International Journal of Energy Economics and Policy

ISSN: 2146-4553

available at http: www.econjournals.com

International Journal of Energy Economics and Policy, 2026, 16(2), 1278-1289.

Digitally Enabling Environmental Agility through a Dynamic Capabilities Framework with Digital Twins and SCOR

Eias Al Humdan*

Faculty of Resilience, Rabdan Academy, Abu Dhabi, United Arab Emirates. *Email: eias.alhumdan@gmail.com

Received: 10 October 2025 **Accepted:** 26 January 2026 **DOI:** https://doi.org/10.32479/ijeep.22814

ABSTRACT

In response to mounting environmental volatility and regulatory pressures, supply chains (SCs) must evolve from efficiency-driven systems into environmentally agile networks. This study introduces the concept of environmental agility (EA); the capability of a SC to sense, respond to, and reconfigure around environmental disruptions in real time. We develop a novel conceptual framework that integrates digital twin (DT) technologies with the dynamic capability view (DCV), the sense-and-respond (S&R) paradigm, and the supply chain operations reference (SCOR) model to operationalize this emerging capability. The framework embeds environmental sensing, predictive simulation, and adaptive reconfiguration into SCOR processes, enabling organizations to reduce emissions, optimize resource flows, and comply with sustainability mandates dynamically. Grounded in a design science methodology and validated through analytical generalization from industry-based DT applications, the model demonstrates both conceptual rigor and contextual relevance. This study contributes to sustainable SC theory by positioning digital twins as enablers of dynamic environmental capabilities and recasting SCOR as a responsive, eco-intelligent infrastructure.

Keywords: Environmental Agility, Digital Twins, Dynamic Capabilities, Sustainable Supply Chains, Sense-and-Respond, SCOR Model
JEL Classifications: L23, O33, Q56, M11

1. INTRODUCTION

Escalating climate risks, tightening environmental regulations, and shifting societal expectations have repositioned sustainability as a strategic imperative rather than a compliance burden for global SCs (Geyi et al., 2020; Jia et al., 2024). From climate-induced disasters to Scope 3 emissions disclosures, today's SCs face increasing pressure to become not only resilient but also environmentally agile, capable of real-time sensing, rapid response, and adaptive reconfiguration in pursuit of sustainable outcomes (Dhanda et al., 2022; Mathiyazhagan et al., 2021).

Historically, agility in SCs has been associated with responsiveness to market dynamics, customer demands, and operational uncertainties (Al Humdan et al., 2020; 2024). However, recent disruptions: From carbon pricing volatility to environmental compliance mandates, underscore that traditional models of agility, often centered around speed and flexibility alone, are insufficient. What is now needed is environmental agility (EA)—a novel construct defined as the capacity of a SC to proactively sense environmental changes (e.g., emissions risks, climate policy shifts), respond adaptively through digital intelligence, and reconfigure processes toward sustainability goals.

Despite growing recognition of the role of digital technologies (DTs) in advancing sustainable SCs, few frameworks explicitly integrate environmental agility as a core capability. Existing models often lack the theoretical grounding to explain how environmental adaptation emerges from dynamic capabilities, and they fall short in offering process-level integration needed for operationalization (Ivanov and Dolgui, 2021; Jia et al., 2024). The concept of agility remains under-theorized in its environmental form and disconnected from digital execution platforms such as DTs.

This study addresses that gap by introducing a conceptual framework that integrates digital twin (DT) technologies with the dynamic capability view (DCV), the sense-and-respond (S&R) paradigm, and the supply chain operations reference (SCOR) model to operationalize EA. Digital twins: Real-time virtual representations of physical systems, enable organizations to simulate, monitor, and reconfigure SC activities in response to live environmental signals, including emissions levels, energy use, and regulatory changes (Guo and Mantravadi, 2025; Qi and Tao, 2018). Yet, their integration into structured theoretical models for sustainability-oriented agility remains limited.

The DCV (Teece et al., 1997) offers a strategic lens to explain how firms sense, seize, and reconfigure resources to adapt under environmental volatility, while the S&R paradigm (Haeckel, 1999) adds behavioral specificity by embedding real-time responsiveness into decision-making. The SCOR model, traditionally used for performance benchmarking, is reimagined here as a dynamic, process-based engine for digitally-enabled environmental agility.

To develop and validate the framework, this study adopts a design science methodology (Gregor and Hevner, 2013) supported by analytical generalization (Wacker, 2008), drawing from documented use cases of DT-enabled sustainability in diverse sectors. The framework is evaluated for conceptual coherence, strategic alignment, and practical relevance to contemporary SC challenges.

The study is guided by the following research questions:
- *RQ1:* How can DT technologies be conceptually integrated to support environmental agility in SCs?
- *RQ2:* How do dynamic capabilities and sense-and-respond mechanisms collectively enable proactive environmental adaptation?
- *RQ3*: How can the SCOR model be reconfigured as a digitally intelligent architecture to operationalize environmental agility?

This paper contributes in three keyways. First, it introduces and defines the concept of environmental agility (EA), extending the literature on sustainable SCs and digital transformation. Second, it operationalizes EA through the integration of DCV and S&R paradigms with DT technologies, offering actionable pathways for emissions tracking, adaptive logistics, and compliance reconfiguration. Third, it recasts the SCOR model as an eco-intelligent infrastructure—transforming it from a static benchmarking tool into a dynamic, real-time decision support system for environmental responsiveness.

The remainder of the paper is structured as follows. Section 2 reviews the literature on EA and digital-environmental integration. Section 3 presents the research design and methodology. Section 4 introduces the integrated conceptual framework. Section 5 details the validation strategy using analytical generalization. Section 6 concludes with implications, future research directions and limitations. endeavours.

2. LITERATURE REVIEW

2.1. From Supply Chain Agility to Environmental Agility

Agility has long been recognized as a cornerstone of SC competitiveness, especially in environments marked by demand volatility, technological disruption, and geopolitical uncertainty (Christopher, 2000; Sharifi and Zhang, 1999). Originally conceived as the ability to swiftly respond to market shifts and customer needs, supply chain agility (SCA) has evolved into a broader strategic construct encompassing speed, flexibility, and responsiveness across sourcing, production, and distribution (Al Humdan et al., 2020). Over time, agility has expanded from being a reactive logistical trait to a proactive, system-wide capability that allows firms to anticipate disruption and reconfigure operations dynamically (Humdan et al., 2023; Wang and Wang, 2024).

This evolution has accelerated in the wake of the COVID-19 pandemic and the intensification of environmental uncertainty. Recent scholarship confirms that agility not only enhances operational responsiveness but also plays a pivotal role in improving environmental and sustainability performance (Cantele et al., 2023; Sharma et al., 2025). Scholars now argue that agility must extend beyond economic value creation to include environmental and social outcomes, particularly in light of tightening climate policies, carbon taxation, and mandatory sustainability disclosures (Bouguerra et al., 2024; Ivanov, 2022). In this context, agility is no longer just a buffer against disruption but a strategic enabler of adaptive sustainability. This shift has led to the emergence of Environmental Agility, a novel conceptualization defined as a SC's ability to sense, interpret, and respond swiftly to environmental changes and pressures—including carbon pricing fluctuations, emission audits, energy volatility, and regulatory reform. EA differs from both traditional agility and resilience: while resilience emphasizes robustness and recovery, and agility emphasizes operational flexibility (Fahimnia et al., 2018; Wieland and Durach, 2021), EA is forward-looking and sustainability-driven, focusing on the anticipation and proactive adaptation to ecological and regulatory shifts.

