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# Lean 4.0 Integration for Sustainable Industrial Performance: A Strategic Framework for Combining Lean Management and Industry 4.0 Technologies

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***Abstract-** Manufacturers are under simultaneous pressure to raise productivity, respond faster to volatile demand, improve resilience and reduce the environmental and social burdens of industrial activity. Lean management and Industry 4.0 are frequently presented as complementary responses, yet the literature still contains fragmented guidance on how their integration should be sequenced, governed and measured. This review synthesises recent evidence on Lean 4.0 and develops a strategic framework that connects lean operating discipline with digital sensing, connectivity, analytics, automation and closed-loop learning. A structured integrative review of peer-reviewed research published from 2020 to 2025 was undertaken, with emphasis on studies that examined explicit interactions between lean practices and Industry 4.0 technologies, implementation conditions, organisational capabilities and sustainability outcomes. The synthesis shows that digital technologies generate stronger benefits when they amplify a stable lean system rather than automate poorly designed processes. Lean provides problem visibility, process ownership, standardisation and customer-value logic; Industry 4.0 extends these capabilities through real-time transparency, predictive intelligence, traceability and adaptive control. The proposed framework therefore organises Lean 4.0 as a five-layer system comprising lean stability, digital visibility, analytical intelligence, responsive execution and sustainability governance. It also specifies a staged implementation pathway and performance architecture spanning operational, environmental, economic and social indicators. The review identifies workforce capability, data governance, interoperability, leadership commitment and disciplined technology selection as critical boundary conditions. The resulting framework positions Lean 4.0 not as a technology programme but as a strategic operating system for sustainable industrial performance.*

***Keywords:** Lean 4.0; lean manufacturing; Industry 4.0; sustainable manufacturing; digital transformation; operational excellence; industrial sustainability*

## I. INTRODUCTION

Industrial firms now compete in an environment characterised by short product cycles, customised demand, disrupted supply networks, rising energy costs and increasing scrutiny of environmental and social performance. Traditional improvement programmes can still remove waste and stabilise processes, but they often depend on periodic observation, manual information flows and delayed feedback. Conversely, advanced digital technologies can provide dense data, connectivity and automation, yet technology investment by itself does not guarantee better flow, quality or value creation. The strategic question is therefore not whether manufacturers should choose lean management or Industry 4.0, but how the two should be combined so that digital capability reinforces process discipline rather than digitising instability.

Recent research increasingly treats this combination as Lean 4.0, Lean Industry 4.0 or digital lean manufacturing. Empirical and review studies generally report complementarity between lean practices and digitalisation, although the strength of the relationship varies with organisational maturity, technology choice and implementation design (Buer et al., 2021; Ciano et al., 2021; Kassem et al., 2024). Lean contributes a logic of customer value, waste removal, standard work, flow, pull and continuous improvement. Industry 4.0 contributes cyber-physical connectivity, industrial Internet of Things platforms, cloud or edge computing, advanced analytics, digital twins, augmented interfaces, autonomous equipment and integrated information architectures. When aligned, these capabilities can turn conventional visual management into real-time process visibility, periodic problem solving into predictive intervention, and local optimisation into coordinated value-stream control (Shahin et al., 2020; Hossain and Purdy, 2023).

The integration challenge is nevertheless substantial. Digital projects may create data without actionable decisions, automate non-value-adding work, introduce technological complexity or weaken employee ownership. Lean initiatives may also underperform when they lack timely information, cross-system visibility or scalable decision support. Recent studies consequently emphasise cumulative capability development, socio-technical balance and the management of paradoxes between standardisation and flexibility, human judgement and automation, or local autonomy and central data governance (Johansson et al., 2024; Powell et al., 2024; Frank et al., 2024). These tensions become more important when sustainability is added to the performance agenda because energy, materials, emissions, safety and workforce development must be managed alongside quality, cost, delivery and productivity.

