Beyond Efficiency: A Comparative Analysis of Technological Foundations and Human-Centric Values in Supply Chain 5.0

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ABSTRACT

This paper discusses the development of Supply chain 4.0 to Supply chain 5.0 where models focus on automation as a result of efficiency to models that focus on human-centric whose focus is on resiliency, sustainability, and ethical mindset. Supply Chain 4.0 combines the use of technologies like IoT, cyber-physical systems, analytics of big data, and robotics to maximise the visibility of operations and responsiveness, it is mainly aimed at maximising throughput and lowering costs. However, Supply Chain 5.0 builds on all these by adding collaborative robots, blockchain verification, digital twins, and AI-driven multi-criteria optimization that manage the economic performance and the environment and social goals. The revolution entails intricate technological incorporation issues, employee adjustment, as well as reorganisation of the enterprise to meet the needs of hybrid man-machine cooperation and sustainability requirements. Other socio-economic and regulatory considerations, such as the problem of replacing workforce, development of skills, and adherence to the new environmental and labour standards, are discussed in this analysis, as well. The next steps include interdisciplinary cooperation in the field of engineering, environmental science, economic, and social policy to create supply chain systems that balance operational efficiency with ecological stewardship and social equity. New trends involve decentralised manufacturing, incorporation of renewable energy and proactive participation of workforce and proactive compliance regulation, all of which define supply chains as dynamic socio-technical ecosystems, able to sustain performance despite systemic disruptions.

Keywords: Supply Chain 5.0, Human-Centric Design, Resilience, Sustainability

INTRODUCTION

Supply Chain 4.0 (SC 4.0) was a natural extension of Industry 4.0, in which the tools of Internet of Things (IoT), big data analytics, blockchain, and artificial intelligence were used to develop a digital supply chain with greater responsiveness, transparency, and flexibility (Boudouaia et al., 2024). Intelligent networks that support this paradigm can result in autonomous communication between machines and operational processes to create integrated environments that simplify the manufacturing process, distribution process, and service of goods (Ralston and Blackhurst, 2020). This phase is still focused on efficiency gains, real-time visibility and data driven agility. In comparison, Supply Chain 5.0 is oriented to the organisational ideals of Industry 5.0, which promote the principles of resilience, sustainability, and values oriented towards people as its core values (Ivanov, 2022). The innovations here are not related exclusively to automation or efficiency but also rethink the place of humans along with new advanced technologies such as collaborative robots, edge computing systems, and digital twins (Golovianko et al., 2023). It also implies non-trivial safety and control considerations in human-robot shared workplaces, where effective real-time sensing and fail-safe human-robot coordination is required to safeguard workers in close-proximate relationships (Jefroy et al., 2022; Boudouaia et al., 2024).

However, implementation comes with its own problems which cannot be ignored. Investment-wise, the move to Supply Chain 5.0 makes the business case more complex since traditional ROI calculations that successfully apply to automation upgrades can hardly succeed when capital costs reach sustainability-associated upgrades, including renewable energy integration or advanced emissions monitoring equipment linked to IoT architectures (Agrawal et al., 2024). Such financial cost will be more limiting to smaller companies with less capital buffer, which can delay the systemic transition when upstream/downstream suppliers are not able to switch as fast as others (Varriale et al., 2023). In addition, a large portion of the value proposition is qualitative, e.g., corporate reputation gains and systemic risk reduction, so initial assessments may not show conclusively even in cases of long-term strategic gains (Agrawal et al., 2024; Nazarian and Khan, 2024). In the absence of rigorous sequencing between the maturity of technology and the training of the workforce, implementation may become stagnant or yield less than optimised hybrids that may not deliver any benefits in a way that is convincing (Boudouaia et al., 2024). At that, the creation of values is shared among physical efficiency improvements and less direct advantages like avoiding downtime and being prepared to comply with standards and reputational capital, which may complicate the payback timeframes to justify in the context of short-term pressure on the margin (Frederico, 2021).

One of the ways through which this transition can be facilitated has been suggested as the proposed hybrid of Industry 4.0 and Industry 5.0 artefacts by preserving the functional elements of the current automation and incorporating human-centric improvements. Nevertheless, this hybrid solution will have to counteract the resistance mentioned in employees because of the quick pace of technology change surpassing the adaptive ability of the workforce (Golovianko et al., 2023). Smart healthcare logistics systems were developed at this time as literal examples of implementing Industry 5.0 thinking: edge computing enabled quicker diagnostics routing and human supervision of the ethical triage of resources in conditions of a shortage.

The aspect of technological convergence further complicates the matter; blockchain implementation with artificial intelligence-enhanced verification can provide supply chain reliability, and the IoT devices can further capture real-time information up until the point of interaction with the consumer (Boudouaia et al., 2024). Nonetheless, sustainability goals do not just seek technological synergy, they seek governance structures that would transform these capacities into specific environmental performance indicators without weakening economic competitiveness. Supply Chain 5.0 (SC 5.0), on the other hand, also seems to encourage wholesomely adaptations by re-setting the objectives so that resiliency is an operational constant as opposed to crisis contingency planning.

Finally, the curve between Supply chain 4.0 and 5.0 can be seen as an evolution where digital automation is initially used to ensure the perfect functioning of the processes and then expanded to encompass fair societal gain through the interconnection of environmental awareness. The conflict is in determining how much investment should be allocated to workforce readiness efforts in conjunction with these technological developments in order to ensure that transitions are not only possible at a mechanical level but that they are possible socially as well (Nazarian and Khan, 2024).

FOUNDATIONS OF INDUSTRIAL REVOLUTIONS AND SUPPLY CHAIN EVOLUTION

Overview of Industrial Revolutions

The historical development of the industrial revolutions offers a very critical context in the analysis of the technological and strategic changes in the supply chain paradigms. The initial industrial revolution emerged in the late eighteenth century, which mechanisms were used to produce goods with the help of waterpower and steam engines, which led to the replacement of manual craftsmanship with machines (Abdirad & Krishnan, 2021). The second one developed at the end of the nineteenth century and brought in electricity-driven mass production systems and improved assembly lines. It was, however, to a greater extent confined to silos of isolated data with no real-time interconnectedness both within and across global supply chains. The advent of Industry 4.0 is a qualitative break over the previous phases and also constitutes cyber-physical systems (CPS), IoT connectivity, cloud computing structures, and big data analytics as a baseline (Akbari et al., 2024). Nonetheless, the excessive focus on automation and the efficiency of Industry 4.0 can result in organisational blind spots in long-term systemic risks or social implications. The following phase is one that keeps the essential technological features of Industry 4.0 but seeks a middle ground between human and technology where collaborative robots, or cobots, operate alongside human beings, but not completely eliminate human input. This shift also introduces stringent real-time safety and control requirements, because this close-proximity human cobot collaboration depends on reliable sensing, low-latency coordination, and fail-safe mechanisms that protect workers under dynamic shopfloor conditions (Jefroy et al., 2022; Boudouaia et al., 2024).

Although the previous stages were dominated by the evaluation of new technology in terms of the output, with regard to speed or cost-effectiveness, the new paradigm is starting to place the idea of carbon footprint, resource circularity, and fair stakeholder gain as essential performance indicators (Boudouaia et al., 2024). Nevertheless, expanded KPIs may complicate investment appraisal due to the fact that value is partially achieved by qualitative benefits (e.g., compliance readiness and reputational capital) that are more difficult to convert into short-term ROI storeys (Agrawal et al., 2024). This is especially limiting to smaller companies with less capital reserves that may impede ecosystem-wide change when supply chain partners are unable to upgrade at the same rate (Varriale et al., 2023). The challenges include a combination of the old infrastructure into the modern high-data-rate digital versions and the need to ensure the flexibility of employees in the face of rapid automation changes at the same time (Bag et al., 2021). Practically, introducing old systems into hyper-connected architectures may also widen the cybersecurity exposure, as more connected systems, interfaces, and third-party integrations open more attack surfaces of the cyber-physical supply chain systems to operations (Jefroy et al., 2022).

Analytically speaking, based on past course trends as well as the current technology environments, it can be seen that the reliance of Supply Chain 4.0 on cyber-physical integration is a continuation of a long-standing trend of automation that started centuries ago. However, its ultimate evolution to Supply Chain 5.0 is an indication of the integration of philosophical changes not based on pure engineering rationale: the importance of societal welfare on top of production excellence (Frederico, 2021). What is important here is the interaction between technology push (enabled by such capabilities as AI-enhanced analytics) and value pull (enabled by sustainability imperatives). Therefore, sequential comprehension of industrial revolutions explains why the latest discussions concerning the introduction of advanced AI or robotics cannot be judged based solely on the operational KPIs that are inherited by the previous phases; they do need multitiers of assessment frameworks, which capture both quantitative performance metrics and qualitative contributions to society (Boudouaia et al., 2024). To assess development in this continuum, one will not only have to question themselves whether systems are offering faster throughput or reduced defects but also whether they are enhancing adaptive capacity to communities embedded within supply chain networks, a question that is especially relevant amid systemic shocks over the past few years (Bag et al., 2021). Figure 1 summarises the progression from traditional supply chains to SC 4.0 and the subsequent transformation toward SC 5.0 through a socio-technical lens.

