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Development of a Compass Framework to Achieve an Agile and Sustainable Supply Network

Lucila Palandella [1,*], Lourdes Perea Muñoz [1] and Angel Ruiz [2]

[1] Centro de Transformación Digital, Laboratorio de Investigación, Desarrollo y Transferencia de la Universidad Austral (LIDTUA), Facultad de Ingeniería, Universidad Austral, Mariano Acosta 1611, Pilar B1629WWA, Argentina; lperea@austral.edu.ar

[2] Faculty of Business Administration, Université Laval, 2325 Rue de Terrasse, Quebec City, QC G1V 0A6, Canada; angel.ruiz@osd.ulaval.ca

* Correspondence: lpalandella@austral.edu.ar

Abstract

Digital transformation offers significant potential to reshape supply chains; however, implementation efforts remain fragmented, technology-centric, and insufficiently aligned with strategic, organizational, and sustainability goals. Existing frameworks and maturity models tend to emphasize the technological dimension, offering limited guidance on how digital transformation should be integrated with people, processes, culture, and sustainability at the supply network level. Building on evidence synthesized through an umbrella review of the state of the art, this paper proposes the Agile and Sustainable Supply Network Compass, a holistic and actionable framework designed to support organizations in advancing toward agile and sustainable supply networks. The Compass incorporates three structural dimensions—Strategy, Processes, and Capabilities (related to digitalization and sustainability)—as foundational pillars for transformation. We hypothesize that an effective transformation requires the joint alignment of strategy, cross-functional processes, and capabilities, as well as the explicit identification of a reduced supply network, a focal firm, and its critical linkages. The results show that positioning agility and sustainability as shared strategic objectives at the supply network level enables coherent decision-making, targeted capability development and improved coordination across interconnected actors. Rather than prescribing specific technologies, the proposed framework provides a guiding methodological logic that explains how digitalization and sustainability can co-evolve within supply networks. This work contributes to both theory and practice by bridging conceptual gaps in the literature and establishing the groundwork for future maturity models and empirical applications.

Keywords: Industry 4.0; supply chain; supply network; digital transformation; agility; sustainability; framework; maturity models; compass

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1. Introduction

Industry 4.0 (I4.0) emerged within the broader context of the Fourth Industrial Revolution, emphasizing the convergence of advanced digital technologies—such as cyber–physical systems (CPSs), internet of things (IoT), data analytics and automation—and their transformative impact on industry. Although these technologies provide the foundation for I4.0, its true potential lies not only in their isolated application, but in their synergic integration, which enables organizations to create new forms of value. Although I4.0 was

initially conceived as a technological vision for industry, subsequent research has demonstrated that its real contribution lies in guiding organizations toward a broader digital transformation (DX). DX places the focus on the cultural, structural and capability-building processes that enable firms to become data-driven, agile and able to generate new forms of value [1]. Taking this into consideration, this paper adopts a broad conceptualization of Industry 4.0 and treats "Industry 4.0" and "digital transformation" as interchangeable terms for the purposes of our analysis.

In this context, the pursuit of DX from a business perspective has captured the attention of both academics and professionals, leading to the development of various methodologies, frameworks, and models designed to guide organizations on their transformation journey. These frameworks have been widely adopted by companies, demonstrating their usefulness and effectiveness for this purpose and enabling a more structured implementation of Industry 4.0 principles.

However, digital transformation does not exhaust its potential within the boundaries of the company; rather, it extends to supply chains. While supply chains are often described as linear flows, supply networks reflect more complex interorganizational structures with multiple actors and interdependencies, as will be discussed in Section 3.2. Within this context, I4.0 represents a deep transformation of the way supply chains operate, integrating technologies, systems, new ways of working, and cultural aspects among different stakeholders. These technological and organizational changes enable data to flow throughout the entire supply chain (SC) and support data-driven collaboration across all stages of value creation, improving visibility, integration and coordinated decision-making [2].

While DX's potential to enhance visibility, responsiveness, sustainability, and resilience is widely acknowledged, the path to its effective implementation remains unclear and fragmented. Many organizations struggle to move beyond isolated technological pilots that fail to generate systemic benefits or align with broader organizational goals [3]. Therefore, achieving successful results across the whole SC implementing I4.0 principles represents a challenge requiring immediate attention.

1.1. Motivation

Global SCs face increasing pressure due to rapidly changing global scenarios, the continuous evolution of technologies, environmental requirements, rising customer expectations, and diverse types of disruptions. In this context, agility and sustainability have become fundamental capabilities rather than optional attributes [4]. Although I4.0 promises to accelerate the development of these capabilities, the literature reveals persistent challenges: technology-driven initiatives lacking strategic alignment, limited integration across processes, insufficient attention to cultural and human dimensions, and a weak connection between DX and sustainability outcomes. A recent umbrella review on the implementation of I4.0 in SCs [5] confirms that there is a lack of holistic frameworks, noting that most existing frameworks and maturity models adopt a predominantly technological perspective, leaving organizations without a comprehensive roadmap to guide implementation.

1.2. Aim and Scope

This paper develops a comprehensive and holistic framework that integrates the strategic, organizational, technological, human, and sustainability dimensions required for meaningful I4.0 transformation of an organization's supply chain. Rather than promoting a technology-centric or prescriptive view, the proposed framework acknowledges that each supply chain follows a distinct transformation path and therefore adopts context-specific digital solutions. The originality of this study does not lie in enumerating or prioritizing specific technologies, but in providing a clear and structured methodological

approach to support a coordinated and joint digital transformation of the organization's supply chain. The aim of this study is to propose a holistic framework that might guide organizations in the transformation of their SCs towards agility and sustainability. This framework, referred to as the Agile and Sustainable Supply Network Compass, adopts a supply network perspective, as further explained in Section 3.2.

The scope of this study includes: (1) synthesizing insights from state-of-the-art research on Industry 4.0 adoption in supply chains; (2) developing an integrative and actionable framework grounded in evidence derived from the literature; and (3) demonstrating how such a framework can provide coherent guidance for building supply chains that are agile, resilient, digitally enabled, and environmentally responsible. The framework is conceptual in nature and establishes the foundation for future empirical validation and the development of assessment tools.

