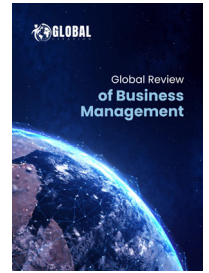




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Sustainable Supply Chain Transformation in the Era of Industry 5.0: A Narrative Review

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Abstract

Background:

Supply chain transformation is moving beyond an automation-centred approach towards the sustainability-, resilience-, and human welfare-centred orientation represented by Industry 5.0.

Objective:

This narrative review aimed to synthesise evidence concerning the redesign of supply chains for sustainability through supporting technologies, including artificial intelligence, digital twins, blockchain technology, collaborative robotics, additive manufacturing, and Internet of Things infrastructures.

Methods:

Literature published between 2020 and June 2026 was examined through socio-technical, circular-economy, and supply-chain-viability perspectives. The evidence was reviewed to identify how Industry 5.0 technologies support sustainable supply chain transformation and the organisational conditions affecting their implementation.

Results:

The findings showed that digital visibility can support forecasting, traceability, resource conservation, and disruption mitigation. However, technology alone does not demonstrate sustainability. Greater benefits were identified when organisations reconfigured supplier relationships, material flows, organisational arrangements, social relationships, skills, responsibilities, and incentives. Major challenges included legacy systems, cybersecurity risks,

variable supply conditions, potential rebound effects, uncertainty regarding return on investment, and the absence of adequate social-performance metrics.

Conclusion:

The review provides recommendations for a transformation pathway and an implementation architecture. Industry 5.0 is interpreted as a change in governance and organisational capability in which technology acts as a facilitator rather than independently transforming supply chain coordination.

Keywords

Industry 5.0; Sustainable Supply Chain; Resilience; Human-Centricity; Circular Economy; Digital Transformation

1. Introduction

Climate change, geopolitical fragmentation, the effects of Covid-19, and the scarcity of labor and resources have presented a great shock to global supply chains, while stakeholders continue to demand a growing number of reports on companies' environmental and social responsibilities in the 2020's. Connectivity, automation, predictive analytics and cost-effective coordination were the topics of discussion in Industry 4.0 top individual responses (Almunawar et al., 2023). These capabilities did help to increase visibility and speed; however, these capacities did not put an end to the logical structure of increasing the short-term win in exchange for ecological damage, exploitation of labour, and vulnerability to the system shock. Among other visions emerging was Industry 5.0, which prioritized human centricity, sustainability and resilience as well as productivity and competitiveness (Castillo et al., 2025).

This change had an impact on SCM. A supply chain is not just a series of transactions or even a digital control issue. This is a distributed socio-technical system which allocates risk and value across multiple actors, including firms, workers, communities, regulators and ecosystems. This led to a transformation from factory automation to network Viability-Industry 5.0. It asked the questions whether supply chains could function

in times of disruption, regenerate resources, offer dignifying employment and be resilient to society (Alves et al., 2023). This agenda, according to Ivanov, is a new triple bottom line: Resilient value creation, human well-being and the sustainability of societal improvements. Subsequent analyses, however, say that Supply Chain 5.0 is not meant to replace the term digital supply chain but is an architecture.

These studies investigated AI, blockchain, IoT, Co-botics, additive manufacturing and also digital twins. Emissions, Circularity, Resource productivity, Responsibility of suppliers and redundancy, regionalization, agility and stress testing were among the characteristics of the resilience studies (Dalati, 2025). Human factors research included: Safety, Ergonomics, skills & participation, human-machine collaboration. Often these streams were parallel, and the intersections were not always clear, and how these intersections changed the nature of the outcome of the supply chain (or how it created new risk(s)) was not clear.

Here, studies have tried to address such an issue by summarising and synthesising the very recent academic and policy evidence through three interdependent lenses related to socio-technical systems, circular economy and (dis)viability of supply chains. It responded to four questions, which were treated.

- **RQ1:** What does 5.0 Industry change the definition of sustainable supply chain transformation to?
- **RQ2:** What were the enabling mechanisms for environmental, resilience and social outcomes with the use of digital technologies?
- **RQ3:** What organization and governance mechanisms fell to the beneficiaries of the technology, and resulted in potential becoming something tangible and measurable?
- **RQ4:** How much potential for change existed, subject as it was to multiple tensions and implementation problems?

The review assisted in answering questions like what should be intervened to meet the need for digital foundations, human capabilities, circular redesign, network resilience and accountability on performance in the context of integrative architecture and a staged roadmap.

2. Conceptual Foundations

The new Industry 5.0 has been referred to as the 'normative reinterpretation and extension of Industry 4.0'. The technological basis was provided by Industry 4.0 in the form of cyber-physical systems, connected machines, cloud platforms, analytics and automation. With the coming of Industry 5.0, these competencies have been redirected towards human and societal purposes. This contrast was telling because work efficiency is now a must, but not a 'must have'. A fragile, social or excessively environmentally damaging supply chain, the capacity of a technologically advanced process would not hold steady shocks (Fares et al., 2025).