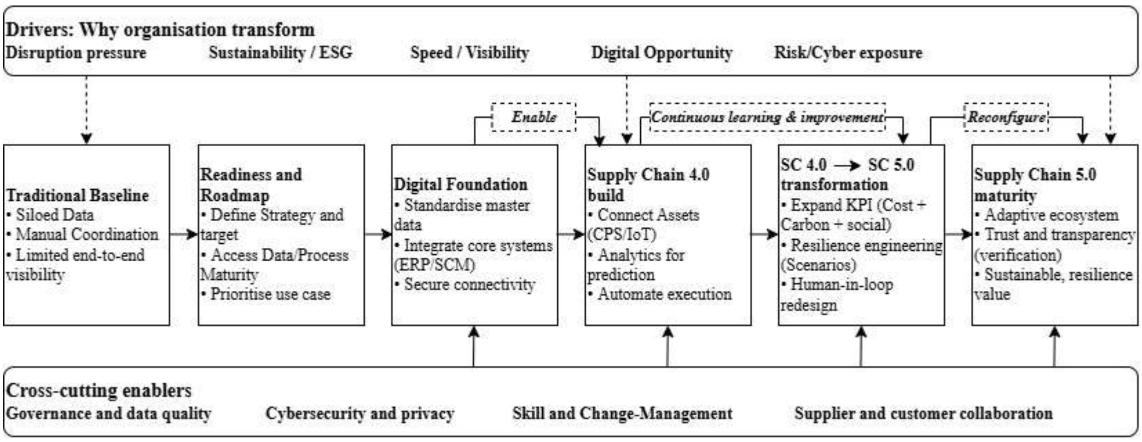

Figure 1 Conceptual Model: Traditional supply chain to SC 4.0 and transformation SC 5.0 (Source: Authors' conceptualisation)

Supply Chain Evolution

The development of the previous variants of supply chain, including the Supply Chain 4.0 and Supply Chain 5.0, is characterised by the change not only in the application of technology but also in the orientation of the strategy toward the interests of the society and the environment. Supply Chain 4.0 is based on the technological platform of Industry 4.0 and is grounded on IoT equipment, cyber-physical systems (CPS), cloud computing, automation, and analytics of big data to allow unprecedented levels of integration between procurement, production, distribution, and retailing processes (Fatorachian and Kazemi, 2021). These tools enhance visibility by performing continuous monitoring and sharing information between supply chain nodes (Mastos et al., 2020), which is necessary to facilitate the quick acquisition of decisions in a new context. However, these strengths can also be in the form of weaknesses with disruptions going beyond manageable levels or geopolitical issues with suppliers or unexpected climate changes that can cause resource scarcity can quickly reveal the events that hyper-optimised processes that were not built resilience as the primary goal. Conversely, the conceptual frame of Supply Chain 5.0 incorporates technological development on the paradigm of human-centred technological advancement in alignment with Industry 5.0 aims (Ghobakhloo et al., 2025). In this case AI-based analytics, blockchain verification tools, cobots, and digital twin simulations remain a component but premeditated balanced with human control (Boudouaia et al., 2024). Older systems tend to be incompatible with high bandwidth networking options that are common to integrated CPS or real-time IoT architectures that can be used to manage cobots and digital twins (Verma et al., 2022). As an example, to implement blockchain traceability as part of sustainable sourcing, it is necessary to align the ledger data framework with the current ERP systems without the loss of transaction speed or security (Boudouaia et al., 2024). These limitations, notwithstanding the potential benefits, prompt the development of Supply Chain 5.0 designs. Digital twins provide scenario modelling at very fine levels of fidelity that allows proactive reduction of risks prior to their physical manifestation but again would demand much upfront investments in digitization that may prove daunting to some firms during transitional periods. The distinguishing characteristic of the current change is especially its twofold pledge to retain high efficiencies that can be achieved through integrated automation but in a systematic way, to instil the protective measures by having the sustainability requirements and the resilience constructions to be managed by human beings. This relational cyclic development particularly displays as continuity, in the dependency on growing technological capacity, and departure, in the widening of values definitions beyond throughput measures to those that measure planetary health and social responsibility. In contrast to Supply Chain 4.0 improving process speed within the multiple principles of functioning, Supply Chain 5.0 incorporates amendable variation in the light of human-machine cooperation that can contextualise performance objectives in line with situational needs and joint ethical engagement ingrained within global supply chains (Akundi et al., 2022).

SUPPLY CHAIN 4.0

Core Concepts and Technologies

Supply Chain 4.0 is deeply entrenched in the technological concept of Industry 4.0 wherein automation, digitalization, and interconnectivity form a highly integrated system of connexions among suppliers, manufacturers, distributors, and customers using sophisticated communication and analytic frameworks (Abdirad & Krishnan, 2021). In these ecosystems, the Internet of Things (IoT), cyber-physical systems (CPS), big data analytics, cloud computing, additive manufacturing, and advanced robotics are interconnected and exchange data with each other in every part of the production and logistics (Santhi and Muthuswamy, 2023). These technical enables enable machines and systems networks to talk to each other in real time, not merely in assessing the state of operation of the machines, but also responding autonomously to variances. There are however some challenges, because of this heavy dependence on automation. On the contrary, Supply Chain 5.0 builds on numerous of these underlying technologies, but reimagines them through a different philosophical prism, in which human-machine cooperation substitutes rigorously automation-focused design approaches (Ghobakhloo et al., 2025). The collaboration robots (cobots), transparent transactions based on blockchain, 6G wireless connectivity, simulations of the digital twin, and AI-based analytics remain the basis of operations (Nazarian & Khan, 2024). However, instead of replacing the human being with automated working processes, the tools, in fact, demand human intervention to make complicated decisions or improvise. Interoperability standards that can convert highly standardised automation pipelines of Supply Chain 4.0 into the dynamic interactive interfaces that are sought in Supply Chain 5.0 will have to work with heterogeneous data formats of CPS sensors, blockchain ledgers, ERP modules, and environmental monitoring instruments all at the same time (Maria et al., 2022). According to Sobb et al. (2020), AI systems integrating with IoT infrastructures expand the range of targets of cyberattacks aiming at physical processes by means of digital intrusions. Supply Chain 4.0 is more of a maximisation of throughput per unit of resource through autonomous adjustments informed by real-time analytics (Figure 2); Supply Chain 5.0 redefines optimality to arrive at a balance between speed or cost and ecosystem health and social equity impacts (Xu et al., 2021). Like any transition based on the underlying philosophies instead of the gradual improvement of tools, transitioning between one paradigm to another requires explicit socio-technical engineering, matching models of governance imposing sustainability goals with infrastructural modernization strategies that can sustain distributed collaborative networks without compromising underlying efficiencies accrued in the previous stages of automation. Therefore, these fundamental ideas and technologies involved are not inherently fixed or universally prescriptive; their effectiveness is determined in large part by the context in which they are entrenched in and the values in terms of which they are tuned. The fundamental friction between the automation purity promoted by Industry 4.0 constructions and human-centred flexibility proposed by Industry 5.0 needs delicate balancing measures between the challenge of interoperability and the need to enforce ethical controls, a tension that is visible across transitional initiatives that seek to bridge the two generations of supply chain (Tiwari, 2021).

Capabilities and Benefits

The capabilities of Supply Chain 4.0 are based on the functionality of interdependent technologies that provide operational visibility and responsiveness of the manufacturing process, logistics, and distribution process. IoT sensors will facilitate real-time granular monitoring of assets and inventory and relay them using networked infrastructure to centralised analytic platforms (Fatorachian and Kazemi, 2021). These inputs are coordinated by cyber-physical systems to ensure that machinery is able to adapt production rates or resource distribution to match the prevailing conditions to minimise delays and wastage. This framework is, however, performance-oriented towards a situation of optimization in the face of stable conditions as opposed to the ability to withstand the effects of large-scale shocks. These vulnerabilities are exactly where Supply Chain 5.0 redefines capabilities in terms of adaptability, human control, and sustainability goals with much of the technological foundation of its predecessor being brought forward. Supply Chain 5.0 is still using IoT sensors, CPS and robotics, blockchain verification systems and digital twins (Nazarian and Khan, 2024). The only difference is that they are governed by new rules and regulations where environmental performance is mandatory in the decision-making process. Robots that work collaboratively execute routine tasks but have human operators as in-the-loop management to handle exceptions or ethical decisions, including the selection of competing deliveries when resources are limited. Digital twin technology is also introducing a new level of flexibility: entire chain simulations allow proactively defining weak spots in the case of hypothetical disruption scenarios to pre-plan interventions instead of responding to them reactively. However, such expansions of capability create barriers that do not exist in models of efficiency focused on efficiency such as Supply Chain 4.0. The problem of technological integration has not gone away: it is often required to make significant reengineering investments to coordinate legacy ERP modules or proprietary production software with blockchain ledger systems or high-speed CPS networking (Chauhan and Singh, 2020). By integrating operational intelligence in the form of real-time functionality that has been implemented in the Supply Chain 4.0 with qualitative resiliency indicators that are unique to Supply Chain 5.0, companies not only enjoy speed benefits, but they also attain adaptive flexibility in unstable situations (Ralston and Blackhurst, 2020). The strike between automation innocence and human judgement is a delicate challenge when at the transition period between these supply chains paradigms (see Section 3.1). When we consider the combined capabilities that Supply Chain 4.0 with its digital integration and Supply Chain 5.0 with its sustainability-driven resilience bring to the table, we can get a complementary value profile when the two are put on the strategic level. Predictive modelling and IoT monitoring, though, still contribute to efficiency in terms of resource allocation, and the realisation of diversification strategies based on the distributed network design decreased exposure risk, human-involved collaborative automation still preserved the ability to solve problems creatively, and verified sustainability metrics could help the company stay competitive in the face of increasing ecological scrutiny (Nazarian and Khan, 2024). These attributes highlight the fact that future-fit supply chains will rely not just on the level of technological advancement, but on integrating such tools into agile governance frameworks that can strike a balance between economic and social requirements, the combination of the best qualities of both generations into consistent working practice.

