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Logistics 5.0 in the 5.0 Ecosystem: Bridging Structural Readiness, Functional Capability, and Sustainable System Performance—A Systematic Review and Conceptual Framework

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Abstract

The transition toward the 5.0 paradigm, encompassing Society 5.0, Industry 5.0, and Service 5.0, positions logistics as a critical enabler of sustainable and resilient socio-economic transformation. Logistics 5.0 is increasingly associated with sustainability and human-centric system design; however, the assumption that higher technological readiness leads to improved sustainability performance remains insufficiently examined. This study conducts a systematic literature review based on the PRISMA methodology, covering the period 2016–2026 and synthesizing a final dataset of 149 peer-reviewed articles, synthesizing research on Logistics 5.0 readiness, digital maturity models, resilience capabilities, and sustainability performance. The results reveal three key gaps: (i) the dominance of techno-centric readiness models that marginalize sustainability outcomes, (ii) fragmented and methodologically inconsistent evidence linking digital transformation to environmental and social performance, and (iii) the prevalence of compensatory logic allowing high digitalization levels to offset weaknesses in resilience or sustainability. In response, the paper conceptualizes Logistics 5.0 as an integrative operational layer within the 5.0 ecosystem and proposes a non-compensatory conceptual framework based on a three-layer architecture comprising structural readiness, functional system capabilities, and sustainability performance outcomes. The findings demonstrate that sustainability should be understood as an emergent system property mediated by resilience and adaptability rather than a direct consequence of digitalization. The study contributes to advancing integrated maturity assessment approaches aligned with sustainable development objectives.

Keywords: Logistics 5.0; sustainability performance; digital maturity; resilience; non-compensatory framework; Industry 5.0; supply chain sustainability; systematic literature review; PRISMA; sustainable development goals

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1. Introduction

The transition from Industry 4.0 toward the broader 5.0 paradigm marks a significant shift in the conceptualization of technological development and its role in socio-economic systems [1]. While Industry 4.0 primarily emphasized automation, digitalization, Industry 5.0 extends this vision by integrating human-centricity, sustainability, and resilience as core design principles of modern production and service systems. The concept of Society 5.0 introduces a macro-level perspective in which advanced digital technologies are embedded

within social structures to address complex societal challenges, including climate change, resource scarcity, and demographic transformations [2]. These developments define an interconnected 5.0 ecosystem oriented toward sustainable and inclusive growth.

Within this emerging paradigm, logistics plays a critical role as the operational backbone that connects production systems, service processes, and end-users. As the "circulatory system" of the 5.0 ecosystem, logistics enables the flow of materials, information, and value across organizational and sectoral boundaries [3]. The evolution toward Logistics 5.0 reflects the integration of digital and physical processes through technologies such as the Internet of Things, artificial intelligence, and digital twins, enabling real-time decision-making, system visibility, and adaptive coordination [4,5]. Logistics systems are directly implicated in key sustainability challenges, including greenhouse gas emissions, energy consumption, and resource efficiency. Logistics 5.0 is increasingly framed as a key enabler of low-carbon transformation, circular economy practices, and resilient supply chain design aligned with global sustainability objectives, including the Sustainable Development Goals (e.g., SDGs 9, 11, 12, and 13) [3].

Despite this growing recognition, the relationship between technological advancement in logistics and sustainability outcomes remains ambiguous. A dominant assumption in the literature suggests that increasing levels of digital maturity and structural readiness naturally lead to improved system performance, including sustainability. However, this techno-optimistic perspective has been insufficiently scrutinized. Highly digitalized logistics systems may still exhibit vulnerabilities, inefficiencies, or unintended environmental impacts if they lack appropriate system-level capabilities such as resilience, robustness, or adaptability. Thus, sustainability in logistics should not be interpreted as a direct outcome of digital transformation, but rather as an emergent property resulting from the interaction between structural conditions and functional system behavior [6,7].

In recent years, a growing body of literature has attempted to synthesize the emerging field of Logistics 5.0 and its relation to Industry 5.0 and smart logistics transformation. Existing review studies have primarily focused on technological enablers, digital transformation pathways, and the evolution toward smart and connected logistics systems [8]. Other contributions have proposed maturity models and measurement frameworks for Logistics 5.0, emphasizing structural readiness dimensions such as technological infrastructure, organizational capabilities, and digital integration [9]. Additionally, domain-specific reviews have explored selected aspects of Logistics 5.0, including reverse logistics [10], green and sustainability-oriented innovation [11], and sectoral applications such as healthcare logistics [12]. However, these studies remain fragmented and predominantly techno-centric, often treating sustainability as an implicit outcome rather than a system-level property. Moreover, limited attention is given to the role of resilience, robustness, and adaptability as mediating factors between readiness and performance. Most frameworks rely on compensatory logic, allowing digitalization to offset weaknesses in other dimensions. As a result, an integrated perspective linking readiness, system behavior, and sustainability remains underdeveloped.

