

Digital Technologies Enabling a "Resilience–Low-Carbon" Dual-Objective Supply Chain: Realization Mechanisms and Synergistic Regulation

Tianrui Ru*

University College Dublin - Kaplan Higher Education Academy (Singapore), Singapore, 189352, Singapore

*Corresponding author

Abstract: Contemporary supply chains are simultaneously confronting two intensifying pressures: the need to absorb and recover from increasingly frequent and severe disruptions, and the obligation to decarbonize operations in line with global climate commitments. Although digital technologies are widely recognized as enablers of both supply chain resilience and environmental sustainability, the two objectives have largely been investigated in separate research streams, leaving the mechanisms through which digitalization jointly advances them poorly understood. This conceptual article develops an integrated framework that treats resilience and low-carbon performance as coupled organizational capabilities of a supply chain and positions digital technology as the enabling and orchestrating layer that connects them. Drawing on the viability perspective and the resilience–sustainability literature, the article articulates four realization mechanisms—sensing and end-to-end visibility, predictive intelligence and scenario planning, dynamic reconfiguration of the network, and coordinated green operations—through which digital technologies generate simultaneous resilience and decarbonization payoffs. It then examines the structural trade-offs between resilience-enhancing redundancy and emission reduction and proposes a multi-level synergistic regulation framework that combines contractual coordination, market-based carbon instruments, and institutional governance to reconcile the two objectives. A set of testable propositions and boundary conditions is advanced to guide future empirical research. The framework contributes to the emerging integration of resilience and sustainability in supply chain research and offers managerial and policy implications for building supply chains that are at once robust and low carbon.

Keywords: supply chain resilience; low-carbon supply chain; digital technology; Industry 5.0; synergistic regulation; sustainability

1. Introduction

The business environment of the twenty-first century is defined by volatility on multiple fronts. Geopolitical tensions, pandemic outbreaks, extreme weather events, and disruptions to key logistics corridors have repeatedly demonstrated that supply chains are fragile in ways that traditional efficiency-oriented design underestimated [1-2]. In parallel, the global consensus on climate action has placed decarbonization at the center of industrial strategy, compelling firms to measure and reduce the carbon footprint of their entire value chains, including the increasingly significant scope-three emissions that originate beyond their own boundaries [3-4]. These two pressures—resilience and low-carbon performance—are no longer peripheral concerns; they have become constitutive requirements of competitive and legitimate supply chain management.

The strategic response to both pressures has been heavily invested in digitalization. Technologies such as the Internet of Things (IoT), blockchain, big data analytics, artificial intelligence (AI), and digital twins are widely credited with improving supply chain visibility, agility, and risk responsiveness [5-6], while a parallel body of work emphasizes their capacity to support greener and more sustainable operations through traceability, optimization, and transparency [7-8]. Yet the two research streams have developed largely in isolation. Resilience scholarship has focused on the ability of a supply chain to prepare for, respond to, and recover from disruptions, while sustainability scholarship has concentrated on the environmental and social performance of the chain over the long run. The question of how digital technologies enable the simultaneous pursuit of resilience and low-carbon objectives—and how the two objectives can be reconciled when they conflict—remains

under-theorized.

This gap is consequential. A growing literature observes that resilience and sustainability are not independent objectives but interact in complex ways: redundancy and buffering that enhance resilience may raise energy and material use, whereas aggressive emission reduction may strip away the slack that a chain needs to survive a shock [9-10]. Treating the two objectives as a binary trade-off, or pursuing them through disconnected programs, risks producing supply chains that are either fragile or carbon-intensive. Digital technology, because it substitutes information and intelligence for physical redundancy and waste, offers a promising route to reconcile the two; yet the precise mechanisms through which it does so, and the governance arrangements required to align them, have not been systematically articulated.