Environment, Economy and Social value were the three dimensions taken for considering the first pillar, Sustainability. Environmental transformation included lower material and energy intensity, decarbonised logistics, preventing waste, reverse flows, repair, remanufacturing, and recycling. The need for finding some viable returns and some productivity capacity of transition and investment was economic sustainability. Social Sustainability included; occupational health, fair work, inclusion, supplier development, and community impact. Industry 4.0 had moved forward in terms of economic value as well as some aspects of environmental values, but ignored or jeopardized some of the social values which gave rise to Industry 5.0 (Fares et al., 2025).

The second – resilience – was not about the transitory. Viability was associated with the ability of the supply chains and their ecosystems to survive, supporting long-term changes in their structure through adaptation and reconfiguration. This vision combined three elements which depict agility, resilience and sustainability. It shifted the attention away from recovery and toward preservation of critical functions, including through alternative sourcing, modular capacity, substitution, demand shaping, and inventory management and ecosystem interactions. Strategic options were only possible with concrete suppliers, skills, capital and governance, but stress testing could be achieved with digital twins/analytics of scenarios.

The third pillar – human-centricity – set the tone

for using technologies in a way that would augment them. Human-centred logistics and production systems designed for enhancing safety, cognitive ergonomics, learning, participation and meaningful decision authority. Collaborative robotics can be used to automate dangerous or repetitive processes, Augmented Reality can be used for training and maintenance, and Artificial Intelligence can be used for improving planning. However, these technologies could contribute to: surveillance, deskilling or centralization of knowledge. It was therefore necessary to use human-centricity, that is to ensure that employee voices were heard, algorithms openly understood and interfaces easily accessible and that benefits were explicitly distributed (Ghobakhloo et al., 2024).

The circular economy theory was used to select the material-flow logic. Key difference, linear supply chains involve the unidirectional moving of resources from extraction to disposal, circular supply chains aim to keep the value of resources by designing products to be durable, reusable, refurbishable, remanufacturable and recoverable. They can be digitally provided product identities, sensing, and traceability may demonstrate the location, condition, origin and environment attributes during the product's lifetime. However, the collection, secondary markets, product design, contractual incentives and customer participation are important conditions for the achievement of circularity. Information continuity was created via technology, and institutions came to know of the materials.

3. Narrative Review Methodology

The study has been done as a critical narrative review and secondary analysis. Of the conceptual, empirical, technological, organizational and policy literatures framing this research question, all had different designs and outcome measures, therefore a narrative approach was utilized. The technique was designed to allow for the inclusion of thematic explanations and tensions, but not effect size.

Academic and policy English publications regarding this were searched from January 2020 to June 2026. The search for sources was carried out by the

combinations of the following: “Industry 5.0”, “Supply Chain 5.0”, “sustainable supply chain”, “human-centric supply chain”, “supply chain resilience”, “viability”, “circular supply chain”, “digital twin”, “artificial intelligence”, “blockchain”, “collaborative robotics”. Peer-reviewed journal articles, systematic reviews, and empirical articles, as well as policy reports produced by authoritative sources, were preferred. The studies related to viability and digital-sustainability bases were found using reference chaining (Ghobakhloo et al., 2024).

Publications that described the Industry 5.0 principles together with 2 or more of the following aspects were selected: Supply chain/ logistics systems, digitalization/ digital transformation, environmental issues/ social issues, circular economy, resilience, and human-centred work. All papers pertaining to the algorithm without identification of the supply chain were excluded. The final evidence base was not

extensive, and focused on key publications, recent reviews and empirical research in manufacturing, logistics, and agri-food and in emerging economy contexts.

The data was deducted and organized in a structured matrix considering the lenses, technology, Supply Chain function, Sustainable outcome, Resilience mechanism, human, barriers and management implications. Data was analyzed using open coding, thematic grouping, integrative interpretation. There were 5 themes developed: Digital visibility and decision support, Circular material transformation, Resilient and viable network design, Human-centric capability development and Governance, risk and measurement. To highlight this, both evidence and implementation barriers were presented and deviant to exclude the option of Industry 5.0 as a naturally sustainable progress of technology (Issa Ali Dungus, 2023).

Table 1. Narrative review design, evidence boundaries, and analytical safeguards

Element	Specification	Analytical implication
Review purpose	Integrate fragmented evidence on Industry 5.0, digital transformation, circularity, resilience, and human-centric supply chains.	Critical narrative synthesis rather than pooled effect estimation.
Coverage	English-language academic and policy evidence published from January 2020 to June 2026	Recent evidence was prioritized while foundational viability studies were retained.
Search concepts	Industry 5.0; Supply Chain 5.0; sustainability; human-centricity; resilience; Viability; circular economy; AI; blockchain; IoT; digital twin; cobots.	Concept combinations were used to capture technological and organizational streams.
Inclusion logic	Publications addressed supply chains or logistics, plus at least one Industry 5.0 pillar and one transformation mechanism.	Technical-only algorithm papers without supply chain interpretation were excluded.
Analytical lenses	Socio-technical systems, circular economy, and supply chain viability.	Evidence was coded for mechanisms, outcomes, tradeoffs, and boundary conditions.
Quality safeguards	Priority to peer-reviewed reviews, empirical studies, influential conceptual work, and authoritative policy sources.	Contradictory findings and implementation risks were retained.