This gap points to a broader limitation in existing maturity and readiness models applied in Logistics 5.0 research. Many of these frameworks focus predominantly on technological and organizational dimensions of preparedness while treating sustainability as a secondary or external outcome. This may overestimate the impact of digital transformation and obscure the conditions required for sustainable outcomes. Empirical evidence linking Logistics 5.0 implementation to measurable environmental, economic, and social performance improvements remains fragmented and methodologically inconsistent, further complicating the assessment of its real contribution to sustainability transitions.

In response to these challenges, this study addresses the following research questions:

RQ1: How is Logistics 5.0 readiness conceptualized and measured?
RQ2: How are resilience and system-level capabilities integrated into these models?
RQ3: How is sustainability performance assessed in Logistics 5.0 research?
RQ4: What conceptual gaps exist between structural readiness and sustainable system outcomes?

Building on these questions, the paper advances the central argument that structural readiness in Logistics 5.0 does not inherently lead to sustainable system-level performance. This relationship is mediated by functional system capabilities, including resilience, robustness, reliability, and adaptability.

To address this problem, the study employs a systematic literature review based on the PRISMA methodology, synthesizing research on digital maturity, logistics transformation, resilience, and sustainability performance. The review identifies key gaps, including techno-centric bias, weak integration of system capabilities, and inconsistent sustainability assessment. Based on this synthesis, the paper develops a conceptual framework that positions Logistics 5.0 as an integrative operational layer within the 5.0 ecosystem, mediating interactions between Industry 5.0 production systems and Service 5.0 value creation processes.

The main contributions of the study are fourfold. First, it provides a structured synthesis of the literature on Logistics 5.0, linking readiness, resilience, and sustainability perspectives. Second, it identifies limitations of existing maturity models, particularly the reliance on compensatory logic and the insufficient consideration of sustainability as a system-level performance outcome. Third, it introduces a conceptual distinction between structural readiness, functional system capabilities, and sustainability performance. Finally, it proposes a non-compensatory conceptual framework in which sustainability is understood as an emergent property of system behavior rather than a direct consequence of technological advancement. This supports the development of more robust and sustainability-oriented maturity assessment models.

2. Theoretical Foundations of the 5.0 Ecosystem

2.1. Society 5.0 and Macro-Level Transformation

The concept of Society 5.0 represents a paradigm shift in the role of digital technologies within socio-economic systems, moving beyond efficiency-driven industrial transformation toward a model focused on sustainability, human well-being, and systemic value creation [13,14]. Society 5.0 positions digitalization as an instrument for addressing complex societal challenges, including climate change, resource scarcity, and demographic transitions [15]. This perspective shifts the focus from technology-centric to human- and sustainability-oriented system design [16,17].

Society 5.0 can be understood as an integrated socio-technical architecture connecting cyber and physical systems across industry, services, infrastructure, and logistics [18]. Its defining feature is the integration of data-driven decision-making with real-world operational processes across interconnected subsystems. Consequently, system evaluation must extend beyond local efficiency metrics toward environmental, economic, and social outcomes [19].

From a sustainability perspective, Society 5.0 adopts a multi-dimensional approach in which environmental performance, economic viability, and social inclusion are treated as interdependent objectives [15,20]. Sustainability should therefore be viewed as an emergent system-level outcome rather than an automatic consequence of technological advancement [21,22].

To clarify the key characteristics of Society 5.0 in the context of this study, Table 1 summarizes its core dimensions and their implications for system-level analysis.

Table 1. Key characteristics of Society 5.0 and implications for system-level analysis. Source: Own contribution based on [19,20,23].