The purpose of this article is therefore to develop a conceptual framework explaining how digital technologies enable a dual-objective supply chain that is simultaneously resilient and low carbon, and how the realization of these objectives can be synergistically regulated. The article makes three contributions. First, it integrates the resilience and low-carbon literatures by framing resilience and low-carbon performance as coupled organizational capabilities of the supply chain, and by adopting the viability perspective that treats them as jointly constitutive of long-term chain functioning [11]. Second, it identifies and elaborates four realization mechanisms through which digital technologies generate simultaneous resilience and decarbonization payoffs, translating them into a set of testable propositions. Third, it proposes a multi-level synergistic regulation framework—combining contractual coordination, market-based carbon instruments, and institutional governance—that addresses the structural trade-offs between the two objectives. The article thus provides an integrative theoretical account that responds to recent calls to bring resilience and sustainability together in supply chain research [12].

The remainder of the article proceeds as follows. Section 2 reviews the two literatures and identifies the integration gap. Section 3 develops the theoretical framework and conceptual model. Section 4 elaborates the realization mechanisms. Section 5 examines synergistic regulation. Section 6 discusses implications, boundary conditions, and future research, and Section 7 concludes.

2. Literature review

2.1 Supply chain resilience and the role of digital technology

Supply chain resilience is generally understood as the adaptive capability of a supply chain to prepare for unexpected events, respond to disruptions, and recover from them while maintaining continuity of operations at a desired level [13]. Foundational contributions emphasized the design principles—redundancy, flexibility, visibility, and a risk-aware culture—through which chains can withstand and rebound from shocks [14], and later work refined resilience into a balance between chain vulnerabilities and the capabilities deployed to manage them [15]. Systematic reviews consolidated these ideas into a capability-based view organized around anticipation, preparedness, response, and recovery [16].

A central theme in recent resilience scholarship is the efficiency–flexibility–resilience trade-off. Lean, efficiency-oriented chains built on low inventories and single-source supply are highly cost-effective in stable conditions but expose the chain to ripple effects when a disruption propagates downstream and upstream through the network. Managing this trade-off traditionally required firms to choose between lean efficiency and resilient redundancy, with resilience typically purchased at the cost of higher inventory, duplicate capacity, and increased operating expense.

Digital technologies are increasingly positioned as a means of resolving or relaxing this trade-off by substituting information for physical slack. IoT-enabled sensing and connectivity provide granular, real-time visibility over assets, inventory, and flows; big data and AI analytics convert this data into predictive insight that supports early warning and scenario-based planning; and digital supply chain twins allow firms to simulate disruption scenarios and evaluate recovery options before committing resources. The consequence, as Ivanov et al. (2019) argue, is that Industry 4.0 technologies transform supply chain risk analytics, enabling data-driven optimization, simulation, and visibility that reduce reliance on physical redundancy while preserving response capability. Digitalization thus holds the potential to make resilience less costly and less trade-off-laden than it has historically been.

2.2 Low-carbon supply chains and green transformation

The low-carbon dimension of supply chain management derives from the broader field of green and sustainable supply chain management, which integrates environmental considerations into the design, sourcing, production, and distribution of products and services. Early frameworks established the analytical foundations for evaluating green alternatives along the chain, while organizational reviews traced how institutional pressures, stakeholder expectations, and competitive dynamics drive the diffusion of environmental practices. Within this tradition, the low-carbon objective is increasingly specified in terms of measurable emission reduction targets, energy efficiency, and carbon footprint management across the entire value chain, including scope-three emissions that arise in suppliers' and customers' operations.

Digital technologies figure prominently in this literature as well. Blockchain-enabled traceability provides tamper-resistant records of provenance and environmental attributes, supporting credible carbon accounting and green claims. Big data and AI optimize routes, loads, and energy use in ways that reduce emissions while maintaining service levels. IoT sensing makes energy consumption and emissions visible at the operational level, enabling targeted reduction. Coordination mechanisms, such as cost-sharing and revenue-sharing contracts, have been shown to align incentives across chain members so that greening investments are shared rather than borne unilaterally.

A distinctive feature of the low-carbon objective is that it is inherently measurement-intensive and value-chain-wide. Unlike a purely cost or service target, low-carbon performance must be quantified—in emissions per unit, per process, and per product—and this measurement must extend beyond the focal firm to suppliers and customers, because a large share of a product's carbon footprint is generated upstream in scope-one and scope-two emissions of suppliers and downstream in use and disposal. This measurement dependence is precisely where digital technology and the resilience objective converge: the same end-to-end visibility and data integrity that reveal a chain's vulnerabilities also make its carbon profile computable. The organizational review literature further emphasizes that the adoption and effectiveness of such environmental practices are shaped by institutional pressures, stakeholder expectations, and inter-organizational relationships, so that low-carbon performance is as much a governance achievement as a technological one. These observations motivate the dual-objective framing developed in the next section.