The contributions of this study are threefold. Firstly, from a theoretical perspective, the paper introduces a holistic and network-oriented framework that explicitly moves beyond a technology-centric view of I4.0. This framework integrates digital transformation, sustainability, processes, culture, and strategy, reinforcing their necessary co-evolution within supply networks and providing a conceptual foundation for future research and assessment tools. Secondly, from a methodological standpoint, the proposed framework provides a guiding, context-aware methodology that guides supply networks through a coordinated digital transformation process, allowing each network to define and adopt its own set of digital solutions while maintaining strategic alignment. Lastly, in practical terms the framework offers a structured, non-prescriptive approach to guide organizations in coordinating digital transformation initiatives, aligning strategy and sustainability objectives at the network level, and prioritizing value-creating cross-functional processes.

The rest of this paper is structured as follows. Section 2 proposes a brief review of the relevant literature. Sections 3 and 4 introduce the Agile and Sustainable Supply Network Compass, designed to synthesize key constructs and gaps identified by the literature and provide a coherent structure for real-world I4.0 implementation in the SC. Conclusions and further research avenues close the paper.

2. Literature Review on Implementation of I4.0 Principles in Supply Chains

I4.0 introduces different concepts, such as CPS, IoT, big data analytics, automation and digital integration across production and logistics networks [6]. In the context of SCs, I4.0 aims to enhance visibility, responsiveness, resilience, sustainability and customer-centricity. However, its implementation remains highly fragmented and is driven mainly by technology-push rather than strategy-led transformation. Specifically, Palandella, Perea Muñoz, and Ruiz [5] conducted an umbrella review analyzing 13 systematic literature reviews on the implementation of I4.0 principles in SCs, addressing maturity models, implementation frameworks, barriers and research gaps (see Appendix A for the list of reviewed papers). Their main conclusions include:

- Technology-centric focus: Most publications emphasize digital technologies (IoT, CPS, AI and automation) while neglecting organizational, cultural, human and sustainability dimensions.
- Lack of holistic integration: Existing frameworks rarely integrate strategy, processes, technologies, systems, ways of working, culture and sustainability into a unified model.
- Few framework proposals: Although some frameworks related to the DX of the SC have been developed, they remain limited and largely theoretical, lacking empirical validation.

- Barriers to implementation: Key barriers include misalignment between corporate strategy and DX, resistance to change, insufficient training, SC complexity, high costs and investment requirements, and risks associated with cybersecurity.
- Limited connection with sustainability: Although sustainability is recognized as essential, most I4.0 frameworks fail to operationalize its integration into SC transformation.

The 13 papers reviewed in [5] agree on the strong need for a comprehensive framework that:

- Guides SC organizations in aligning their corporate strategies associated with incorporation of I4.0 principles.
- Integrates technological, organizational, human, and sustainability perspectives.
- Provides a clear, practical, and actionable structure.
- Supports the development of SCs that are simultaneously agile, resilient, and sustainable.

The following sections present a conceptual and holistic framework designed to foster agility and sustainability across supply networks.

3. Foundations for the Development of the Agile and Sustainable Supply Network Compass

To address some of the drawbacks identified in the literature, an Agile and Sustainable Supply Network Compass was developed based on the following inputs and principles:

1. Understanding the relationship between the DX and sustainability concepts.
2. Integrating strategy, technology, processes, people and sustainability into a unified conceptual model that encompasses the entire SC.
3. Mapping the framework against existing models for the implementation of I4.0 within a specific company.

The following sections develop these key points in greater depth and provide the theoretical foundation for the framework presented in Section 4.

3.1. Digital Transformation and Sustainability—Theoretical Foundation

To analyze the relationship between DX and sustainability in the context of the SC, we begin by defining both. Digital transformation in the SC is a holistic, comprehensive process whereby the development of digital capabilities—encompassing technology, systems, culture, and organizational structures—facilitates the transition of the SC into a data-driven and agile network [4]. On the other hand, the United Nations Global Compact [7] defines sustainable supply chain management as "the management of environmental, social and economic impacts and the encouragement of good governance practices, throughout the lifecycles of goods and services. The objective of SC sustainability is to create, protect and grow long-term environmental, social and economic value for all stakeholders involved in bringing products and services to market."

Considering the previously mentioned aspects, the following facts are also important to consider:

- Competition no longer occurs between individual companies, but rather between entire SCs [8].
- Today's global world forces companies to move towards sustainable development in terms of social, economic, and environmental sustainability. Companies strive to achieve competitive advantages by achieving sustainability in their processes [1].
- The main purpose of DX is to achieve agility through data acquisition, the creation of knowledge, and the ability to make rapid decisions to become more competitive [9].
- Sustainability and innovation are recognized as strategic levers for global economic development [2].

We can conclude that both DX and sustainability are key drivers of competitiveness and, consequently, of global economic development. Since competition now occurs among entire SCs, both dimensions must coexist and evolve together.

However, the coexistence of DX and sustainability also presents significant challenges. For instance, one of the pillars of DX is the implementation of advanced technologies. Nevertheless, greater technological advancement tends to increase the emission of greenhouse gases into the environment, contributing to global warming. At the same time, the effective use of these advanced technologies can help mitigate sustainability-related issues by minimizing lead times and maximizing the efficient use of available resources [2].

Thus, the trade-off between DX and sustainability must be continuously analyzed in an integrated manner, seeking to enhance the positive impacts that digitalization can deliver to sustainability in the SC context, encompassing economic, social, and environmental dimensions. According to Naseem et al. [2], DX can generate significant benefits across multiple dimensions:

- Economic: Increased production driven by reduced cycle times, enabled by faster and more advanced production systems; higher flexibility; shorter lead times; greater automation; and improved information sharing.
- Environmental: Lower fuel consumption, reduced CO_2 emissions and minimized waste generation.
- Social: Creation of new job structures, changes in work practices resulting from technological advancements, improved company reputation, and the development of dynamic SC networks.

In conclusion, integrating both DX and sustainability into the SC strategy is essential for long-term competitiveness.