A growing body of empirical research supports this conceptual reorientation. For instance, Geyi et al. (2020) demonstrate that agile capabilities are necessary for achieving high sustainability performance in volatile contexts. Jia et al. (2024) argue that agility—particularly when enhanced by digital capabilities—is foundational to realizing the promise of the "Triple-A" SC (agility, adaptability, alignment) in sustainable strategies. Similarly, Salandri et al. (2022) and Kazancoglu et al. (2022) highlight that agility moderates the relationship between green practices and operational performance, enabling organizations to align environmental goals with business efficiency. EA also intersects with digital transformation and innovation. Fernández-Miguel et al. (2024) illustrate how agile manufacturing enabled by Industry 5.0 technologies, such as additive moulding, supports sustainability in production systems. Mohaghegh et al. (2025) find that digital transformation enhances sustainable outcomes when mediated by Triple-A SC capabilities. In this context, agility becomes the channel through which digital investments translate into measurable environmental benefits.

Yet despite its growing relevance, EA remains an underdeveloped construct in both theory and practice. Most existing models still treat agility and sustainability as parallel, rather than integrated, domains (Dayioglu et al., 2024). Moreover, the behavioral, technological, and process-level enablers of EA have not been systematically articulated. While recent studies touch upon its elements, e.g., sensing environmental threats, reconfiguring supply networks, or aligning with emissions goals, there is currently no integrative framework that captures how EA is built, operationalized, and enacted within modern SCs.

2.2. Digital Twins DTs as Enablers of EA

Digital twin (DT) technology has rapidly emerged as a transformative enabler of intelligent, responsive, and sustainable operations across the SC ecosystem (Barata and Kayser, 2024). Conceptually defined as a dynamic, real-time digital replica of a physical system or process, DTs integrate multi-source sensor data, simulation models, and AI-driven analytics to monitor, diagnose, and optimize performance across the lifecycle of assets and networks (Ivanov, 2024; Jesus et al., 2024). While originally developed for complex engineering applications such as aerospace and automotive systems (Grieves and Vickers, 2017), DTs have now expanded into SCM, where their potential lies not only in efficiency gains but in supporting proactive sustainability responses.

Within operations and SCs, DTs are increasingly recognized for their ability to operationalize agility through real-time visibility, scenario simulation, and predictive control (Bhandal et al., 2022; Qi and Tao, 2018; Singh et al., 2023). Unlike static digital dashboards, DTs function as cognitive decision environments—enabling firms to sense disruptions, simulate interventions, and reconfigure processes dynamically. These capabilities are central to agility. However, their application in environmental adaptation is particularly novel and underexplored. Emerging studies show that DTs can play a decisive role in advancing EA; a firm's capacity to sense, respond, and adapt to ecological changes such as carbon regulation, emissions surges, or green compliance mandates. For instance, Kamble et al. (2022) propose that DTs enable real-time sustainability analytics by tracking emissions at granular levels and testing green alternatives before physical implementation. Similarly, Mohaghegh et al. (2025) emphasize that DTs mediate the impact of digital transformation on sustainability performance by enhancing agility, adaptability, and alignment—collectively enabling low-carbon SC transitions.

DTs also support regulatory scenario testing, where firms simulate the impacts of carbon taxes, emissions caps, or ESG reporting requirements under different operational configurations (Fernández-Miguel et al., 2024). This allows not only for compliance assurance but also for strategic foresight in redesigning greener supply networks. In manufacturing, Singh et al. (2023) demonstrate that DT-enabled process modeling improves environmental performance by enabling predictive maintenance and resource optimization, ultimately reducing waste and energy usage.

Furthermore, Ivanov (2024) presents a seven-element DT framework that includes environmental data integration, offering a blueprint for how DTs can be structurally embedded in SC models to support environmental responsiveness. These elements include real-time sensing, digital shadowing, closed-loop feedback, and adaptive execution—each of which maps directly onto the capabilities needed for EA.

2.3. Dynamic Capabilities for Strategic Environmental Responsiveness

In the face of climate change, carbon constraints, and sustainability-driven regulations, SCs must evolve from reactive operations to adaptive systems capable of orchestrating continuous environmental responsiveness. The dynamic capability view (DCV) provides a compelling theoretical lens to understand how firms develop and deploy such adaptive capabilities. Introduced by Teece et al. (1997), DCV posits that long-term competitive advantage in turbulent environments stems not from static resources but from dynamic capabilities—the firm's capacity to sense opportunities and threats, seize them through timely actions, and reconfigure assets and structures accordingly.

This foundational triad maps naturally onto contemporary sustainability imperatives. In the context of green SC strategy, sensing involves scanning for environmental disruptions such as carbon pricing, emissions audits, water stress, or biodiversity regulations. Seizing entails translating these insights into actionable low-carbon innovations—such as switching to renewable inputs, investing in circular logistics, or diversifying sourcing networks. Reconfiguring then requires adjusting global production footprints, supplier portfolios, and transport modes to align with sustainability performance goals (Beske, 2012; Vanpoucke et al., 2014).

Recent research affirms the relevance of DCV to EA. Ortiz-Avram et al. (2024) outline how sustainability-oriented innovation, when embedded in dynamic capabilities, enables firms to integrate stakeholder needs and regulatory expectations into core strategic responses. Knoppen and Knight, (2022) show that "born-sustainable" firms inherently cultivate DCs that allow them to balance economic viability with ecological responsibility—demonstrating that sustainability and adaptability can reinforce rather than trade off against each other. Likewise, Siems et al. (2021) reveal that DCs manifest differently across industries but consistently serve as the bedrock of sustainability transitions in both automotive and food SCs. For established SCs grappling with decarbonization, dynamic capabilities offer a pathway to shift from compliance-driven greening to proactive environmental agility. Eikelenboom and de Jong, (2019) emphasize that for SMEs in particular, dynamic capabilities enable the development of strategic flexibility and innovation under sustainability pressures, while Buzzao and Rizzi, (2021) propose a typology for categorizing capabilities, such as learning, sensing, and coordinating—as they relate to sustainability performance.

The integration of dynamic capabilities with digital technologies and structured process frameworks has received limited attention, particularly in terms of how these capabilities are enacted in response to real-time environmental data. In this context, DTs offer a unique operational platform to enact dynamic capabilities by embedding environmental sensing, simulation, and reconfiguration into SC processes. For example, a DT can detect elevated emissions in a distribution route (sensing), simulate lower-carbon alternatives (seizing), and dynamically reroute logistics (reconfiguring), aligning strategic agility with sustainability mandates.

2.4. Reimagining SCOR: From Benchmarking to Environmental Intelligence

The supply chain operations reference (SCOR) model, developed by the Supply Chain Council in 1996, serves as a process-oriented framework that standardizes and benchmarks SC operations. It provides a structured taxonomy of six interconnected processes: Plan, source, make, deliver, return, and enable, that span strategic planning to tactical execution across the SC. This model integrates performance metrics, best practices, and process reengineering principles, making it a foundational tool for diagnosing inefficiencies and driving continuous improvement (Estampe et al., 2014; Stewart, 1997; Supply Chain Council, 2012). SCOR's strength lies in its hierarchical structure, which allows SC functions to be analyzed at varying levels of granularity—from broad process categories to specific transactional activities (Huang et al., 2005). This makes it particularly relevant for complex and data-intensive environments where digital solutions like DTs can be mapped precisely onto operational functions. For instance, digital twins can enable real-time sensing in the "Plan" process or predictive maintenance during "Make," thereby aligning operational responsiveness with strategic foresight.