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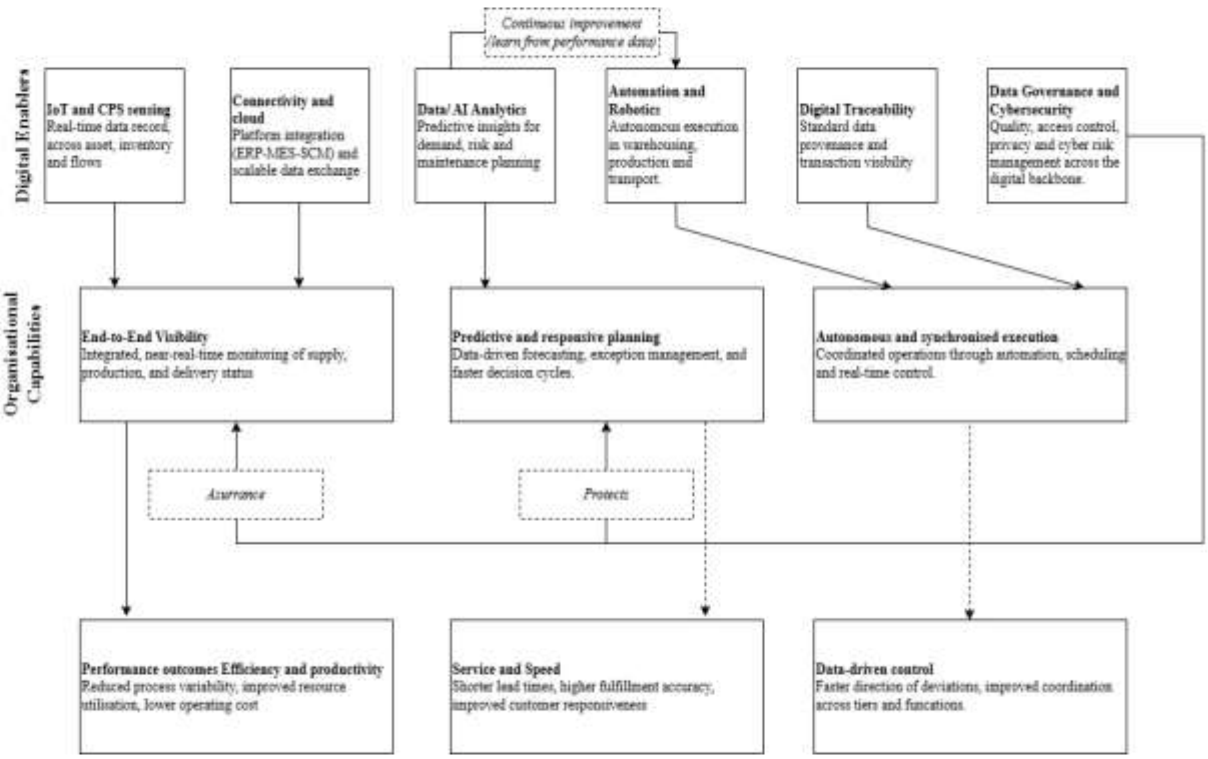

Figure 2 Conceptual model: Supply Chain 4.0 (Source: Authors' conceptualisation)

Limitations and Implementation Barriers

Although the opportunities of Supply Chain 4.0 and Supply Chain 5.0 models are significant, both of them have non-trivial limitations in their implementation, which condition the practical feasibility. Supply Chain 4.0 depends on IoT-based monitoring, cyber-physical systems, and big data analytics necessitating the degree of technological interoperability that is difficult to attain by many organisations, particularly those that have heterogeneous legacy infrastructure (Ghadge et al., 2020). The implementation of real-time streams of CPS information into the organisations existing ERP systems can require several expensive reengineering efforts and harmonisation of data formats (Fatorachian and Kazemi, 2021).

The implementation barriers have increased complexity in Supply Chain 5.0 because it has a human-centric orientation and sustainability imperatives. Most of the core technologies, including collaborative robots, traceability based on blockchain, sixth-generation (6G) connectivity solutions, and AI-driven analytics, are inherited by the previous paradigm, however, they should be set in a way that they do not only improve operational efficiency but also incorporate the values like environmental stewardship and social equity into the logic of operation directly (Jefroy et al., 2022). The shift of completely automated pipelines to hybrid workflows based on the assistance of human-machines requires the interoperability protocols that address the concurrent inputs of CPS sensors, blockchain ledgers, environmental observers, and human overrides without introducing any inconsistencies and latency discrepancies. Regularly standardised communication rules are essential in order to ensure that cobots in an assembly process react appropriately to AI-produced task modifications as well as to supervisory actions on the part of humans (Boudouaia et al., 2024). Still developing interoperability protocols that can balance mixed inputs of manual overrides, blockchain ledgers, environmental sensors and collaborative interface devices are yet to be fully developed and lack of well-developed standards can compromise the reliability of hybrid workflows via latency differences and inconsistent system behaviour (Agrawal et al., 2024). Consequently, Supply Chain 5.0 faces a risk of technical integration due not only to the connection problems but also to the problem of performance and continuity when human judgement and algorithmic recommendations are required to execute at the same time within the same execution loop (Boudouaia et al., 2024).

Both paradigms are associated with large initial capital investment: Supply Chain 4.0 implementations involve spending on sensor arrays, networking systems, cloud-based analytics platforms, and automation equipment; Supply Chain 5.0 involves another round of capital spending attributed to sustainability technologies, including energy-efficient equipment, facilities powered by renewable energy or emissions monitoring systems embedded into digital twins (Varriale et al., 2023). The authors further explained that in smaller businesses with limited budgets, the need to focus on a specific set of upgrades may result in postponement of other potential upgrades, thus creating an uneven supply-chain capability and delaying transition in the network. On the other hand, the sustainability ethos inherent to the Supply Chain 5.0 can restrict the range of quick responses in case the environmental trade-offs are considered impermissible by the governance structures (Jefroy et al., 2022). The way to overcome it is through sequential working steps: implementation stages that synchronise technological preparedness and human resource training processes with the process of adapting performance indicators to a balanced efficiency-resilience-sustainability policy (Boudouaia et al., 2024). Lastly, the knowledge transfer procedure is an underappreciated area of barrier observed by multiple authors: the lack of supply chain experts who possess advanced expertise in data analytics and combine them with the skills of industrial engineering to create end-to-end integrated solutions design based on the principles of Industry 5.0 (Modgil et al., 2025). Sealing this gap in skills will be vital to facilitating not only adoption but also context-sensitive functioning of hybridised supply chains that can achieve various performance goals in the nexus economic-social-ecological matrices that these paradigms conceive.

SUPPLY CHAIN 5.0

Human-Centric Design Principles

The Human-centric design of Supply Chain 5.0 (Figure 3) is based on technological principles inherited by Supply Chain 4.0 but changes the operational focus to the needs of people, values of society and ecological interests directly integrated into supply chain systems architecture (Xu et al., 2021). Such paradigm would necessitate a reassessment of the relationship between technology and workers, as a supplement to human abilities rather than a replacement of it, and would have to introduce such values as inclusivity, wellbeing, and autonomy into the processes that would have been governed by efficiency algorithms up to now (Ghobakhloo et al., 2025). However, contrary to the industry 4.0 models, which focus on automation and tend to concentrate on lean operations and maximising the throughput, the human-centric approaches consider the workers as active participants whose skills and judgement are fundamental to adapt to the complex or unforeseeable circumstances (Modgil et al., 2025).

