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The Industry 5.0 Paradox in Textile Manufacturing: Socio-Technical and Behavioral Operations in Production Optimization

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ABSTRACT

The transition towards Industry 5.0 necessitates a human-centric integration with advanced manufacturing systems. Although Production Planning and Control (PPC) models have mathematically optimised machine parameters, operational inefficiencies and material waste generation remain persistent challenges, particularly in 24/7 yarn spinning industries. This study employs an explanatory quantitative case study approach on a 100% Polyester (PE) yarn production line at PT Excellence Qualities Yarn. Utilising the lenses of Socio-Technical Systems (STS) and Behavioural Operations Management (BOM), this research analyses operational data from the Drawing Breaker machine across three working shifts. The findings reveal significant efficiency variances (Morning Shift: 67.83%; Afternoon Shift: 68.90%; Night Shift: 61.25%). The drastic efficiency drop during the night shift, reaching a low of 28.64% due to 100 minutes of downtime, demonstrates that static technical parameters fail to accommodate the degradation of human capacity. In conclusion, socio-technical imbalances not only reduce production output but also increase material waste ratios, thereby hindering circularity. This research offers novel theoretical insights by bridging machine balancing and operator behavioural factors within industrial sustainability.

Keywords: *behavioral operations management, circular economy, industry 5.0, production optimization, socio-technical systems.*

1. Introduction

The global textile spinning industry currently stands at the crossroads between intensive automation, characteristic of Industry 4.0, and the urgent need for sustainability and human-centric approaches associated with Industry 5.0 (Kaur et al., 2025; Laskurain-Iturbe et al., 2025; Nahid-Ull-Islam et al., 2025; Solomon et al., 2025). Historically, efficiency in the textile industry—such as adjusting parameters for Yarn Number (Ne), Revolutions per Minute (RPM), and Twist per Inch (TPI)—has relied heavily on mathematical optimisation within the domain of Production Planning and Control (PPC). For instance, meticulous mechanical adjustments, such as gear alignment, are fundamentally required to maintain the consistency of the Yarn Number (Ne) during the spinning process (Darmawi & Sari, 2023). However, pure algorithmic models often assume that machines operate in a technical "vacuum," ignoring the reality that floor-level execution is highly dependent on human interaction (Cui et al., 2025). Recognising this interplay between human operators and automated systems is essential for achieving both genuine operational efficiency and long-term sustainability in textile manufacturing.

In yarn spinning plants operating 24 hours a day, 7 days a week, complex variables such as machine balancing and workload mismatch consistently cause severe performance fluctuations (Chen et al., 2023; Khairunnisa et al., 2023; Mahmood, 2020). Furthermore, local studies on winding machines emphasise that inadequate shift supervision exponentially triggers sudden defect occurrences, validating the need for rigorous operational monitoring (Darmawi et al., 2023). This phenomenon not only results in the failure to achieve production targets but also exponentially increases the volume of material waste during critical processing phases, such as carding and drawing. Within a contemporary circular economy framework, reducing this waste at the initial manufacturing stage is a non-negotiable imperative (Jumaniyazov & Anorboev, 2025; Sen et al., 2026). Consequently, unscheduled machine breakdowns and raw material inspection errors should not be viewed merely as mechanical problems, but rather as systemic failures in human–machine interaction (Fani et al., 2025; Salonen, 2024). To address these deep-rooted challenges, it is essential to develop holistic strategies that enhance the synergy between human operators and automated systems, ultimately fostering a more resilient and sustainable textile production environment.

This study explores this literature gap by conducting empirical research on the 100% polyester (PE) production line at PT Excellence Qualities Yarn. Initial field reports indicate a compelling paradox: although the spinplan has been mathematically and precisely set—for instance, the drawing breaker machine is calibrated at a speed of 409 m/min with a target technical efficiency of 77%—the actual output fluctuates extremely across different working shifts. Previous literature often separates mechanical efficiency calculations from circularity goals; however, in practice, reducing downtime and providing timely operator intervention prevents defect propagation that ultimately culminates in permanent material waste. Furthermore, when capacity-balancing models ignore shift-based human performance degradation, the projected output targets become entirely unrealistic. To effectively mitigate these operational discrepancies, a comprehensive approach that integrates real-time data analytics with adaptive scheduling mechanisms is vital for optimising both human and machine performance in the modern textile landscape (Luca et al., 2025; Rahaman, 2024). Therefore, the primary objective of this study is to investigate how the imbalance between static technical parameters and dynamic, shift-based human capacities triggers efficiency fluctuations and downtime. Additionally, this study aims to elucidate how these operational failures impact material waste generation. By integrating Socio-Technical Systems (STS) and Behavioural Operations Management (BOM), this research offers a novel perspective, bridging the gap between purely mathematical machine-balancing models and human-centric industrial resilience.

