Towards An Integrated Lean–Digital Fashion Management Framework for Sustainable Performance: A Conceptual Paper

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ABSTRACT

The fashion industry faces persistent operational waste, short product life cycles, demand volatility, fragmented supply networks, and substantial environmental and social pressures. Although lean management and digital technologies have each been examined as improvement pathways, their combined application in fashion remains conceptually fragmented. This paper develops an integrated Lean–Digital Fashion Management Framework explaining how lean practices and digital fashion capabilities can jointly improve sustainable performance. An integrative review of peer-reviewed literature indexed in Scopus or comparable databases was conducted across lean management, Industry 4.0, digital fashion, circular economy, and triple-bottom-line performance. The synthesis identifies four connected layers: lean management practices, digital fashion capabilities, integration mechanisms, and economic, environmental, and social outcomes. Real-time visibility, data-driven waste elimination, closed-loop learning, and synchronized value flow are proposed as the mechanisms through which digital capabilities amplify lean routines. The framework also recognizes digital readiness, workforce capability, leadership commitment, and supply-chain collaboration as enabling conditions. Five research propositions are developed to guide future empirical testing. The paper contributes a fashion-specific explanation of Lean 4.0 and provides managers with a staged pathway for aligning operational excellence, digital transformation, and sustainability objectives.

Keywords: Circular economy; Digital fashion; Lean management; Industry 4.0; Sustainable performance

INTRODUCTION

The textile, apparel, and fashion sector combines global economic significance with short trend cycles, high product variety, uncertain demand, labour-intensive operations, and geographically dispersed supply networks. These characteristics create familiar operational wastes such as overproduction, waiting, transport, excess inventory, defects, unnecessary motion, overprocessing, and underused human capability while also intensifying material loss, emissions, water use, and social-risk exposure. Recent reviews identify sustainability challenges across consumer behaviour, circularity, corporate responsibility, and the full fashion supply chain, confirming that operational and sustainability problems cannot be treated as separate agendas (Abbate et al., 2024; Jia et al., 2020; Niinimäki et al., 2020).

Lean management offers a process-centred philosophy for defining customer value, stabilising work, exposing problems, improving flow, and pursuing continuous improvement. Yet conventional lean systems can struggle when fashion firms face rapid style changes, small batches, complex bills of materials, variable quality, opaque subcontracting, and weak real-time information. Digital technologies—including radio-frequency identification, the Internet of Things, artificial intelligence, advanced analytics, cloud platforms, three-dimensional design, digital twins, and traceability systems—can reduce these information constraints. The relevant managerial issue is therefore not whether digitalisation replaces lean, but how digital capabilities can reinforce lean problem-solving and flow (Buer et al., 2018; Cifone et al., 2021; Frank et al., 2019; Sony, 2018).

Empirical research increasingly supports complementarity. Lean practices have been associated with Industry 4.0 adoption and performance in general manufacturing (Kamble et al., 2020; Tortorella & Fettermann, 2018), while garment-sector evidence indicates that the joint use of lean production and Industry 4.0 can improve sustainability performance (Saha et al., 2023). Recent apparel studies further position digital lean as the mechanism through which Industry 4.0 contributes to organisational performance (Ta & Zyngier, 2026) and show that digital technologies can address lean barriers caused by frequent product changes and limited operational visibility (Silva et al., 2026). Nevertheless, fashion-specific research often studies isolated technologies, individual lean tools, or separate sustainability outcomes. A coherent management framework connecting these domains remains underdeveloped.

Accordingly, this conceptual paper asks: How can lean management and digital fashion capabilities be integrated to strengthen economic, environmental, and social performance? Its objectives are to synthesise the relevant literature, identify the mechanisms linking lean and digital capabilities, propose an integrated fashion-specific framework, and develop propositions for empirical investigation. The contribution lies in treating digitalisation as an operational capability governed by lean principles rather than as a stand-alone technology programme.

LITERATURE REVIEW

Lean Management in Fashion Operations

Lean management begins with customer value and systematically removes activities that do not contribute to that value. In fashion operations, value-stream mapping can expose delays from design approval to cutting, sewing, finishing, distribution, and return handling. Standardised work and visual management stabilise repetitive activities; quality at source reduces rework and defective garments; pull and just-in-time practices limit work-in-process and finished-goods inventory; cellular layouts shorten movement; and kaizen mobilises employee knowledge. These practices are particularly relevant because overproduction and inventory obsolescence translate directly into markdowns, disposal, and avoidable environmental burdens.

