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Digital Twin For Quality-Aware Production Management In Apparel Sewing Lines

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Abstract: This research investigates the integration of Digital Twin (DT) technology with quality-aware production management in apparel sewing lines. Traditional DT applications focus primarily on production efficiency, often overlooking the critical aspect of quality control (QC). This study proposes a novel digital twin framework that incorporates real-time quality data to enhance decision-making in apparel manufacturing. Using system simulation, real-time data feeds, and quality performance metrics, the model was tested in a simulated apparel production environment. Results show significant improvement in product quality, defect reduction, and production responsiveness, establishing a new paradigm in textile Industry 4.0 practices.

Keywords: Digital Twin, Quality Control, Apparel Manufacturing, Production Management, Industry 4.0, Smart Factory, Real-time Simulation

1. Introduction: The apparel industry is undergoing a significant transformation with the advent of Industry 4.0. Innovations in automation, data analytics, and cyber-physical systems are redefining the landscape of manufacturing. However, most advancements have predominantly emphasized production efficiency, sidelining the equally important domain of quality control (QC). Traditional quality control methods are often reactive and fail to provide the real-time insights necessary for immediate corrective actions.

Digital Twin (DT) technology offers a potential solution. By creating a virtual representation of physical systems, DT enables manufacturers to monitor, simulate, and optimize operations dynamically. While DT has been successfully applied in other industries such as aerospace and automotive, its application in textile and apparel production—especially integrated with QC systems—remains limited.

Problem Statement: Digital twin technologies in apparel manufacturing are mostly utilized for operational optimization, neglecting the integration of real-time quality control data. This gap leads to inefficiencies in production scheduling, increased rework, and reduced overall productivity.

Research Questions:

1. How can real-time quality data be effectively integrated into digital twin frameworks for apparel sewing lines?
2. What impact does quality-aware digital twin integration have on production efficiency and defect reduction?

Objective: This research aims to design, simulate, and evaluate a digital twin model that enables quality-aware production management in apparel sewing lines, thereby improving responsiveness, reducing defects, and optimizing resource utilization.

2. Literature Review: Digital twins are defined as real-time virtual representations of physical entities that enable bi-directional communication and simulation. In manufacturing, they are used for predictive maintenance, process optimization, and decision-making support. Several studies have explored DT's potential in industries like automotive (Jiang et al., 2022), but the textile sector has seen limited penetration.

In textiles, most DT applications (Zhang et al., 2023; Lee & Kwon, 2022) focus on production parameters such as throughput, downtime, and energy usage. These models rarely consider quality-related variables. Patel et al. (2021) implemented IoT-based monitoring for fabric defects but stopped short of integrating this data into a responsive production management system. This lack of integration presents a gap in the current research landscape.

The convergence of IoT, machine learning, and digital twins represents an opportunity to establish quality-aware smart factories. This study aims to advance this integration within the apparel sewing context.

3. Methodology:

3.1 Framework Design: The digital twin framework designed in this study comprises three primary layers:

1. **Digital Model Layer:** Built using AnyLogic and Python, this layer replicates the physical layout of an apparel sewing line. It models machine behavior, operator performance, and production workflows.
2. **Data Acquisition Layer:** Utilizes IoT devices to collect real-time data on machine states, stitch defects, operator output, and rework occurrences. This layer ensures high-resolution data is transmitted continuously to the digital model.
3. **Decision Intelligence Layer:** Applies machine learning algorithms (e.g., decision trees, neural networks) developed using TensorFlow to analyze data patterns, predict quality issues, and recommend adjustments.

3.2 Data Collection: Data was gathered from a mid-sized garment manufacturing unit operating with five sewing lines. Sensors and manual logs were used for data collection. Key parameters and their sources are listed below:

Parameter	Source
Stitch defects	QC inspection camera
Machine health	Vibration/temperature sensors
Output per operator	RFID-tagged production counters
Rework count	Manual QC records

3.3 Simulation Tools:

- **Any Logic:** Used for discrete event and agent-based modeling of the production line.
- **Python:** Utilized for data integration and dashboard development.
- **TensorFlow:** Applied to train predictive models for defect occurrence based on real-time signals.

3.4 Evaluation Metrics:

- Defect Rate (% of total production)
- Mean Time Between Failures (MTBF)
- Line Efficiency (% throughput vs. planned)
- First-Pass Yield (FPY)
- Rework Time (minutes/day)

4. Results and Discussion:

The developed digital twin was implemented in a simulated environment with real input data. Comparative results before and after implementation are presented below:

Metric	Baseline	With DT Framework
Defect Rate (%)	8.5%	3.1%
Production Efficiency	72%	88%
FPY	85%	96%
Rework Time (min/day)	180	55

The reduction in defect rate by 63% and an increase in production efficiency by 22% highlight the model's effectiveness. Predictive analytics identified patterns in defect emergence, which enabled real-time rerouting of tasks and reallocation of skilled operators.

Key Findings:

- Integrating QC data into the digital twin improves both real-time control and long-term planning.
- The system promotes continuous learning through ML models that refine themselves with ongoing data.
- Operator-wise performance analytics enabled better line balancing and training recommendations.

Visual dashboards developed in Python allowed managers to visualize bottlenecks, rework hotspots, and machine downtime.

5. Conclusion: This research successfully developed a digital twin framework that integrates real-time quality control data for optimized apparel sewing line management. The inclusion of QC parameters in DT models leads to proactive decision-making, improved production efficiency, and a significant reduction in defects and rework. The framework establishes a foundation for a holistic smart factory model within the apparel sector.

6. Future Scope:

- Implement the model in a live production environment across multiple lines.
- Extend the framework to include wet processing and dyeing stages.
- Incorporate blockchain to ensure transparency and traceability in quality monitoring.
- Enhance the ML engine for adaptive learning with minimal human intervention.

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