The aim of this review is to develop a coherent strategic framework for integrating lean management and Industry 4.0 technologies to improve sustainable industrial performance. Four objectives guide the analysis: first, to explain the mechanisms through which lean practices and digital technologies reinforce one another; second, to identify the organisational and technological conditions that influence successful integration; third, to connect Lean 4.0 practices with economic, environmental and social performance; and fourth, to translate the evidence into an implementation architecture that managers can use for sequencing investment and governance. The paper extends earlier work by shifting attention from isolated lean-tool and technology pairings toward an integrated operating system in which process stability, data quality, analytical capability, human participation and sustainability measures evolve together.

## II. CONCEPTUAL FOUNDATIONS OF LEAN 4.0

Lean management seeks to maximise customer value by designing processes that expose problems, reduce non-value-adding activity and support continuous improvement. Its practical mechanisms include value-stream mapping, standard work, pull systems, visual management, mistake proofing, rapid changeover, total productive maintenance and structured problem solving. These practices are mutually reinforcing: standardisation makes abnormal conditions visible; flow and pull reduce inventory and delay; visual control shortens feedback loops; and employee-led improvement converts detected problems into learning. Contemporary research also shows that lean can support broader sustainability objectives when waste is interpreted to include unnecessary energy, material, movement, defects and resource consumption rather than only time and inventory (Mathiyazhagan et al., 2022; Ejsmont et al., 2020).

Industry 4.0 extends the information and control capacity of manufacturing systems. Sensors and connected assets increase the frequency and granularity of process observation. Manufacturing execution systems and interoperable platforms create horizontal and vertical integration. Big-data analytics and artificial intelligence detect patterns that are difficult to identify manually. Digital twins permit scenario analysis and virtual experimentation. Augmented interfaces support maintenance, training and standard work, while autonomous systems can execute repetitive or hazardous tasks with high consistency. These technologies may improve sustainable performance through better resource allocation, reduced defects, predictive maintenance, lower downtime and improved working conditions, but the outcomes depend on organisational context and implementation discipline (Jamwal et al., 2021; Nara et al., 2021; Harikannan and Vinodh, 2025).

Lean 4.0 emerges when digital capability is deliberately designed around lean principles and process needs. The relationship is bidirectional. Lean can simplify processes before digitisation, reduce unnecessary automation, clarify performance gaps and define the information required for control. Digital technology can, in turn, strengthen lean by making flows visible in real time, increasing traceability, reducing detection latency and supporting decisions across complex production networks. Buer et al. (2021) found a complementary effect between lean manufacturing and digitalisation, while Ciano et al. (2021) demonstrated specific relationships between Industry 4.0 technologies and lean production techniques. Anosike et al. (2021) similarly showed that Internet of Things capabilities can reinforce many lean methods by improving information flow and decision quality, although people-centred practices require careful design to avoid weakening participation.

The integration should therefore be understood as a socio-technical capability rather than a bundle of tools. Hines et al. (2023) argue that the field is moving toward broader concerns involving people, supply chains and sustainability, while Frank et al. (2024) emphasise the need to integrate lean, technology and human factors beyond a technology-centred Industry 4.0 view. This perspective is important because operational excellence depends on routines, skills, incentives and problem-solving behaviour as much as on hardware or software. A connected machine may reveal a deviation instantly, but the organisation still needs an agreed standard, a causal model, decision rights and an improvement routine to act on that information.

## III. REVIEW METHODOLOGY

A structured integrative review was used to develop an evidence-based framework while preserving the conceptual breadth required for strategy development. The review focused on peer-reviewed journal and conference literature published between 2020 and 2025. Search terms combined variants of "lean manufacturing", "lean production", "Lean 4.0", "digital lean" and "Lean Industry 4.0" with "Industry 4.0", "digitalisation", "Internet of Things", "digital twin", "analytics", "automation", "sustainability" and "sustainable manufacturing". Priority was given to research indexed in major scholarly databases and to studies that explicitly examined the interaction between lean and digital technologies rather than discussing either domain independently.

Screening was guided by four relevance criteria. Studies were retained when they addressed at least one of the following: lean–digital interaction mechanisms, implementation frameworks or maturity, organisational enablers and barriers, or operational and sustainability outcomes. Recent systematic reviews were used to map the knowledge base, while empirical studies, multiple-case analyses and survey research were used to test whether the proposed mechanisms were supported beyond conceptual argument (Kassem et al., 2024; Hossain and Purdy, 2023; Schumacher et al., 2023). Thirty sources were selected for the final synthesis. All cited sources fall within the specified publication window and were checked against their DOI metadata.