2. Research Method

This study employs an explanatory quantitative case study approach, providing a robust empirical basis for analysing operational inefficiencies in the PE production line of PT Excellence Qualities Yarn, as shown in Figure 1.

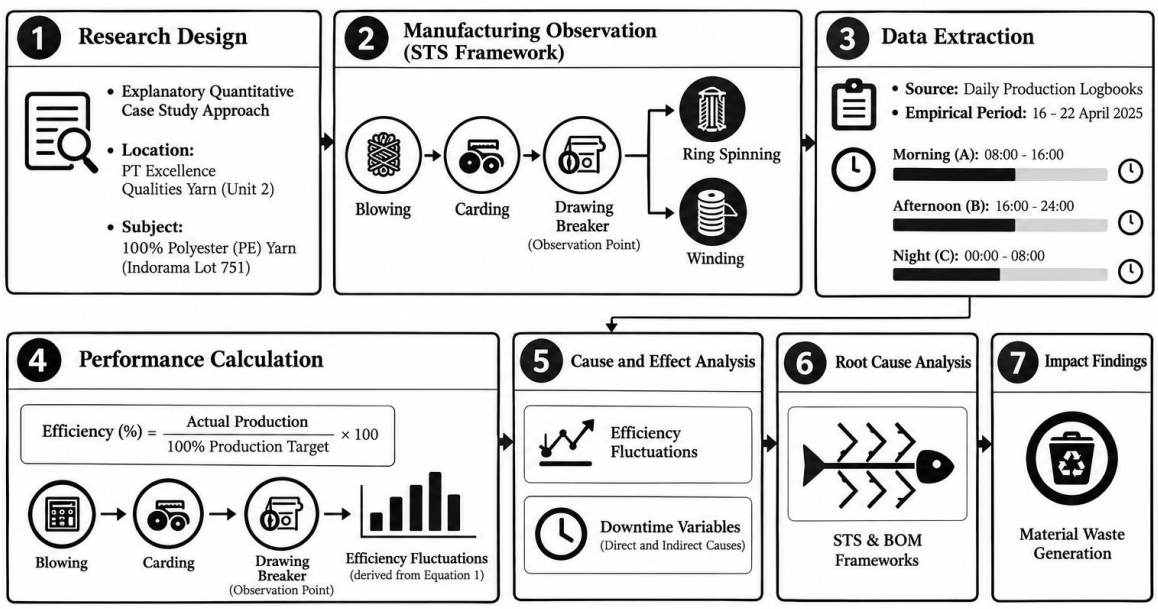


Figure 1. Research methodology flow: explanatory quantitative case study at PT Excellence Qualities Yarn

This research utilises an explanatory quantitative case study approach, providing a robust empirical basis for analysing operational inefficiencies at PT Excellence Qualities Yarn's PE production line. The observation was specifically conducted on the Lakshmi LD2 Drawing Breaker units (manufactured in 2016). The overarching framework of this methodology, from the initial research design to the final causal analysis of material waste generation, is visualised in Figure 1. The manufacturing process flow observed within this socio-technical system framework moves sequentially from initial material preparation (Blowing and Carding) to the critical observation point at the Drawing Breaker machine, followed subsequently by Ring Spinning and Winding. The findings extracted from this specific floor-level observation will contribute to a better understanding of the interplay between human physiological rhythms and machine performance, ultimately guiding actionable improvements in production efficiency and sustainability in textile manufacturing.

Data were empirically extracted from the facility's daily production logbooks covering a continuous seven-day operational period (16 - 22 April 2025). The data encompasses the performance of the assigned shift

operators working under standard factory rotation schedules. Cross-shift performance across three distinct periods (Morning: Shift A, Afternoon: Shift B, Night: Shift C) was evaluated by quantifying and comparing the actual efficiency. To avoid redundancy with Figure 1, the machine's performance is calculated using the standard industrial formulation presented in Equation (1), which directly compares the actual empirical output against the theoretically optimal capacity prescribed by the spinplan.