Supply Chain 5.0 adds cobots into the shared work environment that is designed to be safe in terms of cohabitation between machines and humans (Jefroy et al., 2022). Furthermore, the authors explained that these collaborative workplaces frequently are based on augmented reality (AR) guidance displays that indicate task activities or workplace safety to operators graphically, requiring sophisticated sensing and control algorithms to ensure the safety of workers when working in close proximity. In a case where legacy CPS systems need to be retrofitted to support dynamic operator input and avoid the latency mismatch between the control signals, controlling the safety becomes dependent on robust real-time feedback and a reliable fail-safe coordination between the cobots and supervisory overrides (Boudouaia et al., 2024). The principle of work here is based on a clear division of labour whereby cobots are deployed to do repeating movements and the human operator is left in control to handle exceptions and complex decision-making based on the difference between mechanical accuracy and situational adaptability (Chauhan and Singh, 2020). This design underscores the fact that human beings are not in the loop to only gain an operational understanding but also in an ethical assessment where the outputs of algorithms are not sufficient on their own, which is a cultural change and not just a technical upgrade (Verma et al., 2022; Ghobakhloo et al., 2025). Employees should be educated not only in using machines but also in deciphering information products of AI analytics engines, comprehending the performance of the environment dashboard connected through blockchain traceability networks, and making wise decisions when there is a tradeoff between efficiency targets and sustainability requirements (Modgil et al., 2025). Unlike rigid job descriptions that take place in Industry 4.0 regimes, human-oriented structures expect permeable role descriptions that respond to fluctuating supply chain requirements. Having resilience is emphasised in much of Supply Chain 5.0 appeal to human-centricity. Human beings have cognitive flexibility, which allows them to redefine information in new conditions to change priorities under crises such as pandemics when ethical allocation of scarce resources is more justified than the financial paths.

Nevertheless, there are physical barriers to the shift to the automated paradigm of Supply Chain 4.0. Interoperability between sensors of the IoT, blockchain ledgers, environmental monitors and manual control interfaces must be coherently engineered to avoid conflicts between automated responses and supervisory overrides. Regulatory frameworks make the situation even more complicated, as implementing human-centricity tends to coincide with compliance trends on the topics of workplace rights and sustainability disclosures (Xu et al., 2021). Although such alignment can make the company be more trusted by the people and increase its brand equity, it can also delay the implementation since the process will require more audit procedures that will be required to cheque the implementation of the policy commitments via such technologies as blockchain-based certifications or AI-based social impact reporting (Varriale et al., 2023). The transition is on a shift where decision-making is more algorithmically defined to be under a balanced mode where human beings are the one to adjudicate algorithmic recommendations with expertise based on the operational experience of situations and the long-term community effects. This shift does not deny the merits of automation but re-contextualises them as parts of an ecosystem in which adaptability based on machine accuracy and human discretion is in equal parts, the combination of which alone can bridge the gap between what industry performance needs and what the society demands of working conditions and environmental care.

Potential Advantages over Supply Chain 4.0

Among the benefits of Supply Chain 5.0 as compared to the previous version is the expanded range of goals that the former aims to achieve and the fact that these goals go beyond operational efficiency and include resilience, sustainability, and human-centred design. Whereas Supply Chain 4.0 is exceptional in minimising the lead times and enhances transparency due to the use of the IoT-enabling monitoring, CPS integration, and big data-driven predictive analytics (Fatorachian and Kazemi, 2021), these functions were focused on maximising throughput and cost-effectiveness in a setting of constant conditions (Akbari et al., 2024). Supply Chain 5.0 stands on the shoulders of this fundamental technological base but reorganises it into structures that see societal and environmental results as the equal keys performance indicators (Ghobakhloo et al., 2025). This verifiable transparency can be a competitive advantage to a firm in a market where consumers are increasingly demanding products produced with environmental responsibility, and where the focus of most Supply Chain 4.0 implementations is generally on the logistical precision of traceability solutions as opposed to more comprehensive sustainability reporting. Unlike predictive analytics in Supply Chain 4.0 which elicit the need to optimise operation parameters such as reorder points or transport schedules (Tiwari, 2021), AI in Supply Chain 5.0 is used to balance sets of priorities in complex trade-offs such as selecting slower shipping routes that meet emission targets but also satisfy strategic customer commitments (Wu et al., 2025). This regulatory preparedness doubles up as reputational resilience; stakeholders (investors included) might interpret the active embrace of sustainability-based models as any sign of strategic long-term foresight.

Yet, to accomplish these benefits, it is necessary to overcome implementation challenges reported in other areas: compatibility challenges related to legacy infrastructure imply that hybridised systems have to process mixed data streams at once associated with CPS sensors, ERP modules, blockchain ledgers as well as environmental monitoring devices in a way that does not introduce conflicts in control logic (Boudouaia et al., 2024). The adjustment of the workforce would be necessary to prevent underutilization of collaborative technologies; the fear of job loss should be addressed with the help of organised upskilling methods that will also be able to prepare the personnel, not only technically but also contextually, to participate in digital governance (Modgil et al., 2025). Finally the possible benefits come in as a layered addition to the foundation laid by Supply Chain 4.0: continuing to deliver efficiency through inherited automation capabilities, but with resilience structures preventing impact; high transparency standards with ethical traceability; the ability to conduct complex trade-offs with sustainability in the middle; and making operations adapt to new regulatory environments without loss of flexibility to adapt (Nazarian and Khan, 2024). This synthesis is not one of abandoning previous efficiencies but one of reeducating them in architectures capable of simultaneously addressing both quantitative performance targets and qualitative societal demands, a duality of interaction that is peculiar to Industry 5.0-compatible supply chain strategies.

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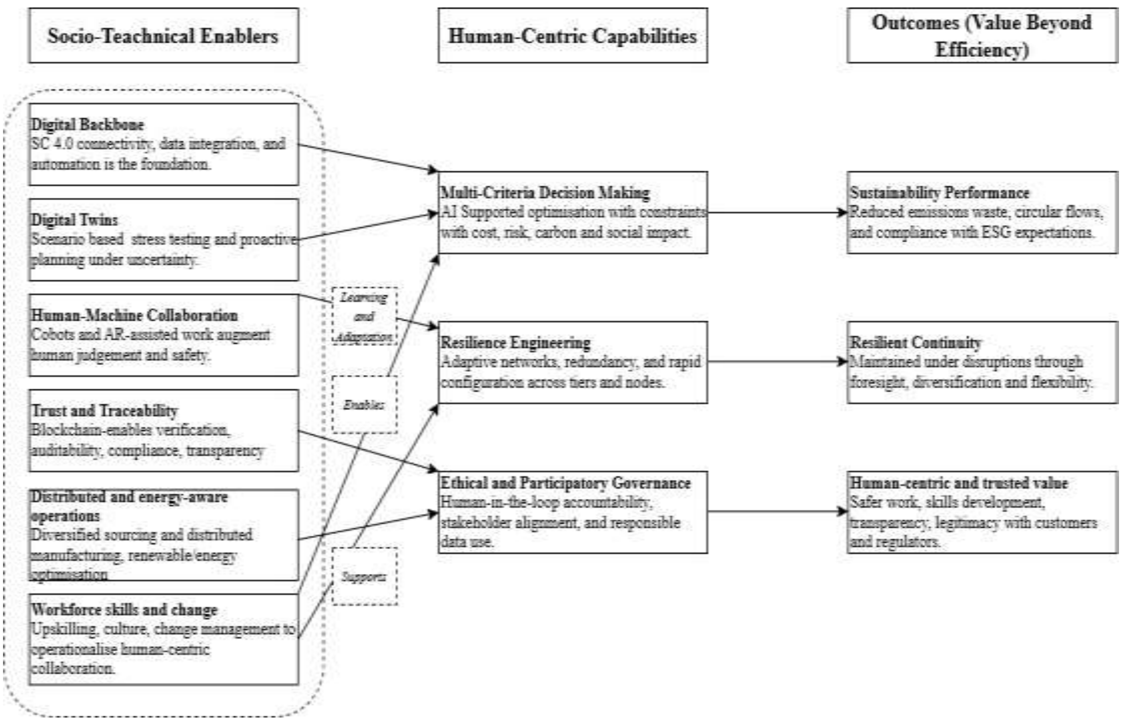

Figure 3 Conceptual model: Supply Chain 5.0 (Source: Authors' conceptualisation)

COMPARATIVE ANALYSIS BETWEEN SUPPLY CHAIN 4.0 AND SUPPLY CHAIN 5.0

Technological Evolution

Technological development between Supply Chain 4.0 to Supply Chain 5.0 is not a straightforward linear improvement of this technology but a re-shuffling of the under-lying capabilities, priorities and integration approaches in an industrial setting as determined by Industry 4.0 and Industry 5.0. The previous paradigm of this development heavily relied on the use of interrelated technologies, IoT sensor networks, cyber-physical systems (CPS), cloud computing architectures, big data analytics, and autonomous robotics to develop highly efficient and transparent operational pipelines (Frederico et al., 2021). These elements interacted at horizontally integrated supply chain nodes and vertically balanced management forms, making predictive analytics available to optimise scheduling or rerouting shipments due to real-time status notifications (Shao et al., 2021). Nevertheless, the architecture implied certain vulnerabilities: the closely integrated lean processes were vulnerable to macro-scale shocks like the pandemic-induced supply disruptions or severe weather conditions interfering with the logistics hubs (Ghobakhloo et al., 2025). The use of technology in Supply Chain 4.0 therefore embodied the ethos of the industry 4.0 which focused on hyper-efficiency based on autonomous digital ecosystems and left the resilience-building mostly beyond the aim of core design.