The analysis used thematic coding rather than statistical meta-analysis because the literature is heterogeneous in constructs, sectors, technologies and performance measures. Evidence was grouped into five themes: process stability and lean maturity; digital visibility and integration; analytics and intelligent decision support; human and organisational capability; and sustainability performance. Relationships recurring across multiple research designs were treated as stronger evidence than isolated technology claims. The resulting framework was then developed by linking these themes into a staged capability architecture and testing its internal logic against published integration models, case evidence and identified implementation tensions.

## IV. EVIDENCE SYNTHESIS: MECHANISMS OF LEAN 4.0 INTEGRATION

The first mechanism is process stabilisation before automation. Lean practices reduce unnecessary variation, clarify process ownership and establish standards against which digital data can be interpreted. This does not mean a factory must reach an ideal state before digitalisation begins; rather, technology should be introduced where a defined operational problem and a measurable baseline exist. Survey evidence from small and medium-sized manufacturers suggests that lean maturity can provide an important foundation for digital transformation because unstable, wasteful processes are poor candidates for sophisticated automation (Tsukada et al., 2024). Rossini et al. (2022) similarly show that lean automation performs best when digital capability is connected to lean production logic rather than installed as isolated assets.

The second mechanism is real-time visibility. Conventional lean systems often rely on boards, audits, manual counts and periodic value-stream studies. Connected sensors, machine data and integrated execution systems can transform these episodic observations into continuous process signals (Silvestri et al., 2022). Digital value-stream information can reveal queue formation, micro-stoppages, energy peaks, quality drift or material shortages early enough for intervention. Rahardjo et

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al. (2023) illustrate how digitalised error proofing and a structured improvement cycle can support process capability and yield improvement. The broader significance is that digital technology shortens the time between deviation, recognition and response, thereby increasing the practical power of lean visual management.

The third mechanism is analytical intelligence. Lean problem solving traditionally depends on observation, root-cause analysis and disciplined experimentation. Analytics does not replace these methods; it extends their reach. Pattern recognition can prioritise abnormal conditions, predictive models can estimate failure risk, and digital twins can test alternatives before physical changes are made. However, the quality of analytics depends on process knowledge and data discipline. Without stable definitions, contextual variables and ownership, algorithms may optimise proxy metrics rather than customer value. This reinforces a central Lean 4.0 principle: analytical sophistication should increase only as the organisation's ability to interpret and act on information develops.

The fourth mechanism is responsive execution. When visibility and intelligence are linked to standardised decision rules, manufacturing systems can respond more quickly to disturbances. Examples include predictive maintenance triggering a planned intervention, electronic kanban adjusting replenishment, digital work instructions adapting to product variants, or mistake-proofing devices preventing a defect from moving downstream. Shahin et al. (2020) show how lean practices and Industry 4.0 technologies can be combined in smart manufacturing, while Sordan et al. (2022) map contact points between improvement methods and digital capabilities. The strategic value lies not in automation itself but in closing the control loop between sensing, interpretation, action and learning.

The fifth mechanism is cumulative organisational learning. Digitalisation can accelerate improvement only when employees understand the process, trust the information and have authority to act. Powell et al. (2024) describe digitalisation in lean firms as cumulative capability development, implying that organisations build new digital routines on prior operational capabilities. Johansson et al. (2024) identify tensions that appear when advanced technologies are inserted into established lean systems, including imbalances between technology pace and organisational absorption. The integration process therefore requires deliberate experimentation, cross-functional teams and governance that protects both technical reliability and frontline engagement.

The sixth mechanism is expanded sustainability control. Lean already targets resource inefficiency through waste reduction, but Industry 4.0 adds measurement precision. Energy use, scrap, water consumption, emissions, equipment health and ergonomic exposure can be associated with specific products, shifts or process states. Nara et al. (2021) show that digital technologies can influence economic, environmental and social dimensions simultaneously. Costa et al. (2024) further demonstrate that lean and Industry 4.0 integration can support a green transition when operational and environmental variables are managed as an interconnected system. Sustainable performance therefore becomes more actionable when resource metrics are integrated into the same daily management routines used for quality, cost and delivery.