4. Findings

4.1 Digital visibility, intelligence, and coordination

Informational infrastructure using digital technologies was set up in Industry 5.0 supply chains. The sensors

of IoT monitored the real-time location, temperature, percent utilization, quality and energy use. Artificial intelligence facilitated the forecasting of demand, the storing of inventory, routes optimization, detecting anomalies and assessing supplier risks. Multiple organizations ensured security over blockchain and distributed ledgers, where there is no trusted central database for holding the provenance and joint records. The digital twins were able to demonstrate disruptions, capacity change, sourcing and circular flows from operational data and simulation before even implementing them physically (Ivanov, 2023). The evidence indicated that, without decision-changing, there was no relationship between visibility and sustainability. If Shapping and Seuring are right,

such research for sustainability has so far remained dedicated to 'echo-efficiency' and to measurable environmental outcomes, but less attention has been paid to more socially nuanced outcomes, which are harder to measure, due to the scale and complexity of the datasets. Traceability could be used to identify high-emission suppliers, but the improvement should be rewarded by contracting and purchasing incentives IN Purchases. To extend the life of assets, organisations needed maintenance capacity and spare part strategies, and so came the vision of predictive maintenance. Optimizing fuel cost could potentially be achieved with routing; however, there may be rebound effects in terms of increased deliveries due to time-sensitive service expectations.

Industry 5.0 Sustainable Supply Chain Transformation Architecture

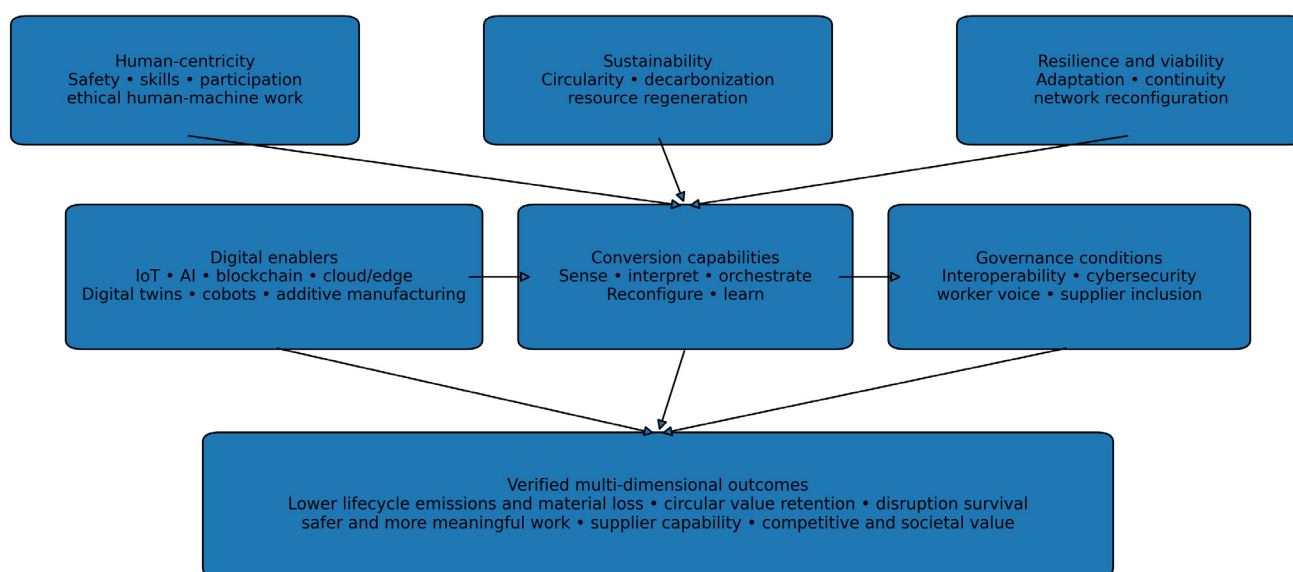


Figure 1. Industry 5.0 sustainable supply chain transformation architecture.

Digital Twins were a key element of resilience and sustainability. A set of supply chain twins could be used to simulate different carbon, cost, lead time, service and disruption scenarios along the network configurations. With the intelligent twins with AI-supported learning and human decision rules, proactive stress testing instead of reactive monitoring became possible. They were evaluated in terms of the competency of model fidelity, competency of interoperability with data and competency of

human and environmental factors. A twin might only be operated for in-country production – the most efficient possible production in the country – and pollute or harm mobile. Thus, for Industry 5.0, a network-level and lifecycle boundary was needed.