However, as sustainability imperatives intensify, SCOR's efficiency-centric and static orientation has become a critical limitation. The traditional SCOR framework is not inherently designed to address real-time environmental disruptions, carbon accounting, or regulatory responsiveness. Its linear focus on throughput, cycle times, and cost efficiency often sidelines the dynamic and multi-dimensional challenges of environmental sustainability (Salandri et al., 2022). As such, SCOR must evolve from a diagnostic benchmarking tool to an environmentally intelligent system, capable of supporting dynamic sensing, predictive adaptation, and ecological performance optimization.

This study proposes such a transformation by embedding SCOR within an integrated framework of DTs and the DCV. Digital twins allow for real-time monitoring and simulation of each SCOR process, effectively turning them into dynamic feedback loops. For example, DTs embedded in the "Plan" and "Source" phases can monitor supplier emissions, model low-carbon sourcing alternatives, and simulate the effects of policy changes such as carbon taxes (Jesus et al., 2024; Ivanov, 2024). Within the "Make" and "Deliver" phases, DTs can track energy consumption, optimize route-based emissions, and anticipate resource constraints, thereby enhancing both responsiveness and eco-efficiency (Fernández-Miguel et al., 2024; Singh et al., 2023).

Through this lens, SCOR becomes the operational conduit through which DCs are enacted. Drawing on DCV principles, firms can embed environmental sensing capabilities into real-time data collection across SCOR activities, seize green opportunities through simulation-based decision-making, and reconfigure networks and processes for carbon reduction and regulatory agility (Beske, 2012; Ortiz-Avram et al., 2024). Importantly, the SCOR model's modular and hierarchical nature makes it uniquely compatible with DT implementation, enabling layered data integration from operational to strategic levels.

This study thus advances a digitally augmented and sustainability-oriented reconceptualization of SCOR. Rather than being a static reference model, SCOR becomes a real-time orchestrator of EA, enabling proactive carbon footprint management, green compliance forecasting, and adaptive sustainability optimization across the end-to-end SC. In doing so, this reconceptualization positions SCOR at the center of digitally intelligent, future-ready SCs aligned with the grand challenge of environmental sustainability.

2.5. Sense-and-Respond Paradigm (S&R): Bridging Behavior, Technology, and Sustainability

Originally conceptualized by Haeckel (1999), the S&R paradigm reframes organizational adaptability as an emergent capability rooted in real-time sensing and rapid, decentralized response. It contrasts sharply with traditional command-and-control systems by emphasizing behavioral plasticity, continuous feedback loops, and embedded decision-making. In the context of SCs, this paradigm is particularly relevant given the increasing need for rapid reaction to disruptions, demand shifts, and unforeseen risks. As SCs increasingly confront ecological turbulence, such as carbon taxation, environmental audits, and climate-linked disruptions, the S&R paradigm becomes central to enabling environmental agility.

At its core, S&R provides the behavioral interface through which strategic intent (as articulated in the DCV is operationalized via technology (i.e., DTs) and embedded into process frameworks (i.e., SCOR). While DCV offers the macro-level logic of sensing, seizing, and reconfiguring, S&R instantiates these capabilities through real-time, bottom-up cognition and action. For instance, digital twins embedded in SC processes can autonomously detect emissions anomalies or regulatory changes (sensing), simulate alternative logistics or production paths (seizing), and initiate system-wide reconfigurations in sourcing, transportation, or packaging (responding), all underpinned by the S&R logic of continuous learning and real-time adjustment.

As Calatayud et al. (2019) argue, digital ecosystems demand agility not only in structure but in cognition—S&R meets this need by aligning human oversight with algorithmic execution. Recent contributions support this integration. Bouguerra et al. (2024) underscore how S&R enables "environmental sensemaking" and facilitates eco-innovation through responsive structures. Similarly, Sharma et al. (2025) highlight that smart SCs become sustainable not merely through digitalization, but through embedded behavioral logics that guide adaptive action across nodes. Moreover, S&R strengthens the feedback control loops that make environmental agility possible. As Dayioglu et al. (2024) note, strategic agility is realized when firms can rapidly detect changes in environmental context and immediately reconfigure their operational models. This responsiveness is neither wholly strategic (as in DCV) nor purely technological (as in DTs), but behavioral; anchored in how organizations interpret, prioritize, and act on sustainability-related stimuli.

By integrating S&R into the SCOR model, each of its processes (plan, source, make, deliver, return, enable) can evolve into real-time, cognitively responsive nodes. For example, the "Plan" phase can incorporate environmental early warning systems, "Source" can respond to supplier emissions breaches, and "Deliver" can dynamically reroute logistics to reduce transport-related carbon output. These are not static activities, but living, feedback-driven cycles of environmental adaptation—precisely what the S&R paradigm enables.

This study positions S&R not merely as a theoretical lens, but as the connective tissue that unites DCV's strategic capabilities, DTs' technological intelligence, and the SCOR model's process modularity into a cohesive system for EA. Through S&R, SCs become not only adaptive and digital—but environmentally sentient and ethically responsive.

3. RESEARCH DESIGN AND APPROACH

This study adopts a conceptual theory-building methodology grounded in design science principles (Gregor and Hevner, 2013) and supported by analytical generalization (Wacker, 2008), to develop a framework that theorizes environmental agility at the intersection of digital technologies, strategic capabilities, and SC operations. Informed by the guidance of MacInnis (2011) and Meredith (1993) on the construction of conceptual contributions, the research design is particularly suited for addressing emerging yet under-theorized phenomena, such as how digital twins (DTs) can be strategically embedded in SCs to support sustainability-driven adaptability.

Given the paucity of empirical models that integrate environmental responsiveness with dynamic capabilities and structured process frameworks, a conceptual approach allows the researcher to synthesize heterogeneous literatures, identify latent intersections, and propose an integrative theory that bridges behavioral, technological, and operational dimensions of sustainable SCM.

The theory development unfolds through four key phases:

1. Conceptual decomposition and construct identification:
   Foundational constructs are derived from four scholarly domains:
   - Dynamic capability view (DCV): Sensing environmental risks, seizing green opportunities, and reconfiguring operations
   - Sense-and-respond (S&R) Paradigm: behavioral adaptiveness and real-time feedback logic
   - SCOR model: standardized and hierarchical operational processes
   - Digital twins: technological affordances of real-time monitoring, simulation, and environmental control.

   This phase isolates the relevant constructs and positions them within a coherent logic chain to enable environmental agility.
2. Integrative conceptual mapping:
   Constructs are then mapped into a unified framework, illustrating how digital twins enable the operationalization of dynamic capabilities through SCOR processes, mediated by S&R behavioral mechanisms. For example, a DT-enabled SCOR "Make" process may support real-time emissions modeling and predictive energy optimization, aligned with the firm's strategic sensing of carbon risks.
3. Scenario-based conceptual simulation:
   The framework is validated conceptually through a series of structured "thought experiments" and scenario walkthroughs. These are modeled after real-world use cases reported in academic and industry literature (e.g., Bhandal et al., 2022; Ivanov, 2024; Jesus et al., 2024), involving DT applications in emission control, green logistics, and sustainable sourcing. Although no numerical simulation is conducted, these simulated scenarios test the internal coherence, contextual fit, and boundary conditions of the proposed model across diverse environmental contingencies and SCOR stages.
4. Comparative alignment and analytical generalization:
   To enhance external validity and practical resonance, the framework's predicted outcomes—such as lower emissions, faster compliance adaptation, and environmentally-informed sourcing—are benchmarked against empirical studies (e.g., Kamble et al., 2022; Singh et al., 2023). This ensures the model's performance logic aligns with documented sustainability performance patterns and supports future empirical testing. The generalization is analytical, not statistical, grounded in explanatory depth rather than data extrapolation (Wacker, 2008). This iterative and reflexive approach fosters theoretical parsimony, originality, and robustness. The framework evolves through continuous construct refinement and critical evaluation against three meta-criteria:
   - Conceptual integrity: Do the elements logically interlink across levels (strategy, technology, process)?
   - Strategic relevance: Does the framework offer a credible response to the challenges of sustainability-driven SC transformation?
   - Empirical plausibility: Are its assumptions and mechanisms consistent with existing sustainability evidence and DT applications?

