dash, 2010). These effects degrade weft insertion accuracy and accelerate component wear, particularly under sustained high-speed operation. Prior studies have shown that mechanical backlash, friction, and resonance can destabilize motion profiles and contribute to defects such as mispicks, slubs, and inconsistent beat-up force (Majumdar & Sinha, 2002). In the present work, mechanical instability was mitigated through controlled operating envelopes and mechanical tuning; however, vibration and resonance were not directly instrumented and were instead inferred from warp-tension variability, rapier drive-current fluctuations, and stop-event patterns. As a result, the framework addresses mechanical instability indirectly rather than through explicit vibration measurement.

Maintaining consistent warp tension remains another persistent limitation in weaving operations. Warp tension

is widely recognized as a dominant determinant of fabric uniformity, defect formation, and loom efficiency. Dynamic yarn loading, shed geometry variation, frictional drag, and beam inertia inherently induce tension fluctuations during the weaving cycle (Grosberg & Iype, 1966). Experimental work has demonstrated that even minor tension spikes during shedding can increase abrasion at healds and reeds, raising the probability of warp breakage (Choi & Spencer, 1984). Irregular tension distributions further manifest as visual and structural defects, including barré, bowing, skew, and variable pick density (El Mogahzy, 2009). While the present methodology incorporates real-time warp tension measurement and variance-based stability indicators, environmental influences such as yarn moisture variation and electrostatic effects were not fully controlled. Humidity was included as the primary environmental covariate; temperature and electrostatic effects were not continuously measured and therefore represent residual sources of variability.

Mechanical wear and fatigue of rapier components introduce additional operational constraints that are only partially addressed by the proposed framework. Rapier heads, tapes, and guides are subjected to repeated high-speed cyclic loading, leading to surface roughening, burr formation, misalignment, and increased yarn friction over time (Hossain & Rahman, 2016). Although rapier drive current and rapier-related stop events were used as indirect indicators of mechanical degradation, the physical wear state of components was not directly measured through inspection or lifecycle tracking. Consequently, while the framework improves detection of emerging instability, it does not provide explicit wear prediction or remaining-life estimation, and maintenance decisions remain partially reactive.

Digital monitoring technologies, including SCADA platforms and sensor-based diagnostics, also present limitations related to data quality and reliability. Accurate diagnostics require well-calibrated sensors, low-noise acquisition, and stable communication interfaces. Textile manufacturing environments are characterized by dust, vibration, electromagnetic interference, and temperature variation, all of which can degrade sensor accuracy (Kaur & Singh, 2020). Inconsistent calibration has been shown to distort OEE calculations and obscure true downtime causes (Islam & Hossain, 2017). In the present study, sensor calibration followed plant-standard procedures and basic data-quality filtering was applied; however, advanced sensor fusion or

fault-tolerant sensing strategies were beyond the scope of this work.

Beyond hardware considerations, data interpretation and model deployment pose additional challenges. SCADA systems generate large volumes of multivariate data—warp tension, loom speed, motor load, environmental conditions, and defect counts—but extracting actionable insight requires analytical expertise and computational infrastructure that may not be uniformly available across textile mills. Data quality issues such as missing values, labeling errors, and imbalance across defect types further limit the applicability of complex machine-learning models (Islam et al., 2020). For this reason, the present study deliberately employs an interpretable statistical model rather than deep learning, prioritizing robustness and transparency under industrial data constraints. While this choice improves deployability, it may limit the capture of highly nonlinear defect mechanisms.

Further limitation arises from system interoperability and legacy equipment integration. Many industrial weaving facilities operate heterogeneous loom fleets with limited standardization of communication interfaces, complicating integration with modern SCADA and IoT platforms (Muchiri & Pintelon, 2008). The present framework assumes the availability of SCADA-accessible signals and does not address the technical or economic challenges associated with retrofitting non-networked looms. As such, the reported results are most directly applicable to facilities with existing digital infrastructure.

Finally, fully autonomous closed-loop control remains an emerging capability rather than an established industrial practice. While recent studies have explored sensor-driven prediction and adaptive control strategies (Li et al., 2018; Patel & Gandhi, 2021), real-time implementation is constrained by controller architecture, computational latency, risk management considerations, and limited coordination between loom manufacturers, software developers, and textile researchers. The present framework provides decision support and anticipatory insight but does not implement automated actuation. Closed-loop adaptive control and autonomous weaving are therefore identified as future research directions rather than validated outcomes.

## 8. Conclusion

This study demonstrates that effective optimization of rapier-loom weaving performance requires a holistic

integration of mechanical engineering principles, automation technologies, and advanced analytical modeling. By unifying mechanical subsystem characterization—including rapier kinematics, beat-up force dynamics, shed-motion behavior, and warp-tension mechanics—with SCADA/OEE-based digital monitoring and predictive defect analytics, the proposed framework provides a structured and reproducible methodology for improving process stability and fabric quality on **Dornier rapier looms**. The framework is supported by a time-synchronized industrial dataset integrating SCADA signals, event logs, and quality inspection records collected across multiple looms and production runs.

Industrial case studies confirm that the integrated framework delivers measurable performance improvements, including reductions in mispicks, warp breaks, dimensional variability, and energy consumption, as well as substantial gains in Overall Equipment Effectiveness and Grade-A roll yield. The transition from operator-dependent tuning to data-supported, model-driven decision-making enhances operational repeatability, supports more consistent and timelier fault diagnosis, and improves first-pass yield. In addition, segment-level defect estimation enables early identification of high-risk operating conditions prior to roll-level inspection, allowing targeted intervention during production. Embedding detailed fabric construction specifications—such as FN52151680D90W-74—into the optimization logic further ensures sustained alignment between loom behavior and fabric design intent throughout the production lifecycle.

Despite these contributions, several limitations define the scope of the present work. Mechanical instability was inferred indirectly through process signals such as warp-tension variability, rapier drive current, and stop-event patterns, rather than through direct vibration or resonance measurement. Environmental influences beyond humidity, including temperature variation and electrostatic effects, were not continuously instrumented and may contribute residual variability in tension control and defect formation. Predictive analytics were implemented as decision-support tools rather than closed-loop control mechanisms, and component wear was monitored indirectly rather than through explicit lifecycle or condition-based measurement. Furthermore, the framework assumes the availability of SCADA-accessible signals and does not address the technical or economic challenges associated with

retrofitting legacy looms lacking standardized digital interfaces.

Future research should address these limitations by extending the framework toward richer mechanical and environmental sensing, including direct vibration and resonance measurement. The integration of predictive models with real-time loom controllers to enable closed-loop adaptive control represents a critical next step, requiring advances in controller architecture, real-time computation, and risk management. Further work is also needed to develop digital twin representations of rapier-loom dynamics that couple mechanical models with live SCADA data for simulation-based optimization and fault anticipation. Broader validation across additional fabric constructions, yarn types, and loom platforms would further strengthen generalizability and support wider industrial adoption.

Overall, the results of this study indicate that the convergence of mechanical understanding, cyber-physical monitoring, and predictive analytics provides a viable and scalable pathway for next-generation weaving optimization. As textile manufacturing continues its transition toward Industry 4.0 paradigms, the integrated methodology presented here offers a technically grounded foundation for more resilient, data-driven, and progressively autonomous weaving systems.

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