4.2 Circular transformation and regenerative material flows

The easiest route from the digital to environmental change was circularity. Industry 5.0 technologies

like condition-based recovery, digital product passports, automatic sorting and repair by additive manufacturing, and coordination of reverse logistics support the product-as-a-service business model. Liu and colleagues read and collated four cloud services, AI, big data analytics, blockchain and IoT, in design, manufacturing, delivery, use and end-of-life. A study by Rejeb et al. revealed the presence of a growing number of points of intersection between Industry 5.0 and literature on circular economy, particularly in areas such as automation, machine learning, 3D printing, blockchains and cybersecurity and human-machine collaboration (Kalsoom et al., 2025).

Informational-Organisational transformation mechanism was applied. Circular supply chain included knowledge about the composition of the product, property rights, condition, reusability and residual value. The sensors and digital records reduced uncertainty, and analytics linked returned products to re-use, re-furbish, remanufacture or recycle activities. Digital twin helped businesses evaluate material loops/reverse capacity. Selective manufacturing of spares by additive manufacturing reduces obsolete stocks. Collaborative robots could result in improved disassembly/sorting processes and protection of employees from hazardous jobs.

But nothing could be assumed which would ensure circularity. Digital systems use energy, hardware, and minerals of critical importance. The additional expense of blockchain architectures may be significant. Additive manufacturing would provide a greater variety of materials for recycling and make it more challenging. It is possible to be more efficient and use more. But there were numerous incremental improvements to digital applications that were seen by Rusch et al., but didn't involve any circular transformation. Product design, EIPR, material requirements for second-use products, take-back solutions and revenue models that are based on product use value and lifespan and not on volume, would mark the deeper transition.

4.3 Resilience, Viability, and Network Redesign

Resilience was further developed in the Industry 5.0 context to mean the capacity to sustain critical resources during the event of longer disturbances and adapt. The geographically tight sourcing, the

low levels of inventory, the lack of visibility, and supplier vulnerability were brought to light by the pandemic. There are complementary post-pandemic responses, such as: regionalization, diversification, collaboration, agility, transparency, employee health, smart technologies and circular practices. Digital tools were used for sensing and response, and structure options determined the resilience. A risk dashboard sharing could provide an indication of concentration without the need for a risk to trigger the need for an alternate supplier. Relying on AI could potentially lead to forecasts of disruption, but with a lack of flexibility in the contract or alternative materials. This involved multi-source, modular product design, postponement, strategic buffers, regional capacities and collaborative planning and qualification procedures. Expanding the concept to the survival of ecosystems, Viability was not limited to restoring a single 'optimal' configuration, but was rather about transitions, or shifts, occurring between alternate network configurations (León et al., 2024). Sustainability and resilience can be complementary, or conflicting. Depending on the production efficiency, regionalization also increased the cost or carbon intensity in some instances while decreasing exposure and transport distance. Continuity was provided with the help of inventory buffers, but other impacts included wasteful resource utilization and the risk of obsolescence. Having redundant suppliers improved resilience; however, this situation also raised the auditing complexity. At the time, it was not a solution itself, but a multi-objective decision framework to be called Industry 5.0 contribution. The portfolios of responses rather than single-point optimization might be possible due to the potential for representation of tradeoffs by using digital twins, scenario analysis and participatory governance.

4.4 Human-centric supply chains and workforce capability

Finally, Industry 5.0 was distinguished by its human-centricity, as opposed to automation-centric transformation. With respect to the role of workers, it was found that they continued to play a significant role in exception handling, supplier relations, ethics, maintenance, improvisation and learning. Technologies that closely fit into Industry

5.0 (Reduced physical efforts, increased safety, knowledge access and better decision-making). Together with collaborative robots and the wearing of wearables that sense danger, AI can provide sense and cohesiveness for planners. If so, operator diversity, human factor (and ethics) need to be taken into account when designing a system and not only as an operator constraint, Große et al. emphasised (Li & Duan, 2025).

Thus, in the case of capability development, it was an investment in the supply chain. The new roles were characterised by data literacy and proficiency with data, systems thinking, sustainability knowledge, and awareness and use of AI suggestions. In particular, supplier-development programs proved very important as the smaller company would probably be skimping on capital and expertise. However, financial constraints, cultural obstacles and sectoral alignment were shown to be restricting factors, whereas proactive leadership, employee engagement, circular economy and personalisation in digitalisation were revealed to be enabling factors by Castillo et al.

In addition, there was a need for the governance of power in terms of human-centricity. Data platforms might obtain knowledge and take surveillance at the same time as well. While there are benefits to automated scheduling, there are risks as well; it can generate more intensive work. Smaller or informal suppliers may not be accepted by the algorithmic supplier scoring, where they may have incomplete supplier data. Cobots might enhance the ergonomics and, at the same time diminish job security. So, considering all the mentioned issues like consultation, retraining, appeal mechanisms, safety validation, privacy protection, and benefit sharing in an Industry 5.0 program is also necessary. Social performance indicators needed to move beyond heads or hours in training to include indicators that move along the lines of injury, workload, progression of skills, voice, quality of wages and wage agreements, diversity and supplier inclusion.