2.3 Toward dual-objective integration: The research gap

Despite these parallel developments, the resilience and low-carbon streams have rarely been theorized together. Systematic reviews that examine the intersection of sustainability and resilience in supply chains find that the two fields use different constructs, emphasize different performance dimensions, and propose different managerial logics, and that integrated treatments remain scarce and fragmented. This separation is problematic because the two objectives interact. Resilience strategies that add redundancy, safety stock, and duplicated capacity tend to increase material and energy consumption and therefore emissions; conversely, stringent low-carbon programs that eliminate waste and slack can reduce the buffering capacity a chain needs to respond to shocks. Understanding these interactions is essential if firms and policymakers are to avoid advancing one objective at the expense of the other.

Digital technology is a natural candidate to mediate this interaction, because it can deliver the information, foresight, and flexibility that resilience requires without the physical redundancy that drives emissions, while simultaneously enabling the measurement and optimization that low-carbon performance demands. However, the specific mechanisms through which digitalization generates these joint payoffs, and the governance arrangements needed to coordinate the dual objectives across the chain, have not been systematically developed. This article addresses that gap by proposing an integrated conceptual framework that links digital technology to both resilience and low-carbon performance and by specifying how the two objectives can be synergistically regulated.

3. Theoretical framework and conceptual model

3.1 Resilience and low-carbon performance as coupled capabilities

The article adopts a capability-based view of the supply chain as the foundation of its framework. Resilience is treated as the adaptive capability of the chain to anticipate, absorb, respond to, and

recover from disruptions while preserving continuity, realized through vulnerabilities and capabilities that together define the chain's zone of robustness. Low-carbon performance is treated as the capability of the chain to design and operate its sourcing, production, logistics, and product-recovery processes so as to minimize greenhouse gas emissions, through measurement, optimization, and coordinated reduction across the value chain.

Rather than viewing these as independent targets, the framework follows the viability perspective, which conceptualizes the long-term functioning of a supply chain as depending on the joint presence of agility, resilience, and sustainability. The Industry 5.0 framework extends this by proposing that industrial value chains should be designed and managed as resilient, sustainable, and human-centric systems, treating these properties as co-constitutive rather than competing. Within this lens, a supply chain is considered viable and functional over time only if it can both withstand disruptions and reduce its environmental burden; a chain that is resilient but carbon-intensive, or low carbon but fragile, is not fully viable in the long run. Resilience and low-carbon performance are therefore coupled capabilities whose joint realization is the object of dual-objective supply chain management.

3.2 The structure of dual-objective synergy and trade-off

The framework distinguishes between synergy and trade-off as two structural states of the dual-objective relationship. Synergy arises when a single digital intervention improves both resilience and low-carbon performance, for example when end-to-end visibility simultaneously reduces the risk of disruption (by revealing weak points) and the waste that causes emissions (by revealing inefficiencies). Trade-off arises when an intervention improves one objective at the expense of the other, for example when resilience-enhancing redundancy raises energy and material consumption. The framework's central premise is that digitalization shifts the balance toward synergy by converting potential trade-offs into complements, but that the residual trade-offs require active regulation to be managed. Figure 1 depicts the conceptual model linking digital technology, the two coupled capabilities, and the regulation layer. As is shown in Figure 1.