3.2. From the SC to the Supply Network

It is important to distinguish between supply chain and supply network. While a supply chain is typically described as a linear and sequential flow of materials, information, and financial resources from upstream suppliers to downstream customers [10], a supply network represents a broader interorganizational structure characterized by multiple actors, interdependencies, and parallel relationships [10]. From this perspective, every organization can be understood as operating within a supply network. This implies that, for any transformation or change to occur within the chain, several actors must align and reach consensus. This is a complex challenge that requires, as a first step, a deeper analysis of the structure and dynamics of the SC (Figure 1).

Focusing on the supply chain of a manufacturing firm, the chain can be understood as comprising the focal manufacturing company, n tiers of suppliers, m tiers of customers, the associated information and product flows, and the supply chain management processes that must be implemented across organizations. These processes are inherently cross-functional and cross-organizational in nature. To enable effective coordination, each organization within the supply chain is required to implement equivalent core business processes; otherwise, linking and managing these processes across firm boundaries becomes extremely difficult [10].

The management of SCs is inherently complex. According to Carter et al. [11], it is necessary to further theorize the concept of SC management, as much of the existing research tends to oversimplify it. These authors recommend conceptualizing the SC as a network of stakeholders (referred to as "nodes" or "agents") who exchange products, information, and financial flows (referred to as "links") to enable a holistic understanding of SC management. In this sense, they suggest the concept of a supply network rather than SC [12].

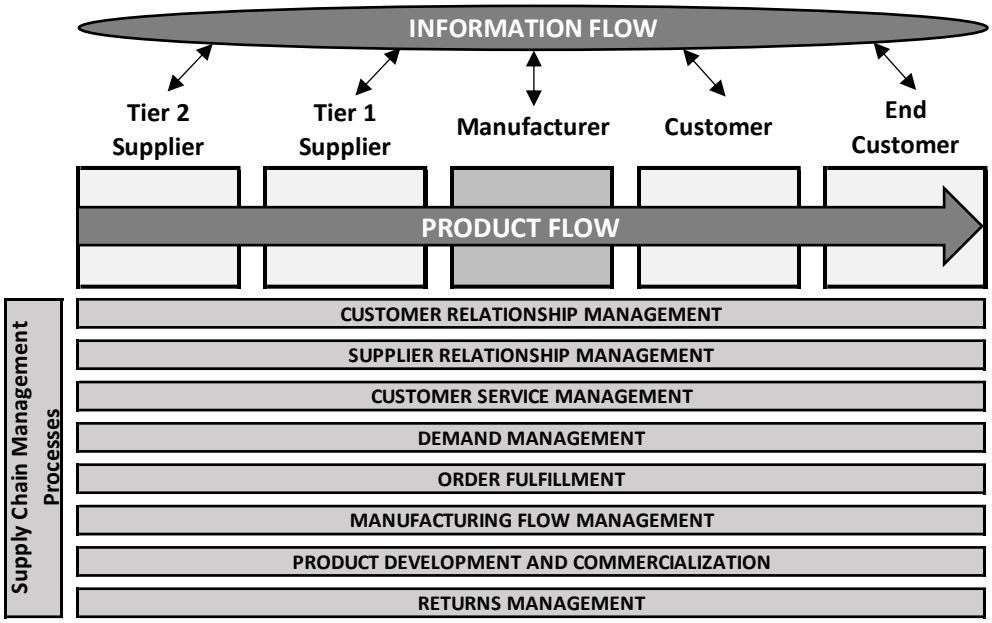

Figure 1. Supply chain structure, flows and processes, adapted from Lambert [10].

However, considering the SC "as a whole" can be challenging. Fritz [12] proposes that a SC consists of a focal firm that coordinates a set of suppliers and customers to deliver a product or service of expected quality, on time, and at the desired speed. The concept of a focal firm—coordinating and orchestrating actions—provides clarity and structure when designing a transformation process or a shared strategy among multiple stakeholders. Along the same lines, Lambert [10] suggests focusing on the critical linkages, since "the whole network is too large to manage effectively." The focal firm becomes the primary driver of change, enabling both upstream and downstream partners to achieve shared objectives.

Available tools can be used to identify and analyze these critical linkages. For instance, the rainbow diagram, proposed by Chevalier et al. [13], classifies stakeholders according to the degree to which they can affect or be affected by a firm's activities. The interest–influence matrix, proposed by Reed et al. [14], categorizes stakeholders based on their level of interest in and influence over the firm. However, these tools require further refinement and deeper analysis to adequately address the complexity of the entire SC [12].

It can therefore be concluded that the term "supply chain" essentially refers to a network. Given the inherent complexity involved in managing the entirety of this network, any proposed framework aiming to facilitate its transformation into an agile and sustainable network must first identify the focal firm that will spearhead the process, along with the key stakeholders with whom it maintains critical linkages (Figure 2). From this point forward, the term "reduced supply network" (RSN) will be used to refer collectively to the focal firm and its critical linkages.

Once the RSN has been identified, the focal company, together with its critical linkages, defines the strategic motive for pursuing digital and sustainable transformation. In this framework, the RSN plays a structuring and coordinating role, providing a pragmatic boundary within which strategic alignment, joint decision-making, and transformation priorities can be established. Rather than representing the entire supply network, the RSN delineates the subset of actors whose coordination is essential to initiating and steering transformation efforts in a feasible and coherent manner.