4.5 Governance, interoperability, and transformation barriers

Challenges weren't so much issues of stand-alone technology performance as the integration of systems. Legacy enterprise systems, inconsistent

master data, proprietary systems and low standards created a challenge to achieve end-to-end visibility. Increased cybersecurity exposure due to greater network coverage of operational technology, suppliers and cloud. This lack of transparency in data quality undercuts AI and models, reducing trust and accountability. Up-front costs and returns were limited for Small and Medium Enterprises. Regulatory differences arose, impacting cross-border traceability, product passports, environmental claims and data sharing.

Governance fragmentation also proved to be an important issue. Sustainability teams use different objectives and time frames than those of other teams (procurement, operations, IT, risk, human resources). A Purchasing Organisation that has a focus on purchase price variance may have a negative effect on Circular Sourcing/supplier development. A logistics function which was only seen through the viewpoint of its service and its costs would be able to simply bury its head in the sand concerning emissions and driver welfare. Thus, an optimal investment in incompatible local metrics could potentially be made through investing in technology. A common ownership, common data definitions and shared suitable performance metrics were essential for Industry 5.0 (Machado & Rodriguez, 2025).

In addition, limitations of evidence were identified via the literature. Most of the studies were conceptual review(s), models or pilot(s) and did not include empirical evidence. Dacre et al. said there's a lot of potential, but the implementation tasks are "amorphic. The social indicators were not analysed as much as technical efficiency and environmental indicators. High-tech input systems were very poor at capturing constraints in emerging economies, primarily due to problems of infrastructure and financing. The different lacunae led to a cautious reading: Industry 5.0 did offer a valuable orientation, but there was a need to make claims for transformation further underpinned by the evidence after the time of multiple layers of real supply networks.

4.6 Technology portfolios and interdependence

The literature indicated not to make a standalone assessment of technologies. Portfolios where complementary technologies act with each other

are required to transform the supply chain. They included timely observations with IoT technologies and infrastructure, cross-firm assurance rooted in the source of the data (such as via blockchain or a governed data space), data transposition to a cloud or an edge, and data transformation to help in predicting and/or intervening: that's a digital twin with a shared simulation environment, and there were human interfaces for data interpretation and data-driven interventions. Carefully removing one layer can cause an impaired system. A robust blockchain-based tracking was unable to detect issues with information flow in the upstream, but in the case of no suppliers reacting or disclosing any capacity, a complex forecasting was unable to bear out.

Portfolio design also played a role in determining the influence on sustainability. These computing-intensive architectures can lead to increased electricity, hardware refresh and demand for critical minerals. Digital sufficiency thus became a prerequisite for all sorts of companies: the most basic possible technological infrastructure to achieve a specified environmental, resilience and/or social objective (Martini et al., 2024). Distributed equipment was added to reduce latency and potentially data transfers may have been reduced via edge processing.

A permissionless blockchain could be more expensive when it comes to energy (or governance) than the latter, due to different characteristics such as openness. The increasing level of resolution of the digital twins has improved the quality of analysis, but also necessitated extensive amounts of data management. An LCA (Lifecycle Assessment) and cybersecurity analysis was performed, and an explicit contribution to the technology selection process was made using digital versus non-digital alternatives.

Technology wasn't the only thing that was interdependent. The digital product passport was only effective if there was a willingness of the network to adopt product identifiers, material taxonomies, repair standards and access rights. Shared definitions and procedures for escalation of supplier-risk systems were needed to help with predicting supplier risk. Not just setting up equipment to enable human-machine collaboration is about the redesign of what the tasks are. Larger questions were not therefore raised regarding the procurement of advanced tools for Industry 5.0, but rather whether the Industry 5.0 maturity portfolio provided a means to make coordinated, verifiable and inclusive decisions across the organizational boundaries.

Table 2. Industry 5.0 technology portfolio: supply chain functions, human roles, and risks

Technology	Supply chain function	Potential contribution	Human role	Key risks
IoT and sensing	Condition, location, energy, quality, and emissions monitoring	Visibility, preventive action, reduced loss	Interpret exceptions; maintain sensors; protect privacy	Data quality, surveillance, device footprint
Artificial intelligence	Forecasting, optimization, anomaly and supplier-risk detection	Efficiency, agility, disruption anticipation	Frame objectives; challenge outputs; manage overrides	Bias, opacity, rebound, automation dependence
Digital twins	Scenario simulation, lifecycle modelling, stress testing	Resilience, circular planning, multi-objective design	Validate assumptions; select scenarios; authorize response	Model boundary errors, high data burden
Blockchain/data spaces	Provenance, shared records, product passports, assurance	Traceability, accountability, circular coordination	Govern access and verify source data	Energy use, interoperability, and exclusion of small suppliers