These mechanisms also expose important failure modes. Technology can automate waste, generate excessive alarms, increase cybersecurity exposure, create incompatible data islands or displace tacit knowledge. Sony et al. (2021) identify implementation challenges and critical success factors that confirm the need for leadership, skills and infrastructure. Chavez et al. (2024) find that digitalisation can strengthen the social-performance effects of lean, but the additional contribution is not unlimited, which cautions against assuming that more technology automatically produces better human outcomes. Lean 4.0 therefore requires selective digitalisation: technologies should be justified by a specific decision, waste mechanism, risk or sustainability objective.

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*Table 1. Lean practice–Industry 4.0 synergy matrix and sustainability logic. Source: authors' synthesis.*

| Lean domain | Digital enablers | Integration mechanism | Sustainable performance logic | Key evidence |
|---|---|---|---|---|
| Value-stream mapping | IoT, system integration, digital twin | Continuous visibility of flow, queues and resource states | Lower lead time and WIP; exposes energy and material losses | Ciano et al. (2021); Wang et al. (2022) |
| Standard work and visual management | Connected workstations, digital instructions, dashboards | Faster detection of abnormality and controlled adaptation to variants | Quality consistency; reduced cognitive ambiguity; faster learning | Schumacher et al. (2023); Frank et al. (2024) |
| TPM and maintenance | Sensors, analytics, digital twins | Condition monitoring and predictive intervention | Higher asset availability; lower breakdown waste and avoidable energy use | Buer et al. (2021); Felsberger et al. (2022) |
| Pull / Kanban | RFID/IoT, integrated planning, real-time inventory data | Dynamic replenishment with stronger material-status visibility | Lower inventory and expediting; improved resource coordination | Anosike et al. (2021); Kassem et al. (2024) |
| Poka-yoke / quality at source | Sensors, machine vision, analytics, traceability | Immediate prevention or containment of process deviations | Less scrap and rework; stronger traceability and safer execution | Rahardjo et al. (2023); Shahin et al. (2020) |
| SMED and flexible flow | Data capture, simulation, augmented work support | Data-assisted setup analysis and repeatable changeover routines | Shorter setup losses; better responsiveness with controlled resource use | Silvestri et al. (2022); Hossain and Purdy (2023) |

## V. STRATEGIC FRAMEWORK FOR SUSTAINABLE INDUSTRIAL PERFORMANCE

Based on the synthesis, Lean 4.0 can be organised as a five-layer strategic architecture. The first layer is lean stability. It establishes process purpose, customer value, standard work, flow, pull, equipment reliability, visual control and structured problem solving. Its output is not a "finished" lean system but an operational baseline with visible abnormalities and accountable process ownership. This layer prevents digital investment from being used to conceal fundamental process weaknesses.

The second layer is digital visibility. Sensors, machine connectivity, traceability, data acquisition and integrated production systems are introduced around high-value information needs. The design question is not what can be connected, but what must be known faster or more accurately to protect flow, quality, resource efficiency or safety. The layer converts physical events into trusted digital signals while establishing common definitions, timestamps, master data and data-quality rules. Hossain and Purdy (2023) emphasise that successful integration depends on a strategic framework rather than disconnected technology adoption, and Kassem et al. (2024) show that some lean–technology interactions are materially stronger than others.

The third layer is analytical intelligence. Once reliable process data exist, descriptive dashboards are supplemented with diagnostic and predictive analysis. The objective is to reduce decision latency and improve causal understanding. Applications include anomaly detection, predictive maintenance, process

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capability monitoring, energy forecasting, quality prediction and digital-twin scenario testing. Felsberger et al. (2022) link Industry 4.0 to dynamic capabilities, indicating that data become strategically valuable when they improve the organisation's ability to sense changes, seize opportunities and reconfigure operations. Analytical models should therefore be evaluated by the decisions they improve, not only by statistical accuracy.