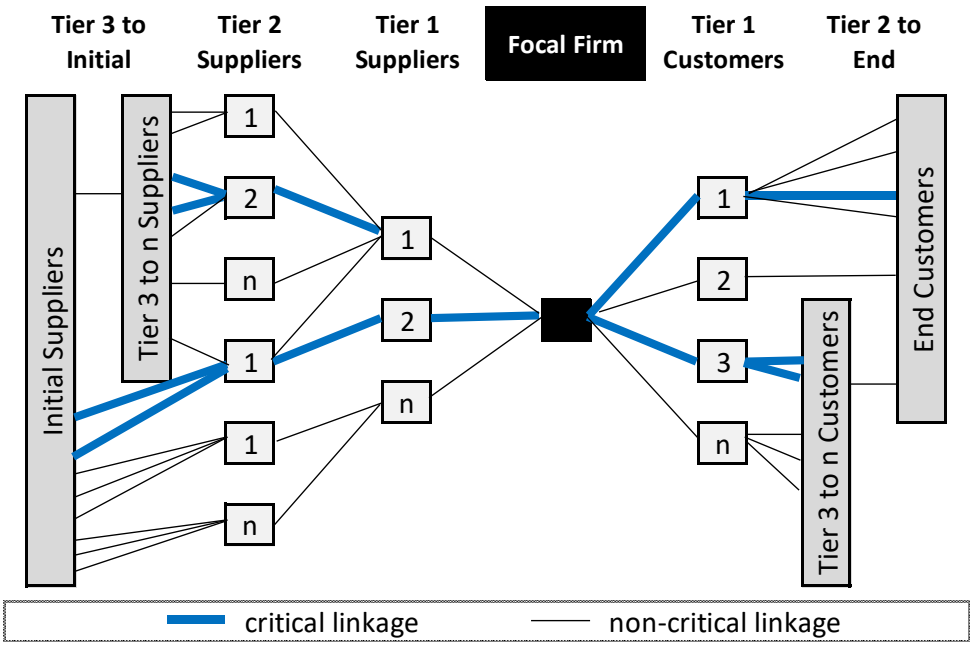

Figure 2. The reduced supply network and its critical linkages, adapted from Lambert [10].

Both Fritz [12] and Lambert [10] adopt a conception of the supply chain as a coordinable interorganizational system, in which actors and relationships exhibit different degrees of strategic relevance. While neither approach is restricted to specific sectors or assumes strict hierarchical control, both implicitly presuppose supply chains that allow for the identification of organizational reference points (focal firms) and critical linkages, thereby implicitly excluding fully fragmented or purely transactional networks. The proposed framework is intended for contexts in which coordination, prioritization of relationships, and joint decision-making across interconnected actors are feasible. Supply chains characterized by multiple equally dominant core firms or by purely transactional and highly fragmented relationships fall outside the scope of this study.

3.3. Managing Digital Transformation (DX) Through a Holistic Approach

There are several definitions of what DX entails and, consequently, several theories related to the management of the DX process. We believe that information systems and technologies are enablers of DX, but it is the culture and organizational structure of a company that make its transformation possible. This perspective highlights the need for holistic approaches that consider DX to be a coordinated and organization-wide change rather than a purely technological shift.

In this context, maturity models (MMs) emerge as tools to discretize the evolution of complex, long-term processes that span all organization levels. MMs support the digital transformation process by enabling organizations to understand their starting point in terms of capability development and to design digital transformation programs (roadmaps) for the systematic enhancement of capabilities toward a desired future state. Angreani et al. [15] conducted a systematic literature review on MMs for manufacturing organizations and analyzed 17 models in terms of their methodological construction, structure and practical orientation. They concluded that almost all of these models have a perfect score in research aims, methods, and theoretical foundations. However, there is considerable variation in the dimensions these models cover. Although all adequately address the technology and operation dimensions, only two of them—Industrie 4.0 Maturity Index [6] and Industry 4.0 maturity of industrial enterprises [16]—cover all nine required SC dimensions: Strategy,

Leadership, Customer, Products, Operations, Culture, People, Governance, and Technology. This finding confirms that a technological view of DX remains prevalent.

It is worth clarifying that this study does not aim to propose, extend, or compare maturity models. The Agile and Sustainable Supply Network Compass is a model-independent methodological framework that adopts a holistic perspective to guide coordinated digital and sustainability transformation at the supply network level, articulated through the concepts of the RSN and focal firm. Nevertheless, we employ a reference framework to illustrate typical digital evolution patterns observed in industrial contexts. To this end, we selected the Industrie 4.0 Maturity Index (I4.0 Maturity Index) [6], as it provides holistic support by assessing digital maturity across multiple interconnected dimensions. The I4.0 Maturity Index is a multidimensional maturity model designed to assess the digital transformation status of manufacturing firms across six stages, integrating technological, organizational, and cultural capabilities [6]. Its practical utility has been broadly documented through case studies showing how it can structure and prioritize digitalization roadmaps in diverse industrial contexts [6,17]. Moreover, academic research has qualified the model as a rigorous framework suitable for both assessment and roadmap development in I4.0 adoption [15,18]. Although originally designed for implementation in the manufacturing sector, it has demonstrated its capability to be applied in other domains, such as logistics, energy, and human resources [15], showing its versatility across different contexts.

To analyze the feasibility of adapting this model to the RSN, we first revisit its key components [6]:

- Industry 4.0 Vision: The model is grounded in a clear vision of what it means to achieve DX maturity within a company. The goal is to generate knowledge from data in order to transform the company into a learning and agile organization and enable rapid decision-making and adaptation processes through every part of the business and across all business process areas [6].
- Maturity levels: Building on this vision, the model's approach is based on a succession of maturity stages, which help companies navigate their way through every stage in the transformation, from the basic requirements for I4.0 to full implementation. The path comprises six development stages:
    1. Computerization: This stage focuses on introducing basic digital tools and systems to improve efficiency and data availability at the task or process level.
    2. Connectivity: At this stage, different digital systems, machines, and applications are connected to allow data exchange across processes and organizational units.
    3. Visibility: The goal is to make relevant data visible across the organization, supporting monitoring, tracking, and basic performance analysis.
    4. Transparency: Data is contextualized and analyzed to explain why events occur, enabling deeper insights into process behavior and performance drivers.
    5. Predictive Capacity: Advanced analytics and predictive models are used to forecast demand, failures, or performance trends, supporting proactive decision-making.
    6. Adaptability: In this stage, systems and processes can dynamically adjust based on predictions and predefined rules, enhancing agility and resilience.
- Digital capabilities: Each stage builds on the previous one and describes the digital capabilities required to reach it.
- Structural areas and guiding principles: Digital capabilities are associated with four structural areas: resources, information systems, culture, and organizational structure. As capabilities mature within each structural area, they evolve into guiding principles that characterize how the organization advances toward higher stages of digital transformation. Specifically, capabilities related to resources are reflected in

the guiding principles of structured communication and digital capability; within information systems, they evolve toward system integration and information processing; capabilities embedded in culture emphasize willingness to change and social collaboration; and those associated with organizational structure give rise to organic internal organization and dynamic collaboration within value networks.