Cobots, AR, wearables	Task assistance, ergonomic support, training, and maintenance	Safety, productivity, knowledge access	Co-design tasks: retain authority and safety stop rights	Deskilling, work intensification, and biometric privacy
Additive manufacturing	Localized spares, repair, customization, and reduced inventory	Longer asset life, resilience, and selected transport savings	Assess material quality and end-of-life pathways	Material complexity, energy intensity, certification
Cloud/edge platforms	Cross-tier data integration and rapid processing	Coordination, scalability, collaborative planning	Define data rights and continuity plans	Vendor lock-in, cyber risk, unequal digital access

5. Discussion

The synthesis indicated that the transformation of the sustainable supply chain happened in a series of conversions instead of the impact of the technology. Digital infrastructure brought about visibility, connectivity and analytical capability. Ability had been organized and information converted to concerted actions. Towards a circular economy, redesign the new flow of materials and revenues. Structural options are created using Resilience capabilities. A governance approach where humans were in the centre ensured agency, safety and learning. Performance systems assessed afterwards whether these were in alignment or not. This architecture can be thought of as a set of three normative pillars: Enabling technologies, Transformation capabilities, and multi-dimensional outcomes, as depicted in Fig. 1.

Thus, this interpretation makes possible the simultaneous merging of two different narratives. The rosy picture suggests that Industry 5.0 technologies can be solutions to emissions, waste and disruption. In terms of the critical voice, the themes were: digital footprint, surveillance, exclusion, cybersecurity and rebound. Both were viable because they could be said to be design-and-governance dependent. AI can help to minimize waste or accelerate consumption. Responsibility could be fostered in blockchain, and data setups could become very costly. Regionalization may reduce vulnerability and/or duplication of ineffective capacity. Cobots can be used to augment workers or erode workers' bargaining power. Thus, Industry 5.0 turned out to be an appropriate description of 'Governance of Tradeoffs' (Nallamala

et al., 2025).

It was also during the review that an extension of the Viability of the supply chain was made possible. Previously, there was a subset of Viability called Agility, Resilience and Sustainability. In Industry 5.0, the issues of human well-being and responsible technology are no longer a side condition, but part and parcel of the future industry. This was, however, an operation resilient supply chain, albeit vulnerable to the excessive risk distribution by the workforce or/ and/or to the vulnerable suppliers, which is not an Industry 5.0 compliant supply chain. Just as with the low-carbon supply chain, it could also be a systemically fragile supply chain, based on opaque algorithms and any digital platforms that can't be replaced.

An identified framework identified the following five conversion capabilities. First, the integration of sensing data with data on the environment, operation and social/risks. Second, there was some mixing of interpretation and analytics, and some human judgment. Third orchestration coordinated the purchasing, production, logistics, suppliers and regulators. Fourth, a whole reconfiguration of Products, Networks, Capacity and Business Models. Fifth, filling in new models, contracts, skills and policies as a result of observing outcomes. These capabilities are not only assets but also operating models of the supply chain to utilize technology (Machado & Rodriguez, 2025).

The measurement was a key controlling factor. Firms should correlate leading indicators (such as provider information accessibility and frequency of scenario-testing, workforce engagement, product traceability) with lagging indicators (such as emissions, material

and energy recovered, disruption losses, injuries, provider survival). Local optimizations had to be avoided by considering lifecycle and multi-tier in the metrics. Business case is: If the strain on the workforce was increased, energy reduction in a warehouse was not necessarily a system improvement, if other parts of the transport chain were increased. Independent assurances and clear baselines were needed to prevent 'green-washing' (Tyagi & Tyagi, 2025).

The discussion revealed that transitioning is not something that needs to be thought of as a one-time process rather as a process requiring time. Material, carbon, risk and human hotspots were the first objects for the identification process by organizations. First, though, they had to define decision rights and what the operating model should look like and do so before buying complex decisioning tools. There needs to be foundational interoperability and supplier "bringing their needs along" before any advanced AI or blockchain can take place. Testing of economic, environmental, social and resilience outcomes should be done simultaneously by pilots, it is recommended.

When governance, skills, cyber security, and benefit-sharing arrangements were credible, scaling should take place.

The other implication had to do with the unit of transformation. Most of the corporate programs were governed at a focal-firm level, and sustainability/simultaneous resilience outcomes were discovered throughout networks. Bigger customers may demand traceability, lower levels of pollution and charge smaller customers. This would lead to higher data replication and less network diversity/integration. Capability sharing from common platforms, technical assistance and long-term contracts, even easily available finance, were needed to launch Industry 5.0. Supplier development was not philanthropy; indeed, it was about protecting data quality, circular recovery and the ecosystem level resilience (Dalati, 2025).