Lean should not be reduced to a cost-cutting toolkit. Its sustainable potential depends on whether improvement routines simultaneously consider material, energy, employee, and customer outcomes. Bilancia et al. (2025) show that lean practices can contribute to sustainability and circularity in luxury fashion, but the effects differ across production stages and lean bundles. This suggests that fashion firms require contextual configuration rather than uniform implementation. Lean must also preserve respect for people: productivity gains that intensify work, transfer risk to suppliers, or weaken employee voice are inconsistent with sustainable performance. Lean–green research likewise indicates that integrated improvement is more likely to strengthen sustainability when environmental objectives are embedded in operational routines rather than treated as a parallel programme (Bhattacharya et al., 2019; Cherrafi et al., 2016; Garza-Reyes, 2015).

Digital Fashion Capabilities

Digital transformation in fashion extends across product development, production, retail, and end-of-life management. Three-dimensional computer-aided design and virtual sampling can reduce physical samples and shorten development cycles. Integrated product-lifecycle-management and enterprise systems improve version control and coordination. Internet-of-Things sensors, RFID, and machine connectivity provide real-time work-in-process and resource data. Artificial intelligence can support demand forecasting, cutting optimisation, defect detection, assortment planning, and waste classification. Blockchain or other traceability architectures can enhance provenance and chain-of-custody visibility. Casciani et al. (2022) emphasise that digital transformation can reshape fashion supply chains and business models, while Ramos et al. (2023) identify supply-chain optimisation, sustainable design, waste reduction, and data analysis as major AI application areas. Digital design tools and circular business-model research further demonstrate how product-development decisions can support lower-impact fashion systems (Brydges, 2021; Kozlowski et al., 2018; Todeschini et al., 2017).

Technology alone does not guarantee improvement. Digital systems can automate waste, generate unused data, increase energy demand, exclude workers, or reinforce high-volume fast-fashion models. The value of a digital capability therefore depends on its connection to a clearly defined operational problem and sustainability objective. This is consistent with lean–digital research showing that digital technologies create value through mechanisms such as faster detection, more precise execution, remote coordination, and better prediction, rather than through acquisition itself (Cifone et al., 2021; Rosin et al., 2020).

Lean–Digital Integration

The lean and Industry 4.0 literature describes several relationships: lean may provide process stability before digitalisation; digital tools may strengthen existing lean practices; both may develop concurrently; and some technologies may substitute for manual information routines while preserving the underlying lean principle. Buer et al. (2018) mapped these research streams, whereas Sony (2018) proposed a broader integration model. Later studies documented one-to-one relationships and emerging lean automation arrangements (Rossini et al., 2022), explained how lean thinking can trigger digital transformation (Bittencourt et al., 2021), and identified operational practices required for integration (Komkowski et al., 2025). The literature also shows that digital technologies can help reconcile lean cost efficiency with the flexibility required under volatile demand (Ding et al., 2023).

For fashion, the most useful interpretation is selective augmentation. Digital tools should strengthen the ability to see demand, material, capacity, quality, and sustainability conditions; lean routines should translate this visibility into disciplined action. A sensor that identifies sewing-machine downtime becomes valuable when it triggers root-cause analysis and preventive maintenance. Digital sampling contributes to lean product development when it reduces approval loops and physical samples rather than encouraging uncontrolled design proliferation. Demand analytics supports pull when forecasts are converted into smaller replenishment decisions and protected from algorithmic overreaction.

Sustainable Performance

Sustainable performance is conceptualised through three interdependent dimensions. Economic performance includes productivity, lead time, quality, flexibility, inventory, cost, responsiveness, and profitability. Environmental performance includes material yield, sample and cutting waste, water and energy intensity, emissions, chemical control, durability, reuse, and recycling. Social performance includes occupational safety, fair wages and working hours, worker voice, skill development, task autonomy, job enrichment, supplier labour due diligence, grievance mechanisms, and customer trust. Lean and digitalisation can redesign jobs by shifting operators from repetitive execution toward monitoring, problem solving, and improvement; however, they can also intensify work, enable intrusive surveillance, or displace lower-skilled roles if implementation lacks participation and reskilling (Cimini et al., 2023). Responsible integration therefore requires employee involvement in standard-work design, transparent use of worker data, accessible digital training, and purchasing practices that do not transfer cost or lead-time pressure to vulnerable suppliers. The triple-bottom-line perspective is especially necessary in fashion because fragmented sourcing can produce apparent efficiency at one firm while transferring environmental or social burdens elsewhere (Abbate et al., 2024; Khan et al., 2021).