Efficiency (%) = (Actual Production / 100% Production Target) x 100 (1)

The fluctuations derived from Equation (1) were causally analysed against the recorded downtime variables, specifically focusing on the duration and nature of the operational disruptions. By utilising the Socio-Technical Systems (STS) and Behavioural Operations Management (BOM) frameworks, this analysis identifies the root causes of inefficiencies and their subsequent impact on material waste generation. To ensure a comprehensive understanding of the ecosystem, the study also considers the profound implications of human factors on machine performance, emphasising the critical need for integrated training programs that align operator cognitive skills with rapid technological advancements (Zhang & Jebelli, 2026).

3. Result and Discussion

3.1. Machine Parameters and Capacity Baseline

Based on the factory's technical spinplan, the processing machinery operates under parameter configurations meticulously designed to yield maximum output while strictly maintaining minimum waste tolerance thresholds (Garbie & Parsaei, 2025; Pawar et al., 2021; Rofi et al., 2025). Table 1 summarises the primary operational parameters established for the observed production line. To address the inherent challenges of these high-speed settings, management must implement continuous improvement initiatives that focus symmetrically on operator training and the continuous refinement of machine settings, thereby enhancing overall production efficiency (Adriel & Harito, 2025; Pedroso et al., 2026).

Table 1. Critical spinplan parameters and waste tolerance for 100% polyester

Machine process	Primary parameter (Speed/RPM)	Target eff. (%)	Waste tolerance (%)
Carding	174 km/hour	97	0.05
Drawing Breaker	409 m/min	77	0.03
Ring Spinning	17,950 m/min	98	0.03
Winding	1,400 km/hour	63	0.03

The parameters listed in Table 1 represent a mathematical ideal; it is a technical subsystem where the machine is optimistically assumed to experience no unplanned human or mechanical interruptions. For the drawing breaker machinery, operating continuously at 409 m/min translates to a theoretically optimal target capacity of 21,250 kg per shift. This theoretical capacity of 21,250 kg is an aggregate factory target calculated based on the maximum mechanical speed, sliver weight, and continuous operational time (8 hours) for the active machine deliveries running concurrently.

3.2. Shift-Based Production Efficiency Variance

Empirical measurements recorded during the seven-day observation period reveal a highly significant divergence between the theoretical capacity outlined in Table 1 and the genuine execution on the factory floor across each individual shift. To capture the volatility of this performance, measures of variability (standard deviation) were calculated. The performance data extracted from the daily logbooks are presented in Table 2.

Based on the empirical data in Table 2, it is evident that Shift C (Night) experiences the most severe performance degradation, recording a low average of 61.25% and exhibiting the highest fluctuation deviation, plummeting to a critical low of 28.64% on April 17. In stark contrast, Shift B (Afternoon) achieved the highest overall peak at 95.09%, demonstrating the machine's capability, albeit with notable day-to-day inconsistencies.

3.3. Downtime Profile and Operational Disruption Analysis

Further rigorous analysis of the downtime profile reveals a direct inverse correlation with the aforementioned efficiency metrics (Dally, 2023; lu, 2026; Rispoli, 2025). A qualitative review of the field

disruption logs summarises the primary operational causes and workforce handling capabilities across the different shifts, as shown in Table 3.

Table 2. Aggregation of drawing breaker machine efficiency comparison across shifts

Date (April 2025)	Shift A efficiency (Morning)	Shift B efficiency (Afternoon)	Shift C efficiency (Night)
16	72.56%	33.25%	53.04%
17	66.63%	49.56%	28.64%
18	76.57%	86.57%	71.05%
19	53.38%	70.00%	67.35%
20	66.11%	95.09%	82.34%
21	63.92%	66.90%	66.58%
22	75.62%	80.91%	59.76%
Average	**67.83% ± 8.03%**	**68.90% ± 21.56%**	**61.25% ± 17.01%**

Table 3. Disruption causes profile and handling performance per Shift

Primary disruption factor	Morning shift (A)	Afternoon shift (B)	Night shift (C)
Operator performance	Moderate variance	Excellent response	High fatigue & minimal supervision
Critical downtime	75 minutes (April 19)	38 minutes (April 16)	100 minutes (April 17)
Maintenance response	Controlled schedule	Rapidly repaired	Recurring lack of intervention

On April 17 (Shift C), machine downtime escalated to an unprecedented 100 minutes owing to unmitigated technical disruptions, such as the need for intensive cleaning and emergency top roll repairs. The logbooks confirm that the maintenance response and operator intervention during the night hours were significantly slower than those during the daytime shifts (Rosenberg, 2024).

