Received 14 September 2025
Revised 18 January 2026
Accepted 9 February 2026

Integration of industry 4.0 technologies to overcome lean manufacturing barriers in Sri Lanka's apparel sector

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Abstract

Purpose – This study aims to examine how Industry 4.0 (I4.0) technologies can enable Lean Manufacturing (LM) practices in Sri Lanka's apparel industry. Although LM has been widely adopted to improve efficiency and reduce waste, persistent barriers such as frequent product changes, limited real-time visibility and infrastructural constraints have restricted its full potential. The purpose of this research is to explore how advanced digital solutions, including Internet of Things (IoT), real-time analytics and augmented/virtual reality (AR/VR), can address these barriers and enhance the competitiveness and sustainability of apparel manufacturing in a dynamic global market.

Design/methodology/approach – A qualitative single-case study design was used to provide an in-depth understanding of digital–lean integration. The research was conducted in collaboration with a leading Sri Lankan apparel manufacturer. Data were collected through on-site factory observations, semi-structured interviews with managers and employees and examination of company records. Using Yin's (2018) case study methodology as a guiding framework, the study analyzed how selected I4.0 technologies were implemented alongside lean tools and how these interventions addressed identified operational inefficiencies.

Findings – The study found that I4.0-enabled solutions significantly enhanced lean practices by improving production workflow transparency, defect detection and downtime reduction. Tools such as IoT-linked dashboards, electronic Kanban systems and automated performance monitoring minimized non-value-adding activities and reduced bottlenecks. AR/VR applications demonstrated potential for training and machine setup, while predictive maintenance improved equipment reliability. However, the research also identified persistent shortcomings, including data confidentiality issues, workforce adaptability challenges and high capital investment requirements. The findings highlight both the opportunities and practical limitations of integrating digital technologies into lean environments.

Research limitations/implications – The research was limited to a single case study of a large apparel manufacturer in Sri Lanka, which constrains the generalizability of findings. Data confidentiality policies restricted access to detailed financial information, preventing quantitative analysis of productivity gains and return on investment. Future studies could extend this research by including multiple firms across varying scales and geographies, enabling comparative insights. Broader empirical studies that quantify the financial outcomes of digital–lean integration would provide further validation and support for industry-wide adoption.

Declaration of interest statement: The authors report there are no conflicts of interest to declare.

International Journal of Lean Six Sigma
Vol. 17 No. 8, 2026
pp. 80-108
Emerald Publishing Limited
2040-4166
DOI 10.1108/IJLSS-09-2025-0257

Practical implications – For practitioners, the study offers a roadmap for integrating I4.0 technologies with lean practices in apparel manufacturing. The evidence suggests that digital lean tools can enhance transparency, improve workflow efficiency and support more accurate decision-making. Managers should prioritize investments in IoT-enabled monitoring, predictive maintenance and digital visual management systems while addressing workforce readiness through training programs. Attention must also be given to cybersecurity and change management to ensure sustainable implementation. These findings are particularly relevant for resource-constrained firms seeking to maximize operational efficiency while navigating global competitive pressures.

Social implications – The integration of I4.0 and LM in Sri Lanka's apparel sector holds broader social benefits by safeguarding employment in a critical export industry that provides livelihoods for over 300,000 workers. Enhanced productivity and competitiveness contribute to economic stability and foreign exchange earnings. Moreover, digital lean practices can reduce waste, contributing to environmental sustainability and aligning with global sustainable development goals. By strengthening the resilience of the apparel sector, these advancements can help sustain jobs and improve working conditions, particularly in developing country contexts where apparel remains a cornerstone of industrial growth.

Originality/value – This study provides one of the first in-depth examinations of how I4.0 technologies can act as enablers of LM in the Sri Lankan apparel industry. Unlike prior studies that treat lean and digital transformation as separate trajectories, this research highlights their synergies and tradeoffs in practice. By capturing both the benefits and shortcomings of digital lean tools, the paper contributes to theory by extending understanding of lean–I4.0 integration in emerging economy contexts. It also offers practical value by providing industry-specific insights that can inform managers' strategic decisions on digital transformation.

Keywords Sri Lanka, Lean manufacturing, Industry 4.0, Digitalization, Apparel industry

Paper type Case report

Abbreviations

AI = artificial intelligence;
AR = augmented reality;
CPS = cyber-physical systems;
ERP = enterprise resource planning;
I4.0 = industry 4.0;
IE = industrial engineering;
IoT = internet of things;
JIT = just-in-time;
KPI = key performance indicator;
LM = lean manufacturing;
OEE = overall equipment effectiveness;
PLC = programmable logic controllers;
QR = quick response;
RFID = radio frequency identification;
ROI = return on investment;
SAP = system applications and products in data processing;
SMED = single-minute exchange of dies;
TPM = total productive maintenance;
VSM = value stream mapping;
VR = virtual reality; and
WIP = work-in-process.

1. Introduction

Global apparel manufacturers are under pressure to deliver high-quality garments at low cost within shorter lead times (Embuldeniya, 2015). In Sri Lanka, the apparel sector, the country's leading export industry has responded by adopting strategies such as in-house design, seamless garment technology, Six Sigma, enterprise resource planning (ERP) and notably lean manufacturing (LM) (Board of Investment of Sri Lanka, 2024; Fernanado, 2009; Lankanewsweb, 2024; Mindya and Wickramasinghe, 2016). LM is defined as "a systematic approach to identify and eliminate waste through continuous improvement by flowing the product at the demand of the customer" (Feld, 2000; Womack *et al.*, 1990). It aims to deliver value to customers while reducing non-value-added activities (waste) in all processes (e.g. defects, waiting, overproduction) (Liker, 2004; Sadiku *et al.*, 2023). The success of LM hinges on continuous waste identification and elimination to foster a productive workflow (Liker, 2004; Paramawardhani and Amar, 2020; Sadiku *et al.*, 2023)

Despite its proven benefits, Sri Lankan apparel firms face specific barriers in practicing LM. Frequent changes in product styles, order sizes and machinery needs can render traditional lean methods less effective (Gamage *et al.*, 2012; George *et al.*, 2022). Wasteful practices may remain hidden in complex production processes, and conventional improvement methods often fall short in addressing these issues (Hoellthaler *et al.*, 2018). Prior studies note that many Sri Lankan companies initially implemented lean tools from the automotive context without adapting them to apparel, leading to suboptimal outcomes (Silva *et al.*, 2012).

In contrast, industry leaders who customized LM practices to the apparel context achieved better alignment with operational needs, though even they encountered persistent challenges that limited lean's full potential (Aryarathne and Galahitiyawe, 2020; Gamage *et al.*, 2012). Common barriers include workforce resistance to change, inadequate communication, technological constraints and insufficient investment in new infrastructure (Dias *et al.*, 2022; Kumar *et al.*, 2023; Maware and Parsley, 2022; Singh and Singh, 2023). These barriers have hindered the realization of lean benefits in the apparel sector, indicating a clear research problem: how to overcome entrenched LM barriers in this context.

Industry practitioners and researchers have increasingly looked at Industry 4.0 (I4.0) technologies as potential enablers to address lean implementation gaps (Begum and Sumi, 2024; Costa *et al.*, 2024; Jamari and Fedouaki, 2025; Narula *et al.*, 2022; Saraswat *et al.*, 2024; Sony, 2018). I4.0 encompasses advanced digital technologies such as Internet of Things (IoT), artificial intelligence (AI), cyber-physical systems (CPS), cloud computing, big data analytics, and others that enable real-time data capture, connectivity and automation in manufacturing (Rüßmann *et al.*, 2015). By leveraging these technologies, manufacturers can gain unprecedented visibility into operations, identify waste more effectively and respond faster to process issues, theoretically complementing and enhancing LM practices (AIIEM, 2024; BOSS Editorial, 2021; Pereira and Sachidananda, 2021).

However, bridging the gap between traditional lean tools and digital technologies is not straightforward (Holmemo and Korsen, 2023; Karthikeyan and Jerald, 2025; Sah *et al.*, 2024). Adoption levels vary greatly between firms; some find it relatively easy to implement "digital lean" solutions, while others face significant technical and organizational challenges (Begum and Sumi, 2024; Kassem and Staudacher, 2021; Wiese *et al.*, 2024). Most Sri Lankan apparel manufacturers have yet to fully deploy I4.0 innovations to overcome lean barriers (beyond basic IT/ERP systems), and there is limited knowledge on the shortcomings of digitalization in this context (Gamage, 2020; Lakmali *et al.*, 2020; Nasra and Bandara, 2025; Sachin and Bandara, 2021). This gap motivates the present study.

Research aim and questions: This research aims to identify the major LM barriers faced by a selected Sri Lankan apparel firm and to explore how integration of I4.0 technologies can effectively overcome these barriers. To address this aim, the study focuses on the following research questions:

RQ1. What are the currently digitized lean tools and techniques in the selected apparel firm?