In its turn, Supply Chain 5.0 carries a lot of similar technical foundation but redeploy these tools within the philosophical principles of Industry 5.0 with the objective of resilience and sustainability and human-centred operational rationale (Frederico, 2021). As opposed to the mainly automated feedback loops of Supply Chain 4.0, where the personnel input very little context into the system, Supply Chain 5.0 needs active involvement of the supervisors whenever machine outputs are incompatible with the ethical policy rules or situational priorities set at the higher governance levels (Ghobakhloo et al., 2025). Whereas the adoption strategies of Industry 4.0 focus on the embedded disruptive technologies in operational chains to increase productivity (Frederico et al., 2021), Industry 5.0 re-focuses the multi-agent systems and complex adaptive networks on interaction with operators instead of isolation (Frederico, 2021). The economic patterns of investments are also of the same complexity: both of the paradigms demand significant capital upfronts in the form of sensor arrays, robotics platforms, or analytic engines, but Supply Chain 5.0 introduces expenditure lines associated with sustainability-related upgrades, such as the introduction of renewable energy into the plant workflow or emissions monitoring devices with specific applications to the IoT (Agrawal et al., 2024). This multifaceted technological shift indicates that the success of adoption will not rely on the availability of technical capability as much, but on integrative engineering practise of connecting physical infrastructure upgrades with socio-environmental performance modelling (Wu et al., 2025). The shift of paradigm requires not only plug and play substitution but both reengineered software logic level, with optimization criteria broadened, and reengineered hardware interface design, where humans interact dynamically without eroding systemic coherence that is accrued in the maturation stage of Industry 4.0. In Figure 4, this layered view highlights that SC 5.0 extends the SC 4.0 digital core by adding governance, human-in-the-loop decision-making, and sustainability performance layers.

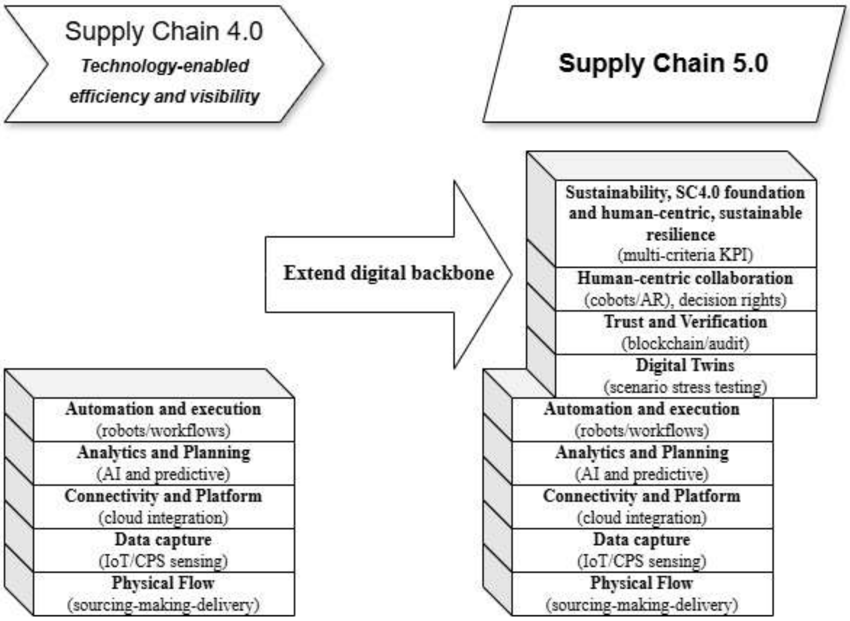

Figure 4 Layered socio-technical architecture: SC4.0 foundation extended into SC5.0 (Source: Authors' conceptualisation)

Strategic and Operational Differences

The differences in the strategic and operational aspects of supply chains between Supply Chain 4.0 and Supply Chain 5.0 can be attributed to varying value orientations despite this technology having a common technological heritage of Industry 4.0 platforms, including IoT-enabled monitoring, CPS integration, big data analytics, and robotics (Fatorachian and Kazemi, 2021). The previous paradigm puts the maximisation of efficiency, cost management, and lead time minimization in the forefront, and these objectives are in-built in automated workflows with a minimum number of human steps (Tiwari, 2021). The frameworks of decision-making are designed in a way to emphasise the quantifiable performance indicators, throughput per resource unit, delivery rate, accuracy of inventory status, which are determined by real-time streams of data processed by AI systems independently. The subsequent paradigm, in contrast, transforms the concept of strategic intent to incorporate additional assessments of it independent of operational KPIs to resilience, sustainability, and human-centric governance (Frederico, 2021).

AR-guided systems require operators to be in the same workspace as cobots, yet humans can always have the final word when it comes to multi-criteria decisions where the results of an algorithm conflict with ethical or situational considerations, such as prioritising delivery to vulnerable populations during shortages over commercial orders. To shift to a hybrid human-machine management, interoperability solutions that would help to balance various data streams generated by CPS sensors, blockchain ledgers that record the provenance and sustainability compliance, and environmental sensors to monitor emissions are needed (Tiwari, 2021). Unlike models of the previous generation, which depended on reactive mitigation after the anomalies were realised in predictive analytics framework (Shao et al., 2021), newer models are based on digital twin simulations that are applied to exercise the supply chain structures under different disruption conditions in advance before they can be deployed to practise (Wu et al., 2025). Supply Chain 5.0 implements compliance frameworks like automated emissions reporting or blockchain-based supplier practises verification in the daily operations so that compliance is not an occasion but an ongoing process, which is more in line with predicting the tightening of legal frameworks around sustainability but is also more costly to implement initially. The introduction of interactive human-machine interfaces in Industry 5.0 compliant systems creates more points of contact where attacks can occur and, at the same time, when suspected attacks occur, the systems can provide a context to allow human intervention, which is absent where all corrective functions are carried out automatically only. All these differences suggest that the adoption choices cannot be made as mere adoption of one technology set to another; they involve a complete change of priorities according to which the network design and day-to-day business operations in industrial supply chains should be organised (Frederico, 2021). Supply Chain 4.0 is closely allied to throughput optimization via autonomous integration under foreseeable circumstances; Supply Chain 5.0 goes a step further by providing a broader calculus between efficiency and societal impact and environmental responsibility by encompassing collaborative adaptability within its internal operational architecture, and not as an overlay to it. Table 1 summarises the key distinctions between SC 4.0 and SC 5.0 across major dimensions.

Dimension	Supply Chain 4.0	Supply Chain 5.0
Foundational orientation	This responsiveness in advance is the core value proposition of Supply Chain 4.0: the efficiency in terms of downtime and throughput optimization without the need to involve a human operator all the time.	Human-centric design Supply Chain 5.0 is based on the technological legacy of Supply Chain 4.0 and shifts the operational principle towards the direct connexion of human needs, societal values, and ecological factors directly to the design of supply chain systems (Xu et al., 2021).
Core enabling technologies	The massive scale of IoT implementation also creates enormous amounts of data that must be backed up and processed by powerful cybersecurity solutions to deter industrial spying or subversion.	Supply Chain 5.0 brings cobots to the shared workspace that is specifically designed to provide safe interactions between people and machines (Jefroy et al., 2022).
Operational capabilities	The capabilities of Supply Chain 4.0 are based on the presence of interdependent technologies providing operational visibility and responsiveness in the manufacturing process, logistics, and distribution processes.	Such regulatory preparedness doubles into reputational resilience; stakeholders, including investors, might consider active implementation of the models of sustainability orientation as a sign of long-term strategic futurism.
Performance logic and metrics	Another notable ability is the capability of sustaining efficiencies in response to changing loads of demands.	Among the most evident benefits of Supply Chain 5.0 compared to its predecessor, one must note the expansion of the range of goals it is meant to achieve, including resilience, sustainability, and human-centric design.
Governance and human role	Over dependence on autonomous optimization may tend to lock out ethical or socially intelligent reactions, and the reverse may be true.	This integration implies system flexibility is not only improved with algorithmic learning but also direct human intervention when ethical considerations arise or site-specific considerations such as delivering routes that impact a community the most instead of delivering routes that demonstrate abstract logistics.
Implementation barriers	To pass through the streamlining automation ethos of Supply Chain 4.0 to the diverse-faceted optimization terrain of Supply Chain 5.0 means reengineering at interface design tiers, rebalancing analytic modelling to broader goals sets, providing enhanced cybersecurity to interactive structures, aligning the integration of renewable sources with CPS operations, and ensuring interoperability across a	The socio-economic and regulatory issues encountered in the execution of Supply Chain 4.0 and Supply Chain 5.0 are due to the fact that the philosophical orientation of Industry 4.0 and Industry 5.0 is highly different, and yet they share certain technical infrastructures.

	mosaic of legacy systems and new collaborative platforms, all whilst ensuring seamless functional continuity across global supply chain networks with both societal and economic objectives.	

Table 1. Distinctions between Supply Chain 4.0 and Supply Chain 5.0

CHALLENGES FOR IMPLEMENTATION

Organisational Challenges

The philosophies underlying Industry 4.0 and Industry 5.0, and the maturity of internal processes and workforce make significant organisational issues in adopting and operating within the context of the Supply Chain 4.0 and Supply Chain 5.0 paradigms. Although Supply Chain 4.0 applications are aimed at automation, lean processes, and information-driven optimization through IoT networks, CPS frameworks, and big data analytics (Tiwari, 2021), these technical applications require organisations to redefine their management hierarchies in order to incorporate information flows in real time across departments. This horizontal and vertical integration is not only based on the compatibility of the software but also on the economic adjustment of strategic goals at the top tiers and the operational preparation of factory floors (Modgil et al., 2025).