The fourth layer is responsive execution. Insights are connected to work routines, control rules, maintenance actions, replenishment logic and employee problem solving. Automation is appropriate where response speed, consistency, safety or complexity exceed the practical limits of manual control. Human-in-the-loop design remains essential where judgement, creativity or contextual trade-offs dominate. Frank et al. (2024) and Hines et al. (2023) both support a broader view in which technology augments a people-centred production system rather than replacing it. This layer closes the loop from information to action while preserving accountability for outcomes.

The fifth layer is sustainability governance. Economic, environmental and social indicators are integrated into policy deployment and daily management. Instead of treating sustainability as a separate reporting stream, energy intensity, material yield, emissions, water, safety, ergonomics, skill development and workforce participation are connected to operational drivers. Skalli et al. (2024) provide evidence that lean-related improvement, digital technologies and circular-economy practices can jointly influence sustainable performance. Elnadi et al. (2025) likewise show that Industry 4.0 can support sustainability through lean, agile and circular manufacturing pathways. Governance at this layer therefore aligns local optimisation with enterprise-level value and sustainability priorities.

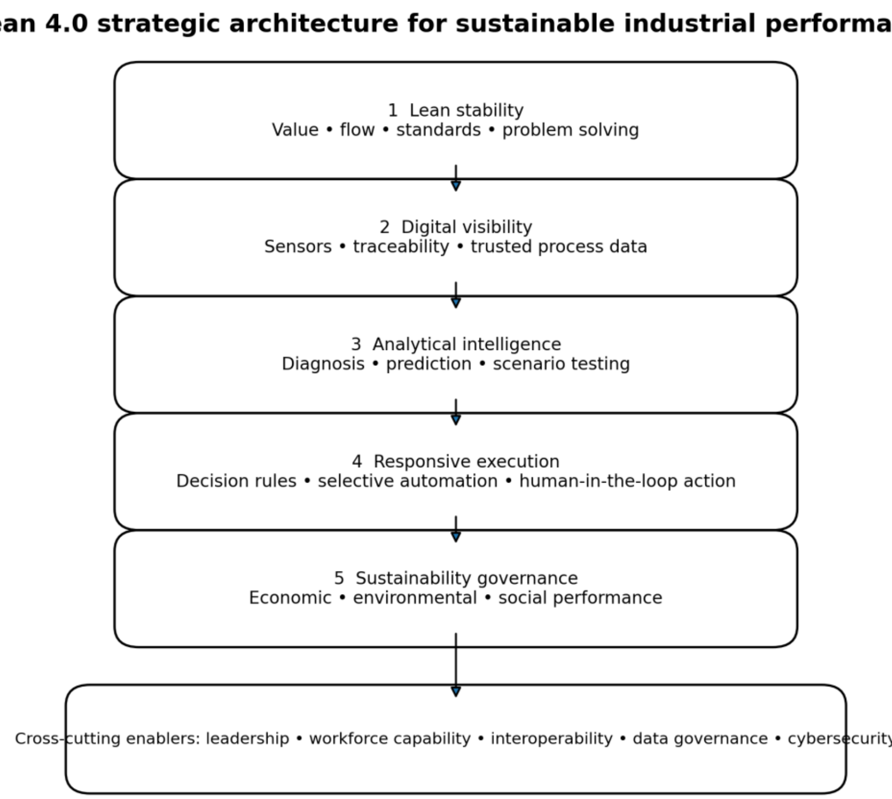


*Figure 1. Lean 4.0 strategic architecture for sustainable industrial performance. Source: authors' synthesis.*

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The five layers should be implemented through a staged roadmap. Stage one diagnoses the value stream and establishes baseline performance. Stage two stabilises critical processes and defines the information required to manage them. Stage three digitises selected measurements and removes manual information delays. Stage four integrates data across functions and applies analytics to priority problems. Stage five closes selected control loops and scales successful solutions. Stage six institutionalises learning through standardisation, capability building, portfolio governance and sustainability review. Schumacher et al. (2023) show that digital transformation of lean methods is an evolutionary process, while Calabrese et al. (2022) emphasise the importance of knowing where to start, what to target and what risks to anticipate in Industry 4.0 transformation.