RQ2. What are the major lean barriers in Sri Lanka's apparel industry (as exemplified by the case firm)?

RQ3. How can I4.0 technologies support the elimination of the identified lean barriers in the selected firm?

RQ4. What are the barriers and shortcomings encountered when digitalizing lean tools?

By investigating how advanced digital technologies can be used to address lean barriers in a leading apparel manufacturer, this study offers insights for both industry and academia on merging lean practices with I4.0. The findings are expected to inform practitioners in the apparel sector and other industries on strategies to sustain competitiveness through "Lean 4.0," the synergy of lean and digitalization.

The subsequent sections of this paper are organized as follows: Section 2 introduces the relevance and key concepts of LM and I4.0. Section 3 outlines the research methodology, while Section 4 presents the findings, and Section 5 offers a comprehensive discussion. Section 6 provides the conclusion, contributions, discusses limitations and suggests directions for future research.

2. Literature review

2.1 Lean manufacturing and its challenges

"Lean Manufacturing" emerged from the Toyota Production System and gained global prominence as a philosophy of continuous improvement focused on waste elimination (muda), value enhancement and flow efficiency (Skhmot, 2017). Lean thinking is underpinned by principles such as specifying value, mapping value streams, ensuring continuous flow, establishing pull production, striving for perfection and respect for people (Bohdan, 2011; Liker, 2004; Womack and Jones, 1996). Over the decades, a toolbox of lean techniques (5S, Kanban, Just-in-Time, Kaizen, Value Stream Mapping (VSM), etc.) has been developed to operationalize these principles (Silva *et al.*, 2011; Silva *et al.*, 2012). When implemented properly, LM can yield more efficient and profitable manufacturing systems by eliminating both obvious and hidden wastes (e.g. overproduction, waiting, defects, excess inventory) (Black, 1999). However, successful lean implementation requires significant management commitment, employee involvement, and often cultural change, without which companies risk poor results or even failure (Cendrowski and Martin, 2012; Silva *et al.*, 2011).

In the apparel industry, lean practices have been adopted to improve productivity and quality, but contextual barriers often impede their success (Silva *et al.*, 2011). Sri Lanka's apparel sector, which has been the country's top export earner since the late 20th century (Gamage *et al.*, 2012; Kelegama and Wijayasiri, 2004), operates in a high-mix, rapidly changing environment that tests the adaptability of lean systems. Many apparel manufacturers initially tried to apply Toyota's standard lean tools "out of the box" and found limited success due to differences in product nature and workforce dynamics. As noted, companies that did not tailor lean methods to the apparel context often saw employees revert to old routines ("backsliding") and failed to sustain improvements (Silva *et al.*, 2012). In Sri Lanka, leading firms like MAS Holdings and Hirdaramani Group adopted more customized lean approaches aligned to apparel production, yielding better results, yet even these firms experienced barriers that constrained full lean benefits (Kumarasiri and Gunarathne, 2017).

Lean implementation barriers documented in prior research include both organizational and technical issues. Table 1 summarizes key barriers identified in the literature for manufacturing (including apparel) and their implications:

These barriers highlight that implementing lean is not merely a matter of introducing tools but requires addressing deep-rooted organizational practices, employee mindsets and system capabilities. In Sri Lanka's apparel sector, such challenges are compounded by the need to handle diverse styles, fluctuating orders and strict global buyer requirements (Gamage *et al.*, 2012). Innovative solutions are needed to overcome these constraints and sustain lean performance.

2.2 Industry 4.0 and digital lean integration

I4.0, often termed the "fourth industrial revolution," was initiated in Germany in 2011 as a strategy to digitize manufacturing (Bartodziej, 2017). I4.0 envisions smart factories where physical production systems are integrated with digital technologies to enable autonomous, adaptive operations. Core I4.0 technologies include: IoT – networks of sensors and devices that collect and exchange data; big data analytics and AI – for real-time decision support; CPS – linking physical machinery with computational control; cloud computing – enabling ubiquitous data access; autonomous robots and automation; simulation and digital twins; horizontal and vertical system integration across the supply chain; additive manufacturing (3D printing); and augmented reality (AR) for enhanced human-machine interaction (Rüßmann *et al.*, 2015).

Together, these technologies drive increased automation, self-optimization of processes, predictive capabilities and enhanced flexibility and efficiency in production (Cortina, 2022; Gobble, 2018). In essence, I4.0 allows organizations to track operations and assets in real time through sensors and interconnected systems, yielding smarter and more responsive production environments (Roblek *et al.*, 2016).

Early discourse on I4.0 sometimes raised the question of whether digital automation would make lean methods obsolete. However, emerging research emphasizes the synergy between I4.0 and lean rather than a conflict (Sanders *et al.*, 2017; Tissir *et al.*, 2020). Lean's own history includes Jidoka, or automation with a human touch, as introduced by Taiichi Ohno, indicating that automation can complement lean principles if implemented properly (Valamede and Akkari, 2021). In the 1990s, concepts of Lean Automation (the integration of new technologies into lean practices) gained traction, and the advent of I4.0 has strengthened this trend (Rossini *et al.*, 2019). Traditional lean automation efforts, however, often lacked the flexibility and connectivity that modern I4.0 systems provide (Tortorella and Fettermann, 2018). The key is alignment: new technologies must be applied in ways that reinforce lean principles (such as waste elimination, continuous flow, pull systems) rather than introducing complexity for its own sake (Buer *et al.*, 2018; Ghobakhloo, 2020).

Recent studies suggest that I4.0 technologies can enhance and stabilize lean practices, making them more effective and sustainable. For example, Sanders *et al.* (2017) argue that lean principles will become even more essential for successful I4.0 implementation – most lean tools stand to benefit from I4.0 integration, creating a symbiotic relationship. Empirical evidence is also emerging, firms that combine lean methods with I4.0 innovations report significantly greater performance improvements than those implementing either alone. One analysis by Daniel Küpper *et al.* (2017) found that while applying lean or I4.0 individually can yield approx.15% cost reductions, integrating both approaches can lead to up to 40% cost reduction – a substantially higher impact. Such results highlight that a coordinated Lean-I4.0 strategy can amplify operational gains by leveraging the strengths of each.

Table 1. Lean barriers

Lean barrier	Implications
Resistance to change	Employees and middle managers may be reluctant to embrace new lean practices, reverting to conventional methods due to inadequate training or fear of job loss. This "backsliding" undermines lean initiatives and is frequently observed in Sri Lankan apparel plants (Silva *et al.*, 2011)
Poor communication and information flow	Ineffective communication with suppliers and within the organization is a major barrier, leading to misaligned supply deliveries and internal coordination breakdowns. Irregular or unclear communication makes it hard to maintain just-in-time flows (Jadhav *et al.*, 2014)
Slow responsiveness to market changes	LM practices must adapt to market changes. Sudden fluctuations in product mix, design and customer demand pose challenges, compromising the benefits of lean unless a well-designed structure supports these changes (Jadhav *et al.*, 2014)
Quality and tracking of supplied materials	Vendors play a crucial role in the lean process, and the quality of materials supplied is paramount. Ensuring the quality of these materials through rigorous checks is essential (Jadhav *et al.*, 2014)
Failures in logistic support	Effective lean implementation requires robust logistical support. Poor transportation logistics can lead to significant struggles in maintaining a synchronized lean structure (Jadhav *et al.*, 2014)
Inflexible legacy processes and layouts	Factories with outdated machinery and suboptimal layouts struggle to implement lean, as poor layout causes excessive material movement, high work-in-process (WIP) and underutilized equipment. Lacking modernized machines or adaptable processes limits lean improvements (Jadhav *et al.*, 2014)
Limited technological infrastructure	Traditional lean relies on manual data and human effort; without supporting digital infrastructure, firms find it hard to monitor processes in real time or sustain improvements. High investment costs for new technologies deter especially small and medium enterprises from upgrading, contributing to lean failures (Zhang *et al.*, 2017)
Lack of lean knowledge and methodology	Some firms embark on "lean journeys" without sufficient expertise or a clear methodology, resulting in partial implementations and confusion. Inadequate training and organizational structure to support lean can derail the effort (Silva *et al.*, 2011)
Cultural issues and short-term focus	Shifting a traditional production culture to a lean mindset is challenging. Without top management vision and a long-term commitment, lean initiatives may be abandoned when immediate results are not seen. In addition, customer-driven design changes and market fluctuations can disrupt lean processes, requiring agile adjustments that not all firms manage well (Zhang *et al.*, 2017)

(*continued*)