In doing so, this study contributes a novel, theory-grounded architecture for digital sustainability in SCs—one that not only expands the concept of agility but also positions Environmental Agility as a foundational capability for navigating climate-related volatility and ecological disruption in a digitally intelligent manner.

4. CONCEPTUAL FRAMEWORK

4.1. Foundations: From Adaptive Capabilities to Environmental Intelligence

Environmental agility (EA), defined as the capability of a SC to sense environmental signals, adaptively respond, and reconfigure its processes to deliver sustainable outcomes, has become increasingly critical as firms navigate carbon taxation, climate-induced disruptions, and sustainability regulations. Unlike traditional agility which is primarily reactive and demand-driven, EA integrates environmental imperatives into real-time operational cognition and strategic foresight.

This framework builds on three foundational pillars:
- The dynamic capability view (DCV) provides the theoretical underpinning for how firms sense carbon-related risks, seize low-carbon opportunities, and reconfigure supply networks for sustainable competitiveness (Beske, 2012; Siems et al., 2021; Ortiz-Avram et al., 2024).
- The sense-and-respond (S&R) paradigm introduces a behavioral systems logic that embeds cognition, continuous monitoring, and real-time adaptation into environmental decision-making (Dayioglu et al., 2024).
- The SCOR model offers a structured operational backbone across six core processes—plan, source, make, deliver, return, and enable—now reoriented for environmental intelligence.

Digital twins (DTs) act as the enabling infrastructure that integrates strategic intent (DCV), behavioral adaptation (S&R), and structured process control (SCOR), translating them into measurable, environmentally responsive actions.

4.2. Role of DTs in Enabling Environmental Agility

DTs represent a foundational enabler in the transformation of SCs into environmentally agile systems. Far beyond traditional operational efficiency tools, DTs provide an intelligent, dynamic, and responsive digital infrastructure that allows firms to monitor environmental performance in real time, simulate low-carbon alternatives, and proactively adapt to sustainability disruptions. As SCs confront increasing environmental volatility—ranging from climate-related risks to regulatory compliance mandates—DTs emerge as critical technological mediators that translate environmental signals into timely and effective action (Mohaghegh et al., 2025; Singh et al., 2023).

Their functionality aligns directly with the DCV—serving as the technological mechanism by which firms develop the capacity to sense, seize, and reconfigure in response to environmental threats and opportunities (Ortiz-Avram et al., 2024). DTs are particularly powerful in operationalizing environmental agility, a capability that enables real-time environmental sensing, rapid adaptation, and sustainability-oriented reconfiguration across the SC (Kamble et al., 2022).

4.2.1. Sensing

DTs integrate data from IoT sensors, RFID tags, ERP systems, and external environmental databases to continuously monitor energy consumption, GHG emissions, water use, and waste outputs across the SC. This data fusion capability supports granular, real-time visibility that is critical for detecting sustainability risks as they emerge—such as exceeding emissions thresholds or violating environmental compliance benchmarks (Bhandal et al., 2022; Jesus et al., 2024). This real-time sensing layer serves as the backbone of environmental intelligence, enabling both early warning and predictive alert systems (Alkaraan et al., 2024).

4.2.2. Seizing

Building on this environmental intelligence, DTs deploy AI-driven simulations and decision models to evaluate and compare low-carbon alternatives. These include renewable energy sourcing, route optimization for green logistics, supplier switching based on ESG ratings, or redesigning packaging for circularity. By enabling digital prototyping of environmental scenarios, DTs allow firms to seize green opportunities with reduced risk and shorter time-to-implementation (Fernández-Miguel et al., 2024; Ivanov, 2024). This capacity supports proactive compliance with regulatory frameworks and voluntary ESG commitments while driving innovation in green product and process design (Evans et al., 2017; Marchi et al., 2013).

4.2.3. Reconfiguring

DTs enable dynamic SC reconfiguration based on both internal and external environmental signals. This includes the ability to reroute transportation flows in response to climate disruptions (e.g., flooding, extreme heat), reallocate inventory to lower-emission distribution centers, or simulate end-of-life circular scenarios such as reverse logistics and product reuse (Centobelli et al., 2020). These capabilities empower firms to move beyond resilience and embrace adaptive sustainability—that is, the ability to optimize environmental and operational performance simultaneously under changing conditions.

Through these mechanisms, DTs bridge the long-standing gap between strategic sustainability goals and operational execution. As highlighted by Handfield et al. (2005), true environmental integration in SCs requires the alignment of monitoring systems, decision-making logic, and execution platforms—DTs offer exactly this convergence. Furthermore, by embedding DTs within SCOR-aligned processes, organizations can ensure that carbon metrics, SDG targets, and compliance thresholds are not only tracked but used to dynamically guide real-time SC behavior.

4.3. Embedding Environmental Agility into SCOR Processes

The SCOR model provides a globally recognized framework for SC design, analysis, and improvement, offering a structured taxonomy across six process categories: Plan, source, make, deliver, return, and enable. While traditionally geared toward performance benchmarking and operational efficiency, SCOR has historically lacked integration with sustainability metrics and real-time responsiveness to environmental volatility.

To align with sustainability imperatives and dynamic adaptation, this study proposes a reconfiguration of the SCOR model as a digitally intelligent, environmentally responsive system, capable of operationalizing environmental agility. This reimagining is not only conceptual—it is necessary. As sustainability becomes embedded in regulatory frameworks (e.g., CSRD, TCFD), market expectations (e.g., net-zero commitments), and global standards (e.g., SDGs), organizations must embed carbon consciousness and environmental intelligence into day-to-day SC operations.

By integrating digital twin (DT) technology, dynamic capabilities (DCV), and sense-and-respond (S&R) paradigms, each SCOR process becomes an active node of sustainability execution, capable of sensing, interpreting, and adjusting in real-time. DTs serve as the technological infrastructure that enables this transformation—embedding data-driven intelligence across every SCOR function. DCV provides the strategic direction (e.g., sensing carbon risks, seizing low-carbon opportunities), while S&R injects the behavioral responsiveness necessary to drive action at the operational edge.

For example:
- In the plan phase, DTs enable real-time carbon forecasting, allowing firms to plan procurement and production around emissions constraints
- In source, dynamic capabilities facilitate environmentally informed supplier selection and ESG monitoring, while DTs simulate sourcing scenarios under shifting regulatory and carbon pricing conditions
- In make, smart manufacturing systems powered by DTs enable predictive energy optimization and waste minimization, contributing directly to scope 1 and 2 emissions reduction.
- In deliver, DT-enabled logistics platforms allow for real-time emissions monitoring and low-carbon routing optimization
- In return, environmental agility supports reverse logistics, product take-back schemes, and circularity—key to closing material loops in the circular economy (Centobelli et al., 2020; Moktadir et al., 2020)
- Finally, the enable process functions as the data and governance backbone, ensuring emissions tracking, SDG alignment, and real-time reporting for sustainability dashboards (Dyllick and Hockerts, 2002; Figge et al., 2002).