Tradeoff means that with the lapse of time, some modifications were processed too. May appear to be overkill during a time of peace but could prove useful during time of crisis/redundancy or local capacity. Circular design of a product could entail an

Staged Roadmap: From Digital Visibility to Supply Chain Viability

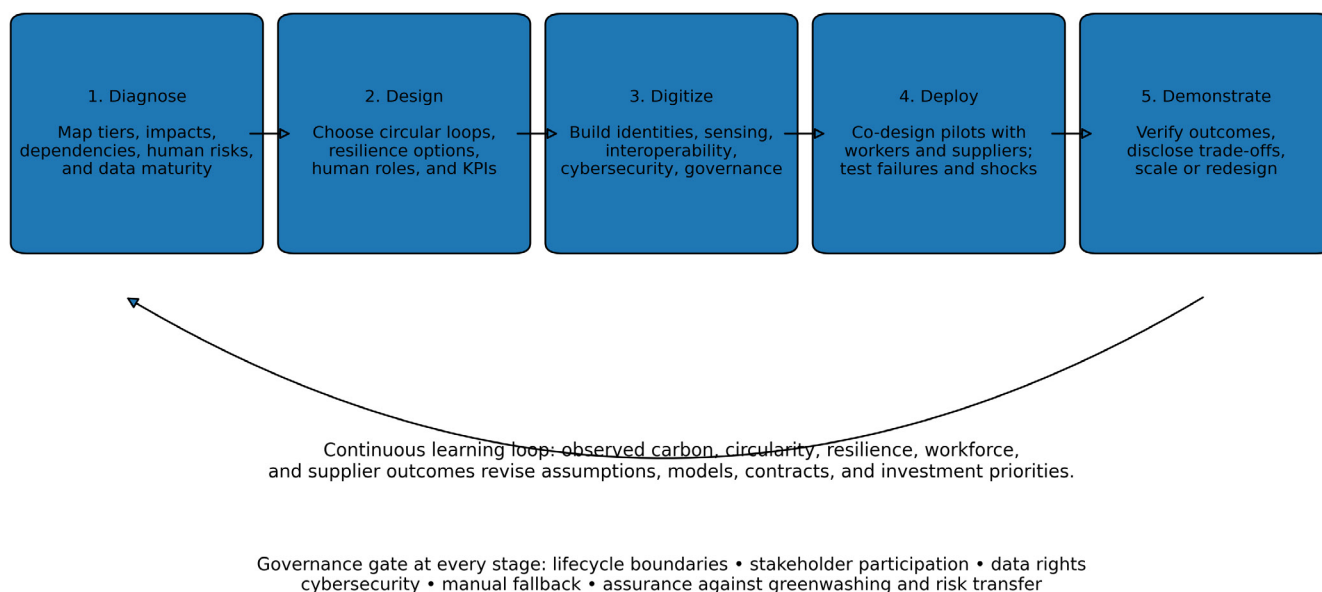


Figure 2. Staged implementation roadmap from digital visibility to supply chain viability

investment for the initial design phase, but can result in reduced lifecycle cost and risk of virgin material utilisation. Reskilling may result in overall lowered productivity, but raise adaptability and innovation in the short term. All these risks and benefits have been overlooked in traditional investment valuation. The real-options approach, along with scenario planning as well as business cases focusing on resilience, would be a suitable way to capture flexibility and survival value (Alves et al., 2023).

Finally, the concept of “transformation” and “optimization” was differentiated. Optimisation improved the products, networks and the commercial assumptions within the existing products. Transformation has come to an end for those assumptions: products have become services, waste is transformed into feedstock, suppliers are co-innovation partners, and workers become co-designers of technology. Industry 5.0 promises to be pretty empty if its businesses continue to take the same actions as before: faster forecasts, more efficient routing, where the spread of risks and value remain unchanged.

6. Managerial and Policy Roadmap

There were 5 phases to the roadmap, with a focused, practical approach. For diagnosis, stacks of supply tiers, impact on the lifecycle, critical dependency, workforce risks and data maturity were identified. At the design phase, a circular strategy, resilience options, human role and a balanced score card, were selected. At the digitize stage is setting up interoperability data, identity, sensing, cyber security and model administration. Use cases with workers and suppliers were tested in the deploy stage, including failure and disruption scenarios. Most importantly, the demonstration stage has resulted in results being validated, compromises being identified and investments being reduced (Martini et al., 2024). Managers’ #1 priority should be addressing known problems in the supply chain through use cases, not to posture technology supremacy. This included quite some important candidates such as energy and material monitoring, predictive maintenance, supplier risk-sensing, digital product passports, return-flow

optimization, and digital-twin stress-tests. Next, baseline, affected stakeholder and decision owner for each case were identified, along with control limits/exit criteria. Several strategies regarding carbon reduction and carbon recovery demonstrators should be promoted in the procurement contracts, alongside the carbon price per unit, for incentives and funding purposes.

Fast track transition through interoperable standards, digital infrastructure, cyber security support, circular-product-regulation and skilled systems and targeted SME finance is possible. Low-carbon and socially responsible products required in public procurement must be traceable and reusable. Data spaces need to avoid being a means for dominant firms to get supplier data without giving back. Environmental claims should be allowed to be made under regulation, and personal data and commercially sensitive information should be protected (León et al., 2024).