Table 1. Continued

Lean barrier	Implications
Adopting primary and basic lean concepts	Applying Toyota's lean philosophy directly to the apparel sector without adaptation is a significant barrier. Companies that attempt to mimic Toyota's structure often fail due to miscommunication and misapplication (Zhang *et al.*, 2017)
Company cultural issues	LM requires a shift from traditional manufacturing cultures. Companies that fail to modernize their culture face significant barriers in lean implementation (Zhang *et al.*, 2017)
Customer pressure and specific design changes	Expanding customer requirements and design changes pose barriers. Sudden changes in design and production during lean implementation can be particularly challenging (Zhang *et al.*, 2017)
Conflicts in Cross-Functional teams	Cross-functional teams, essential in modern apparel production, can become a barrier if communication gaps exist. Effective concurrent engineering requires seamless communication among team members (Jadhav *et al.*, 2014)
Lack of control in machine breakdowns and inventory management	Machine breakdowns and poor inventory control are critical issues. Continuous identification and management of these problems are essential for successful lean implementation (Sanders *et al.*, 2016)
Insufficient investment costs	Lean implementation demands significant investment in employee training, technology upgrades and business process improvements. Inadequate funding, both internal and external, can impede successful lean practice (Zhang *et al.*, 2017)

Source(s): Authors developed based on literature

2.2.1 I4.0 as an enabler for specific lean goals. Literature identifies multiple domains where I4.0 directly supports lean objectives. For instance, lean production highly values strong supplier relationships and just-in-time (JIT) delivery (R.Schmidt *et al.*, 2015). Here, I4.0 can help by improving information sharing and logistics coordination: IoT-based tracking and cloud platforms facilitate real-time monitoring of shipments and inventory, reducing delays and mismatches in the supply chain. In fact, IoT-enabled logistics can tag and trace materials from dispatch to delivery, enhancing JIT reliability (Caballero-Gil *et al.*, 2013; Bose and Pal, 2005).

Similarly, big data analytics allows manufacturers to incorporate customer feedback and demand trends rapidly into production planning, addressing the lean challenge of responding to changing customer requirements (Sanders *et al.*, 2016). Advanced simulation and VR (virtual reality) can be used to optimize factory layouts and line balancing in a virtual environment, identifying waste (e.g. unnecessary movement or imbalanced workloads) before physical changes are made (Gong *et al.*, 2019; Hovanec *et al.*, 2023). AR and VR technologies also offer new ways to train employees and transfer knowledge, potentially overcoming skill gaps and resistance by making training more interactive and efficient (Adhershini *et al.*, 2024; Li *et al.*, 2025).

In addition, predictive maintenance systems equipped with sensors and machine learning can anticipate equipment failures, thereby supporting lean's goal of zero downtime by fixing issues before breakdowns occur (Daniel Küpper *et al.*, 2017). These examples illustrate that I4.0 provides tools to tackle many traditional lean pain points – from supply chain coordination and quality control to equipment reliability and workforce development.

In summary, the convergence of I4.0 and lean (sometimes termed "Lean 4.0") is increasingly seen as the next stage in operations management evolution. Lean provides a proven conceptual framework for efficiency, while I4.0 contributes the technological means to achieve real-time, data-driven continuous improvement. This study builds on this theoretical foundation, examining how such integration plays out in practice within a Sri Lankan apparel manufacturing case. The next section details the methodology for the case study.

3. Methodology

3.1 Research design and case selection

This research uses a qualitative case study methodology to deeply explore the integration of I4.0 technologies with LM in its real-life context. A single-case study design was chosen to allow an in-depth, nuanced understanding of the phenomenon, as opposed to a broader survey of multiple cases (Coombs, 2022; Hunziker and Blankenagel, 2024; Yin, 2017). The selected case is a leading Sri Lankan apparel manufacturer (hereafter "the case company") that has partially adopted I4.0 solutions and was willing to participate in detailed research. Focusing on one revelatory case enables capturing industry-specific nuances and contextual factors that might be overlooked in a multi-case or quantitative study.

The case company has a strong global presence in the apparel value chain and specializes in high-quality garment production. It employs several thousand workers and has been a pioneer in implementing lean methods in Sri Lanka's apparel sector. This firm was identified as an ideal case because it has begun integrating digital technologies into its lean practices, providing a unique opportunity to study how I4.0 can help overcome lean barriers in a developing country context. To comply with research ethics and confidentiality requirements, the company's name is withheld (no formal consent was obtained to disclose it). Instead, contextual information is provided in aggregate – the insights can thus be generalized without revealing proprietary details.

3.2 Data collection

Data were collected using a qualitative case study approach with multiple sources of evidence to enable triangulation and enhance methodological rigor. The primary data collection methods comprised on-site observations and semi-structured interviews, supplemented by a comprehensive review of academic literature:

- *Literature review*: A review of academic literature was conducted at the outset to establish the theoretical foundation of the study and to frame the study and inform data collection instruments. Peer-reviewed publications indexed in databases like Scopus, Web of Science and IEEE Xplore (covering the period 1988–2024) were analyzed to understand known LM barriers and potential I4.0 solutions. Keywords included "Industry 4.0," "Lean Manufacturing," "Apparel Industry," "Lean Barriers" and "Digitalization." Insights from the literature (as summarized in the previous section) helped formulate the interview guide and identify specific aspects to observe at the case site.
- *Factory Observations*: Researchers conducted multiple factory visits at the case company to directly observe operational processes on the production floor. These non-participant observations focused on identifying instances of waste (e.g. bottlenecks, idle time, excess inventory) and noting any digital tools or systems in use. The observers paid particular

attention to how traditional lean practices (such as Kanban, Andon signals and 5S) were being applied, and whether/where digital technology was incorporated. Field notes and photographs were used to document findings systematically, ensuring reliability through consistent observation protocols. Observation provided contextual understanding of the workflow and helped validate or cross-check information from interviews.

- *Semistructured interviews*: In-depth interviews were conducted with ten key stakeholders at the case company. Using purposive sampling, we selected participants who had rich knowledge of the firm's lean initiatives and digital adoption. The selection was guided by predefined criteria: (i) direct involvement in lean implementation and digital system deployment, (ii) functional responsibility for production, operations, logistics, engineering or information systems, and (iii) practical knowledge of operational challenges and improvement initiatives. The interviewees included senior managers (overseeing production and operations), industrial engineers, IT specialists involved in automation and production supervisors on the shop floor. These individuals together represented a cross-functional perspective on both managerial and technical challenges. Interviews were carried out on-site in a semi-structured format, following an interview guide but allowing respondents to freely elaborate on relevant issues. Interviews were conducted until thematic saturation was achieved, with no significant new themes emerging beyond the tenth interview. Key topics covered were: current lean practices and tools in use; pain points and barriers encountered in lean implementation; extent and examples of I4.0/digital tools deployed; perceived impacts of these tools on operations; and challenges or concerns with adopting digital solutions.

All interviews were conducted in English (the business language of the firm), audio-recorded with consent and transcribed *verbatim* for analysis. Each interview lasted approximately 45–60 min. The semi-structured format ensured that core questions were addressed while giving flexibility to probe interesting points raised by participants.

Multiple data sources and stakeholder perspectives were thus obtained. Importantly, to address confidentiality constraints, no identifiable company data (such as financial figures or proprietary product details) were collected or disclosed, in accordance with the company's policies. Any sensitive information encountered (for example, internal process metrics) was used only to derive general patterns and interview insights without attribution. Findings are therefore presented at the level of process behavior and mechanism explanation, consistent with qualitative case study research objectives.

3.3 Data analysis

The qualitative data from observations and interview transcripts were analyzed using thematic analysis. An inductive coding approach was used: the researchers read through transcripts and field notes multiple times and iteratively developed a coding scheme based on recurring ideas and themes emerging from the data. Initial codes (e.g. "machine downtime issue," "inventory tracking system," "resistance to new system," "data accuracy concerns") were gradually grouped into higher-level categories aligned with the research questions. For instance, codes related to production inefficiencies, communication gaps, or cultural pushback were grouped under "lean barriers," while codes on IoT systems, dashboards or automation were grouped under "I4.0 solutions." This process yielded a set of prominent themes. In particular, inefficient workflows, resistance to change among staff, and limitations in digital infrastructure emerged as key themes describing the lean barriers at the case company. Correspondingly, themes around the role of I4.0 solutions, such as real-time data monitoring to improve workflows, or digital training tools to address resistance, also became evident.

After coding, patterns were analyzed to understand relationships between themes. For example, we examined how specific I4.0 implementations corresponded to particular lean problems (linking to RQ3). We also noted any themes representing shortcomings or new issues introduced by digitalization (addressing RQ4). The analysis was primarily qualitative and descriptive, but it incorporated some simple counts (e.g. number of interviewees mentioning a certain challenge) to gauge the prevalence of issues.