Digital traceability and analytics expand measurement capability, while lean provides routines for acting on measurement. Circular economy principles broaden the system boundary beyond factory efficiency to product longevity, repair, reuse, remanufacturing, and fibre recovery (Jia et al., 2020). Thus, the proposed framework regards circularity as an application context and outcome pathway rather than a separate improvement programme.

METHODOLOGY

This study used an integrative conceptual review to combine mature lean-management knowledge with emerging digital-fashion and sustainable-manufacturing evidence. The approach was appropriate because the focal phenomenon spans operations management, information systems, fashion management, and sustainability, and because the purpose was theory integration rather than estimation of a pooled effect.

Searches were structured around combinations of "lean management," "lean production," "Lean 4.0," "Industry 4.0," "digital fashion," "apparel," "garment," "textile," "circular economy," and "sustainable performance." Only English-language peer-reviewed journal articles indexed in Scopus and ranked Q1 or Q2 in a relevant subject category were retained, with emphasis on publications from 2018 to 2026. Earlier or adjacent works were retained only when conceptually foundational. Inclusion required a direct contribution to at least one of four domains: lean–digital integration, fashion digitalisation, apparel operations, or triple-bottom-line/circular performance. DOI metadata and publisher records were checked for all retained sources. The final evidence base comprised 30 journal articles, each cited in the paper and linked through a DOI for independent verification.

Analysis proceeded in four stages. First, concepts and practices were coded into lean, digital, integration, enabling-condition, and outcome categories. Second, causal mechanisms were compared across studies rather than merely listing technologies or tools. Third, fashion-specific operating conditions were used to refine the relationships. Fourth, the resulting constructs were organised into a process model and expressed as research propositions. The method provides conceptual transparency, but it is not claimed as a complete systematic review or meta-analysis.

RESULTS

Thematic Synthesis

The synthesis produced four primary layers and one contextual layer. The first layer contains lean management practices that create process discipline and a problem-solving architecture. The second comprises digital fashion capabilities that improve connectivity, visibility, analytical intelligence, virtualisation, and traceability. The third captures integration mechanisms through which the two domains interact. The fourth represents sustainable performance. Enabling conditions influence the strength and reliability of the relationships.

Table 1. Components of the Integrated Lean–Digital Fashion Management Framework

Framework layer	Illustrative elements	Primary function
Lean management practices	Value-stream mapping; pull/JIT; standardised work; quality at source; visual management; TPM; kaizen	Stable flow, waste exposure, disciplined problem solving
Digital fashion capabilities	3D/CAD and virtual sampling; IoT/RFID; AI and analytics; cloud/PLM/ERP; digital twin; traceability	Real-time visibility, prediction, connectivity, virtualisation
Integration mechanisms	Data-driven waste elimination; closed-loop learning; synchronised value flow; rapid quality feedback; lifecycle transparency	Conversion of digital information into lean action
Enabling conditions	Leadership commitment; digital readiness; workforce capability; data governance; supplier collaboration	Implementation quality and responsible scaling
Sustainable performance	Economic, environmental, and social outcomes	Balanced operational and stakeholder value

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Proposed Framework and Hypotheses

The framework proposes that lean management establishes the operating logic, digital fashion provides sensing and analytical capability, and integration mechanisms convert both into performance. Sustainable results are strongest when the organisation begins with value and waste, digitises priority constraints, embeds information into daily management, and extends visibility across the product lifecycle and supply network.