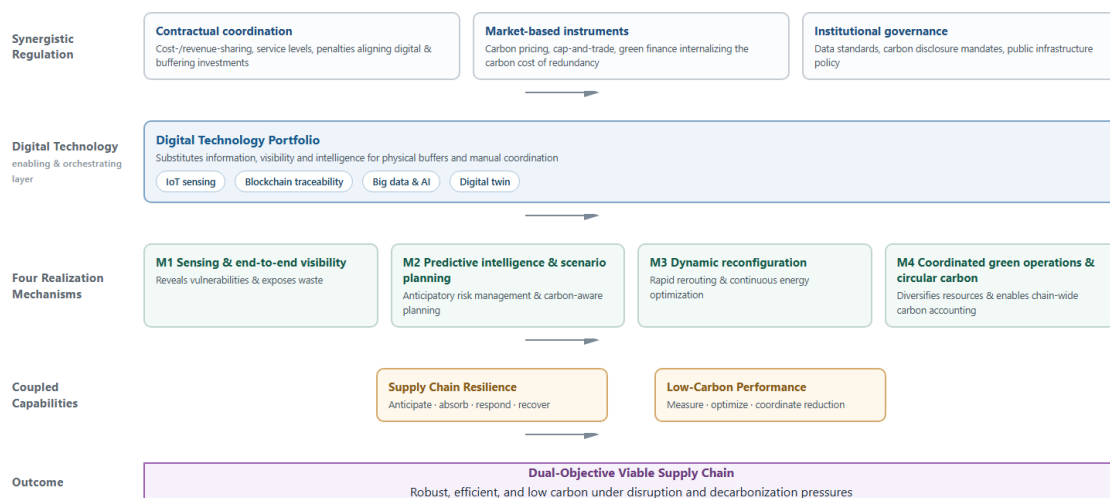


Figure 1. Conceptual model of the digital-enabled resilience–low-carbon

Dual-objective supply chain: digital technology as the enabling and orchestrating layer feeds four realization mechanisms that jointly build the two coupled capabilities (supply chain resilience and low-carbon performance), with the whole regulated by a multi-level synergistic regulation layer.

The synergy–trade-off distinction is consequential for practice because it determines whether dual-objective management is a matter of aligning complementary investments or of adjudicating conflicting ones. Where synergy prevails, digitalization presents a rare opportunity to advance both objectives with a single intervention, and the managerial task is to recognize and capture the joint payoff. Where trade-off prevails, the task shifts to explicit balancing: the chain must decide how much carbon cost is acceptable to secure a given level of resilience, and how much robustness can be sacrificed for a given emission target. The framework does not assume that digitalization eliminates the trade-off; rather, it holds that digitalization converts many latent trade-offs into synergies while rendering the remaining trade-offs visible, measurable, and therefore manageable. This distinction also disciplines the empirical agenda: tests of the framework should examine both whether digitalization raises each capability and whether it changes the shape of the trade-off frontier between them, rather

than treating the two as independent outcomes.

4. Realization mechanisms: How digital technology jointly enables resilience and low-carbon performance

4.1 Mechanism 1: Sensing and end-to-end visibility

The first mechanism operates through the sensing and visibility functions of digital technology. IoT devices, radio-frequency identification, and sensor networks generate continuous, granular data on the location, condition, and status of materials, inventory, and assets across the chain. Blockchain, when layered on this data, provides tamper-resistant, shared records of provenance and flow that can be trusted across organizational boundaries. Together these functions produce end-to-end visibility: a real-time, accurate picture of where goods are, what their condition is, and how the network is performing.

This visibility advances resilience by revealing the structure of the network and its vulnerabilities. When a disruption occurs, a visible chain can identify affected nodes, quantify exposure, and target response with far greater precision than a chain whose state is opaque. Visibility also enables proactive monitoring, so that emerging risks can be detected before they escalate. At the same time, the same visibility advances low-carbon performance by exposing waste: idle capacity, inefficient routes, excess inventory, and unnecessary handling all become measurable and therefore reducible. The dual effect arises because visibility substitutes information about actual conditions for the conservative physical buffers that opacity forces firms to hold. Proposition P1 captures this: end-to-end digital visibility is positively associated with both supply chain resilience and low-carbon performance, because it enables targeted rather than blanket buffering and exposes inefficiencies that drive emissions.

4.2 Mechanism 2: Predictive intelligence and scenario planning

The second mechanism operates through the predictive and prescriptive functions of big data analytics and AI. Machine-learning models trained on operational, market, and external data can anticipate demand shifts, identify supplier risk, and forecast the likelihood and propagation of disruptions. Digital twins extend this by creating dynamic, simulable representations of the chain, allowing firms to stress-test alternative configurations and recovery policies in silico before committing physical resources.