Collectively, these digital and strategic enhancements convert SCOR from a static process model into an eco-intelligent decision architecture, enabling firms to navigate environmental disruption with speed, accuracy, and foresight.

Table 1 summarizes how each SCOR process is digitally augmented and environmentally reoriented to support EA:

4.4. The Integrated Framework for Environmental Agility EA

This study introduces a novel, multidimensional framework, the integrated framework for environmental agility, which operationalizes the emerging concept of environmental agility by strategically aligning DCs, real-time behavioral responsiveness, and structured SC processes through the enabling power of DT technologies. As illustrated in Figure 1, the framework reflects a layered architecture that enables SCs to dynamically sense, interpret, and respond to environmental disruptions while optimizing performance against sustainability imperatives.

4.4.1. Strategic layer: Dynamic capability view (DCV)

At the strategic level, the framework is grounded in the DCV, which enables firms to sense, seize, and reconfigure in response to fast-changing environmental conditions. Environmental agility is thus conceptualized as a dynamic capability wherein:
- Sensing involves continuous environmental scanning, including carbon pricing trends, regulatory changes, and resource scarcities
- Seizing refers to the timely exploitation of green opportunities, such as transitioning to renewable logistics or implementing closed-loop systems
- Reconfiguring involves structural changes to SCs—e.g., redesigning sourcing networks or investing in circular economy infrastructure—to align with sustainability objectives.

This capability-based grounding ensures that environmental agility is not a reactive posture but a strategic competency embedded in the firm’s innovation logic and resource orchestration (Knoppen and Knight, 2022; Ortiz-Avram et al., 2024).

4.4.2. Behavioural layer: Sense-and-respond (S&R) paradigm

The S&R paradigm adds a crucial behavioral and cognitive dimension to the model, serving as the execution logic through which dynamic capabilities are enacted. This layer emphasizes:
- Continuous feedback mechanisms between the environment and internal processes;
- Decentralized adaptation, enabling real-time decision-making across SC nodes; and
- Learning loops, which institutionalize environmental responsiveness into routines.

By linking strategic sensing to operational adaptation, the S&R layer ensures that the system does not merely react, but learns, evolves, and internalizes sustainability responsiveness as a behavioral norm (Dayioglu et al., 2024).

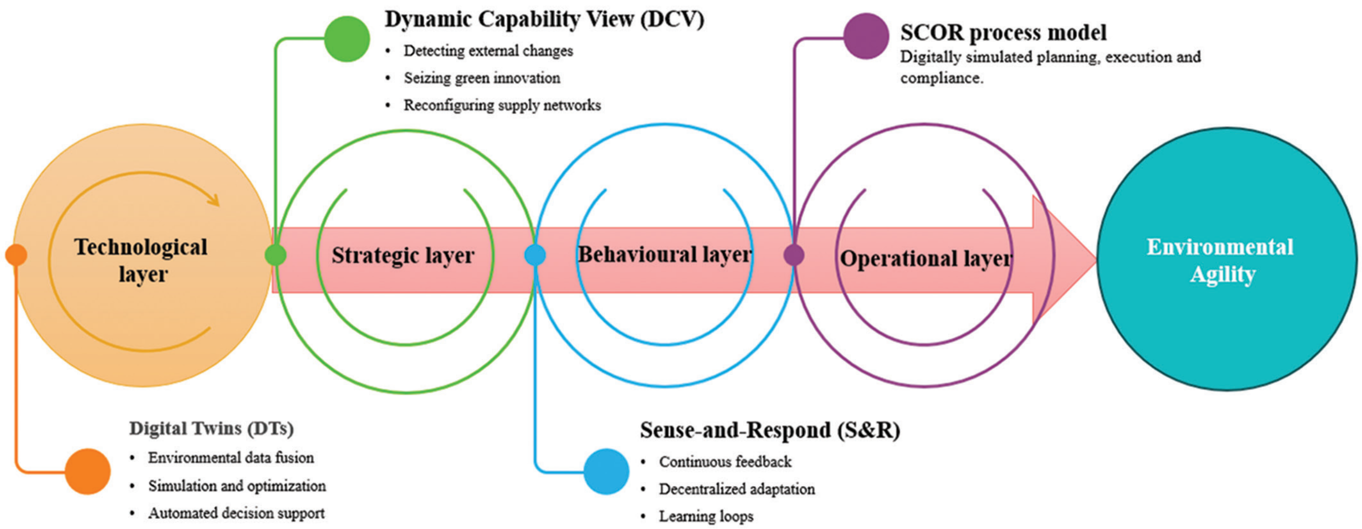
4.4.3. Operational layer: SCOR process model

The framework’s operational backbone is the SCOR model, which provides a standardized process structure (plan, source, make, deliver, return, enable) that is digitally augmented to manage sustainability KPIs. Traditionally criticized for being static and efficiency-centric, SCOR is reconceptualized here as a digitally intelligent environmental operating system. DTs are embedded within each SCOR process, enabling:
- Carbon-aware planning through predictive analytics;
- Green sourcing based on supplier ESG profiles;
- Sustainable manufacturing via energy optimization;
- Low-impact delivery using route and mode simulation; and
- Closed-loop return systems that support circular economy practices (Marchi et al., 2013; Moktadir et al., 2020).

Table 1: Reconfiguring SCOR processes for environmental agility

SCOR process	DT functionality	Environmental application
Plan	Real-time sensing, simulation	Carbon footprint forecasting, emissions-constrained planning
Source	Predictive sourcing optimization, ESG analytics	Low-carbon supplier selection, green procurement scenario testing
Make	Energy monitoring, digital production twin	Predictive energy optimization, eco-efficiency in operations
Deliver	Emissions tracking, dynamic routing	Green logistics routing, mode switching for emissions reduction
Return	Closed-loop feedback, reverse logistics	Waste tracking, circularity modeling, reverse SC design
Enable	Environmental data governance, KPI tracking	SDG-linked metrics, sustainability scorecards, real-time ESG compliance

Figure 1: Integrated framework for environmental agility



This digital infusion transforms SCOR from a benchmarking tool to an eco-responsive management architecture.

4.4.3. Technological layer: DTs as enablers

Serving as the foundational enabler, DT technologies operationalize each layer of the model. They enable:

- Environmental data fusion through integration of IoT, ERP, RFID, and emissions sensors;
- Simulation and optimization of various green scenarios, including regulatory compliance and carbon offsetting; and
- Automated decision support, enhancing both tactical agility and long-term sustainability alignment (Ivanov, 2024; Singh et al., 2023).

DTs serve as the nervous system of the environmentally agile SC—connecting data, decisions, and performance across organizational layers in real time.

The proposed framework not only introduces environmental agility as a distinctive and necessary evolution of SC strategy, but also demonstrates how it can be conceptually grounded, digitally enabled, and operationally embedded. By integrating dynamic capabilities (DCV), behavioral execution (S&R), and structured processes (SCOR) through DTs, the model provides a transformative pathway for advancing climate-resilient, circular, and sustainable SCs—positioning environmental agility as a critical strategic differentiator in the age of ecological accountability.

5. VALIDATION STRATEGY

To assess the credibility, coherence, and practical relevance of the proposed framework for environmental agility, this study adopts a two-pronged validation strategy. First, a scenario-based conceptual simulation is employed to test the logical robustness and process fit of the framework under sustainability-driven conditions. Second, analytical generalization is used to compare the framework's constructs and mechanisms with real-world applications of digital twins in sustainable SCM.