3.4. The Machine Balancing Paradox through Socio-Technical Systems (STS)

The compelling findings presented in Tables 2 and 3 empirically validate the foundational STS thesis that technical perfection inherently decays without the sturdy scaffolding of social capacity. The Drawing Breaker machine does not detect whether it is day or night; its mechanical speed parameter remains relentlessly constant at 409 m/min (E.-S. & Yun, 2023). However, human operator capacity inevitably shrinks at night owing to natural circadian rhythms and physical limitations. The catastrophic 100-minute downtime on the night shift represents a profound failure of STS integration (Heinrich et al., 2021). Minor technical anomalies, such as thin or thick areas on the drafted sliver, which can typically be isolated and resolved in under 30 minutes during the day shift using systematic problem-solving approaches (Rosida et al., 2022), dragged on excessively at night owing to a critical lack of senior supervision. This supervision mismatch transforms minor mechanical errors into lengthy, costly breakdowns, robustly validating the argument that mathematical machine balancing models must transcend technical parameters to account for shift-based human performance variables (Finhold et al., 2020; Rizka et al., 2024).

3.5. Behavioral Operations and Preventive Maintenance Failure

From a Behavioural Operations Management (BOM) perspective, operator cognitive fatigue triggers dangerous negligence towards mandatory inspection and maintenance schedules (Bohrey & Chatpalliwar, 2024; Rodriguez, 2024). Although the textile facility enforces strict standard maintenance protocols, on-the-ground execution is frequently and severely reduced during the night shift. While direct physiological fatigue was not medically measured in this study, the observed operational output—specifically the prolonged Mean Time to Repair (MTTR) and neglected cleaning schedules—strongly aligns with BOM literature regarding cognitive fatigue and preventive delay behaviour (ányi et al., 2026; Dereje et al., 2025). This behavioural lapse directly compromises the sensitive calibration of the fibre-straightening rollers, triggering frequent emergency repairs on the top roll, as consistently noted in the operator logbooks (Belis et al., 2026). Ultimately, this behavioural deviation directly impacts and diminishes the overall mechanical reliability of the entire 24/7 production line.

3.6. Implications for Textile Circularity

The ramifications of these socio-technical imbalances extend to environmental sustainability; every downtime incident forces the massive machinery to stop and undergo a chaotic restart. This unstable mechanical transition phase is the largest contributor to sliver waste generation (Khairunnisa et al., 2023), causing the output to easily exceed the factory's stringent standard tolerance of 0.03%. Although 100% PE material waste is sometimes routed back to the blowing process for internal recycling, this attempt at a circular process demands significant extra energy consumption and risks permanently degrading the tensile strength of the delicate fibre polymer (Rizka et al., 2024; Velzen et al., 2021). Therefore, excessive machine breakdowns triggered primarily by human fatigue factors actively and absolutely distance the manufacturing company from achieving its sustainable, zero-waste manufacturing targets (Garbie & Parsaei, 2025; Tkitek et al., 2024).

4. Conclusion

This study conclusively demonstrates that optimising the production planning and control (PPC) system in the textile spinning industry cannot be executed simply as an isolated theoretical mathematical function. The dramatic and highly volatile efficiency variances observed across different shifts operating the same machinery firmly affirm the core reality of Industry 5.0: socio-technical system imbalances—specifically, the severe absence of technical supervision and the accumulation of operator cognitive fatigue during the night shift—are the primary catalysts for prolonged mechanical downtime. This operational instability simultaneously plummets overall productivity levels and exponentially exacerbates material waste generation ratios, thereby posing a tangible, systemic threat to textile manufacturing circularity targets. Theoretically, this research bridges a significant gap by introducing an integrative STS and BOM approach into traditional machine balancing and capacity determination models. From a practical managerial standpoint, production leaders are strongly recommended to transition away from static models towards dynamic, human-centric scheduling. Essential interventions include implementing adaptive task rotations, ensuring the deployment of dedicated senior supervisors during night shifts to drastically reduce mean time to repair (MTTR), and fostering an environment where technological advancements are matched by workforce readiness.

5. Acknoledgement

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