To enhance credibility and validity, we applied data triangulation. Findings from interviews were cross-checked against observations and even against published literature. For instance, if a manager claimed a certain benefit from an IoT system, we looked for evidence of that benefit in the observed production metrics or reports, and also considered whether similar claims appear in the literature. We also triangulated between interviewees: points raised by one participant were corroborated or elaborated by others, ensuring that conclusions did not rely on any single informant's opinion. This multi-source confirmation strengthens the reliability of the results, as consistent patterns emerging from different angles indicate robustness. In addition, interim findings were discussed among the research team (which included academic supervisors familiar with case study methods) to minimize individual bias in interpretation.

3.4 Ethical considerations

The study was conducted under the oversight of relevant institutional review boards. All participants provided informed consent after being briefed on the study's purpose and their rights (voluntary participation, anonymity and confidentiality). Interview recordings and transcripts were securely stored with access limited to the research team. As noted, the case company's identity remains confidential; only aggregated or anonymized information is reported to protect the organization's privacy. These measures ensured compliance with research ethics and built trust with participants, leading to candid discussions, especially on sensitive topics like internal shortcomings.

4. Findings

4.1 Digitalized lean practices in the case company

The case company has a long history with lean manufacturing and, in the past few years, has invested in digital technologies to enhance its lean initiatives. The study found that several core lean practices had been partially digitized at the case company, integrating I4.0 components into traditional lean tools. Below, we describe the key digitalized lean solutions in place and how they contribute to waste reduction and efficiency improvements:

4.1.1 Continuous flow via custom enterprise resource planning (system applications and products) system. To support the continuous flow of materials and information, the company developed a customized System Applications and Products (SAP) enterprise resource planning system as its primary IT platform for production. This ERP system is integrated across all departments, as well as with external suppliers and customers, enabling end-to-end tracking from raw materials in the warehouse to finished goods in distribution. By centralizing data and using IoT connectivity, the SAP system provides real-time visibility into inventory levels, production status, and order information. For example, a manager can instantly see the status of fabric supplies or work-in-progress at any sewing line. This significantly reduces the waste of waiting and overproduction: materials are pulled based on actual demand signals, and any delays or shortages are flagged early.

In addition, the system's integration ensures that information silos are eliminated. Previously, communication gaps between production and procurement led to overstock or stockouts, but now the ERP's live data helps maintain just-in-time flows. The SAP system operates on the company's secure servers with strict cybersecurity controls (no external data extraction is allowed), addressing confidentiality concerns while leveraging IoT data streams. This digital backbone exemplifies how I4.0 technology (enterprise integration and IoT) facilitates lean continuous flow and pull production, minimizing inventory waste and improving information sharing across the value stream.

4.1.2 Machine maintenance and real-time production monitoring (digital Andon system). The case company has transformed its traditional Andon system into a digital, real-time monitoring network. Each of the 20 production modules on the factory floor is equipped with an Andon board that displays the module's current operating status using a color-coded "traffic light" scheme. A green light indicates normal operations with zero defects, a yellow signal that a defect or problem has been detected, and red means the line has stopped due to a significant issue. These Andon lights are IoT-connected: whenever a machine in the module encounters a problem (e.g. a malfunction or quality defect), the system automatically triggers the yellow or red alert and sends a notification to maintenance technicians' devices. This has dramatically reduced response time for machine repairs – maintenance staff no longer wait to be told of an issue; they are alerted in real time, which cuts down unplanned downtime.

Moreover, the company installed programmable logic controllers (PLC boxes) on each sewing machine to capture operational data continuously. These controllers log metrics such as machine run time, idle time and stoppages and feed the data into a centralized database via wireless routers on each machine. The aggregated data is visualized on digital Andon display boards at each module, which show real-time production metrics like current output, efficiency and downtime for every machine and operator in that section. The displays use intuitive charts and the same universal color cues (green/yellow/red) to indicate performance status. This real-time production monitoring motivates operators (they can immediately see if they are meeting targets or if a defect was logged) and enables supervisors and managers to make quick decisions to resolve issues.

For example, if one module's efficiency drops, a supervisor can spot it on the dashboard and investigate or reallocate resources promptly. Lean principles of Jidoka (detecting defects immediately) and Andon (calling attention to problems) are thus significantly strengthened by digital technology: problems are not only made visible instantly but also recorded for analysis. Over time, the maintenance logs have allowed engineering teams to analyze patterns of machine failures. For instance, identifying a particular sewing machine model that frequently breaks down and proactively scheduling its replacement or overhaul. The digital Andon system exemplifies eliminating the waste of equipment downtime and defects through I4.0-enabled quick feedback loops and data-driven maintenance.

4.1.3 Inventory and bin management with E-Kanban. Inventory control and internal logistics were traditionally managed by Kanban cards in the case company. Each sewing line would accumulate finished garments in bins, and when a bin was full or a certain color card was sent, downstream processes would be triggered to move materials. This manual system was prone to delays and sometimes caused excess work-in-progress. To improve this, the company introduced an Electronic Kanban (E-Kanban) system and simple automation for bin management. All finished goods bins and material containers are now tagged with barcodes or QR (Quick Response) codes, and every department has a digital Kanban dashboard (displayed on monitors) to track the status of each bin in real time.

Under the E-Kanban system, material movement and replenishment are triggered exclusively by real-time consumption events, thereby strengthening the realization of pull flow. When a bin of finished goods is filled at the end of a line, an operator scans the bin's QR code with a handheld device, which automatically updates the central dashboard, indicating that the bin is ready for pickup. The system then signals the material handling team (or the next department) that this line has output ready and may require an empty bin or the next batch of inputs. Similarly, for raw material supply, the E-Kanban boards show consumption rates of materials by style and issue alerts when replenishment is needed, following the pull system. This digital pull system has reduced the waste of excess inventory and waiting: material handlers no longer make rounds checking each line needlessly; they only intervene when the system shows a need, and production lines are less likely to starve or overflow because the signaling is timely and accurate.

In addition to reinforcing pull flow, the E-Kanban system extended Jidoka from machine-level control to logistics and information flows. The digital dashboards continuously record time stamps for bin completion, pickup and replenishment, automatically highlighting abnormalities such as prolonged bin waiting times or delayed material supply. These deviations are made visible to supervisors in real time, enabling timely human intervention before disruptions propagate to subsequent processes. While no autonomous stoppage was implemented, this form of information-based Jidoka enhanced process transparency and early problem detection beyond what was feasible with manual Kanban cards.

Operational records and managerial interviews indicated a noticeable reduction in excess work-in-progress and waiting time within internal logistics, primarily due to improved synchronization between sewing lines and material handling. One manager noted that previously, a lot of time was wasted with workers walking around to find out which lines had finished their bins or needed more materials. Now the centralized E-Kanban dashboard "gives a simple, at-a-glance view of what every line needs, almost like an airport flight board for our production" (Manager interview). This has improved internal logistics efficiency and helped maintain just-in-time flow by aligning production rate with material supply and removal. It also aids in identifying bottlenecks: the system records the time between one bin being filled and the next, flagging if a particular department is not keeping up (indicating a possible imbalance or problem to address). Although this study does not statistically quantify inventory reduction or defect escape rates across the supply chain due to confidentiality, the findings demonstrate how E-Kanban functionally strengthens pull flow and Jidoka principles through digitalization, contributing to more responsive and controlled lean operations.

4.1.4 Overall equipment effectiveness digital dashboard. In line with lean's focus on eliminating downtime and improving equipment utilization, the case company implemented a real-time Overall Equipment Effectiveness (OEE) monitoring system. Overall Equipment Effectiveness is a lean metric combining availability, performance and quality to indicate how effectively a machine or line is operating. The digital OEE system in the factory captures all downtime events, speed losses, and quality losses through the machine-mounted sensors and operator inputs. A centralized OEE dashboard displays the live status of every machine across the floor, with color codes similar to the Andon system for easy recognition.

For example, if a machine is down, it flashes red on the OEE board with a timestamp and an error code or short description of the issue (mechanical fault, material stockout, etc.). Each department is responsible for logging the cause of any downtime via a tablet interface; they select standardized reason codes when a stoppage occurs (e.g. "mechanical failure – replace needle" or "no raw material – waiting for fabric"). The system timestamps and records these incidents in a database. This wealth of data is analyzed daily and weekly to identify recurring issues and their root causes. For instance, analysis might reveal that a particular module experiences frequent short stoppages due to thread breaks – signaling a need to improve thread quality or machine tuning.

By systematically capturing downtime, the company can target the biggest contributors to lost productivity, aligning with lean's continuous improvement (Kaizen) philosophy. Since implementation, managers report a noticeable improvement: "When we started measuring OEE digitally, our true downtime was higher than we thought. It was a wake-up call. But now we have cut it down by about 20% by tackling the top issues" (Engineering manager interview). The OEE dashboard thus functions both as a visual management tool to make problems immediately visible and as a data source for Kaizen teams to prioritize improvement projects.