The same stress is intensified under the objectives of the Supply Chain 5.0 when the notion of resilience, human-centricity, and sustainability are instilled as the objectives of Supply Chain 5.0 in addition to efficiency (Frederico, 2021). Conversely, Supply Chain 5.0 aims at active human involvement in the chain of decisions and sophisticated robotics and AI (Jefroy et al., 2022), which requires an interdisciplinary training process where the employees should be familiar not only with the functionality of collaborative robots (cobots) but with the overall organisational objectives associated with sustainability indicators. As an illustration, blockchain-verifiable sustainability data needs to be integrated into procurement decisions all around the world, and the digital preparedness of the various supplier's bases is very different (Frederico, 2021). With the hybrid workflows of Supply Chain 5.0, with more layers added, where environmental monitoring sensors provide sustainability indicators that are directly fed into AI algorithms or manual overrides due to human operator intervention, the work of synchronisation becomes even more complicated (Boudouaia et al., 2024). To integrate resilience, which is one of the main features of Supply Chain 5.0, it is necessary to accept that some redundancies are desirable even though they seem to contradict lean principles on which Industry 4.0-based thinking is based (Nazarian and Khan, 2024).

The initial expenses of integrated IoT arrays, cobot implementation initiatives, manufacturing facility renewable energy initiatives, emissions metering systems linked to blockchain accountability mechanisms, all need multiyear funding contracts, which frequently conflict with quarterly objectives of shareholders or boards whose perspective on innovation is constrained to short term margins. This conflict is strengthened by the fact that the Supply Chain 5.0 investment appraisal commonly demands valuation techniques beyond the direct labour replacement or the cycle-time savings. Such evaluations should include regulatory penalties that have been avoided, appreciated reputational capital and cost-related risks (e.g., avoiding downtime) to ensure that those investments that have been partially supported by intangible advantages may be protected against short-term financial burden (Agrawal et al., 2024). Policy and governance expertise simultaneously become central: organisations are becoming more and more required to integrate compliance and accountability procedures into operational decision rules either via mechanisms like blockchain audits or automated reporting channels instead of viewing compliance as a periodical activity referred to as a check (Boudouaia et al., 2024; Frederico, 2021). All these interconnected issues emphasise the idea that the effective implementation will be based not only on the introduction of technical infrastructure but on the change of managerial practises, workforce quality, cultural values regarding collaboration and valuation of resilience, definition of the levels of decisions between automated and human-intervention, and long-term investments plans on the basis of the economic indicators and the assessment of the social-environmental impacts of the actions (Frederico, 2021). In the absence of such integrative reorganising activities in keeping with the ethos and technical complexity of the adopted paradigm be they efficiency-oriented or generally adaptive, the potential of either of the two supply chain generations will languish in the realm of industrial practise.

Technological Challenges

The technological issues with supply chain transformation are a complexity of infrastructure limitations, interoperability problems, and the development of performance expectations as organisations change their focus in automation towards efficiency to resilience-based human-machine interactions. Within the architecture common in Supply Chain 4.0, there is the implementation of IoT-based monitoring, CPS, and big data platforms that build coordinated operational ecosystems (Fatorachian & Kazemi, 2021). These integrated systems are based on a high level of data harmonisation between suppliers, manufacturing nodes, and distribution channels. The high-bandwidth networking required to support CPS operation in Supply Chain 4.0 (Frederico et al., 2021) needs to be in place to support a wider range of communication requirements: AR-guided cobots that provide a visual cue in shared environments; distributed manufacturing nodes as a part of resiliency efforts; environmental monitoring devices that feed live compliance information (Agrawal et al., 2024). However, in most organisations, legacy infrastructure cannot keep up with the real-time throughput and integration needs of mixed-ioT and AR-enabled cobot spaces, which may obstruct the need to either deliver retrofitting at high cost or implement incompletely, thereby dispelling the desired benefit (Shao et al., 2021). It is further complicated by the lack of a uniform infrastructure readiness in geographies and levels of the supplier base; that is, architectures need to operate on both high-connectivity locations and low-bandwidth regional partners without violating interoperability or control logic (Agrawal et al., 2024).

Supply Chain 5.0 interactive systems increase the attack surfaces through the addition of more human-machine interfaces and third-party validation interfaces, such as blockchain APIs (Jefroy et al., 2022). This threat does not concern data only, as when AI systems are linked with IoT networks, digital intrusions to sabotage operation pathways can be created by physical means, without losing information per se (Sobb et al., 2020). Resilience-by-design therefore necessitates fail-safe designs where humans have access to rapid direct control when symptoms of manipulation become apparent through the occurrence of anomalous patterns rather than plunge on complete reliance on opaque algorithmic diagnostics in high-stakes situations (Jefroy et al., 2022).

The digital twins applied to Supply Chain 4.0 largely model the efficiency variables on controlled assumptions (Wu et al., 2025), whereas their counterparts in Supply Chain 5.0 should model the multi-domain disruption related to climate variability or geopolitical unrest and incorporate human decision paths into the modelled responses (Ghobakhloo et al., 2025). IoT network scaling between localised pilots and global coverage in the context of Industry 4.0 relies mostly on hardware replication and connectivity provision; scalability in Industry 5.0-oriented deployments will depend also on human resources availability to communicate with collaborative technologies in different locations (Modgil et al., 2025). The connexion of these intermittent energy sources to high-load IoT infrastructures requires adaptive load-balancing algorithms based on input patterns to the grid as well as operational priorities, a facet that is not commonly considered in Industry 4.0 due to its relatively limited emphasis on throughput regularity. Although harmful in any scheme, such disruptions are crucial when integrated systems have customization levels not only to operational sequences but also to internal compliance verification logics that engage them into contractual relationships to sustainability commitments. All technological issues are, in part, based on how they maintain operational velocity in the face of increasingly varied processing of inputs and in part, how they maintain consistency between autonomous system behaviour and real-time human supervision coupled into hybrid structures (Ghobakhloo et al., 2025). The shift between the streamlined ethos of automation in Supply Chain 4.0 and the more versatile landscape of optimization in Supply Chain 5.0 requires the reengineering of interfaces at the design stage, rebalancing analytic models in favour of broader objective sets, enhancing cybersecurity on interactive infrastructures, reconfiguring renewable energy-integration with CPS operation, and ensuring interoperability in a mosaic of legacy system and a new cooperative platform, all these as the functional continuity across global supply chain networks, which are now focused on societal as well.

Socio-Economic and Regulatory Challenges

The challenges to be encountered in implementing Supply Chain 4.0 and Supply Chain 5.0 are socio-economic and regulatory issues related to the strongly different philosophical orientations of Industry 4.0 and Industry 5.0 but still have common technical infrastructures. In the supply chains based on the major principles of Industry 4.0, automation and digitalization are implemented to enhance the efficiency, productivity, and transparency of the supply chain with the help of the IoT-connected devices, cyber-physical systems, robotics, and big data analytics (Santhi and Muthuswamy, 2023). Although this is seen to personalise the economic rewards through the restructuring of workflows, it also initiates socio-economic controversies about the workforce substitution as machines take over jobs that were once done by people (Modgil et al., 2025). In contrast to Industry 4.0-related practises that may introduce environmental monitoring only when required by outside pressures, Industry 5.0-related supply chains actively embed the emission monitoring through IoT-connected sensors into the selection engines (Frederico, 2021). The sustainable and human control embedded in Supply Chain 5.0 presupposes some infrastructural foundations, such as high-bandwidth communications of sensor data flows, the implementation of the blockchain standards among suppliers, the legal status of digital certification tools in the jurisdictions concerned.

As a matter of fact, such foundations are not equal: solutions have to bend to the conditions of high-connectivity smart facilities to low-bandwidth regional suppliers that work with varying legal codes and capabilities (Agrawal et al., 2024). Cultural and psychological organisational pressure is also present due to the fact that Supply Chain 5.0 is transferring employees who are not used to working in symbiotic human-machines mode to the mode of participation since this can provoke resistance among those layers of the workforce who are less accustomed to the symbiotic mode of human-machines collaboration (Ghobakhloo et al., 2025). Besides, demographic and generational factors have the potential to decelerate adoption, ageing managerial generations might be less receptive to experimental hybrid operating models compared to digital native professionals (Verma et al., 2022). Inequality in socio-economic terms finds its internal reflection through the differences in skills between workforce groups that can utilise developed interfaces and those that have problems with digital illiteracy (Modgil et al., 2025). Such imbalance requires specific skills development initiatives to consider the educational limitations in the region and ensure that technical skills in the job dealing with the AI-driven systems or cobot platforms are met. As mentioned in 6.2 of this paper, the lack of bridging these gaps may result into underuse of immense technological potential because of lack of human capital congruency.