- Functional areas and processes: In the I4.0 Maturity Index, the capabilities are investigated separately for each of a company's functional areas: Development, Production, Logistics, Services, and Marketing and Sales. The specific maturity stage of each capability may be different for different functional areas and the business processes contained within them.
- Corporate and Digital Strategy: The use of the Index involves the identification of the current maturity stage of digital capabilities in the different functional areas and the definition of the target development stage that the company wishes to attain at the end of the transformation process, in alignment with its corporate strategy.

The following paragraphs aim to assess whether the I4.0 Maturity Index components can be adapted to develop an extended model that encompasses the entire supply network. These components will be examined in reverse order compared to the previous listing.

Regarding strategy, it has been shown that it is possible to define a digital strategy aligned with the overall strategy of the network, provided that the focal firm and its critical linkages come to a consensus and adopt it collectively. The role of the focal firm is crucial in driving this process forward. The proposed vision and maturity stages provide a clear direction for advancing toward a data-driven and agile supply chain, capable of adapting to changing conditions while enhancing visibility and transparency across all nodes and fostering collaboration among stakeholders.

Concerning processes, it is feasible to consider those defined by Lambert [10], as they are cross-functional throughout the entire SC (Figure 1). Depending on the specific SC analyzed and the defined strategy, all processes or only a subset of them may be considered.

In terms of structural areas and guiding principles, these can be redefined to allow for the analysis of the network from a holistic perspective that incorporates sustainability considerations. Figure 3 proposes a structure that should be examined in greater depth in future research.

The proposed structural areas and their associated guiding principles at the network level are as follows:

- Technology and resources: Integrated communication and digital capability.
- Information flows and systems: System implementation and integration, and information processing.
- Culture and sustainability: Ways of working and change management, and sustainability orientation.
- Structure and integration: Supply network organization and supply network collaboration.

Finally, the capabilities associated with each structural area and guiding principles remain to be defined. Identifying these capabilities is entirely possible; this analysis, however, lies beyond the scope of this paper.

The analysis conducted in this section suggests that the holistic acatech model associated with I4.0 can be meaningfully adapted to the context of DX in SCs. While this phase focuses on developing a theoretically grounded, conceptually driven and literature-based framework, empirical validation will constitute the next stage of the research. In this regard, the acatech I4.0 Maturity Index has already been applied in multiple companies to guide digital transformation processes toward Industry 4.0, demonstrating its applicability beyond the theoretical domain [19]. This proven practical relevance reinforces its suitability and represents a key factor behind the decision to adopt it as a well-established supporting

reference for this work, without implying exclusivity or limiting the applicability of the Compass to alternative maturity models.

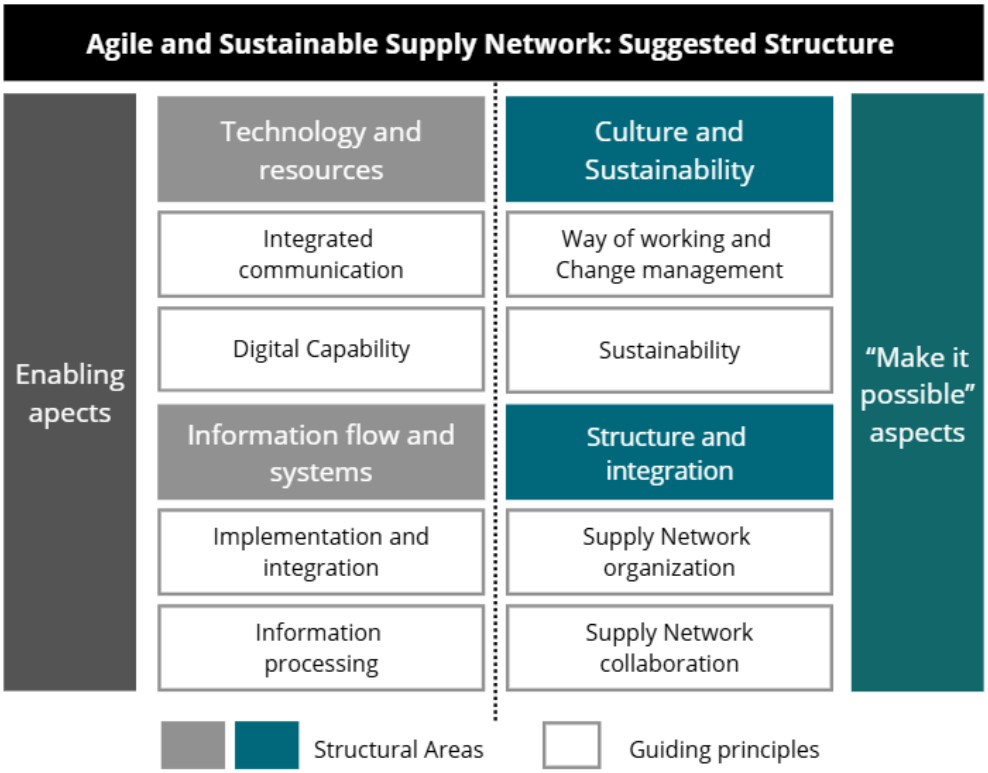

Figure 3. Structural areas and guiding principles for an Agile and Sustainable Supply Network framework (adaptation from acatech I4.0 Maturity Index [6]).

Section 4 introduces a methodological framework that guides coordinated digital and sustainability transformation at the supply network level. While the proposed framework extends the perspective of digital transformation from the enterprise level to cross-organizational supply networks, this extension is not intended as a direct extrapolation of firm-level maturity to the network level. Rather, the framework adopts a structuring and guiding perspective, aimed at supporting coordinated reflection and alignment across interconnected organizations. Issues such as network governance structures, power asymmetries, and revenue distribution mechanisms are recognized as critical factors influencing network-level transformation, but their detailed analysis lies beyond the scope of this study. Instead, these aspects are implicitly considered through the concepts of the reduced supply network (RSN) and the focal firm, which provide a pragmatic boundary for coordination and joint decision-making, while leaving space for future research to address governance and economic dynamics in greater depth.

4. The Agile and Sustainable Supply Network Compass

This section presents an analytical framework—the Sustainable and Agile Supply Network Compass—to guide the digital transformation of the SC towards an agile and sustainable supply network. The framework, shown in Figure 4, focuses on the alignment and assessment of the SC's strategy, processes, and capabilities and is grounded in the two following principles: (1) DX and sustainability must be embedded in the SC strategy; and (2) the Focal Firm and its critical linkages have agreed on the adoption of a global strategy for the RSN.