4.1.5 Shop-floor production management and skill matrix systems. Another digital initiative is the introduction of shop-floor management displays at each sewing module, which overlap with the Andon/OEE systems but focus on operator performance and quality metrics. These displays (sometimes called digital production boards) show real-time output against targets, efficiency percentages per operator and defect rates for the module. They draw data from the same machine control boxes and operator tablet inputs described earlier.

The purpose is to engage workers in meeting their goals. For example, an operator can see their hourly output and efficiency, which encourages them to achieve the set target (a form of immediate feedback and motivation). It also fosters a bit of friendly competition or teamwork, as the module's team can collectively monitor if they are lagging behind the expected pace. Importantly, defect tracking is integrated: if a defect is detected (either automatically by a sensor or manually input by a quality checker), it is registered so that the efficiency calculation accounts for only good products. One challenge in digitalizing lean was ensuring that defects are accurately captured; the company found that automated sensors might not catch every minor flaw, so they allow manual defect entries to override the system when needed.

Over time, the system compiles defect data into "measles charts" (visual maps of where defects occur on the garment), helping quality engineers focus on trouble spots in the process (as one interviewee noted, they identified that most defects were occurring on a particular seam operation, so they retrained those operators). In essence, these shop-floor dashboards and connected quality tracking help sustain lean visual management and rapid problem identification, ensuring issues are not hidden.

The company has also begun digitalizing aspects of its human resources and skills management in line with lean principles of workforce optimization. A digital skill matrix records each worker's skill level on various operations, and tablet-based interfaces allow supervisors to update training progress and allocate workers to tasks that match their skill profile. Previously, such skill matrices were large charts on office walls, updated infrequently. Now, the digital system can quickly identify, for example, which sewing operators are capable of handling a new style or who needs further training on a machine. This reduces the waste of misallocated labor and unnecessary training: employees can be assigned optimally, and performance evaluations are data-driven.

One innovation the case company implemented is using a networked system for employee feedback and work allocation: each worker has an account on the company's internal network accessible via a touchscreen kiosk or tablet. Management can push out daily work plans or training modules, and workers can input suggestions or concerns, which are routed to the relevant department. This acts like a digital Kaizen suggestion system. According to the industrial engineering manager, "Operators regularly submit small improvement ideas through the tablet now. It's easier than filling a form, and we've been able to implement a number of their ideas, which keeps them engaged." In lean terms, this addresses the often-cited barrier of lack of employee involvement by using digital tools to facilitate bottom-up communication.

4.1.6 Emerging technologies augmented reality/virtual reality – pilot initiatives. While not fully deployed, the case company has experimented with augmented reality/virtual reality

(AR/VR) technologies in certain areas. For example, they ran a pilot using AR glasses for machine setup and changeover training. When switching a sewing line to a new product, historically, an expert would physically guide technicians on the adjustments needed (a time-consuming process). In the pilot, technicians wore AR glasses that overlaid step-by-step setup instructions and checkpoints onto their field of view, guided remotely by an expert. This trial demonstrated that AR could reduce changeover time and errors, aligning with lean's SMED (Single-Minute Exchange of Dies) goals.

Similarly, the firm has collaborated with a technology partner to explore VR for factory layout planning and operator training. Using a VR model of the shop floor, engineers virtually tested several layout changes for a new product line, identifying potential bottlenecks before actually rearranging machines. This helped avoid the waste of physical trial-and-error in layout design. In addition, VR simulation has been used to train new operators in a risk-free environment.

For example, a VR module simulates the experience of operating a sewing machine or a cutting machine, allowing trainees to practice basic motions and troubleshooting without impacting real production. While these AR/VR applications are still in early stages, they illustrate the company's forward-looking approach to I4.0. The expectation is that such technologies can further tackle lean barriers like long training times, setup delays and layout inefficiencies. However, managers acknowledge that these require significant investment and change management to implement at scale, which is a consideration discussed later.

Overall, the case company's adoption of digital tools has been incremental but impactful. Each digitalized lean practice described above maps to a specific lean objective: ERP for continuous flow and pull, Andon/monitoring systems for zero defects and downtime, E-Kanban for just-in-time and inventory minimization, OEE dashboards for maximizing equipment utilization, and digital skill management for workforce flexibility. Table 2 provides a summary mapping of which lean wastes/barriers are addressed by these I4.0-integrated solutions.

Through these implementations, the case company has achieved notable improvements. Production managers reported a 20–30% reduction in average line downtime and a moderate boost in labor productivity after the digital tools were introduced, attributing it to faster responses and better information. Inventory levels (measured as days of stock) have also been cut, thanks to the E-Kanban and ERP integration that enable more precise just-in-time delivery. Furthermore, the workforce displays greater ownership of processes, as evidenced by increased suggestion submissions and higher adherence to standard work (possibly because the digital systems make any deviation or slowdown immediately visible). These outcomes illustrate the practical benefits of aligning I4.0 with lean in a real factory setting.

4.2 Lean barriers identified and challenges in digitalizing lean

Despite the progress made, the study also uncovered several barriers and shortcomings that either persisted in the lean implementation or arose as new challenges from digitalization. Not all lean wastes have been eliminated, and the introduction of advanced tech has its own constraints. The major issues identified include:

- *Data connectivity and system dependence:* The heavy reliance on digital systems means that any network downtime or IT failure can disrupt production. Interviewees highlighted instances of network outages causing machine stoppages. Certain machines are programmed to operate only when connected to the central server, so a server crash immediately halts those machines. For example, an IoT-enabled sewing line went down for an hour when the factory's Wi-Fi network briefly dropped, because the real-time tracking system froze and machines defaulted to "pause" for data safety.

  This exposed a new vulnerability: while lean aims to make processes robust, digital dependence introduced a single point of failure (the network

Table 2. Lean waste/barriers addressed by I4.0 technologies in the case company

Lean waste/barrier	I4.0-Enabled Solution	Effect on waste reduction
Waiting/delays (e.g. for materials or maintenance)	– IoT-integrated SAP ERP (real-time inventory visibility) – Digital Andon alerts (instant maintenance notification) – E-Kanban dashboard (signals when action is needed)	Reduces waiting time for material supply and machine repair by prompting immediate responses. Ensures smooth flow without idle gaps
Excess inventory/ WIP	– SAP ERP and E-Kanban (JIT pull system with live tracking)	Prevents overproduction and excess stock by aligning production with demand; inventory is only delivered as needed
Defects/quality issues	– Digital Andon and quality sensors (immediate defect detection) – Data analytics (defect trend analysis, measles charts)	Catches defects in real time so they are fixed or removed early. Allows targeted quality improvements by analyzing defect patterns
Machine downtime	– Andon system with alerts – OEE monitoring and predictive maintenance sensors	Minimizes downtime by quickly addressing breakdowns and predicting failures before they occur. Supports higher machine availability
Inefficient motion / labor utilization	– Shop floor dashboards (identify bottleneck operations) – Digital skill matrix and smart task assignment	Exposes where workers/machines are underutilized or overloaded so that workflow can be rebalanced. Ensures the right skills at the right place, reducing unnecessary motions and training
Communication gaps (internal and external)	– Integrated IT system (single source of truth for production data) – Real-time collaboration tools (tablets for feedback, supplier links via cloud)	Enhances transparency and information flow across departments and with suppliers, addressing delays due to miscommunication
Employee resistance to change / lack of engagement	– Digital suggestion system (employees provide input via tablets) – AR/VR training tools (engaging, hands-on learning)	Increases engagement by empowering staff to contribute ideas and by making training more interactive. Builds confidence in new processes, easing change adoption

Source(s): Case study findings and authors’ analysis

infrastructure). The company recognized the need for backup connectivity and offline modes to mitigate this risk. In addition, operators have become so accustomed to the digital dashboards that when the screens went blank, work visibly slowed because the usual signals and prompts were absent, highlighting a human reliance on digital aids that could be problematic if those aids fail. Robust IT support and redundancy plans (fail-safe mechanisms) are thus essential to maintain continuous lean operations in a digital environment.

- *High implementation and maintenance costs:* Deploying I4.0 tools requires substantial capital investment, which was identified as a barrier, especially for smaller firms. In the case company, top management justified the expenditures by expecting long-term gains, but they stressed the importance of a reasonable return on investment (ROI) period. A senior Industrial Engineering executive noted, “It is vital that there will be a return on investment in a short period of time to make sure the development doesn’t go to waste.”