This dual approach reflects best practices in conceptual research design where empirical data are limited or emergent, and theoretical synthesis is needed to structure and inform future empirical investigations (Gregor and Hevner, 2013; Wacker, 2008).

5.1. Scenario-Based Conceptual Simulation

5.1.1. Scenario A: Carbon pricing shock

A regulatory body imposes a sudden carbon tax of €80/metric ton, requiring organizations to recalculate their cost-to-serve and redesign supplier portfolios.

- Strategic layer (DCV): The firm activates sensing mechanisms to detect shifts in regulatory environments and forecast compliance costs. Using the "seizing" capability, it explores green sourcing options and renewable energy adoption
- Behavioral layer (S&R): Cross-functional teams initiate real-time decision loops to reprioritize procurement strategies based on new ESG metrics
- Operational layer (SCOR): The "Plan" and "Source" processes are digitally simulated to evaluate cost and emissions trade-offs across multiple sourcing routes and inventory policies
- Technological enabler (DT): DTs simulate cost and emissions impact across alternative supply networks, supporting scenario-based optimization under the new regulatory constraint.

5.1.2. Scenario B: Climate-induced port disruption

A key maritime port is temporarily closed due to severe flooding, disrupting global logistics for high-volume SKUs.

- Strategic layer (DCV): The disruption is sensed early through predictive analytics tied to satellite weather data. The firm seizes opportunities by activating nearshoring plans and adjusting safety stock levels
- Behavioral layer (S&R): Autonomous decision agents and human operators collaborate to assess risk exposure and initiate re-routing strategies based on real-time capacity and inventory levels
- Operational layer (SCOR): "Make"and "Deliver" processes are reconfigured in digital simulations to identify alternate

Table 2: Analytical generalization—mapping framework components to use case analogues

Theoretical component	Framework mechanism	Empirical analogue	Source
Sensing (strategic layer)	Real-time environmental monitoring via IoT-embedded DTs	Continuous emissions and energy monitoring using DTs in green manufacturing	Singh et al., 2023
Seizing (strategic layer)	AI-driven scenario modelling for sustainable sourcing and logistics	Use of DT simulations to optimize low-emission transport and supplier ESG scoring	Kamble et al., 2022
Reconfiguring (strategic layer)	Dynamic process adaptation based on environmental disruptions	SC route re-optimization during flood risks using digital simulations	Ivanov, 2024
SCOR integration (operational layer)	Embedding DTs into "Plan," "Source," 'Deliver' for sustainability outcomes	SCOR-guided DTs for green logistics network design and predictive compliance updates	Fernández-Miguel et al., 2024
S&R execution (behavioral layer)	Feedback-driven adaptation and decentralized action	DTs enabling adaptive decisions in decentralized energy and waste management units	Jesus et al., 2024

suppliers and logistic paths with minimal environmental impact
- Technological enabler (DT): The DT monitors freight movements, port congestion, and lead time variances, dynamically updating transportation plans while minimizing emissions and cost.

5.1.3. Scenario C: Sustainability audit and ESG disclosure

An international audit requires the company to demonstrate carbon reduction measures across Tier 1 and Tier 2 suppliers over the past fiscal year.
- Strategic layer (DCV): The sensing mechanism aggregates sustainability performance data from upstream partners, while seizing involves the activation of compliance dashboards for transparency
- Behavioral layer (S&R): Stakeholder collaboration teams initiate supplier engagement protocols and adaptive performance coaching based on benchmark scores
- Operational layer (SCOR): The "Enable" and "Return" processes are mobilized to support traceability, reverse logistics, and circularity audits
- Technological enabler (DT): DTs visualize emissions data across nodes, generate ESG reports, and simulate future audit preparedness based on alternative sustainability strategies.

5.2. Comparative Alignment and Analytical Generalization

To reinforce external validity and practical relevance, this study adopts analytical generalization as a validation technique appropriate for theory-building research in dynamic, complex domains such as sustainability and digital transformation (Yin, 2014). Unlike statistical generalization, which extrapolates findings from sample data, analytical generalization assesses the logical coherence and explanatory strength of a conceptual model by comparing its predictions and mechanisms with documented empirical patterns in the field.

This method is particularly suitable for design-oriented conceptual frameworks where emergent technologies, behavioral processes, and sustainability imperatives intersect in relatively novel configurations. As noted by Gregor and Hevner (2013), analytical generalization allows theory-driven constructs to be validated through convergence with "naturally occurring implementations" and "externally observed configurations." In this study, we use comparative alignment to evaluate whether the proposed framework's outcomes—such as emission reduction, agile compliance, green sourcing, and digital responsiveness—are mirrored in published case studies and empirical investigations of DT applications in sustainable SCs. Several high-impact studies were selected for their methodological rigor, thematic relevance, and sustainability focus (e.g., Fernández-Miguel et al., 2024; Ivanov, 2024; Kamble et al., 2022; Singh et al., 2023).

Each theoretical component of the framework—namely sensing, seizing, and reconfiguring dynamic capabilities embedded within SCOR processes via DTs, is mapped to real-world cases that demonstrate similar functional outcomes. This mapping confirms that the proposed mechanisms not only possess theoretical legitimacy but also reflect emergent strategic practices in environmentally adaptive SCs.

This process serves three purposes:
1. Contextual plausibility – aligning theory with empirically observed behavior in practice
2. Explanatory robustness – validating that causal pathways (e.g., DT-enabled emissions reduction) are conceptually consistent with field applications
3. Empirical groundwork – setting the stage for simulation-based or field-based empirical testing in future research.

Table 2 presents this comparative mapping:

6. CONCLUSION AND IMPLICATIONS

This study introduces the Integrated Framework for Environmental Agility, a novel conceptual model that addresses a critical limitation in current sustainable SC strategies—the absence of an integrated, process-level mechanism that translates environmental goals into real-time, data-driven actions. By interweaving the strategic perspective of the DCV, the behavioral insights of the S&R paradigm, and the operational rigor of the SCOR model, all enabled by DT technologies, our framework bridges the long-standing gap between strategic intent and executional capability.

Our framework responds directly to the growing need for SCs to evolve from static, efficiency-oriented systems to dynamic, eco-responsive architectures capable of continuous adaptation. The layered structure enables firms to sense environmental signals such as carbon risks, seize emerging opportunities for green innovation, and reconfigure operations on-the-fly—thus enhancing agility and sustainability simultaneously. This integrated approach addresses the fragmented nature of current sustainability practices by embedding environmental intelligence into decision-making processes across the entire SC.

Through scenario-based conceptual simulation and analytical generalization anchored in documented industry use cases, we demonstrate that the framework not only aligns with theoretical constructs but also resonates with practical sustainability performance patterns, such as lower emissions, accelerated compliance adaptation, and environmentally informed sourcing. The comparative alignment confirms that our model's performance logic is consistent with empirical evidence from digitally-enabled, sustainable SCs.

By introducing and operationalizing environmental agility, this framework advances both theory and practice. It provides SC managers with an actionable blueprint for leveraging digital technologies to achieve sustainable competitive advantage while addressing escalating environmental pressures. Consequently, this work makes a significant contribution to the literature, offering a comprehensive, digitally intelligent system that transforms traditional SC operations into future-ready, sustainability-driven ecosystems.

6.1. Practical Implications

The integrated framework for environmental agility developed in this study provides a robust foundation for organizations seeking to embed sustainability within their core SC operations. It enables firms to transition from static compliance-based strategies to real-time, data-driven environmental responsiveness. By integrating DT technologies into SCOR processes and aligning them with DCs and behavioral adaptability, the framework empowers SC managers to convert strategic sustainability intent into operational execution.