Dimension	Description	Conceptual Implication	Implications for This Study
Technological integration	Integration of cyber and physical systems (AI, IoT, big data) and advanced automation technologies, enabling real-time interaction between digital and physical environments	Technological integration enhances data availability, connectivity, and system visibility, but does not inherently ensure improved system performance or stability	Technological integration is treated as part of structural readiness rather than a direct determinant of performance, and its effects are mediated through functional system capabilities
Human-centricity	Focus on human well-being, inclusiveness, and quality of life, positioning humans as central actors within socio-technical systems rather than passive users of technology	Human-centric design introduces social and behavioral dimensions into system evaluation, requiring consideration of human-system interaction and social sustainability aspects	Explicit incorporation of human-centricity within the structural readiness layer, but evaluates its actual impact through functional capabilities and system-level performance outcomes
Sustainability orientation	Emphasis on a balance between environmental protection, economic efficiency, and social well-being, aiming at long-term systemic stability and resource efficiency	Sustainability should be interpreted as a multi-dimensional and system-level construct rather than a direct outcome of technological advancement	Sustainability is modeled as an emergent performance outcome resulting from the interaction between structural readiness and functional capabilities
System integration	Integration of multiple subsystems across industries, services, and logistics networks into a unified, interconnected socio-technical ecosystem	System integration increases complexity and interdependence, requiring multi-level analytical approaches that capture interactions across macro-, meso-, and micro-levels	Adoption of a multi-layer modeling structure to reflect system integration and explicit separation of structural, functional, and performance layers
Data-driven decision-making	Real-time data analytics, adaptive algorithms, and AI-based decision-support systems to enable dynamic and responsive system control	Data-driven systems improve responsiveness and adaptability, but require appropriate system capabilities to translate data into robust operational performance	Data-driven decision-making is considered an enabler within structural readiness, while its effectiveness depends on functional capabilities such as resilience and adaptability

Within this macro-level framework, logistics emerges as a critical enabling subsystem that translates digital decisions into physical flows of goods, resources, and services [13,14]. However, improvements in logistics digitalization do not automatically translate into system-level sustainability and resilience outcomes, as these effects depend on functional system capabilities.

This perspective highlights limitations of techno-centric maturity models that focus on structural readiness while overlooking system behavior. Consequently, the Society 5.0 improvements in logistics digitalization do not automatically translate into system-level sustainability and resilience outcomes, as these effects depend on functional system capabilities.

2.2. Industry 5.0 and Service 5.0

Industry 5.0 extends the technological paradigm of Industry 4.0 by integrating human-centricity, sustainability, and resilience into industrial systems, shifting the focus from automation-driven efficiency toward collaborative and adaptive production environments [24,25]. In this context, advanced technologies such as AI and cyber–physical systems are used not only to optimize processes but also to support human capabilities and sustainable production [2,26]. This transition redefines value creation by balancing productivity with environmental and social objectives [27,28].

A key characteristic of Industry 5.0 is the increasing integration of human expertise with intelligent systems, enabling flexible and adaptive production processes [29]. Decision-making increasingly combines data-driven support with human oversight, supporting responsiveness and customization in dynamic production environments [25].

Parallel to these developments, Service 5.0 emphasizes data-driven service innovation and value co-creation enabled by advanced analytics, cloud architectures, and AI-based systems [30–36]. This transition supports smart and personalized services as well as digital servitization, where firms extend traditional products into integrated product–service systems [34,35]. Existing studies further highlight interoperability, scalability, and user-centricity as key principles of Service 5.0 ecosystems [37–40].

Despite their conceptual alignment, Industry 5.0 and Service 5.0 address different but interdependent dimensions of the 5.0 ecosystem. Industry 5.0 focuses on the transformation of production systems, while Service 5.0 emphasizes value creation through data-driven services and customer interaction. The integration between these domains remains insufficiently conceptualized, particularly regarding the interaction between production and digital service layers. This relationship is conceptually illustrated in Figure 1, which presents the positioning of Industry 5.0, Service 5.0, and Logistics 5.0 within the 5.0 ecosystem. This gap directly affects the ability to evaluate system-level efficiency, resilience, and sustainability outcomes.