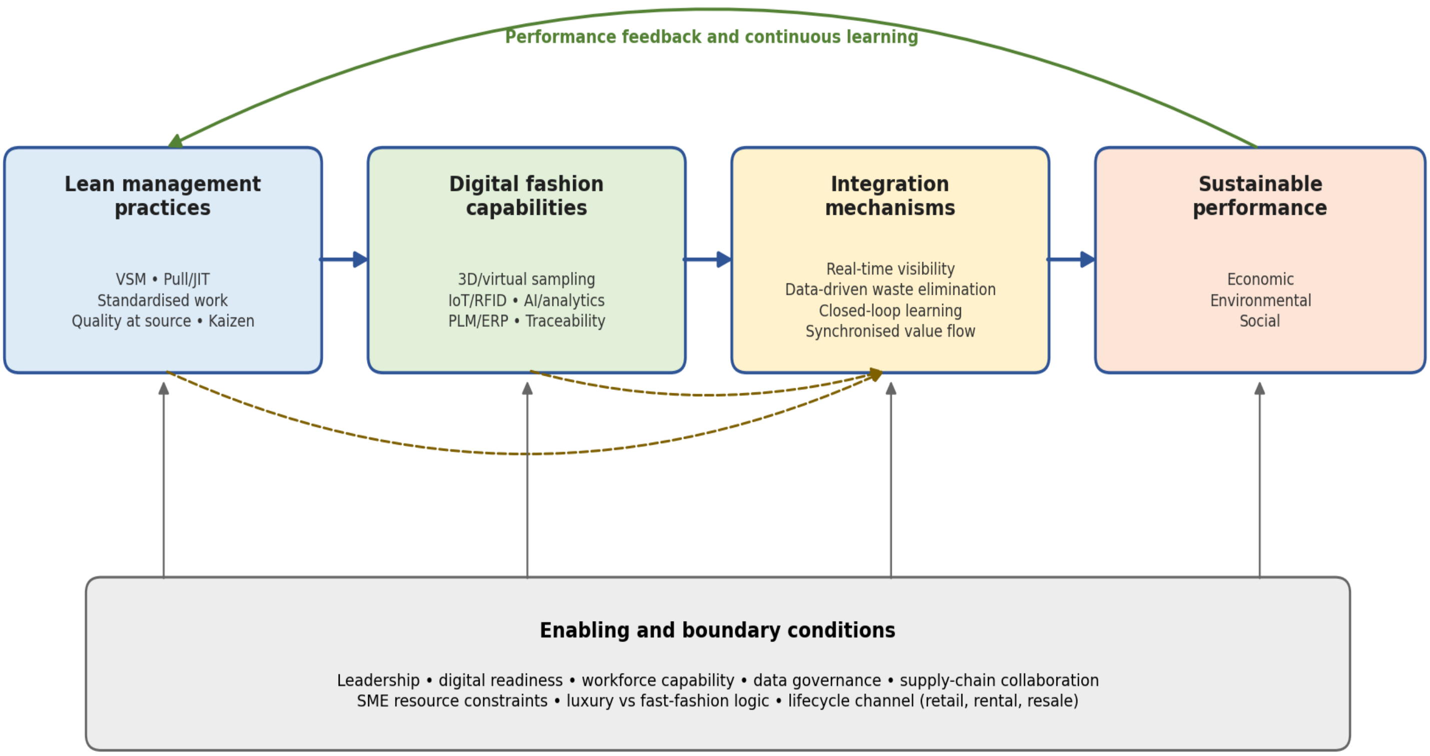

Figure 1. Integrated Lean–Digital Fashion Management Framework

Note. Solid arrows indicate the primary causal sequence; dashed arrows indicate complementary inputs to the integration mechanisms; the upper arrow represents performance feedback and continuous learning. Enabling and boundary conditions affect all stages.

Proposition 1: The integration of Lean Management and Digital Fashion capabilities, including sensing, connectivity, analytics, virtualisation, and traceability, has a stronger positive relationship with sustainable performance than the independent implementation of either Lean Management or Digital Fashion capabilities.

Proposition 2: The relationship between Lean and Digital Fashion integration and sustainable performance is mediated by four mechanisms: (a) real-time visibility, reflected in data latency, traceable work-in-process, and exception-detection speed; (b) data-driven waste elimination, reflected in material yield, reductions in defects and rework, and improvements in resource intensity; (c) closed-loop learning, reflected in problem-resolution time, recurrence rates, and employee participation in improvement activities; and (d) synchronised value flow, reflected in lead-time reliability, inventory turnover, replenishment responsiveness, and end-to-end coordination.

Proposition 3: The relationship between Lean and Digital Fashion integration and sustainable performance is strengthened by leadership commitment, digital readiness, workforce capability, data governance, and supply chain collaboration. However, the strength and nature of this relationship may vary according to organisational and industry conditions, including SME resource constraints, differences between luxury and fast fashion operating models, and the lifecycle channel in which the organisation operates, including manufacturing, retail, rental, and resale.

DISCUSSION

The framework advances the literature in three ways. First, it moves beyond a technology-list approach by explaining integration through operational mechanisms. The distinction matters because technologies do not directly eliminate waste; they improve the speed, scope, accuracy, or accessibility of information that people and routines use. This mechanism-based logic aligns with Cifone et al. (2021) and clarifies why identical technologies can produce different outcomes across firms.