One critical implication is the ability to embed environmental intelligence into day-to-day decision-making. Through continuous monitoring of emissions, resource usage, and ecological impact, SC professionals can proactively identify and mitigate sustainability risks across sourcing, manufacturing, and logistics. The framework also enables firms to reconfigure SC networks in response to carbon pricing mechanisms, regulatory shifts, or disruptions linked to climate change. This reconfiguration capacity strengthens a firm's agility to adapt to sustainability demands while maintaining performance and competitiveness.

Moreover, the framework facilitates enhanced preparedness for evolving environmental regulations. By simulating policy scenarios and forecasting compliance outcomes, firms can reduce regulatory uncertainty and accelerate their response to emerging standards such as the EU Carbon Border Adjustment Mechanism or climate-related financial disclosures. The integration of DCs and the S&R paradigm also enhances cross-functional collaboration, enabling procurement, operations, and sustainability teams to act on real-time insights and adapt rapidly to changes in the external environment.

Perhaps most significantly, this framework bridges the persistent gap between strategic sustainability goals and operational reality. It allows firms to manage green key performance indicators—such as emissions intensity, energy efficiency, and resource circularity—across each layer of the SCOR model. This alignment between strategy and execution is essential for firms striving to meet ambitious environmental targets while maintaining operational agility.

By grounding environmental agility in digital infrastructure and strategic theory, the framework positions SCs not merely as logistical systems, but as digitally intelligent, environmentally responsive ecosystems. This transformation supports a new generation of SC strategies that are both adaptive and accountable to global sustainability imperatives.

6.2. Limitations and Future Research Agenda

While this study advances the conceptual foundation for environmental agility in SCs, it is not without limitations. As a theory-building effort grounded in design science and analytical generalization, the proposed framework has not yet been empirically tested through primary data or simulation modeling. Although the scenario-based conceptual simulation and comparative alignment with documented use cases enhance theoretical rigor and contextual relevance, future research is needed to assess the framework's empirical robustness and practical transferability across varied industrial and institutional contexts.

The abstraction inherent in conceptual generalization may also limit granularity in operational contexts. For instance, environmental priorities vary across sectors—such as energy-intensive industries versus service-based supply networks—and the application of the framework will likely require sector-specific adaptation. Similarly, while the SCOR model provides a structured operational lens, its standardization may not fully capture the process complexity or governance challenges faced by decentralized, multi-tier global SCs. Further research could examine how environmental agility plays out in fragmented ecosystems with limited data interoperability and regulatory heterogeneity.

Additionally, the behavioral dimension introduced through the S&R paradigm remains underexplored in empirical settings. Future studies could delve into how cognitive, cultural, and leadership factors mediate the execution of environmental agility in real-time decision-making. This includes exploring how organizational learning, psychological safety, or digital readiness influence a firm's capacity to operationalize the sensing and reconfiguring capabilities required for environmental responsiveness.

A promising avenue lies in operationalizing and measuring environmental agility as a construct distinct from environmental resilience or flexibility. This would entail developing valid and reliable indicators to capture proactive environmental sensing, carbon-sensitive decision agility, and rapid reconfiguration tied to green objectives. Such measures would be essential for empirical validation through surveys, case studies, or longitudinal designs. Furthermore, the framework could be extended to explore the interaction between digital twins and emerging ESG performance analytics, sustainability accounting standards, and AI-enabled governance systems. This could position environmental agility as a central capability not only for compliance but also for environmental strategy formation and stakeholder engagement.

REFERENCES

AI Humdan, E., Shi, Y., Behina, M., Chowdhury, M. (2024), Examining agile supply chains: An empirical study in Australia. Production Planning and Control, 35(11), 1313-1331.

Al Humdan, E., Shi, Y., Behnia, M., Najmaei, A. (2020), Supply chain agility: A systematic review of definitions, enablers and performance implications. International Journal of Physical Distribution and Logistics Management, 50(2), 287-312.

Alkaraan, F., Elmarzouky, M., Hussiney, K., Venkatesh, V.G., Shi, Y., Gulko, N. (2024), Reinforcing green business strategies with Industry 4.0 and governance towards sustainability: Natural-resource-based view and dynamic capability. Business Strategy and the Environment, 33(4), 3588-3606.

Barata, J., Kayser, I. (2024), How will the digital twin shape the future of industry 5.0? Technovation, 134, 103025.

Beske, P. (2012), Dynamic capabilities and sustainable supply chain management. International Journal of Physical Distribution and Logistics Management, 42(4), 372-387.

Bhandal, R., Meriton, R., Kavanagh, R.E., Brown, A. (2022), The application of digital twin technology in operations and supply chain management: A bibliometric review. Supply Chain Management: An International Journal, 27(2), 182-206.

Bouguerra, A., Hughes, M., Rodgers, P., Stokes, P., Tatoglu, E. (2024), Confronting the grand challenge of environmental sustainability within supply chains: How can organizational strategic agility drive environmental innovation? Journal of Product Innovation Management, 41(2), 323-346.

Buzzao, G., Rizzi, F. (2021), On the conceptualization and measurement of dynamic capabilities for sustainability: Building theory through a systematic literature review. Business Strategy and the Environment, 30(1), 135-175.

Calatayud, A., Mangan, J., Christopher, M. (2019), The self-thinking supply chain. Supply Chain Management: An International Journal, 24(1), 22-38.

Cantele, S., Russo, I., Kirchoff, J.F., Valcozzena, S. (2023), Supply chain agility and sustainability performance: A configurational approach to sustainable supply chain management practices. Journal of Cleaner Production, 414, 137493.

Centobelli, P., Cerchione, R., Chiaroni, D., Del Vecchio, P., Urbinati, A. (2020), Designing business models in circular economy: A systematic literature review and research agenda. Business Strategy and the Environment, 29(4), 1734-1749.

Christopher, M. (2000), The agile supply chain: Competing in volatile markets. Industrial Marketing Management, 29(1), 37-44.

Dayioglu, M., Küskü, F., Cetindamar, D. (2024), The impact of business environmental factors on performance through strategic agility and business model innovation: An analysis based on dynamic capabilities theory. IEEE Transactions on Engineering Management, 71, 3656-3670.

Dhanda, K.K., Sarkis, J., Dhavale, D.G. (2022), Institutional and stakeholder effects on carbon mitigation strategies. Business Strategy and the Environment, 31(3), 782-795.

Dyllick, T., Hockerts, K. (2002), Beyond the business case for corporate sustainability. Business Strategy and the Environment, 11(2), 130-141.

Eikelenboom, M., De Jong, G. (2019), The impact of dynamic capabilities on the sustainability performance of SMEs. Journal of Cleaner Production, 235, 1360-1370.

Estampe, D. (2014), Supply Chain Performance and Evaluation Models. United States: John Wiley and Sons.

Evans, S., Vladimirova, D., Holgado, M., Van Fossen, K., Yang, M., Silva, E.A., Barlow, C.Y. (2017), Business model innovation for sustainability: Towards a unified perspective for creation of sustainable business models. Business Strategy and the Environment, 26(5), 597-608.

Fahimnia, B., Jabbarzadeh, A., Sarkis, J. (2018), Greening versus resilience: A supply chain design perspective. Transportation Research Part E: Logistics and Transportation Review, 119, 129-148.

Fernández-Miguel, A., García-Muiña, F.E., Jiménez-Calzado, M., San Román, P.M., Del Hoyo, A.P.F., Settembre-Blundo, D. (2024), Boosting business agility with additive digital molding: An Industry 5.0 approach to sustainable supply chains. Computers and Industrial Engineering, 192, 110222.