The vision in the roadmap (Fig. 2) envisioned the change as a learning process. Evolving technologies and risks/expectations of stakeholders were also brought into the diagnosis with the feedback of the demonstrated outcomes. The idea of a target or end state of the Industry 5.0 was thus dismantled. The aim was to establish a concept of adaptive governance capable of making constant compromises between competitiveness, the survival of a network, human well-being, and ecological limitations.

Boards need to be responsible for supply chain, sustainability, technology, finances, human resource management, and cybersecurity details and supplier representation, to mention a few issues. Capital approval should be tied in with decisions for each of the technologies, stakeholders and confirmed impacts should be tied in. The ability to lock-in was restricted in three ways: (1) modular architectures, (2) open standards, and (3) portable data for use in a staged contracting approach. Testing algorithms, worker interfaces, and circular logistics in a pilot sandbox before scaling. However, during disruption events with a longer time scale and/or multiple layers of failure, there was still the need for manual fallback procedures, when the sensor fails or if a cyber-attack is made, model miscalculations and/or supplier disconnections.

Table 3. Industry 5.0 transformation roadmap, performance indicators, and governance gates

Stage	Priority actions	Indicative KPIs	Governance gate	Policy enabler
Diagnose	Map multi-tier network, lifecycle hotspots, critical dependencies, skills, and data maturity.	Tier coverage; Scope 1-3 baseline; critical-source concentration; injury/workload baseline	No technology business case without a system boundary and stakeholder map.	Open data standards; SME diagnostic support
Design	Select circular strategies, resilience options, human roles, and target operating model.	Repairability; recovered-value target; alternate-source readiness; participation rate	Document tradeoffs and decision authority	Circular-product rules; skills and just-transition policy
Digitize	Establish product identity, sensing, interoperability, cybersecurity, and model governance.	Data completeness; latency; model calibration; cyber recovery time	Lifecycle and security review before connection.	Shared data spaces, cybersecurity grants, interoperability standards
Deploy	Pilot with suppliers and workers; test disruption, failure, and rebound scenarios.	Pilot carbon/material effect; service recovery; worker safety; supplier adoption	Scale only after independent verification and fallback testing.	Regulatory sandboxes; collaborative innovation funding
Demonstrate	Assure outcomes, disclose tradeoffs, share benefits, and revise priorities.	Absolute emissions; circular revenue; time-to-recover; supplier survival; skill progression	Audit against baseline and prevent burden shifting.	Public procurement, disclosure assurance, targeted transition finance

7. Limitations and Future Research

This review was narrative and purposive, and not a comprehensive coverage and quantitative estimates of effects of databases. The majority of evidence found was in conceptual frameworks, systematic reviews, simulations, and early-stage case studies. The key differences between all the terminology that was used were Industry 5.0, Supply Chain 5.0, viable supply chains, smart circular supply chains and human-centric logistics. As a result, there were few causal assertions with regard to performance. Longitudinal investigations/ longitudinal trials are required to follow a technology from starting a pilot to scaling up via Multi- Tier Designs. Absolute impacts and rebound, as well as impacts of labour

and distribution of value to the key companies and suppliers, should always be provided as part of all studies. Comparative studies are required to be done in sectors, firms and institutional setting. In digital-twin and AI studies, the influence of human decision behavior and the modelling of failure should be included. Retained value and NOT just collection rate, should be studied in connection with circularity. Finally, universities should study the benefits of the integrated Industry 5.0 portfolios regarding baseline and edge efficiency of combo disruptions, as well as the standalone digital, green and resilience portfolios.

8. Conclusion

Human-centricity, resilience, and sustainability were added to the mix with advanced digital capabilities, which give Industry 5.0 a broader logic for 'sustainable' chains. From the review, improvements in visibility,

the simulation, traceability and coordination through the use of AI (Artificial Intelligence), IoT (Internet of Things) technologies, blockchain, digital twins, cobots and additive manufacturing were identified, but they did not provide any sustainable results individually. Circular product design, the availability of circular products and materials, cooperation with suppliers, employee competences and responsible governance proved to be important drivers to facilitate a transition.

The one main point I think I would retain is that technology presented the ability to select and Institutions presented effects as they walked down the lonely road of Sustainable Supply Chain 5.0, decisions needed to be made to ensure that the four fundamentals – cost and service – along with the sustainability – carbon, material recovery and disruption survival, as well as safety and inclusion – are in the mix. Firms should therefore get rid of technology pilots and switch to integrated operating models featuring interoperable data, worker engagement, lifecycle metrics, cyber security, and transparent learning. Once industry was intelligent, it was able to sustain itself, renew itself and transform itself, with the approval of the people and societies that had nourished it, then Industry 5.0 was something.

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Conceptualization, Methodology, Investigation, Data Curation, Formal Analysis, Visualization, Writing – Original Draft, and Project Administration.

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