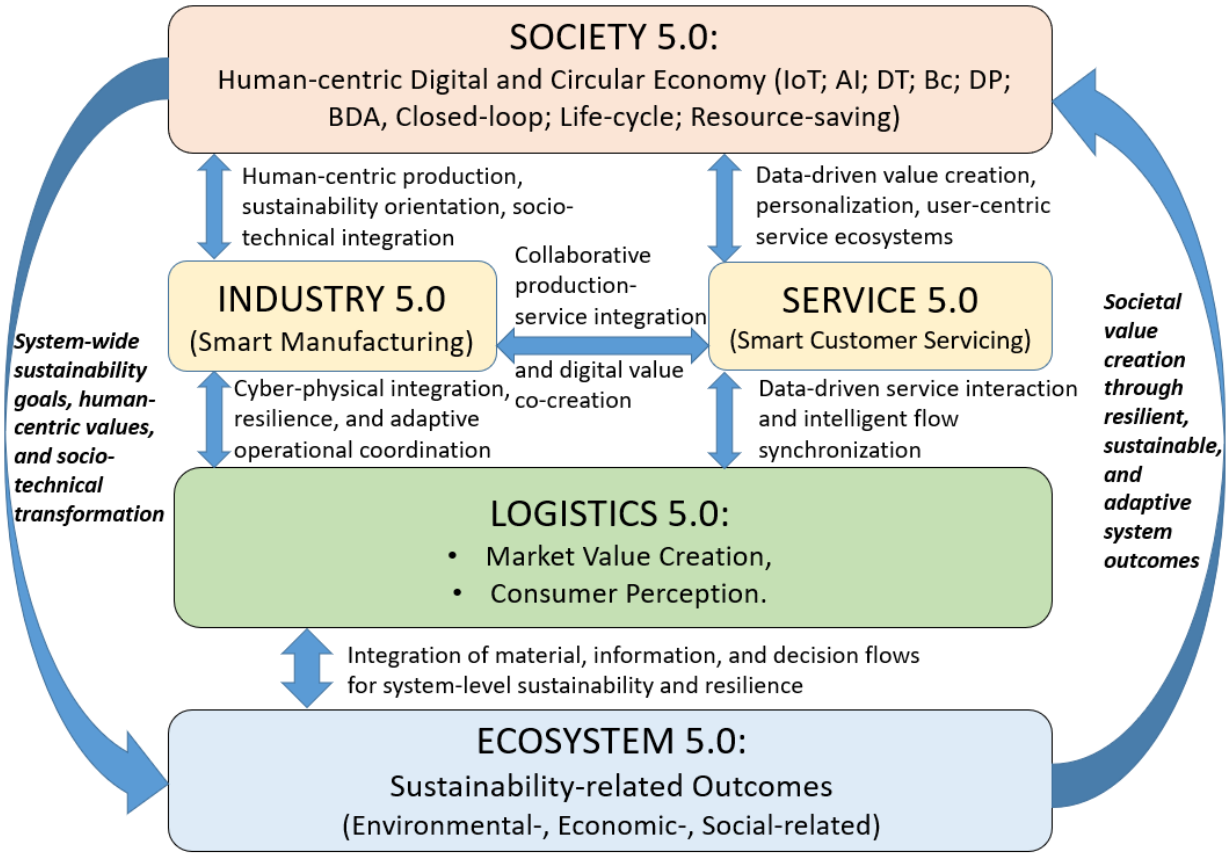

Figure 1. Conceptual positioning of Industry 5.0, Service 5.0, and Logistics 5.0 within the 5.0 ecosystem. The figure illustrates the directional interactions and coordination mechanisms between Society 5.0, Industry 5.0, Service 5.0, and Logistics 5.0 within the broader 5.0 ecosystem. The arrows represent the transfer of socio-technical principles, digital capabilities, and operational coordination functions contributing to system-level sustainability and resilience outcomes. Source: Own contribution based on [2,26,39,40].

Figure 1 illustrates the multi-level structure of the 5.0 ecosystem. In this context, logistics plays a critical role as the operational interface between Industry 5.0 and Service 5.0. Logistics acts as the operational interface between Industry 5.0 and Service 5.0 by coordinating material and information flows across interconnected systems. This limitation supports

the need for an integrated Logistics 5.0 perspective focused on system-level coordination and performance.

From the perspective of logistics systems, the transition toward the 5.0 ecosystem implies a fundamental shift from isolated efficiency-oriented logistics operations toward integrated, human-centric, resilient, and sustainability-driven system coordination. In this context, the principles of Society 5.0 introduce the broader socio-technical and sustainability-oriented perspective, Industry 5.0 contributes collaborative and adaptive production logic, while Service 5.0 extends customer-oriented and data-driven value creation mechanisms. Logistics 5.0 emerges at the intersection of these paradigms by integrating material, information, and decision flows across interconnected production and service ecosystems. Consequently, Logistics 5.0 should not be interpreted merely as a technologically advanced version of Logistics 4.0, but rather as a system-level coordination paradigm in which operational performance depends on the interaction between digital readiness, functional system capabilities, and sustainability-oriented outcomes.

2.3. Logistics 5.0 as an Integrative and System-Oriented Operational Paradigm

Building on the principles of Society 5.0, Industry 5.0, and Service 5.0, Logistics 5.0 represents the logistics-specific operational manifestation of the broader 5.0 ecosystem. Logistics 5.0 can be defined as a socio-technical logistics paradigm that extends Logistics 4.0 by shifting the focus from technology-enabled automation and efficiency optimization to system-level coordination, resilience, and sustainability-oriented performance emergence. While Logistics 4.0 primarily emphasizes cyber-physical integration and operational efficiency through digital technologies, Logistics 5.0 introduces a higher-order system logic in which logistics functions as an integrative coordination layer across production and service ecosystems, and where performance outcomes emerge from the interaction between structural readiness and functional system capabilities rather than from technology adoption alone [41,42]. In contrast to Logistics 4.0, which is predominantly technology-centric and efficiency-driven, Logistics 5.0 is characterized by a human-centric, resilience-oriented, and sustainability-driven system perspective in which digitalization acts as an enabler rather than a determinant of performance. This evolution aligns Logistics 5.0 with the broader Society 5.0 paradigm, in which socio-technical systems are designed to generate multi-dimensional societal value rather than isolated operational efficiency [25,43].