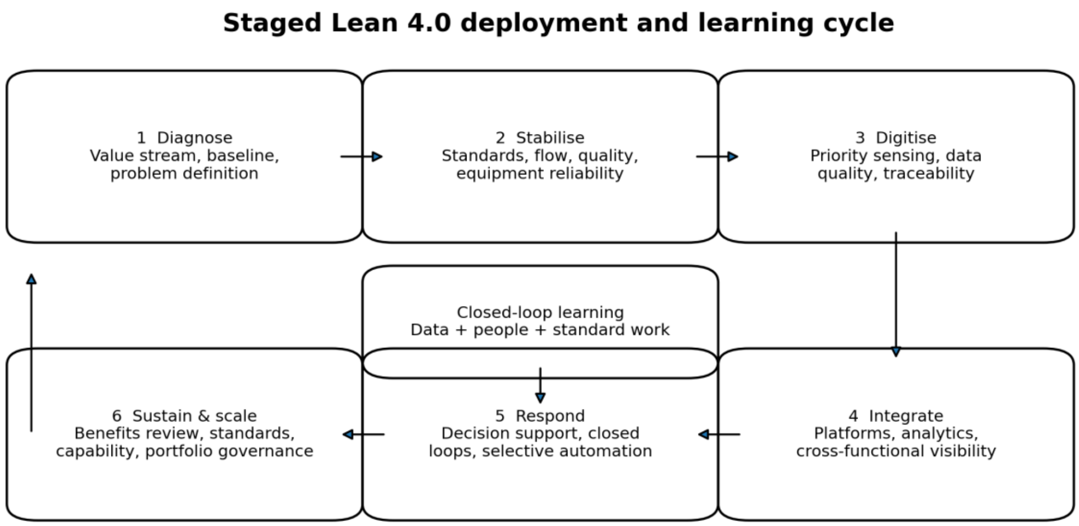


*Figure 2. Staged Lean 4.0 deployment and closed-loop learning cycle. Source: authors' synthesis.*

Technology selection within the roadmap should follow a problem-first rule. A proposed digital use case should specify the current performance gap, the lean mechanism involved, the decision or action to be improved, the required data, the expected operational benefit and the sustainability effect. It should also identify new risks, including cybersecurity, dependence on vendors, model drift, worker acceptance and maintenance burden. This discipline prevents "pilot proliferation", where many demonstrations are launched but few become embedded capabilities. It also creates a basis for comparing projects using value rather than technological novelty.

Performance measurement should use a balanced architecture. Operational indicators include first-pass yield, overall equipment effectiveness, lead time, changeover time, work-in-process, schedule adherence and process capability. Environmental indicators include energy per unit, material yield, scrap, water intensity and emissions where measurable. Economic indicators include conversion cost, downtime cost, working-capital effects and return on digital investment. Social indicators include safety incidents, ergonomic exposure, training, employee participation, problem-solving autonomy and job redesign. Harikannan and Vinodh (2025) argue for layered frameworks that connect Industry 4.0 with sustainable manufacturing, and this integrated scorecard makes those links explicit at the operating level.

Governance must match the architecture. A cross-functional Lean 4.0 steering mechanism should define enterprise principles, data standards and investment criteria, while value-stream teams retain responsibility for local problem solving and benefit realisation. Information-technology and operational-technology specialists should work with process owners rather than act as separate implementation channels. Benefits should be reviewed after deployment and compared with the original baseline. If a digital tool adds complexity without improving a defined operational or sustainability measure, it should be redesigned, simplified or removed. Such governance keeps technology subordinate to value creation and preserves the continuous-improvement logic at the centre of lean management.

*Table 2. Staged Lean 4.0 implementation roadmap and control gates. Source: authors' synthesis.*