Second, the framework contextualises Lean 4.0 for fashion. Fashion operations include creative product development, physical manufacturing, omnichannel distribution, reverse flows, and outsourced suppliers. Integration must therefore cross functional and organisational boundaries. Virtual sampling can reduce physical iterations during design; connected production systems can stabilise flow and quality; demand analytics can support replenishment; and traceability can connect operational control with social and environmental assurance. Saha et al. (2023) provide direct garment-sector evidence for the combined contribution of lean and Industry 4.0, while newer apparel studies reinforce the relevance of digital lean and barrier-removing technologies (Silva et al., 2026; Ta et al., 2026).

Third, the framework positions sustainable performance as a balanced design criterion rather than a downstream benefit. Lean improvement targets should include material yield, resource intensity, worker conditions, and product lifecycle outcomes alongside conventional cost, quality, delivery, and flexibility. This guards against local optimisation. For example, reducing production lead time while increasing air freight or unstable subcontracting would improve one metric but weaken system-level sustainability.

Fourth, the framework extends beyond factory-centric heavy-manufacturing assumptions. In fashion retail, lean–digital integration links point-of-sale and inventory visibility to smaller, faster replenishment and markdown prevention. In rental, it coordinates booking, cleaning, repair, condition grading, and asset utilisation. In resale, it supports authentication, grading, pricing, provenance, and reverse logistics. These downstream models feed demand, condition, and recovery data back to design and sourcing, allowing the framework to cover product development, production, retail, use-extension, and end-of-life loops rather than treating rental and resale as peripheral activities.

Managerial Implications

Managers can implement the framework as a staged roadmap. The first stage is diagnostic: map the end-to-end value stream and establish baseline economic, environmental, and social measures. The second stage stabilises critical processes through standard work, quality at source, visual control, preventive maintenance, and employee problem solving. The third stage digitises specific information constraints, prioritising use cases with measurable waste and sustainability benefits. The fourth stage integrates dashboards and alerts into daily lean routines. The fifth stage extends learning and traceability across suppliers, logistics providers, retailers, repair partners, and recyclers.

Implementation should begin with use cases rather than technology purchases. Suitable early applications include digital sample approval, fabric-yield optimisation, real-time defect feedback, work-in-process visibility, energy monitoring, and demand-driven replenishment. Each application should have a problem owner, baseline, target, review cadence, workforce-training plan, and safeguards for data quality and worker autonomy.

Boundary Conditions and Illustrative Vignettes

The framework is configurational rather than universal. SMEs may favour modular cloud tools, shared platforms, and a narrow set of high-value use cases because capital, specialist staff, and data maturity are constrained. Luxury firms may prioritise craftsmanship visibility, provenance, small-batch quality, repair, and product longevity, whereas fast-fashion firms may prioritise demand sensing, rapid replenishment, inventory exposure, and supplier coordination. These differences change the appropriate technologies, cadence of lean routines, performance targets, and acceptable social safeguards.

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Vignette 1: Luxury SME. A small luxury label maps its sample-development stream and finds repeated physical prototypes and approval delays. It combines standardised digital approval gates with 3D virtual sampling and a supplier-facing product-lifecycle platform. The immediate mechanisms are faster visibility and closed-loop learning; expected indicators include fewer physical samples, shorter approval time, reduced material use, improved artisan participation, and documented provenance. Limited digital skills and investment capacity remain the principal boundary conditions.

Vignette 2: Fast-fashion retailer with resale. A retailer connects point-of-sale, RFID inventory, returns, and resale-condition data to a pull-based replenishment routine. Daily exception review identifies demand mismatches, recurring defects, and products suitable for repair or resale. Expected indicators include lower markdowns, higher inventory turns, reduced disposal, faster recovery cycles, and stronger supplier corrective action. The social risk is that compressed response times intensify work or shift instability to suppliers; purchasing lead times, overtime, worker grievances, and supplier remediation therefore form part of the control system.

Research Implications and Future Testing

Future studies can operationalise lean management as a multidimensional construct and distinguish digital capability from simple technology adoption. Sustainable performance should be measured through economic, environmental, and social indicators, with integration mechanisms tested as mediators and enabling conditions as moderators. Longitudinal case studies, digital trace data, material-flow analysis, and lifecycle assessment could complement surveys using PLS-SEM or covariance-based SEM. Comparative research across luxury, fast-fashion, modest-fashion, SME, and export-oriented garment settings would reveal boundary conditions.

The framework also creates opportunities for sub-dimensional research. Three-dimensional design may interact most strongly with lean product development; IoT and RFID with flow and inventory control; artificial intelligence with forecasting, cutting, and quality; and traceability systems with responsible sourcing and circularity. Testing these uneven pairings would avoid treating both lean and digitalisation as undifferentiated bundles.