Predictive intelligence advances resilience by shifting the chain from reactive to anticipatory risk management. Rather than waiting for a shock and then scrambling to respond, the chain can pre-position resources, diversify sourcing, and rehearse contingency plans based on projected scenarios, thereby compressing the response time and reducing the magnitude of ripple effects. The same intelligence advances low-carbon performance by enabling demand-driven rather than forecast-padded operations. More accurate forecasts reduce the overproduction, expedited shipping, and buffer inventory that constitute unnecessary emissions; scenario planning that evaluates carbon implications alongside risk implications ensures that resilience investments are screened for their emission footprint. Proposition P2 follows: predictive intelligence and scenario planning are positively associated with both resilience and low-carbon performance, because they convert reactive slack into anticipatory and carbon-aware preparation.

4.3 Mechanism 3: Dynamic reconfiguration of the network

The third mechanism operates through the capacity of digital technology to support dynamic reconfiguration of the supply network. The resilience literature has long recognized that the network structure—its nodes, links, and redundancies—determines how disruptions propagate and how quickly the chain can recover. Digital technologies enable this structure to be monitored, simulated, and adjusted in response to changing conditions, rather than being fixed at design time. Visibility and predictive models feed reconfiguration decisions, and digital twins allow candidate reconfigurations to be evaluated before implementation.

Dynamic reconfiguration advances resilience by allowing the chain to reroute flows, reallocate capacity, and re-source materials when a disruption strikes, thereby reducing the need for permanently maintained redundancy. The same capability advances low-carbon performance by enabling the network to be continuously optimized for energy efficiency: routing decisions can weigh carbon

alongside cost and lead time, capacity can be allocated to reduce empty mileage, and consolidation can be adjusted dynamically. Because the same digital infrastructure supports both risk-driven and carbon-driven reconfiguration, the two objectives can be jointly optimized rather than set against each other. Proposition P3 states that the digital-enabled capacity for dynamic reconfiguration is positively associated with both resilience and low-carbon performance, as it allows structural adjustments that reduce both risk exposure and emissions.

4.4 Mechanism 4: Coordinated green operations and circular carbon management

The fourth mechanism operates through the coordination functions of digital platforms in the operational and product-recovery domains. Low-carbon performance ultimately depends on coordinated action across chain members: a manufacturer's emission profile is shaped by its suppliers' processes, and its products' carbon footprint extends into customer use and end-of-life handling. Digital platforms enable this coordination by sharing environmental data, aligning operational standards, and supporting joint planning across boundaries. Blockchain-based traceability, in particular, provides the shared, credible records needed for chain-wide carbon accounting and for the verification of green claims.

Coordinated green operations advance low-carbon performance by enabling emissions to be reduced where they are generated rather than only where they are visible, through shared measurement, collaborative process improvement, and the orchestration of circular flows such as reuse, remanufacture, and recycling. The same coordination advances resilience by diversifying the chain's resource base: access to alternative suppliers, recovery channels, and reuse options reduces dependence on any single source and provides backup pathways during disruption. Circular flows, for example, give the chain a secondary source of materials that can buffer against supply interruptions. Proposition P4 holds that digital-enabled coordination of green operations is positively associated with both low-carbon performance and resilience, because chain-wide coordination reduces emissions and simultaneously broadens the set of accessible resources.

The four mechanisms are presented separately for analytical clarity, but in practice they are mutually reinforcing rather than independent. Sensing and visibility supply the data that predictive intelligence analyzes and that dynamic reconfiguration and coordinated green operations act upon; without the first mechanism, the others have no reliable foundation. Predictive intelligence, in turn, converts visibility into foresight that makes reconfiguration and coordination more effective, because the chain can act before a disruption or an inefficiency fully materializes. Coordinated green operations and dynamic reconfiguration both depend on the visibility and intelligence generated upstream of them. This interdependence implies that the mechanisms function best as a portfolio rather than as isolated point solutions: a chain that invests in prediction without visibility, or in coordination without intelligence, is likely to realize only a fraction of the potential joint payoff. It also implies a sequencing logic for implementation, in which foundational sensing and data integration precede the higher-order analytic, reconfiguration, and coordination capabilities. The aggregate effect of the portfolio is captured in the following proposition.