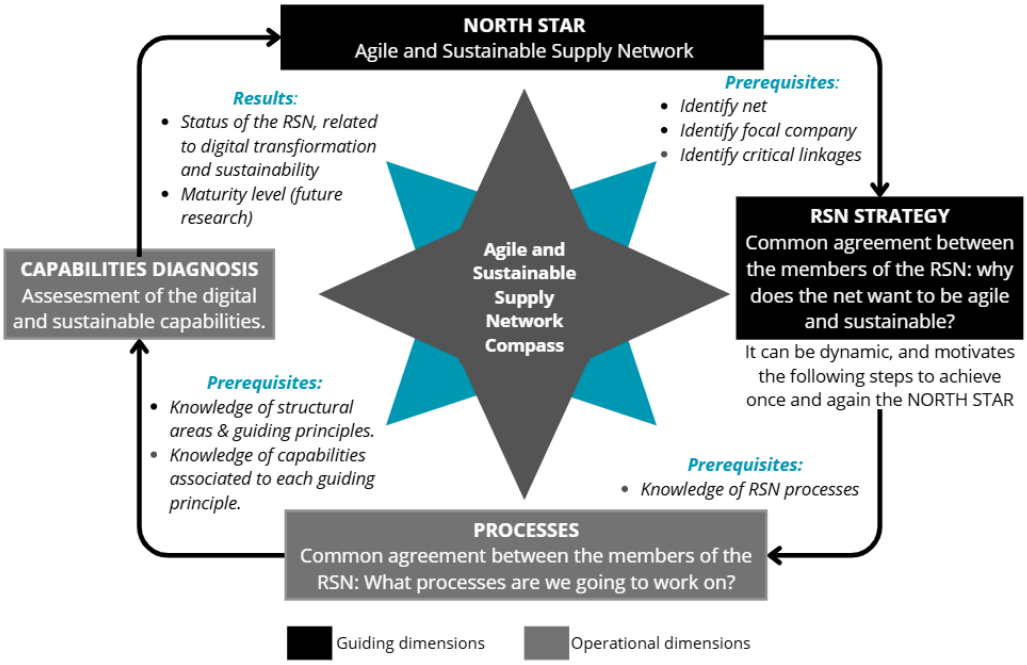

Figure 4. The Agile and Sustainable Supply Network Compass (own source).

4.1. North Star

To define the North Star of the proposed Compass, two facts must be taken into consideration:

- Fact 1: As mentioned before, both DX and sustainability are key drivers of competitiveness and, therefore, of global economic development. Since competition now takes place between entire SCs, both dimensions must coexist and evolve together. The trade-off between DX and sustainability must be continuously analyzed in an integrated manner, and it is essential that both DX and sustainability are embedded in the SC strategy.
- Fact 2: On the other hand, an isolated company does not achieve the same levels of efficiency, agility, or compliance with the Sustainable Development Goals (Appendix B)—particularly SDG 8 (Decent Work and Economic Growth), SDG 9 (Industry, Innovation and Infrastructure), SDG 12 (Responsible Consumption and Production), and SDG 13 (Climate Action)—as it would when collaborating within a network [20].

Considering the two facts discussed above, the current North Star of a SC is to become an agile and sustainable network. With this objective in mind, the first step is to identify the RSN, determine which company is the "focal firm", and establish its "critical linkages."

4.2. Supply Chain Strategy

Once the RSN has been identified, the focal firm, together with its critical linkages, must agree on the strategic motive of the RSN for pursuing a digital and sustainable transformation. This strategic motive should be aligned with a broader business strategy; the mere implementation of technology or systems is not, in itself, a sufficient reason to embark on the path toward DX, just as sustainability initiatives should not be pursued unless they align with the overall strategy of the RSN. A shared strategy will provide the future direction, guidelines, and activities required to achieve the overarching objective (the North Star). Strategy is dynamic, and therefore, the process of continuous "adjustment" to remain aligned with the North Star must also be ongoing.

To move forward, it is essential to identify the cross-functional processes within the RSN under consideration.

4.3. Identification of Processes

Once the entire set of cross-functional processes within the RSN has been identified, its various members must jointly assess and determine which processes will become the focus of improvement or transformation efforts. The specific processes will depend on the type of business in which the network is engaged; for instance, in the case of a network focused on product manufacturing, the eight processes proposed by Lambert can be useful as a reference (Customer Relationship Management, Customer Service Management, Demand Management, Order Fulfilment, Manufacturing Flow Management, Supplier Relationship Management, Product Development and Commercialization, Returns Management). The inclusion of all processes or only a selected subset will be a decision that must be made by the stakeholders of the RSN, considering the strategy mentioned in Section 4.2.

Once the processes to be jointly addressed have been defined, it becomes essential to establish the dimensions that will be considered in the evaluation of each process. These dimensions represent the structural areas and guiding principles through which the level of agility and sustainability of each of the selected processes and the whole RSN will be assessed. Within these dimensions, a distinction must be made between those that are structural and serve as enablers of the transformation process required to achieve the overarching objective (the North Star), and those that make its execution feasible.

In the I4.0 Maturity Index, resources and information systems are conceptualized as enabling structural areas of transformation, while organizational structure and culture are regarded as the areas that make transformation possible. Building on this underlying logic, Figure 3 presents a conceptual proposal at the reduced supply network (RSN) level. In this proposal, resources and technologies, together with information flows and systems, act as enabling structural areas, whereas supply chain structure and integration, culture, and sustainability represent the structural areas that make coordinated transformation across the network possible.

4.4. Capability Diagnosis

In order to determine how closely the considered processes and the RSN as a whole align with the desired North Star—that is, to assess their level of maturity in terms of agility and sustainability—capabilities must be defined within each structural area and guiding principle. At this stage, the defined capabilities, which will be either digital or sustainability-related depending on the structural area in question, undergo an evaluation process to determine their current state and to plan a roadmap of activities and projects that will enable their development. As these capabilities are progressively developed, the RSN advances in its maturity level, becoming an increasingly agile and sustainable network aligned with its defined strategy.