| Stage | Primary objective | Lean discipline | Digital capability | Governance gate / example KPI |
|---|---|---|---|---|
| 1. Diagnose | Define value-stream problem and baseline | VSM, problem definition, process ownership | Minimal: trusted baseline data | Problem tied to strategy; lead time, FPY, energy/unit |
| 2. Stabilise | Reduce avoidable variation before scaling technology | Standard work, flow, TPM, visual control | Basic data capture and master-data discipline | Stable definitions and ownership; process capability, OEE |
| 3. Digitise | Remove information delay at priority points | Visual management, quality at source | Sensors, traceability, connected work support | Data accuracy and availability; detection latency |
| 4. Integrate | Create cross-functional visibility and analysis | Value-stream control, A3/root-cause routines | Interoperable systems, analytics, digital twin where justified | Interoperability and model validity; forecast / diagnostic accuracy |
| 5. Respond | Convert insight into timely, controlled action | Pull, Jidoka, maintenance, standardised response | Decision support, selective closed-loop automation | Human override and risk controls; response time, defects, downtime |
| 6. Sustain & scale | Institutionalise learning and portfolio benefits | Kaizen, policy deployment, standardisation | Reusable architectures and governance | Benefits verified; ROI, resource intensity, safety, skills |

## VI. SUSTAINABLE PERFORMANCE PATHWAYS

The economic pathway operates through waste reduction, asset utilisation, quality improvement and faster response. Digital visibility can reduce hidden losses; predictive analysis can reduce unplanned downtime; and integrated flow control can lower inventory and expediting. Rahardjo et al. (2023) provide case evidence that digitally enabled error proofing can improve process capability and yield. Buer et al. (2021) similarly indicate that lean and digitalisation can complement one another in operational performance. However, benefits must be assessed net of implementation cost, system maintenance, training and integration effort. Lean 4.0 creates economic value when digital capability changes process behaviour, not merely when a system is installed.

The environmental pathway is driven by resource transparency and avoidance. Lean practices reduce overproduction, defects, transport, waiting and excess processing; digital technologies can quantify the energy and material consequences of these wastes. Costa et al. (2024) connect lean–Industry 4.0 integration with green transition, while Mathiyazhagan et al. (2022) demonstrate the relevance of sustainable lean manufacturing frameworks in industrial settings. Digital monitoring also enables environmental variables to enter root-cause analysis. For example, an energy spike can be traced to a machine state, product family or maintenance condition rather than treated only as a monthly utility variance.

The social pathway is more complex. Automation may reduce exposure to hazardous, repetitive or ergonomically difficult tasks, and digital work support can improve consistency and training. At the same time, poorly designed systems may increase surveillance, cognitive load, deskilling or resistance. Chavez et al. (2024) show that digital technology can complement lean effects on social performance, while Johansson et al. (2024) demonstrate that integration creates organisational tensions requiring active management. Social sustainability therefore depends on participation in system design, transparent use of performance data, skill development and clear reallocation of work when automation changes task content.

A final pathway concerns resilience and adaptability. Lean is sometimes criticised for reducing buffers, while Industry 4.0 is sometimes presented as a universal solution to volatility. A more useful interpretation is that lean identifies where buffers are unnecessary and where flow is vulnerable, while digital technologies improve sensing, scenario analysis and coordinated response. Felsberger et al. (2022) connect digital capabilities with organisational adaptation, and Sony et al. (2021) highlight the importance of implementation readiness. The combined system can therefore support resilience when it provides earlier warning, faster diagnosis and disciplined reconfiguration rather than simply increasing inventory or technological complexity.

## VII. DISCUSSION AND MANAGERIAL IMPLICATIONS

The central finding of this review is that Lean 4.0 should be managed as capability orchestration. Lean and Industry 4.0 are neither substitutes nor automatically complementary. Their value depends on sequencing, fit and governance. Lean contributes an operating logic that defines value, exposes abnormality and creates routines for learning. Digital technologies contribute speed, scope and analytical depth. Integration becomes strategic when the organisation uses these strengths together to improve decisions across the value stream and to connect operational excellence with sustainability outcomes.

For managers, three implications follow. First, start from process problems and strategic outcomes rather than technology catalogues. Second, build digital capability in cumulative stages so that data quality, workforce skills and governance mature alongside automation. Third, measure benefits across operational and sustainability dimensions because a project that improves throughput while increasing material loss, ergonomic burden or energy intensity may only shift waste. Kaswan et al. (2023) show the value of integrating green improvement methods with Industry 4.0, while Wang et al. (2022) demonstrate how digitalised value-stream approaches can support human-centred process design.