Even the enforcement of regulations is not consistent across the world despite the increased international agreement on sustainability objectives (Frederico, 2021). There is a subtle socio-economic factor based on the consequences of such a redistribution of supply chain nodes on a community level as part of the resilience measures that are characteristic of Supply Chain 5.0 (Nazarian and Khan, 2024). Governance decisions have to therefore strike a balance between aggregate ecological good and localised economic disturbance, which is hardly modelled in a purely efficiency-infused paradigm as exemplified by Supply Chain 4.0. These AI systems have the capacity to improve the predictive accuracy of both paradigms and raise ethical issues regarding amplification of bias in decision outputs influencing supplier selection or labour work scheduling models; the solution to these issues is still evolving under new legal interpretations across jurisdictions. The general challenge is the ability to design architecture and governance systems capable of meeting performance divergent and conflicting imperatives, performance speed, resilience continuation, ecology, and achieve this in quite heterogeneous socio-economic settings and changing legal demands (Frederico, 2021). Organisations that have shifted to this new state should go further than reactive compliance to a multi-angle accountability that is part of the workflow logic: a cultural change no less lasting than technological change that will require an extended investment in social equity as well as engineering innovation.

FUTURE RESEARCH DIRECTIONS AND BROADER IMPLICATIONS

Interdisciplinary Approaches

Interdisciplinarity is becoming a prerequisite to the nature of closing the philosophical and operational gaps between the automation-oriented orientation of Supply Chain 4.0 and the resilience, sustainability, and even human-centricity orientations of Supply Chain 5.0. Unlike the previous changes in supply chains that were manageable within the framework of industrial engineering and optimization of logistics, the shift towards the models of Industry 5.0 currently requires the integrated effort of economics, environmental science, ergonomics, computer science, and social policy (Nazarian and Khan, 2024). It is not a case of collaboration among multidomains and is instead an outcome of the broadening of the spectrum of objectives represented in the decision-making frameworks, where high-speed throughput has to coexist with the objectives like climate impact mitigation and fair labour practises. The performance models in an Industry 4.0-inspired Supply Chain 4.0 environment are typically based on quantified measures that are obtained through measurements of IoT sensing infrastructure and process records of the CPS (Boudouaia et al., 2024). In contrast, a Supply Chain 5.0 design needs to complement such metrics with qualitative inputs, survey information about the satisfaction of the workforce, registers of ecological footprint as provided by environmental sensors, blockchain-validated supplier ethical certificates, all of which enter into multi-criteria optimization models fed by AI (Ghobakhloo et al., 2025).

The conventional ROI calculations that would be comfortable to determine Supply chain 4.0 upgrades such as automated packaging that cut labour costs are no longer accurate once capital costs encompass renewable energy infrastructure to run plants or advanced emissions monitoring arrays linked to IoT networks (Agrawal et al., 2024). As a matter of fact, the construction of blockchain based traceability across the global supplier networks is a perfect representation of the multidisciplinary engagement: cryptographers ensure integrity of the ledgers; jurisdictional legal counsel helps to determine admissibility of digital certifications; sustainability auditors certify ecological and labour-related claims prior to the entry into the block; IT architects connect these ledgers with ERP modules without introducing latency differences that harm the workflow schedule (Nazarian and Khan, 2024). The potential of transparent yet efficient accountable networks cannot be achieved without a coordinated effort within all of these competencies because of fragmented architectures that undermine the speed of transactions, security assurances, and decision reliability (Nazarian and Khan, 2024).

But obstacles still, disciplinary silos but tend to be uncombustible with differences between validation norms, engineers can be directed towards statistical model performance, but sociologists are interested in the depth of their ethnographies, environmental scientists might want long-range climate projections, but production planners are required to make immediate projections (Nazarian and Khan, 2024). It takes meta-level governance frameworks that can arbitrate between methodological preferences and maintain collective attention to collective goals unique to Industry 5.0 ethos to overcome such tensions. Finally, interdisciplinary solutions allow the shift in which technology no longer works harder but works differently, and calibrated to match societal priorities, as well as the production metrics, instead of the strictly mechanistic performance goals that the implementations of Supply Chain 4.0 pursue (Ghobakhloo et al., 2025). Organisations can have much greater opportunity to create resilient systems that are harmonious both technically and ethically in the turbulent global environments by building supply chain architectures out of inputs that are refined collectively in engineering precision, ecological stewardship, and equity models in the workplace, legal compliance rigour, and economic valuation sophistication. Future investigation might therefore be able to measure relative increases, e.g. decreases in emissions per dollar expended, in AI-assisted routing schemes as compared to automated inventory management systems.

Emerging Trends in Supply Chain Management

The new tendencies of the supply chain management are based on the transition between the efficiency systems narrowly designed to meet the needs of only one aspect to integrated systems that would consider the needs of economic productivity, resilience, environmental responsibility, and human welfare. Most operational foundations can be attributed to the technological advancements that took place in line with Industry 4.0, IoT sensing systems, CPS coordination, real-time analytics systems, but the more recent paths that can be associated with Industry 5.0 redefine these tools by considering them in the context of broader strategies (Ghobakhloo et al., 2025). This re-invention involves real-time inclusion of sustainability metrics in optimization logic and refocusing humans as active agents within automated systems, and as passive supervisors. The previous methods of predictive modelling in Supply Chain 4.0 tended to maximise single solutions based on past datasets, least path, minimum holding costs, but currently needs to handle datasets, which also involve the emissions output of transport fleets or blockchain-verified fair labour compliance certificates (Boudouaia et al., 2024). Isolated operation Industrial robots are frequently deployed in isolation areas in Supply Chain 4.0, and under Supply Chain 5.0 principles, cobots socialise dynamically with humans with AR visualisation and adaptive motion control (Jefroy et al., 2022). This cooperation provides flexibility in production reconfiguring in the case of disruption and does not compromise human oversight of context-specific decision making, which is especially appreciated in ethical prioritising situations. Nevertheless, to achieve this potential, interoperability protocols balancing between the cobot control systems and environmental monitoring outputs and ERP scheduling modules are needed to avoid latency gaps in cases where humans are involved in a manual manner. These in Industry 4.0 terms could have been explained away by purely logistically optimal considerations; in Industry 5.0-aligned thought these are constituents of resilience engineering that seeks to keep things running in a variety of risk conditions, including pandemics and extreme weather events.

Simulations of digital twins have a pivotal role in this approach as they simulate various failure scenarios and certify the location of redundancy prior to actual implementation (Ghobakhloo et al., 2025). Digital twins enhance the proactive risk management approach, as the granular modelling of scenarios can be performed at a fine level of fidelity, and mitigation measures can be assessed ahead of time when constraints become real in the physical world (Wu et al., 2025). Nevertheless, such functions demand significant initial investments in digitisation, which may delay the adoption process at the transitional stages, especially as organisations are also investing in connectivity upgrades, interoperability retrofits, and monitoring systems based on compliance (Agrawal et al., 2024). The staged implementation approach consequently proves to be viable: companies can build up on pilot simulations to broader operational integration as the quality of data, the maturity of infrastructure, and the competence of workforce improves (Ghobakhloo et al., 2025).

Supply Chain 4.0 frequently involve employees adjusting passively to the results of automation; the new practises focus on participatory functions in which operators jointly make a decision on AI recommendations about sustainability trade-offs or moral limits in procurement (Modgil et al., 2025). On the whole, these new trends indicate an increased area in which technological sophistication stays as a condition but gets rediscovered in terms of socio-environmental demands as part of the industry 5.0 design logic (Ghobakhloo et al., 2025). The amalgamation of cooperative automation, ecological accountability incorporated via blockchain and sensors, decentralisation of resilience approaches verified through simulation, renewable energy assimilation synchronised with CPS processes, proactive regulatory compliance measures, and profound workforce engagement programmes are all paths that are visibly different than the lean-efficiency automation philosophy of Supply Chain 4.0 implementations (Nazarian and Khan, 2024). The continued transformation is indicative of the acknowledgement of the fact that future-ready supply chains should work as coherent socio-technical ecosystems capable of sustaining economic performance without undermining the integrity of the environment or social equity on which their legitimacy is based.

CONCLUSION

The evolution of Supply Chain 4.0 to Supply Chain 5.0 is a radical change of the conceptualization and management of industrial supply networks. This shift transcends automation and efficiency to the holistic approach that incorporates resilience, sustainability and human concerns. Although Supply Chain 4.0 can use interconnected technologies, including IoT, cyber-physical systems, and big data analytics to streamline the throughput and transparency, it can be rich in lean operations that do not provide ample buffers against systemic disruption. In comparison, Supply Chain 5.0 reforms these information pillars into systems that strike a balance between operational efficiency and ecological responsibility and social justice, with human discretion and cooperation and hi-tech automation.

In this new paradigm, the concept involves the development of multi-criteria optimization models where the factors of environmental impact and ethical consequences are directly included in the decision-making processes. AR interfaces and collaborative robots allow a human and machine to cooperate seamlessly and increase their adaptability and contextual responsiveness in case of complex or unexpected events. The further contribution to supply chain resilience includes better-distributed manufacturing and diversified sourcing strategies to reduce risks related to concentrated dependencies. Also, blockchain-powered traceability moves transparency further than logistical precision to verifiable sustainability and labour criteria to keep supply chain operations within changing regulatory environments and consumer demands.