The definition of maturity levels and the association of capability development with each level are part of the development of a maturity model, which exceeds the scope of this paper and may represent a potential area for future research.

In the Agile and Sustainable Supply Network Compass, Strategy, Processes, and Capabilities are defined as structural dimensions, as they represent core and interdependent pillars that shape and sustain transformation over time. These dimensions are presented at the same conceptual level to emphasize their systemic relevance. However, within this structure, Strategy plays an overarching and guiding role, as it drives the identification of key Processes and the consequent Capabilities' diagnosis. Adjustments in strategy continuously reorient the Compass, maintaining focus on the agreed transformation direction, the North Star. Building on the previous analysis, in Figure 4, the North Star and the RSN Strategy are identified as guiding dimensions, while the Processes and Capabilities' diagnosis are identified as operational dimensions, as they constitute the mechanisms

through which strategic intent is translated into concrete actions, routines, and measurable transformation outcomes.

Sustainability plays a transversal and enabling role across these structural dimensions. It is embedded in strategic priorities, translated into process-level decisions, and realized through the development of specific capabilities. Accordingly, sustainability is treated as an integral component of the transformation logic, achieved through the continuous alignment of strategy, process redesign, and capability diagnosis and development.

5. Summary

The Agile and Sustainable Supply Network Compass consolidates key insights from the literature and integrates them into a unified framework for guiding SC transformation. It emphasizes the necessity of aligning digital and sustainability strategies, identifying the RSN and its critical linkages, and selecting cross-functional processes whose improvement will drive agility and sustainability. Drawing inspiration from the I4.0 Maturity Index, a holistic model, the Compass also structures the analysis around foundational dimensions—Strategy, Processes and Capabilities (related to digitalization and sustainability)—that act as enablers and execution drivers of transformation. As such, the Compass provides organizations with a clear starting point, a structured analytical path, and a coherent conceptual foundation to guide decision-making and capability development.

Having introduced the structure and underlying logic of the proposed framework, the following section discusses its theoretical and practical implications, examining how it contributes to the existing literature on digital transformation and sustainability in supply chains, as well as its relevance for managerial practice. The discussion also reflects on the limitations of the study and outlines directions for future research.

6. Discussion

The insights gained in this study position the Compass as a meaningful contribution to both the academic literature and managerial practice.

6.1. Theoretical Contributions

- Holistic Integration: The Compass unifies aspects that are typically treated separately—DX, sustainability, processes, culture, and organizational strategy—offering a truly integrated perspective.
- Conceptual Advancement: It reinforces the argument that DX and sustainability must co-evolve within supply networks, contributing to emerging discussions around sustainable digitalization.
- Framework Development: By grounding the Compass in a structured synthesis of the literature and SC management theories, and by positioning maturity models such as I4.0 Maturity Index as supporting references, the paper provides a conceptual framework on which future maturity models and assessment tools may be built.

6.2. Practical Contributions

- Actionable Guidance: The Compass equips organizations with a structured and actionable approach to initiate transformation aligned with shared objectives.
- Strategic Alignment: It emphasizes the definition of a common digital and sustainability strategy at the RSN level, coordinated by the focal firm.
- Process-Centric Approach: It encourages organizations within the SC to prioritize cross-functional processes driving value creation, enabling targeted development of digital and sustainability capabilities.

6.3. Limitations

- Throughout the development of this paper, both Lambert's process and the I4.0 Maturity Index were proposed, as they were considered sufficiently aligned with the intended purpose. Although other approaches to SC management and DX maturity were reviewed, only the aforementioned models were analyzed in depth.
- The framework is conceptual and requires empirical validation.
- The definition of maturity levels and capabilities, while feasible, remains outside the scope of this study.

6.4. Future Research

- Empirical testing of the Compass in real RSNs.
- Identification and definition of capabilities under each structural area.
- Development of maturity levels and an assessment tool.
- Integration of the Compass into a complete roadmap for DX and sustainability implementation in an RSN.
- In-depth analysis of network governance structures, power asymmetries, and revenue distribution mechanisms and their influence on network-level digital and sustainability transformation.

The discussion highlights how the proposed framework contributes to reframing digital transformation beyond technology-centric views and approaches focused on a single, isolated organization, emphasizing the need to support coordinated decision-making at the supply network level. Building on these insights, the following section synthesizes the main conclusions of the study, reflects on the feasibility and implications of adopting a holistic and integrated transformation approach, and outlines directions for future research.

7. Conclusions

This study conceptually demonstrates the feasibility of designing a holistic framework to guide supply chains in becoming agile and sustainable through integrated digital transformation. By addressing key theoretical and practical gaps, the Agile and Sustainable Supply Network Compass contributes to the literature through an integrative perspective on digital transformation in supply chains, showing that agility and sustainability are unlikely to be effectively pursued through isolated technological initiatives. Instead, transformation must be approached as a coordinated, network-level process, in which strategic intent, process redesign, and capability development co-evolve over time.

A central insight of this work is that defining a reduced supply network (RSN), together with a focal firm and its critical linkages, provides a conceptual framing for coordination, particularly in complex interorganizational settings. This framing enables supply networks to move beyond firm-centric views and to explicitly address the interdependencies that are critical for both digital and sustainability outcomes.

The Compass positions agility and sustainability as the shared North Star of modern supply networks, while the remaining dimensions—strategy, processes, resources and technologies, people and culture, and sustainability—operate as dynamic and interrelated elements that must be continuously aligned. In this sense, the framework highlights that sustained transformation depends less on one-time implementation efforts and more on ongoing strategic alignment across organizational and network boundaries.

Sustainability emerges in this study not as a standalone objective, but as a structural and transversal driver of transformation, embedded in strategic priorities, translated into cross-functional processes, and realized through the development of dedicated capabilities. This interpretation reinforces the view that sustainability-oriented transformation requires persistent coordination rather than episodic initiatives.

Future research should focus on operationalizing sustainability-related capabilities, defining maturity levels that capture the co-evolution of digitalization and sustainability, and developing assessment tools to support practical application. Empirical validation of the proposed framework across real reduced supply networks (RSNs) and diverse industrial contexts represents a critical next step. Additional research may also explore the integration of the Compass into comprehensive transformation roadmaps. Finally, issues such as network governance structures, power asymmetries, revenue distribution mechanisms, and policy contexts are recognized as influential factors shaping network-level digital and sustainability transformation and merit deeper investigation in future studies.