Figge, F., Hahn, T., Schaltegger, S., Wagner, M. (2002), The sustainability balanced scorecard-linking sustainability management to business strategy. Business Strategy and the Environment, 11(5), 269-284.

Geyi, D.A.G., Yusuf, Y., Menhat, M.S., Abubakar, T., Ogbuke, N.J. (2020), Agile capabilities as necessary conditions for maximising sustainable supply chain performance: An empirical investigation. International Journal of Production Economics, 222, 107501.

Gregor, S., Hevner, A.R. (2013), Positioning and presenting design science research for maximum impact. MIS Quarterly, 37, 337-355.

Grieves, M., Vickers, J. (2017), Digital Twin: Mitigating Unpredictable, Undesirable Emergent Behavior in complex systems. Transdisciplinary perspectives on complex systems: New findings and approaches. Berlin: Springer. p85-113.

Guo, D., Mantravadi, S. (2025), The role of digital twins in lean supply chain management: Review and research directions. International Journal of Production Research, 63(5), 1851-1872.

Haeckel, S.H. (1999), Adaptive Enterprise: Creating and Leading Sense-and-Respond Organizations. Cambridge: Harvard Business Press.

Handfield, R., Sroufe, R., Walton, S. (2005), Integrating environmental management and supply chain strategies. Business Strategy and the Environment, 14(1), 1-19.

Huang, S.H., Sheoran, S.K., Keskar, H. (2005), Computer-assisted supply chain configuration based on supply chain operations reference (SCOR) model. Computers and Industrial Engineering, 48(2), 377-394.

Humdan, E.A., Shi, Y., Behina, M., Chowdhury, M.M.H., Mahmud, A.S. (2023), The role of innovativeness and supply chain agility in the Australian service industry: A dynamic capability perspective. International Journal of Physical Distribution and Logistics Management, 53(11), 1-25.

Ivanov, D. (2022), Viable supply chain model: Integrating agility, resilience and sustainability perspectives-lessons from and thinking beyond the COVID-19 pandemic. Annals of Operations Research, 319(1), 1411-1431.

Ivanov, D. (2024), Conceptualisation of a 7-element digital twin framework in supply chain and operations management. International Journal of Production Research, 62(6), 2220-2232.

Ivanov, D., Dolgui, A. (2021), A digital supply chain twin for managing the disruption risks and resilience in the era of Industry 4.0. Production Planning and Control, 32(9), 775-788.

Jesus, V., Kalaitzi, D., Batista, L., Lopez, N.L. (2024), Digital twins of supply chains: A systems approach. IEEE Transactions on Engineering Management, 71,14915-14932.

Jia, F., Li, K., Zhang, T., Chen, L. (2024), Triple A supply chain management and sustainability. Industrial Management and Data Systems, 125(10), 2725-2752.

Kamble, S.S., Gunasekaran, A., Parekh, H., Mani, V., Belhadi, A., Sharma, R. (2022), Digital twin for sustainable manufacturing supply chains: Current trends, future perspectives, and an implementation framework. Technological Forecasting and Social Change, 176, 121448.

Kazancoglu, I., Ozbiltekin-Pala, M., Mangla, S.K., Kazancoglu, Y., Jabeen, F. (2022), Role of flexibility, agility and responsiveness for sustainable supply chain resilience during COVID-19. Journal of Cleaner Production, 362, 132431.

Knoppen, D., Knight, L. (2022), Pursuing sustainability advantage: The dynamic capabilities of born sustainable firms. Business Strategy and the Environment, 31(4), 1789-1813.

MacInnis, D.J. (2011), A framework for conceptual contributions in marketing. Journal of Marketing, 75(4), 136-154.

Marchi, V.D., Maria, E.D., Micelli, S. (2013), Environmental strategies, upgrading and competitive advantage in global value chains. Business Strategy and the Environment, 22(1), 62-72.

Mathiyazhagan, K., Agarwal, V., Appolloni, A., Saikouk, T., Gnanavelbabu, A. (2021), Integrating lean and agile practices for achieving global sustainability goals in Indian manufacturing industries. Technological Forecasting and Social Change, 171, 120982.

Meredith, J. (1993), Theory building through conceptual methods. International Journal of Operations and Production Management, 13(5), 3-11.

Mohaghegh, M., Blasi, S., Russo, I., Baldi, B. (2025), Digital transformation and sustainable performance: The mediating role of triple-a supply chain capabilities. Journal of Business and Industrial Marketing, 40(4), 896-910.

Moktadir, M.A., Kumar, A., Ali, S.M., Paul, S.K., Sultana, R., Rezaei, J. (2020), Critical success factors for a circular economy: Implications for business strategy and the environment. Business Strategy and the Environment, 29(8), 3611-3635.

Ortiz-Avram, D., Ovcharova, N., Engelmann, A. (2024), Dynamic capabilities for sustainability: Toward a typology based on dimensions of sustainability-oriented innovation and stakeholder integration. Business Strategy and the Environment, 33(4), 2969-3004.

Qi, Q., Tao, F. (2018), Digital twin and big data towards smart manufacturing and industry 4.0: 360 degree comparison. Ieee Access, 6, 3585-3593.

Salandri, L., Rizzo, G.L.C., Cozzolino, A., De Giovanni, P. (2022), Green practices and operational performance: The moderating role of agility. Journal of Cleaner Production, 375, 134091.

Sharifi, H., Zhang, Z. (1999), A methodology for achieving agility in manufacturing organisations: An introduction. International Journal of Production Economics, 62(1-2), 7-22.

Sharma, M., Antony, R., Sharma, A., Daim, T. (2025), Can smart supply chain bring agility and resilience for enhanced sustainable business performance? The International Journal of Logistics Management, 36(2), 501-555.

Siems, E., Land, A., Seuring, S. (2021), Dynamic capabilities in sustainable supply chain management: An inter-temporal comparison of the food and automotive industries. International Journal of Production Economics, 236, 108128.

Singh, G., Singh, S., Daultani, Y., Chouhan, M. (2023), Measuring the influence of digital twins on the sustainability of manufacturing supply chain: A mediating role of supply chain resilience and performance. Computers and Industrial Engineering, 186, 109711.

Stewart, G. (1997vSupply-chain operations reference model (SCOR): The first cross-industry framework for integrated supply-chain management. Logistics Information Management, 10(2), 62-67.

Supply Chain Council. (2012), Supply Chain Operations Reference Model (SCOR) Version 11.0. Available from: https://www.supply-chain.org

Teece, D.J., Pisano, G., Shuen, A. (1997), Dynamic capabilities and strategic management. Strategic Management Journal, 18(7), 509-533.

Vanpoucke, E., Vereecke, A., Wetzels, M. (2014), Developing supplier integration capabilities for sustainable competitive advantage: A dynamic capabilities approach. Journal of Operations Management, 32(7-8), 446-461.

Wacker, J.G. (2008), A conceptual understanding of requirements for theory-building research: Guidelines for scientific theory building. Journal of Supply Chain Management, 44(3), 5-15.

Wang, M., Wang, B. (2024), Supply chain agility as the antecedent to firm sustainability in the post COVID-19. The International Journal of Logistics Management, 35(1), 281-303.

Wieland, A., Durach, C.F. (2021), Two perspectives on supply chain resilience. Journal of Business Logistics, 42(3), 315-322.

Yin, R.K. (2014), Case Study Research Design and Methods. Thousand: Sage Publications.