Logistics 5.0 is enabled by a set of interconnected digital technologies, such as AI, IoT, digital twins, and advanced communication infrastructures [44–46]. These technologies enhance operational visibility and adaptive decision support [47,48], although their effects are often analyzed separately from broader system-level outcomes.

At the operational level, Logistics 5.0 coordinates material and information flows across interconnected production and service systems [31,34,49–51]. Despite this integrative role, logistics is still frequently treated as a supporting operational function rather than a system-level coordination layer.

Existing empirical research on Logistics 5.0 and sustainability remains highly heterogeneous in terms of methodology, sectoral focus, and performance evaluation criteria. Survey-based and maturity-oriented studies frequently report positive relationships between digitalization and sustainability performance, often assuming that higher technological readiness directly improves operational and environmental outcomes [9,52]. In contrast, simulation and optimization studies mainly demonstrate efficiency gains related to routing, automation, or resource utilization, while providing limited real-world validation of sustainability effects [43,46]. Case-specific applications, including healthcare logistics and reverse logistics, report context-dependent improvements in adaptability

or waste reduction, although their findings remain difficult to generalize across logistics systems [10,12].

The reported sustainability effects of Logistics 5.0 also vary across sectors and operational contexts. Studies on smart warehousing and intelligent transportation systems typically emphasize efficiency and automation benefits [3,43], whereas resilience-oriented supply chain research focuses primarily on disruption response and continuity [53,54]. Moreover, sustainability is measured inconsistently across studies, ranging from energy consumption and emissions to service efficiency or operational continuity. Geographic and economic contexts further contribute to this variability, as studies conducted in highly industrialized economies tend to emphasize decarbonization and advanced automation, while research in emerging economies more frequently highlights infrastructure limitations, interoperability challenges, and implementation barriers [4,8,54].

Although recent studies increasingly associate Logistics 5.0 with resilience and sustainability improvements [3,11,53,54], the reported effects remain fragmented and difficult to compare due to differences in methodologies, system boundaries, and sustainability metrics [8]. Table 2 synthesizes the main sources of inconsistency identified in the current Logistics 5.0 literature.

Table 2. Sources of inconsistency in empirical Logistics 5.0 sustainability studies.

Dimension	Typical Findings in the Literature	Main Inconsistency/Problem	Implication
Methodology	Conceptual and optimization-oriented studies frequently report positive relationships between digitalization, efficiency, and sustainability [4,25,43,44,46], while case-based studies emphasize context-dependent outcomes [10,12,51]	Different methodological approaches produce non-comparable findings and use different validation logics	Limited comparability and weak cumulative empirical evidence
Sector	Sustainability effects differ across logistics domains, including transportation [49], reverse logistics [10], healthcare logistics [12], and manufacturing systems [51]	Strong dependence on operational context and sector-specific constraints	Low generalizability of reported sustainability benefits
Geography and implementation context	Studies emphasize different priorities depending on regional and infrastructural conditions, ranging from smart automation and connectivity [4,45] to sustainability-oriented supply chain transformation [11,54]	Technological readiness, infrastructure maturity, and regulatory environments differ substantially across contexts	Uneven assumptions regarding Logistics 5.0 maturity and implementation feasibility
Performance metrics	Sustainability is evaluated using heterogeneous indicators, including efficiency, emissions reduction, resilience, responsiveness, and service quality [3,53–55]	Lack of unified and multi-dimensional sustainability evaluation criteria	Fragmented and difficult-to-compare empirical evidence
Maturity assumptions	Maturity and implementation studies often associate higher digitalization levels with improved sustainability and competitiveness [9,52,56]	Digital readiness is frequently treated as a proxy for system performance, leading to compensatory bias	Risk of overestimating sustainability gains without evaluating functional system capabilities

These inconsistencies are also reflected in the dominant analytical orientations adopted in Logistics 5.0 research. The identified inconsistencies indicate that the fragmented nature of current Logistics 5.0 research is not solely the result of differing technologies or application domains, but also stems from the absence of integrated evaluation frameworks capable

of distinguishing between structural readiness, functional system capabilities, and sustainability outcomes. Moreover, most existing studies do not explicitly distinguish causal relationships between technological readiness, operational capabilities, and sustainability performance. Consequently, existing studies frequently conflate digital maturity with operational performance, while overlooking the mediating role of resilience, adaptability, and system behavior.