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Abbreviations

The following abbreviations are used in this manuscript:

I4.0	Industry 4.0
DX	Digital Transformation
SC	Supply Chain
SCs	Supply Chains
CPS	Cyber–Physical Systems
IoT	Internet of Things
CPSL	Conference on Production Systems and Logistics
Acatech	German Academy of Science and Engineering
RSN	Reduced Supply Network

Appendix A. Umbrella Review: Purpose, Systematic Literature Reviews (SRLs) Analyzed and Main Conclusions

Appendix A.1. Purpose

An umbrella review was conducted for the purpose of gathering the state of the art associated with I4.0 implementation in SCs.

Appendix A.2. Systematic Literature Reviews Analyzed

- SRL 1:
  Büyüközkan, G.; Göçer, F. Digital supply chain: Literature review and a proposed framework for future research. *Comput. Ind*. 2018, 97, 157–177. https://doi.org/10.1016/j.compind.2018.02.010 [21].
- SRL 2:
  Chauhan, C.; Singh, A. A review of Industry 4.0 in supply chain management studies. *J. Manuf. Technol. Manag.* 2020, 31, 863–886 [22].
- SRL 3:
  Sony, M.; Naik, S. Key ingredients for evaluating Industry 4.0 readiness for organizations: A literature review. *Benchmarking* 2020, 27, 2213–2232. https://doi.org/10.1108/BIJ-09-2018-0284 [23].

- SRL 4:
  Núñez-Merino, M.; Maqueira-Marín, J.M.; Moyano-Fuentes, J.; Martínez-Jurado, P.J. Information and digital technologies of Industry 4.0 and Lean supply chain management: A systematic literature review. *Int. J. Prod. Res.* 2020, 58, 5034–5061. https://doi.org/10.1080/00207543.2020.1743896 [24].
- SRL 5:
  Ansari, Z. A systematic literature review on adoption of Industry 4.0 in supply chain. *Int. J. Res. Appl. Sci. Eng. Technol.* 2020, 8, 60–67. https://doi.org/10.22214/ijraset.2020.31250 [25].
- SRL 6:
  Zekhnini, K.; Cherrafi, A.; Bouhaddou, I.; Benghabrit, Y.; Garza-Reyes, J.A. Supply chain management 4.0: A literature review and research framework. *Benchmarking* 2021, 28, 465–501. https://doi.org/10.1108/BIJ-04-2020-0156 [26].
- SRL 7:
  Tiwari, S. Supply chain integration and Industry 4.0: A systematic literature review. *Benchmarking* 2021, 28, 990–1030. https://doi.org/10.1108/BIJ-08-2020-0428 [27].
- SRL 8:
  Hellweg, F.; Lechtenberg, S.; Hellingrath, B.; Thomé, A.M.T. Literature review on maturity models for digital supply chains. *Braz. J. Oper. Prod. Manag.* 2021, 18, 1–14. https://doi.org/10.14488/BJOPM.2021.022 [28].
- SRL 9:
  Jahani, N.; Sepehri, A.; Vandchali, H.R.; Tirkolaee, E.B. Application of Industry 4.0 in the procurement processes of supply chains: A systematic literature review. *Sustainability* 2021, 13, 7520. https://doi.org/10.3390/su1314752 [29].
- SRL 10:
  Naseem, M.H.; Yang, J. Role of Industry 4.0 in supply chains sustainability: A systematic literature review. *Sustainability* 2021, 13, 9544. https://doi.org/10.3390/su13179544 [2].
- SRL 11:
  Weerabahu, W.M.S.K.; Samaranayake, P.; Nakandala, D.; Hurriyet, H. Digital supply chain research trends: A systematic review and a maturity model for adoption. *Benchmarking* 2022, in press. https://doi.org/10.1108/BIJ-12-2021-0782 [30].
- SRL 12:
  Bentaher, C.; Rajaa, M. Supply chain management 4.0: A literature review and research framework. *Eur. J. Bus. Manag. Res.* 2022, 7, 117–127. https://doi.org/10.24018/ejbmr.2022.7.1.1246 [31].
- SRL 13:
  Deepu, T.S.; Ravi, V. A review of literature on implementation and operational dimensions of supply chain digitalization: Framework development and future research directions. *Int. J. Inf. Manag. Data Insights* 2023, 3, 100156. https://doi.org/10.1016/j.jjimei.2023.100156 [32].

Appendix A.3. Main Conclusions

- There is still a tendency to treat the issue from a technological perspective, leaving aside other aspects that are part of the holistic view.
- The development of frameworks or maturity models is still in the initial and theoretical phase. There are still few publications that propose a framework or maturity model for the implementation of I4.0 in the SC.

- When it comes to the development of a roadmap that guides SCs in the implementation of digital capabilities associated with I4.0, no proposals were found.
- There are still barriers to overcome in order to start and advance in the SC digital transformation process. These barriers are associated with several lines of work and represent big challenges to the SC's progress.
- Detected GAPs are an issue that has been highly investigated. The most frequent gap, mentioned by 6 of the 13 SLRs, is "the empirical validation of the proposed frameworks and maturity models", confirming that this issue needs to be addressed. The second most frequent gaps concern "the need of developing a framework or maturity model to guide the SC in the digital transformation process", "the need of considering this process from a holistic perspective", and the need to "study the relationship of SCM4.0 with sustainability". Each of these gaps is mentioned in 5 SLRs.

Appendix B. Sustainable Development Goals

1. No Poverty;
2. Zero Hunger;
3. Good Health and Well-Being;
4. Quality Education;
5. Gender Equality;
6. Clean Water and Sanitation;
7. Affordable and Clean Energy;
8. Decent Work and Economic Growth;
9. Industry, Innovation and Infrastructure;
10. Reduced Inequalities;
11. Sustainable Cities and Communities;
12. Responsible Consumption and Production;
13. Climate Action;
14. Life Below Water;
15. Life on Land;
16. Peace, Justice and Strong Institutions;
17. Partnerships for the Goals.

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