Regardless of these bright qualities, the implementation of Supply Chain 5.0 principles is associated with significant organisational, technological, and socio-economic dilemmas. The compatibility of legacy infrastructure, the ability to communicate with heterogeneous data sources, and the skills of the personnel to work with interactive digital governance are coordinated measures that need to be undertaken with regard to system redesigning and staff training. The presence of cultural resistance and generational differences, as well as the necessity of cross-functional cooperation, complicate the change management, and the involvement of high capital investments and intricate compliance with regulations forces the company to plan strategically on a long-term basis. The solution to these problems requires interdisciplinary cooperation that cuts across the fields of engineering, environmental science, economics, social policy, and ergonomics to establish supply-chain ecosystems that are efficient and ethically based.

The emerging trends show a shift towards supply chain architectures operating as coordinated socio-technical frameworks, which can be economically viable and ensure the health of the planet and social wellbeing. This involves the integration of sustainability measures into AI-based analytics, the alignment between renewable energy feeds and production timelines, and the use of proactive compliance processes that preempt regulatory changes. Employee engagement is no longer a passive observation, but an active involvement in decision-making, and it is enhanced by extensive upskilling programmes, which develop contextual knowledge in addition to technical skills.

Finally, this development is an indication of the redefinition of success in the supply chain whereby operational excellence is not only gauged based on speed or cost but rather on the ability to adjust, survive and play a positive role in society and the environment. Automation and human understanding synthesised in resilient, transparent, and sustainable frameworks provide an avenue through which industries can address the present-day challenges and at the same time arrive at the objectives of the greater society. Further investigation and field testing will be required to enhance these models, to come up with interoperable standards as well as to build the human capital to achieve maximum potential of this integrated approach.

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Conflict of Interest

The authors declare no conflicts of interest regarding the publication of this manuscript.

REFERENCES

1. Abdirad, M., & Krishnan, K. (2021). Industry 4.0 in logistics and supply chain management: A systematic literature review. *Engineering Management Journal*, *33*(3), 187–201. https://doi.org/10.1080/10429247.2020.1783935
2. Agrawal, S., Agrawal, R., Kumar, A., Luthra, S., & Garza-Reyes, J. A. (2024). Can industry 5.0 technologies overcome supply chain disruptions? –a perspective study on pandemics, war, and climate change issues. *Operations Management Research*, *17*(3), 453–468. https://doi.org/10.1007/s12063-023-00410-y
3. Akbari, M., Kok, S. K., Hopkins, J., Frederico, G. F., Nguyen, H., & Alonso, A. D. (2024). The changing landscape of digital transformation in supply chains: Impacts of industry 4.0 in vietnam. *The International Journal of Logistics Management*, 1040–1072. https://doi.org/10.1108/IJLM-11-2022-0442

4. Akundi, A., Euresti, D., Luna, S., Ankobiah, W., Lopes, A., & Edinbarough, I. (2022). State of industry 5.0–analysis and identification of current research trends. *Applied Systems Innovation*, *5*, 27. https://doi.org/10.3390/asi5010027
5. Bag, S., Telukdarie, A., Pretorius, J. H. C., & Gupta, S. (2021). Industry 4.0 and supply chain sustainability: Framework and future research directions. *Benchmarking: An International Journal*, *28*(5), 1410–1450. https://doi.org/10.1108/BIJ-03-2018-0056
6. Boudouaia, M. A., Ouchani, S., Qaisar, S. M., & Almaktoom, A. T. (2024). Supply chain 5.0: Vision, challenges, and perspectives. In *2024 21st Learning and Technology Conference (L&T)* (pp. 203-208). IEEE.
7. Chauhan, C., & Singh, A. (2020). A review of industry 4.0 in supply chain management studies. *Journal of Manufacturing Technology Management*, *31*(5). https://doi.org/10.1108/JMTM-04-2018-0105
8. Fatorachian, H., & Kazemi, H. (2021). Impact of industry 4.0 on supply chain performance. *Production Planning & Control*, *32*(1), 63–81. https://doi.org/10.1080/09537287.2020.1712487
9. Frederico, G. F. (2021). From supply chain 4.0 to supply chain 5.0: Findings from a systematic literature review and research directions. *Logistics*, 49. https://doi.org/10.3390/logistics5030049
10. Frederico, G. F., Garza-Reyes, J. A., Kumar, V., & Kumar, A. (2021). Performance measurement for supply chains in the industry 4.0 era: A balanced scorecard approach. *International Journal of Productivity & Performance Management*, *70*(4), 789–807. https://doi.org/10.1108/IJPPM-08-2019-0400
11. Ghadge, A., Kara, M. E., Moradlou, H., & Goswami, M. (2020). The impact of industry 4.0 implementation on supply chains. *Journal of Manufacturing Technology Management*, 669–686. https://doi.org/10.1108/JMTM-10-2019-0368
12. Ghobakhloo, M., Iranmanesh, M., Fathi, M., Rejeb, A., Foroughi, B., & Nikbin, D. (2025). Beyond industry 4.0: A systematic review of industry 5.0 technologies and implications for social, environmental and economic sustainability. *Asia-Pacific Journal of Business Administration*, *17*(4), 889–914. https://doi.org/10.1108/APJBA-08-2023-0384
13. Golovianko, M., Terziyan, V., Branytskyi, V., & Malyk, D. (2023). Industry 4.0 vs. Industry 5.0: Co-existence, Transition, or a Hybrid. *Procedia Computer Science*, *217*, 102–113. https://doi.org/10.1016/j.procs.2022.12.206
14. Ivanov, D. (2022). The industry 5.0 framework: Viability-based integration of the resilience, sustainability, and human-centricity perspectives. *International Journal of Production Research*, *61*(5), 1683–1695. https://doi.org/10.1080/00207543.2022.2118892
15. Jefroy, N., Azarian, M., & Yu, H. (2022). Moving from industry 4.0 to industry 5.0: What are the implications for smart logistics? *Logistics*, *6*, 26. https://doi.org/10.3390/logistics6020026
16. Maria, E. D., Marchi, V. D., & Galeazzo, A. (2022). Industry 4.0 technologies and circular economy: The mediating role of supply chain integration. *Bus Strat Env*, *31*. https://doi.org/10.1002/bse.2940
17. Mastos, T. D., Nizamis, A., Vafeiadis, T., Alexopoulos, N., Ntinas, C., Gkortzis, D., Papadopoulos, A., Ioannidis, D., & Tzovaras, D. (2020). Industry 4.0 sustainable supply chains: An application of an IoT enabled scrap metal management solution. *Journal of Cleaner Production*. https://doi.org/10.1016/j.jclepro.2020.122377
18. Modgil, S., Singh, R. K., & Agrawal, S. (2025). Developing human capabilities for supply chains: An industry 5.0 perspective. *Annals of Operations Research*, *348*, 2075–2105. https://doi.org/10.1007/s10479-023-05245-1
19. Nazarian, H., & Khan, S. A. (2024). The impact of industry 5.0 on supply chain performance. *International Journal of Engineering Business Management*, *16*, 1–19. https://doi.org/10.1177/18479790241297022
20. Ralston, P., & Blackhurst, J. (2020). Industry 4.0 and resilience in the supply chain: A driver of capability enhancement or capability loss? *International Journal of Production Research*, *58*(16), 5006–5019. https://doi.org/10.1080/00207543.2020.1736724
21. Santhi, A. R., & Muthuswamy, P. (2023). Industry 5.0 or industry 4.0S? Introduction to industry 4.0 and a peek into the prospective industry 5.0 technologies. *International Journal on Interactive Design and Manufacturing (IJIDeM)*, 947–979. https://doi.org/10.1007/s12008-023-01217-8
22. Shao, X.-F., Liu, W., Li, Y., Chaudhry, H. R., & Yue, X.-G. (2021). Multistage implementation framework for smart supply chain management under industry 4.0. *Technological Forecasting & Social Change*. https://doi.org/10.1016/j.techfore.2020.120354

23. Sobb, T., Turnbull, B., & Moustafa, N. (2020). Supply chain 4.0: A survey of cyber security challenges, solutions and future directions. *Electronics*. https://doi.org/10.3390/electronics9111864
24. Tiwari, S. (2020). Supply chain integration and Industry 4.0: a systematic literature review. *Benchmarking an International Journal*, *28*(3), 990–1030. https://doi.org/10.1108/bij-08-2020-0428
25. Varriale, V., Cammarano, A., Michelino, F., & Caputo, M. (2023). Industry 5.0 and triple bottom line approach in supply chain management: The state-of-the-art. *Sustainability*, *15*(7), 5712. https://doi.org/10.3390/su15075712
26. Verma, A., Bhattacharya, P., Madhani, N., Trivedi, C., Bhushan, B., Tanwar, S., Sharma, G., Bokoro, P. N., & Sharma, R. (2022). *Blockchain for industry 5.0: Vision, opportunities, key enablers, and future directions*. https://doi.org/10.1109/ACCESS.2022.3186892
27. Wu, H., Liu, J., & Liang, B. (2025). AI-driven supply chain transformation in industry 5.0: Enhancing resilience and sustainability. *Journal of the Knowledge Economy*, *16*, 3826–3868. https://doi.org/10.1007/s13132-024-01999-6
28. Xu, X., Lu, Y., Vogel-Heuser, B., & Wang, L. (2021). Industry 4.0 and industry 5.0, inception, conception and perception. *Journal of Manufacturing Systems*, *61*, 530–535. https://doi.org/10.1016/j.jmsy.2021.10.006