Proposition P4a holds that the joint effect of the four realization mechanisms on resilience and low-carbon performance is superadditive: chains that deploy the mechanisms as an integrated digital portfolio achieve greater combined improvement than the sum of what each mechanism delivers in isolation, because each mechanism amplifies the operation of the others. As is shown in Table 1.

Table 1. Realization mechanisms and their dual effects

Mechanism	Digital foundation	Resilience effect	Low-carbon effect
M1 Sensing and end-to-end visibility	IoT, RFID, blockchain records	Reveals vulnerabilities; enables targeted response and proactive monitoring	Exposes waste; enables measurement and reduction of inefficiencies
M2 Predictive intelligence and scenario planning	Big data analytics, AI, digital twins	Anticipatory risk management; compresses response time	Reduces overproduction and buffer waste; carbon-aware planning
M3 Dynamic reconfiguration	Visibility, simulation, digital twins	Rapid rerouting, reallocation, and re-sourcing	Continuous energy and routing optimization
M4 Coordinated green operations	Digital platforms, blockchain traceability	Diversifies resource base; provides backup pathways	Chain-wide carbon accounting; collaborative reduction and circular flows

5. Discussion

The framework contributes to the literature in three ways. First, it integrates two research streams that have largely developed in parallel—supply chain resilience and low-carbon supply chain management—by framing their objects as coupled capabilities of a single chain. This addresses a gap identified in systematic reviews of the resilience–sustainability interface and extends the viability perspective, which holds that resilience and sustainability jointly constitute the long-term functioning of a chain, into a more specific account of the digital mechanisms that realize them.

Second, the article specifies how digital technology shifts the historical trade-off between resilience-enhancing redundancy and low-carbon resource efficiency. Where much of the resilience literature frames digitalization as improving risk analytics and much of the green literature frames it as enabling traceability and optimization, this article shows that the same digital functions simultaneously perform both roles, and it articulates the four mechanisms through which this joint payoff arises. The propositions translate this into a testable research agenda.

Third, the article conceptualizes synergistic regulation as a multi-level arrangement that reconciles the residual trade-offs that digitalization cannot eliminate. This extends the coordination literature in green supply chains by situating contractual coordination within a broader system of market-based carbon instruments and institutional governance, and it responds to the practical reality that the dual objective cannot be realized by any single firm acting alone.

Taken together, these contributions refine the emerging union of resilience and sustainability research in an actionable direction. Prior reviews have established that the two literatures use different constructs and rarely speak to one another; the framework developed here specifies how they can be brought together analytically—by locating their common enabling condition in digital technology and their common governance requirement in synergistic regulation. In doing so, it also gives the resilience–sustainability union a mechanism-level vocabulary that is directly convertible into empirical measures: resilience capacity and low-carbon performance as the dependent variables, the digital functions and regulation instruments as the explanatory and moderating constructs, and the propositions as the relationships to be tested. This translation from abstract synergy to measurable relationships is arguably the framework's most concrete contribution to the field.

6. Conclusion

This article has developed an integrated framework for understanding how digital technologies enable a supply chain that is simultaneously resilient and low carbon. Building on the viability perspective and the resilience–sustainability literature, it framed resilience and low-carbon performance as coupled capabilities, positioned digital technology as the enabling and orchestrating layer, and specified four realization mechanisms—sensing and visibility, predictive intelligence, dynamic reconfiguration, and coordinated green operations—through which digitalization jointly advances both objectives. It then examined the structural trade-off between resilience-enhancing redundancy and emission reduction and proposed a multi-level synergistic regulation framework that combines contractual coordination, market-based carbon instruments, and institutional governance to reconcile the dual objectives. The framework advances research at the intersection of resilience and sustainability and offers managers and policymakers a structured basis for building supply chains that are at once robust, efficient, and low carbon. The central message is that resilience and decarbonization need not be competing ends; with digital technology as the enabling layer and synergistic regulation as the governance layer, they can be pursued as complementary dimensions of a viable supply chain.

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