The framework also implies that leadership should protect time for experimentation and learning. Digital transformation frequently fails when pilots are treated as isolated engineering projects or when frontline users receive systems after key design decisions have been made. Cross-functional teams should jointly define the problem, data, response logic and standard work. Successful use cases should then be codified into reusable architectures and governance rules. This creates a portfolio of scalable capabilities rather than a collection of disconnected applications.

### 7.1. Strategic trade-offs and deployment logic

Strategic trade-offs are especially important when managers decide how far and how fast to automate. A lean system deliberately makes work, queues and abnormalities visible, whereas highly automated systems may conceal causal relationships behind software logic and aggregated dashboards. The appropriate design is therefore not maximum automation but sufficient automation to improve a defined control problem. A manual process with clear ownership may outperform a sophisticated digital process whose alarms are ignored or whose data cannot be trusted. Conversely, where reaction time, process complexity or safety risk exceeds human capability, automated sensing and response can protect both flow and people. This contingency perspective is consistent with evidence that the effects of digitalisation depend on existing lean capabilities, organisational readiness and the way technologies are embedded in routines rather than on technical availability alone (Buer et al., 2021; Tsukada et al., 2024; Powell et al., 2024).

A second trade-off concerns local optimisation versus enterprise integration. Lean improvement often begins close to the workplace, where teams can observe waste and test countermeasures quickly. Industry 4.0 architectures, by contrast, create strong incentives for common platforms, central data models and enterprise standards. Excessive centralisation can slow experimentation, but excessive local autonomy can create incompatible systems and duplicated data. The framework therefore recommends federated governance: enterprise rules should govern cybersecurity, interoperability, data ownership and architectural principles, while value-stream teams retain discretion over problem selection, experimentation and daily use. This arrangement supports standardisation where scale matters and flexibility where learning matters.

A third trade-off concerns efficiency versus redundancy. Lean reduces unnecessary buffers, but sustainable performance also requires resilience to supply, equipment and demand disruptions. Digital twins, predictive maintenance and real-time supply information can help distinguish wasteful buffers from deliberate protective capacity. Rather than removing every reserve, managers should identify which buffers protect customer value and which merely compensate for poor information or unstable processes. This distinction allows Lean 4.0 to support resilience without abandoning waste reduction.

Finally, investment decisions should include an explicit learning value. Early pilots may have modest financial returns yet generate reusable data standards, integration skills, workforce confidence or analytical models that enable later projects. Calabrese et al. (2022) and Sony et al. (2021) both indicate that transformation capability develops through organisational learning and critical success factors rather than isolated purchases. A portfolio view should therefore assess direct benefits, risk reduction, sustainability contribution and capability accumulation. This prevents short-term return metrics from rejecting foundational projects while still requiring every initiative to demonstrate a clear connection to future operating performance. Accordingly, governance maturity is itself a Lean 4.0 capability, because organisations must continuously revise standards, decision rights and technology portfolios as processes, risks, workforce skills and sustainability expectations evolve.

## VIII. LIMITATIONS AND FUTURE RESEARCH

This review is interpretive and does not estimate pooled effect sizes because the literature uses heterogeneous technologies, lean practices, industries and outcome measures. The framework therefore represents a synthesis of recurring mechanisms rather than a universal causal model. Future research should test the proposed layers longitudinally, compare alternative implementation sequences and examine whether specific technology–lean combinations produce consistent sustainability effects across sectors. More evidence is also needed on cybersecurity, digital obsolescence, workforce redesign, small-firm constraints and the rebound effects that can offset efficiency gains.

## IX. CONCLUSION

Lean 4.0 offers a credible route to sustainable industrial performance when digitalisation is anchored in lean operating discipline. The evidence reviewed here indicates that process stability, real-time visibility, analytical intelligence, responsive execution and sustainability governance form a logical capability sequence. The framework shifts attention away from technology acquisition and toward the design of an integrated production system in which information improves action, action improves learning and learning improves both value creation and resource performance. Organisations should therefore digitise selectively, preserve human problem-solving capacity, measure economic, environmental and social outcomes together, and scale only those technologies that strengthen a clearly defined lean mechanism. Under these conditions, Lean 4.0 becomes more than a collection of smart-factory tools: it becomes a strategic management architecture capable of linking continuous improvement, adaptive digital control and long-term industrial sustainability.

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