The firm faced decisions like purchasing RFID (Radio Frequency Identification) readers for tracking or AR devices for training. These technologies are expensive, and without a clear short-term payoff, it's hard to justify the cost. While large companies like the case firm can absorb initial investments, the concern is that smaller apparel manufacturers would struggle to adopt such technologies without external support or proven quick wins. Even for the case company, careful cost-benefit analysis was needed for each digital initiative (e.g. the AR training pilot was limited in scope because equipping the whole factory with AR devices was not yet cost-effective). Thus, the high implementation cost and uncertainty of immediate financial benefits remain significant barriers to widespread digital lean adoption.

- *Workforce adaptability and skill gaps:* Introducing advanced digital systems changes job roles and skill requirements, posing a challenge for the workforce. The case company experienced some resistance to change among employees, particularly older supervisors who were used to manual control and paper reports. As operators increasingly rely on automated systems, their ability to revert to manual methods in case of system failure has diminished. A few veteran line leaders expressed discomfort: "If the tablet doesn't work, the younger staff wait for it instead of using a manual log - they don't know the old ways." This suggests a new kind of waste, the erosion of tacit process knowledge due to over-reliance on digital tools.

  Moreover, implementing digital tools required extensive staff training. The company had to train operators not only on how to use tablets or interpret dashboards, but also on basic digital literacy and cybersecurity (e.g. not sharing passwords, understanding data privacy). This training effort is continuous and adds to the operational workload. Table 3 summarizes these barriers to digital lean implementation as identified in our case (which mirror challenges noted in broader studies).

Despite these challenges, the case company has generally viewed the digitalization of lean as a positive, necessary evolution. They acknowledge that change management is crucial: continuous communication with employees about the benefits of the new systems, involving them in development (some operators were consulted when designing the tablet interfaces, which improved buy-in), and gradually building a digital culture.

One notable finding is that younger employees adapted quickly and even expected modern tools, whereas some long-serving staff were more skeptical, indicating a generational aspect to technology acceptance. Over time, success stories (like reduced overtime due to better planning from the SAP system, or less frustration on the line thanks to quick problem fixes via Andon alerts) have helped convert many skeptics. The company also fostered cross-functional teams (IT, production, IE and quality personnel together) to implement these solutions, reflecting a holistic approach rather than siloed efforts.

In summary, the findings from the case study show that integrating I4.0 technologies into lean manufacturing yielded substantial improvements in addressing classic lean barriers: real-time data and automation helped reduce wastes related to delays, defects and inefficiencies. The case firm's experience demonstrates concrete examples of Lean 4.0 in action (answering *RQ1* and *RQ3*). At the same time, the implementation process uncovered new challenges such as technical dependency, cost and change management issues (addressing *RQ4*). The next section discusses these findings in light of the broader literature and theoretical implications, and how they answer the research questions, including *RQ2* on the nature of lean barriers in this context.

Table 3. Key barriers to digitalization of lean tools in the case company

Barrier	Description of challenge in case context
Data privacy and security	Expanding connectivity raised concerns about sensitive production data leaking or being hacked. The firm had to invest in cybersecurity measures (firewalls, access controls). Even so, managers remain cautious about connecting certain systems to external networks. Protecting data while enabling broad information flow is a delicate balance
High implementation cost	Upfront costs for sensors, devices, and software are high. The case company managed this via phased implementation, but cost remains a barrier to scaling some solutions (like factory-wide AR/VR)
Uncertain ROI period	Management pressure for quick returns means digital tools must show savings or efficiency gains soon after deployment. Some benefits (like cultural change or system resilience) are harder to quantify, making it challenging to justify certain investments to stakeholders
Dependence on connectivity	As noted, slow or unstable internet connectivity (especially in some of the company's more remote facilities) hampers digital tool effectiveness. The main factory has good infrastructure, but backup plans for network outages are needed to avoid halts in production
Additional training needs	The workforce needed new skills to use and maintain digital systems. This involved training sessions and learning curves that temporarily reduced productivity. There's an ongoing need for IT support personnel on the shop floor – a role that didn't exist before – to troubleshoot devices and software for operators

Source(s): Case study findings and authors' analysis

5. Discussion

This single-case study offers valuable insights into how I4.0 can be leveraged to overcome LM barriers in an apparel production context. Here, we discuss the findings related to each research question, linking them to existing literature and drawing out theoretical and practical implications.

RQ1: Digitized lean tools and techniques – The case study identified several lean practices that had been enhanced through digital technologies: customized ERP supporting continuous flow, digital Andon boards for real-time problem signaling, E-Kanban for pull production, OEE and productivity dashboards for equipment and performance monitoring, and digital skill management for human resource optimization. These implementations exemplify the concept of "Digital Lean" or Lean 4.0 in practice. They echo what recent literature describes as the shift from traditional lean visual controls to cyber-physical lean systems. For instance, Kolberg and Zühlke (2015) argue that lean production boards can be replaced or augmented by interconnected digital boards to respond faster to issues. The case company's digital Andon/OEE boards confirm this, showing dramatically faster response and greater transparency than the old manual boards.

In line with Buer *et al.* (2018)'s mapping of lean-I4.0 research, our case illustrates that nearly every traditional lean tool used (Andon, Kanban, VSM, TPM, etc.) has a digital counterpart or support system. The theoretical implication here is that lean's fundamental principles remain intact, but their execution is evolving: I4.0 provides the means (real-time data, connectivity, computation) to reinforce lean principles (waste elimination, JIT, continuous improvement).

This supports the idea of a "symbiotic relationship" between lean and I4.0 technologies. Rather than viewing I4.0 as a new paradigm that replaces lean, the case study aligns with scholars like Sanders *et al.* (2017) who assert that lean is even more crucial in an I4.0 world, because digital tech without lean direction can lead to automating waste. The practical takeaway is that companies should not abandon lean fundamentals when digitizing; instead, they should digitize in service of lean goals. The case company, for example, digitized Kanban to better achieve pull flow and implemented sensors to better achieve Jidoka (autonomation). This reinforces lean theory by demonstrating its adaptability: lean tools are media-flexible, they can shift from analog to digital mediums and, if anything, become more powerful.

RQ2: Major lean barriers in the sri lankan apparel context – The research identified that many barriers documented in general lean literature (resistance to change, communication issues, outdated equipment, etc.) manifest strongly in Sri Lanka's apparel sector, alongside some context-specific nuances. Consistent with Jadhav *et al.* (2014) and Zhang *et al.* (2017), the case confirmed organizational culture and human factors as significant barriers: e.g. backsliding to old habits and lack of lean knowledge among staff made initial lean efforts hard to sustain. In a developing country context like Sri Lanka, such barriers can be exacerbated by lower exposure to modern manufacturing philosophies and a workforce less accustomed to participative improvement programs (a point also noted by Wickramasinghe and Wickramasinghe (2017), and observed in our case, where initial lean training didn't fully stick).

Another major barrier is information flow inefficiency. Our case backed prior findings that poor supplier-manufacturer coordination and internal communication gaps impede lean (as lean's reliance on JIT and quick responses suffers when information is delayed). The case company pre-I4.0 had issues responding to sudden order changes or line stoppages, partly because information traveled slowly up the chain. In addition, limited technology infrastructure in Sri Lankan factories (relative to global leaders) was a barrier: antiquated machines and manual data handling made it hard to achieve fine-tuned lean operations, resonating with Zhang *et al.* (2017)'s identification of technological constraints as lean barriers.

A context-specific insight is the role of Sri Lanka's economic conditions: rising labor costs and intense competition (as Sri Lanka competes with other Asian manufacturers) put pressure on firms to be lean, but also limit available funds for investing in improvements. A kind of barrier where financial constraint meets lean. Embuldeniya (2015) had noted the apparel sector's impact on the economy and the need for efficiency; our study adds that firms feel a tension between needing lean transformation and affording it. Thus, the lean barriers in Sri Lanka's apparel industry are not fundamentally different from those elsewhere, but their impact is heightened by resource constraints and perhaps a late start in lean adoption (lean took hold in Sri Lanka mainly in the 2000s, giving less time to build lean culture). This highlights the importance of targeted interventions – and as our findings suggest, I4.0 can be one such intervention to break through certain barriers.

RQ3: How I4.0 technologies help eliminate lean barriers – One of the most significant contributions of this study is detailing the mapping between specific lean barriers and I4.0 solutions observed in the case. The discussion below systematically links our findings to known barriers and supports them with literature:

- *Barrier*: Lack of real-time information/Poor communication. *I4.0 Solution*: IoT-enabled systems and integrated data platforms. In this case, the custom SAP ERP and digital dashboards ensured that information about production status, inventory and quality was available instantly across the organization. This directly addressed communication gaps. For example, it became far easier to coordinate with suppliers and customers because data was up-to-date and accessible, mitigating the barrier of irregular information flow noted by Jadhav *et al.* (2014). Literature supports this benefit: Brettel *et al.* (2014) discuss how networked, decentralized production (characteristic of I4.0) changes the manufacturing landscape by improving information transparency. Our case confirms that, showing improved supplier-manufacturer synchronization (a lean requirement) via collaborative digital platforms. In lean terms, this helps with JIT and responsiveness (no waiting for a weekly meeting to know a status – it's on the screen). Hence, I4.0 effectively tackles the lean barrier of communication lag.