To further clarify the analytical orientation of existing Logistics 5.0 research, Table 3 summarizes the dominant research streams and their primary system-level limitations. It synthesizes the dominant research streams in Logistics 5.0, highlighting their primary focus areas and key limitations. The overview reveals a strong emphasis on technological and domain-specific perspectives, with limited integration across structural readiness, system capabilities, and sustainability performance. Most studies focus either on enabling technologies [4,44], specific applications such as reverse logistics [10] or sectoral implementations [12], or maturity assessment frameworks emphasizing structural dimensions [9]. As a result, the mechanisms linking technological readiness to system-level performance remain underexplored.

Table 3. Main research streams in Logistics 5.0 literature and their analytical limitations.

Research Stream	Analytical Focus	Level of Analysis	Link to Sustainability	Key Limitation	Representative Studies
Enabling technologies	AI, IoT, digital twins, connectivity	Micro/technological	Indirect—sustainability assumed through efficiency gains (e.g., energy optimization, routing) but rarely measured explicitly	Lack of empirical validation of sustainability outcomes; focus on technological potential rather than system performance	[4,44,48]
Smart and intelligent logistics	Automation, optimization, real-time control	Micro–meso (operational systems)	Efficiency-oriented; sustainability treated as a secondary effect	Narrow performance perspective; neglect of social and systemic sustainability dimensions	[43,46]
Sustainable and green logistics	Emissions, circular economy, resource efficiency	Meso (supply chain/logistics networks)	Direct—environmental metrics explicitly analyzed	Fragmented metrics; weak integration with digitalization and system capabilities	[3,11]
Resilient supply chains	Risk management, adaptability, disruption response	Meso–macro (network/system level)	Partial—Sustainability addressed indirectly through continuity and risk mitigation	Lack of integration with digital maturity and limited quantification of sustainability impacts	[53–55]
Maturity and readiness models	Digital maturity, capability assessment	Organizational/structural	Implicit—sustainability included as a dimension or outcome, but rarely operationalized	Compensatory logic; overemphasis on structural readiness; lack of causal linkage to performance	[9,52]
Domain-specific applications	Sectoral implementations (e.g., healthcare, reverse logistics)	Micro–meso (case specific)	Context-dependent—sustainability addressed in specific use cases (e.g., waste reduction, service efficiency)	Limited generalizability; lack of system-level perspective	[10,12]
Logistics in Ecosystem 5.0	**Integrated system perspective (readiness–capabilities–performance)**	**Multi-level (macro–meso–micro)**	**Explicit and multi-dimensional—environmental, economic, and social sustainability treated as system-level performance outcomes**	**Addresses fragmentation through non-compensatory and systemic integration**	**This paper**

Existing Logistics 5.0 frameworks often rely on compensatory evaluation logic, where high digital maturity is assumed to offset weaknesses in resilience or sustainability dimensions [52,56]. Such approaches risk overestimating the benefits of digital transformation by neglecting the mediating role of functional system capabilities. As a result, current models often fail to distinguish between structural readiness, actual system behavior, and observable sustainability outcomes.

Building on Sections 2.1 and 2.2, Logistics 5.0 can therefore be interpreted as an integrative operational layer, linking production, service, and sustainability dimensions within the broader

5.0 ecosystem. The inconsistency of empirical findings suggests that sustainability outcomes cannot be directly inferred from technological readiness alone, but instead emerge from the interaction between structural conditions and functional system capabilities. This highlights the need for integrated and non-compensatory evaluation frameworks explicitly separating structural readiness, functional capabilities, and sustainability performance outcomes.

3. Conceptualizing Readiness, Capabilities, and Sustainability

To ensure conceptual clarity and avoid ambiguity, the key constructs used throughout this study are defined as follows:

- Structural readiness refers to the availability and maturity of technological, organizational, and human resources that enable the implementation and support of Logistics 5.0 systems.
- Functional capabilities denote the system's ability to operate effectively under dynamic conditions, including its capacity to ensure reliability, robustness, resilience, and adaptability in response to variability and disruptions.
- Sustainability performance represents the observable environmental, economic, and social outcomes of system operation, emerging from the interaction between structural conditions and functional system behavior.

3.1. Structural Readiness and Functional Capabilities

Building on the conceptual definitions introduced at the beginning of Section 3, this subsection elaborates the distinction between structural readiness and functional capabilities within Logistics 5.0 systems. The conceptualization of Logistics 5.0 requires a clear distinction between structural readiness and functional system capabilities, which are often conflated in existing literature but represent fundamentally different dimensions of system development. Structural readiness refers to the availability and maturity of technological, organizational, and human resources that enable digital transformation [9,42]. In Logistics 5.0, structural readiness includes digital infrastructure, data integration architectures, automation technologies, and organizational conditions supporting digital transformation [57]. Organizational readiness further includes governance structures, process integration, and human competencies supporting collaboration with intelligent systems [58].