CONCLUSION

This paper developed an Integrated Lean–Digital Fashion Management Framework for sustainable performance. The framework connects lean practices and digital fashion capabilities through real-time visibility, data-driven waste elimination, closed-loop learning, and synchronised value flow. It proposes that economic, environmental, and social performance improves when technology is governed by customer value, process discipline, employee involvement, and lifecycle responsibility. Leadership, digital readiness, workforce capability, data governance, and supply chain collaboration determine whether integration translates into durable results.

The paper is limited by its conceptual and integrative design; it does not provide causal estimates or claim exhaustive systematic coverage. Its propositions therefore require empirical validation. Nevertheless, it offers a coherent foundation for fashion organisations seeking to align operational excellence with digital transformation and sustainability, and for researchers developing fashion-specific models of Lean 4.0.

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Appendix A. Operational Definitions and Example Measures

The following definitions convert the conceptual framework into testable constructs. Survey items may use a five- or seven-point agreement scale, while objective operational indicators should be normalised to the firm, product category, and reporting period. Multi-item scales should be validated through expert review, pilot testing, reliability analysis, and convergent and discriminant validity assessment before hypothesis testing.

Construct	Operational definition	Example perceptual measures	Example objective indicators
Lean management practices	Extent to which value, flow, pull, quality at source, standardised work, visual management, maintenance, and employee problem solving are routinely applied.	Processes are mapped end to end; work standards are jointly maintained; deviations trigger structured problem solving.	Lead time; WIP; first-pass yield; changeover time; kaizen participation.

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Construct	Operational definition	Example perceptual measures	Example objective indicators
Digital fashion capabilities	Ability to deploy and combine digital tools for virtualisation, sensing, connectivity, analytics, integration, and traceability across the fashion lifecycle.	Data are captured in near real time; systems share reliable product and process data; analytics support operational decisions.	Data latency; system integration coverage; virtual-sample ratio; traceable SKU/supplier share.
Lean–Digital Fashion integration	Degree to which digital capabilities are deliberately embedded in lean routines and directed at defined customer-value, waste, flow, and lifecycle problems.	Digital investments begin with a mapped problem; digital signals are reviewed in daily management; improvement teams act on system data.	Share of digital use cases tied to lean KPIs; alert-to-action rate; cross-functional adoption.
Real-time visibility	Timeliness, completeness, and accessibility of demand, material, capacity, quality, worker, and sustainability information.	Managers and operators can see current status and exceptions across processes and partners.	Data latency; WIP traceability; exception-detection time; data completeness.
Data-driven waste elimination	Use of verified data to identify, prioritise, and remove operational and resource waste.	Improvement priorities are selected using defect, material, energy, and delay data.	Material yield; scrap/sample reduction; rework; energy or water per unit.
Closed-loop learning	Speed and reliability with which detected deviations generate analysis, corrective action, standard updates, and organisational learning.	Corrective actions are verified; lessons update standards and training; workers contribute to improvements.	Problem-resolution time; recurrence rate; implemented suggestions; training completion.
Synchronised value flow	Alignment of design, supply, production, fulfilment, use-extension, and recovery activities with actual demand and capacity.	Replenishment and production decisions are coordinated across functions and partners.	Schedule adherence; inventory turns; order lead time; stockouts; rental utilisation; recovery-cycle time.
Sustainable performance	Balanced economic, environmental, and social results achieved without transferring burdens across firms, workers, lifecycle stages, or stakeholder groups.	The firm improves cost, resource outcomes, and working conditions simultaneously.	Economic: cost, quality, delivery, margin. Environmental: waste, emissions, water, durability, recovery. Social: safety, overtime, autonomy, skills, grievances, supplier remediation.

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Construct	Operational definition	Example perceptual measures	Example objective indicators
Enabling conditions	Organisational and inter-organisational capabilities that strengthen responsible implementation.	Leaders provide resources; workers have digital and problem-solving skills; data ownership and supplier collaboration are clear.	Training hours; data-quality score; leadership review cadence; supplier-data coverage; joint-improvement projects.
Boundary conditions	Contextual characteristics that change the appropriate configuration or effect size of the framework.	Resource availability, market logic, product complexity, channel model, and supply-network structure shape implementation.	Firm size; digital maturity; luxury/fast-fashion positioning; make/buy ratio; retail/rental/resale revenue share.