- *Barrier*: Overproduction and inventory waste. *I4.0 Solution:* Digital pull systems (E-Kanban) and IoT tracking. The case company's E-Kanban and inventory scanning reduced excess WIP and ensured production only when needed, which is lean's ideal. Traditional Kanban cards might be lost or not real-time; the digital version provided a reliable, instantaneous pull signal. This aligns with Rüßmann *et al.* (2015), who noted that IoT and integration enable much tighter inventory control and production synchronization. By tagging items and monitoring them through IoT, the case firm could practice a near-real-time Kanban, thus overcoming the barrier of excess inventory due to a lack of visibility. The result was closer adherence to JIT and reduced warehousing costs, a clear lean gain facilitated by I4.0.
- *Barrier*: Machine downtime/unreliable equipment. *I4.0 Solution*: Predictive maintenance and real-time monitoring. The case's digital Andon and OEE systems dramatically improved response to breakdowns and enabled preventive fixes. This speaks to the classic lean waste of downtime and the barrier of old machines breaking unexpectedly. With sensors predicting failures and maintenance being alerted immediately, the firm addressed what Sanders *et al.* (2016) call the need for Industry 4.0 as an enabler for lean maintenance. Our findings resonate with their claim that I4.0's monitoring and analytic capabilities ensure equipment issues are managed proactively, thus supporting lean TPM (Total Productive Maintenance). In essence, I4.0 helped turn a reactive maintenance culture into a proactive one, overcoming the barrier of inadequate control over machine health.
- *Barrier*: Defects and quality control limitations. *I4.0 Solution*: Sensors, data analytics, and automation in quality inspection. The case introduced automated quality checks (to some degree) and digital defect tracking (measles charts), which helped catch defects earlier and analyze root causes. This directly addresses lean's "quality at the source" goal and barriers where manual inspection might miss issues. The case did find that human judgment still caught some defects that sensors missed, which is an interesting point: it suggests that while I4.0 can enhance quality control (e.g. vision systems to detect flaws), it's not foolproof. However, over time, machine learning can improve these systems. Literature like Mrugalska and Wyrwicka (2017) posits that I4.0 will advance quality management in lean by providing more data and consistency. Our case partially validates that. Defect rates did decrease after implementing digital monitoring, indicating fewer escaped defects thanks to immediate alerts. So I4.0 contributes to overcoming the barrier of quality control limitations, though a hybrid approach (human + tech) was necessary in our scenario.
- *Barrier*: Resistance to change/lack of continuous improvement engagement. *I4.0 Solution:* Digital platforms for employee involvement (e.g. suggestion systems, training via AR/VR). Lean literature (e.g. Liker's Toyota Way) always emphasized respect for people and engagement, and a barrier often seen is employees not participating or fearing change (Liker, 2004). The case company's use of tablets for suggestions and interactive

training tools helped involve workers in the improvement process, addressing skepticism through demonstration of benefits. The data feedback (like seeing your efficiency on a screen) also directly engages employees by making performance visible and somewhat gamified. This approach supports the idea that I4.0 can augment the human element of lean, an argument made by recent studies on the "augmented operator" concept.

AR and VR in training, as our case piloted, are highlighted by authors such as Arica *et al.* (2022) as ways to empower operators for continuous improvement. Our findings suggest that while technology can't change culture alone, it can be a tool to facilitate cultural change: e.g. workers saw that using the Andon tablet to call maintenance got faster results than shouting for a mechanic, which gradually convinced them to embrace the new process. Thus, I4.0 aided in overcoming the barrier of change resistance by providing user-friendly systems that clearly improved daily work (reducing frustration and workload).

Importantly, the case demonstrates that lean and I4.0 act in synergy against these barriers. For example, lean provides a structured approach to problem-solving and waste identification, while I4.0 provides advanced means to solve or mitigate those problems. This synergy is well captured by Tortorella and Fettermann (2018), who found that Brazilian firms implementing both lean and I4.0 achieved better performance than those implementing one or the other. Our case adds qualitative evidence to that: many barriers that had plateaued in the lean-only environment (e.g. they could only reduce downtime so much with manual methods) saw further reduction when digital tools were introduced. It validates the perspective that I4.0 technologies serve as "enablers" or amplifiers of lean. They don't automatically solve problems, but when guided by lean thinking, they can accelerate improvements.

RQ4: Barriers and shortcomings in digitalizing lean - While the integration was largely beneficial, our study also highlights a crucial aspect: the introduction of I4.0 is not without its own challenges. The findings on challenges (network dependence, cost, training needs, etc.) echo and extend the recent literature on digital transformation barriers. For instance, Bajpai and Misra (2022) identify high cost and cybersecurity as top barriers in digitalization initiatives, which matches our case, where cost justification and data security were major concerns. The case highlights that even as I4.0 tackles traditional lean barriers, it brings new barriers; sometimes, a trade-off occurs. We can discuss this paradox: digital tools solved some problems but created new risk points (e.g. if Wi-Fi goes down, production stops, whereas a fully manual system doesn't have that issue - it has others). This finding supports a balanced view often noted in lean/I4.0 debates: one must "lean" the I4.0 implementation itself to avoid waste like over-reliance or complexity (Roy *et al.*, 2015) described the need to not digitize unnecessarily.

From a theoretical perspective, this suggests that change management and capability building are as important as the technologies. The case firm had to invest in workforce training and developing an IT support structure, essentially building a new capability that lean alone didn't require to that extent. This aligns with Ghobakhloo (2020), who noted that organizational readiness and employee skills are determinants of successful smart manufacturing adoption. Our case confirms that without addressing the human and organizational side (through training, involving people in design, etc.), the best technology can falter. It also highlights the continued relevance of lean thinking during digital transformation: for example, when the firm encountered the problem of network outages causing stoppages, they applied root cause analysis (a lean problem-solving tool) to find countermeasures (like installing backup routers and an offline mode in machines). This indicates that the journey to digital lean is iterative and must be continuously improved, true to lean's nature.

In summary, the discussion of *RQ4* leads to a critical insight: lean and I4.0 integration requires a holistic approach. Companies must not only invest in technology but also in workforce competencies, infrastructure reliability and economic feasibility analysis. If any of these are neglected, new forms of "waste" can appear (e.g. wasted investment if ROI doesn't materialize, or downtime waste if systems aren't robust).

5.1 Integration of findings with theory

Overall, our case study reinforces the growing body of literature suggesting that LM and I4.0 are complementary paradigms that, when combined, lead to superior performance (often termed Lean 4.0 or Smart Lean). We observed that lean provided clear problem areas (barriers) to target, and I4.0 provided effective tools to target them. This aligns with the view of Sanders *et al.* (2016) that I4.0 implementations function as enablers for lean manufacturing. In particular, our findings exemplify some of the specific synergies identified in prior research: for instance, Sanders *et al.* (2016) discussed how shop-floor management is changing with digital tools, which we saw directly with digital boards; Schuh *et al.* (2015) described using smart devices for work-based learning, which is mirrored in our case's tablet-based training and feedback system; and Valamede and Akkari (2021) emphasize integration perspectives, which our case showcases by integrating multiple technologies (IoT, cloud, AR) under the lean umbrella.

At the same time, the case contributes nuance to theory by highlighting limitations and contingency factors: for example, the benefit of Lean 4.0 might depend on infrastructure quality (a factory with unstable electricity or internet might struggle to implement I4.0 effectively, a concern in some developing regions) and on scale (larger firms can better absorb costs than smaller ones). It suggests that while Lean 4.0 has high potential, its implementation path may differ in emerging economic contexts, requiring perhaps more incremental adoption and external support or sharing of best practices to reduce cost and risk.

5.2 Practical implications

For practitioners in the apparel industry (and similar manufacturing settings), this study provides a concrete roadmap of what digital lean can look like and what to watch out for. Managers can see that implementing IoT and digital dashboards can directly solve pain points like delays and lack of visibility. However, they should also plan for the challenges: ensure robust IT infrastructure, prepare a clear ROI analysis and phased investment plan, and invest in change management (train and involve employees, address fears). The case company's success in reducing downtime and improving flow using I4.0 could serve as a benchmark for others, particularly in developing countries where such examples are still emerging. While exploratory in nature, the findings provide a structured basis for future empirical research and offer practical guidance for context-sensitive digital lean implementation in labor-intensive manufacturing sectors.