Despite its importance, structural readiness represents only the potential for improved system performance rather than a guarantee of effective operation. The actual behavior of logistics systems under dynamic and uncertain conditions is determined by functional system capabilities, which define how the system responds to variability, disturbances, and changing operational requirements. These capabilities include reliability, robustness, resilience, and adaptability, which determine the system's ability to maintain performance, withstand disruptions, recover from disturbances, and adjust to changing operational conditions [51,58,59].

Structural readiness reflects system potential, whereas functional capabilities determine how this potential is translated into operational performance under real conditions [47,58]. The distinction between these dimensions is summarized in Table 4.

Distinguishing structural readiness from functional capabilities is critical for understanding the limitations of current Logistics 5.0 research. Many existing approaches implicitly assume that investments in digital infrastructure directly translate into improved system performance, overlooking the mediating role of system capabilities. In highly digitalized environments, insufficient resilience, robustness, or adaptability may increase system vulnerability despite high levels of technological readiness.

Table 4. Distinction between structural readiness and functional capabilities in Logistics 5.0. Source: Own contribution based on [9,47,58,59].

Dimension	Structural Readiness	Functional Capabilities
System role	System potential	System behavior
Analytical nature	Static/resource-based	Dynamic/performance-based
Key components	Digital infrastructure, organizational structures, human competencies	Reliability, robustness, resilience, adaptability
Functional role	Enables possible actions	Determines the actual system response
Relation to performance	Indirect	Direct
Typical assessment approach	Maturity models, readiness indices	Behavioral and performance assessment

3.2. Sustainability as System-Level Performance Outcome

System performance refers to operational behavior of Logistics 5.0 systems under dynamic conditions, including reliability, robustness, adaptability, and efficiency, whereas system-level performance outcomes represent environmental, economic, and social results emerging from system operation.

Sustainability in Logistics 5.0 should be understood as a system-level performance outcome rather than a direct result of technological advancement or structural readiness. Although the literature often reports positive relationships between digital transformation and sustainability, these relationships are frequently assumed rather than empirically validated, leading to oversimplified interpretations of digitalization effects [60,61].

Sustainability must be assessed through a multi-dimensional lens encompassing environmental, economic, and social performance. However, it cannot be directly inferred from technological readiness alone, as it depends on the interaction between structural conditions and functional system behavior [62,63].

This between readiness, capabilities, and sustainability is mediated, where structural readiness influences outcomes only through functional system capabilities. Readiness defines system potential, capabilities determine system behavior, and sustainability reflects system-level outcomes. This relationship is summarized in Table 5, which highlights the distinct roles of each element within Logistics 5.0 systems.

Table 5. Conceptual relationship between readiness, capabilities, and sustainability performance. Source: Own contribution based on: [9,52,58,59,62].

Element	System Role	Description	Relation to Sustainability
Structural readiness	Enabling layer defining system potential	Represents the availability and maturity of technological infrastructure, data integration, organizational structures, and human competencies required to support digital transformation	Indirect and conditional—creates the preconditions for sustainability but does not ensure its achievement; may also generate negative effects (e.g., increased energy use) if not properly utilized
Functional capabilities	Operational layer defining system behavior	Reflects the system's ability to operate under dynamic conditions through reliability, robustness, resilience, and adaptability, enabling response to disruptions and variability	Mediating and determining—translates structural potential into actual performance; the quality of capabilities determines whether sustainability goals are achieved
Sustainability performance	Outcome layer reflecting system-level results	Captures the observable environmental, economic, and social outcomes of logistics system operation, including emissions, resource efficiency, cost stability, safety, and inclusiveness	Direct and emergent—results from system interactions and cannot be directly inferred from readiness alone; depends on how capabilities shape system behavior

Consequently, improvements in digital maturity do not guarantee sustainability gains unless they are accompanied by appropriate system-level properties such as resilience,

robustness, and adaptability. In some cases, increased digital complexity may generate adverse effects, such as higher energy consumption or reduced system robustness.

This conceptualization challenges techno-centric assumptions in Logistics 5.0 by highlighting that digitalization does not directly translate into sustainability outcomes. Instead, sustainability emerges from the interaction between structural readiness and functional system capabilities, providing a foundation for integrated assessment frameworks.

3.3. The Compensation Problem in Maturity Models

A critical limitation of existing maturity and readiness models in Logistics 5.0 lies in their reliance on compensatory evaluation logic, which allows high performance in one dimension, typically digitalization, to offset deficiencies in others. Most models adopt linear aggregation approaches, where individual criteria are combined into a single maturity score. While this enables straightforward comparison and benchmarking, it also introduces significant distortions in the interpretation of system performance [6,59].