In conclusion to the discussion, the evidence strongly supports the idea that I4.0 and lean, when combined thoughtfully, can overcome many traditional operational barriers. But achieving this requires treating the digital transformation itself as a lean process, iteratively improving, eliminating new wastes and always keeping the end goal (delivering customer value efficiently) in focus. The next section will conclude the paper, acknowledge limitations, and suggest areas for future research to further explore the nexus of lean and I4.0 in manufacturing.

6. Conclusion

This study examined the integration of I4.0 technologies into LM practices through an in-depth case study of a leading apparel manufacturer in Sri Lanka. The research set out to identify the lean implementation barriers faced by the firm and to explore how digital solutions can help overcome these barriers. The findings demonstrate that I4.0 integration can significantly enhance lean initiatives by providing real-time visibility, automation and data-driven decision-making, thereby addressing many of the inefficiencies and wastes that traditional lean tools struggled with.

In the case company, a range of digital lean tools were adopted, including IoT-linked production monitoring (digital Andon boards and OEE dashboards), an electronic Kanban system, a customized ERP platform for end-to-end integration and pilot uses of AR/VR for training and layout planning. These innovations collectively streamlined operations reduced unplanned downtime, improved quality control, and increased workforce productivity and engagement. For example, the digital Andon and maintenance alert system led to faster response times to machine issues, cutting machinery idle time substantially, while the E-Kanban and inventory tracking system optimized internal logistics and eliminated excessive work-in-progress. The smart human resource management tools (like the digital skill matrix and performance tracking) improved the allocation of labor and supported ongoing training and Kaizen activities, contributing to better workforce utilization. The introduction of AR/VR in limited trials showed promise for reducing setup times and enhancing operator training effectiveness, aligning with lean's continuous improvement and SMED principles, though these require further scaling and investment.

Crucially, the study clearly linked specific lean barriers to corresponding I4.0 solutions implemented by the firm. Lean barriers such as communication lags, slow feedback loops, hidden production losses and employee resistance were mitigated by technologies like IoT-based monitoring, data analytics and digital communication platforms. This indicates that, in practice, I4.0 can act as a direct enabler to achieve lean objectives, validating the theoretical synergy proposed by prior researchers. For instance, the lack of real-time information (a barrier to JIT and quick problem resolution) was overcome by the integrated dashboards and IoT alerts, and poor supplier coordination was improved through digital connectivity tools. These outcomes confirm that Lean 4.0 (the integration of lean and I4.0) is not just a buzzword but a viable strategy for manufacturing firms seeking to boost efficiency and responsiveness.

At the same time, the study highlighted that adopting I4.0 in a lean context comes with its own challenges. The case company encountered issues such as the need to ensure data security and system reliability (to avoid new forms of downtime caused by network outages), the high initial costs of digitalization, the pressure to achieve a return on investment, and the necessity of extensive training and change management to bring the workforce up to speed with new systems. These challenges are a reminder that technology is not a silver bullet; organizations must proactively manage the transition to digital lean. The case company addressed some of these by phasing implementations, investing in IT infrastructure and support, and involving employees in the development of digital tools (thereby improving user acceptance). Nonetheless, certain barriers like resource constraints for smaller manufacturers or the risk of over-reliance on technology remain areas that require careful planning and ongoing mitigation.

6.1 Theoretical contributions

This research contributes to the growing literature on lean and I4.0 integration by providing a detailed case narrative from a developing economy context. It reinforces theories that posit lean and I4.0 as complementary (rather than conflicting) and provides empirical evidence that combining them yields superior results in terms of waste reduction and performance improvement. In addition, it adds nuance by documenting the barriers to digital lean – an area less explored in prior studies. Understanding these second-order barriers (like connectivity dependence and skill gaps) is important for refining models of Lean 4.0

implementation. The findings suggest that existing lean change management frameworks (e.g. Kaizen, Kotter's change steps in a lean rollout) may need to be augmented to address digital competencies and infrastructure readiness, potentially expanding lean theory into the domain of digital transformation. This case also broadens the geographical scope of Lean 4.0 research, as most published examples have been from high-income countries; showing success in Sri Lanka indicates the concepts are transferable but must be adapted to local contexts.

6.2 Practical implications

For industrial practitioners and decision-makers, especially in the apparel manufacturing sector, this case study serves as a valuable example of how to practically implement digital technologies to support lean goals. It provides insight into which technologies can be prioritized for common pain points. For instance, using relatively accessible technologies like IoT sensors and data dashboards to gain quick wins in productivity, before moving to more advanced ones like AR/VR. Managers can learn from the case company's experience by ensuring they have a robust IT backbone, securing buy – in across all organizational levels early on, and setting clear metrics to monitor improvements due to digitalization (as the case company did with OEE and other KPIs). Moreover, the study highlights the importance of scalability and cost management: it may be prudent to start with pilot projects (as was done with AR/VR) and build a business case with pilot data before full-scale investment. Perhaps most importantly, the case shows that maintaining a lean mindset is key, even with high-tech tools; the focus was always on eliminating specific wastes and enabling people to solve problems better. Companies embarking on Lean 4.0 transformations should thus train their teams not just in new tech, but in identifying value vs waste, so that they digitize the right processes in the right way.

6.3 Limitations

As a single-case study, the findings are context-specific and may not be universally generalizable. The case company is a relatively large and advanced manufacturer in Sri Lanka; smaller firms or those in different industries might face different constraints or have different results. That said, this research intended to provide depth and insight, not broad statistical generalization. Future research could expand on this by studying multiple cases across the apparel sector or comparing results between industries (e.g. apparel vs automotive in the same country) to see how Lean 4.0 implementation differs. Another limitation is that this study focused qualitatively on implementation and perceived outcomes; it did not include a detailed quantitative before-and-after analysis of performance metrics (due to data confidentiality). Thus, while improvements were noted (like downtime reduction), a more rigorous measurement of performance gains attributable to I4.0 would strengthen the evidence. In addition, the study's timeframe captured a snapshot during/shortly after the implementation of certain technologies. It might not reflect long-term issues that could arise (such as technology obsolescence or evolving workforce dynamics).

6.4 Future research

Building on this work, several avenues are suggested. First, a longitudinal study following the case company (and possibly others) over several years would be valuable to observe the sustained impacts of I4.0 on lean performance and how initial challenges are overcome or whether new challenges emerge. Second, research could delve into the human factors of digital lean more deeply. For example, investigating how worker roles, satisfaction and skills evolve in a Lean 4.0 environment and what training or HR strategies are most effective.

Third, further studies could attempt to quantify the benefits of specific I4.0 interventions on lean metrics (for instance, using a controlled experiment or simulation to estimate how much each technology contributes to waste reduction). Fourth, comparative studies between different countries or regions (developed vs developing economies) could shed light on contextual factors such as infrastructure maturity or labor skill levels that influence Lean 4.0 success.

Importantly, future research should also extend beyond I4.0 by incorporating Industry 5.0 (I5.0) perspectives into the lean digitalization discourse. Recent literature positions I5.0 as a complementary evolution that emphasizes human-centricity, sustainability and resilience alongside technological advancement (Breque *et al.*, 2021; Xu *et al.*, 2021). While I4.0 primarily supports lean objectives through automation, real-time visibility and efficiency gains, I5.0 re-centers the human operator as a key value creator through human–machine collaboration, augmented decision-making, and worker empowerment. These principles strongly align with core lean philosophies such as respect for people and continuous improvement (Longo *et al.*, 2020; Romero *et al.*, 2016). In the context of Sri Lanka's apparel industry, characterized by high labor dependency and sensitivity to workforce engagement, future studies could investigate how I5.0 technologies, including collaborative robotics, human-centric AI and digital ergonomics, help overcome persistent lean barriers such as resistance to change, skills mismatches and social sustainability concerns.

Finally, exploring financial aspects in detail – e.g. developing models to calculate ROI for digital lean investments or to optimize the sequencing of technology adoption – would help businesses plan their I4.0 roadmaps in alignment with lean objectives. Given the rapid advancement of I4.0 technologies, future research might also examine emerging tools (like AI-driven decision systems or blockchain in supply chains) and how they integrate with lean and I5.0 principles to support resilient, inclusive and sustainable manufacturing systems.

In conclusion, this study reaffirms that LM and I4.0 technologies, when synergized, can overcome many traditional barriers in manufacturing systems. The case of Sri Lanka's apparel sector shows that even in a labor-intensive, cost-sensitive environment, digital transformation of lean is both feasible and beneficial. Success lies in carefully aligning technology with lean goals, investing in people and processes alongside hardware and software and continuously improving the integrated system. As global competition and customer demands intensify, such integration will likely become not just an advantage but a necessity for manufacturers seeking operational excellence. The journey to merge lean and digital is challenging, but as evidenced by this case, it holds the key to unlocking new levels of efficiency, quality and responsiveness in the industry.

Funding
This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

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