In particular, the dominance of technological indicators in maturity assessments leads to a systematic overestimation of the impact of digitalization. High levels of investment in digital infrastructure, automation, or data integration are often interpreted as indicators of overall system advancement, even when functional system capabilities such as resilience, robustness, or adaptability remain underdeveloped. As a result, systems may be classified as "mature" despite being vulnerable to disruptions, inefficient in resource utilization, or unable to sustain stable performance under dynamic conditions [6,64].

This issue is further reinforced by the limited integration of system-level validation mechanisms in existing models. Most maturity frameworks focus on the presence of enabling conditions rather than on the actual performance of logistics systems in real operational environments [9]. Consequently, there is a disconnect between assessed maturity levels and observable outcomes, particularly in terms of environmental and social sustainability. Empirical evidence linking digital maturity to measurable sustainability improvements remains fragmented and methodologically inconsistent, which undermines the reliability of maturity-based evaluations [65,66].

From a systemic perspective, the compensation problem reflects a fundamental misalignment between structural readiness and functional performance. By aggregating heterogeneous dimensions into a single index, existing approaches obscure the interdependencies between technological resources, system capabilities, and performance outcomes. This not only limits their diagnostic value but also creates a false perception of progress, where improvements in digitalization mask critical weaknesses in other areas. These limitations motivate the development of non-compensatory, threshold-based evaluation frameworks, which explicitly prevent trade-offs between critical system dimensions and are further elaborated in the proposed Logistics 5.0 framework in Section 7.

While these limitations are widely acknowledged, existing maturity models differ not only in their degree of compensatory behavior but also in their scope, modeling assumptions, and treatment of system-level dynamics. In particular, prior studies such as Machado and Rodriguez [59], Trstenjak et al. [52], and Hellweg et al. [67] emphasize digital readiness and technological adoption, whereas others (e.g., Nicoletti and Appolloni [11,68] or Wu et al. [69]) focus on sustainability or resilience in isolation, without providing an integrated system-level evaluation framework.

To provide a systematic and transparent benchmarking of these approaches, Table 6 presents a side-by-side comparative analysis of representative Logistics 5.0 and Industry 4.0/5.0 maturity models, explicitly highlighting differences in aggregation logic, treatment of sustainability, functional capabilities, and system validation approaches.

Table 6. Comparative analysis of existing Logistics/Industry 4.0/5.0 maturity models and the proposed non-compensatory framework.

Model/Approach	Scope	Aggregation Logic	Functional Capabilities (Resilience, Adaptability, etc.)	Sustainability Treatment	Causal Structure (Readiness–Capabilities–Performance)	System Perspective (Static vs. Dynamic)	Human-Centricity	Key Limitation	Gap Addressed by Proposed Framework
Logistics 5.0 maturity model [59]	Logistics 5.0 maturity assessment (digital transformation, readiness)	Weighted composite index (compensatory)	Not explicitly modeled; capabilities assumed implicit	Environmental focus, separate dimension	No causal linkage; aggregated dimensions	Static, score-based evaluation	Limited (indirect via organization)	Overestimation of maturity due to aggregation	Non-compensatory thresholds + causal layering
Logistics 5.0 DSS-based model [52]	Decision-support for Logistics 5.0 implementation	Partially compensatory multi-criteria DSS	Implicit; emerges via decision support functions	Weak integration; sustainability as criterion	No hierarchical structure	Semi-static	Limited (user as decision-maker)	Focus on tools, not system behavior	Explicit modeling of system capabilities
Digital supply chain maturity model [67]	Digital maturity in supply chains, focusing on IT integration and digital infrastructure	Compensatory scoring model	Not included; assumes that digital maturity translates into improved performance	Not central; sustainability largely omitted or indirectly assumed	No causal structure linking digitalization to performance outcomes	Static maturity levels	No explicit consideration of human-centricity	Overemphasis on digitalization as proxy for performance	Balances digitalization with resilience and sustainability
Industry 5.0 enabling technologies [44]	Enabling technologies supporting Logistics and Supply Chain 5.0	Not formalized; descriptive analysis without explicit aggregation mechanism	Not modeled; technology-centric	Implicit; sustainability as expected outcome of technology adoption	No causal modeling; assumes linear impact of technology on performance	Static (technology-focused)	Limited; human-centricity acknowledged conceptually but not operationalized	Assumes technology adoption leads directly to performance improvements	Introduces functional capability layer as mediator
Smart logistics roadmap [4]	Strategic roadmap for smart logistics transformation	Not formalized; roadmap-based qualitative prioritization	Partially addressed; includes agility and responsiveness	Weakly operationalized; sustainability included at strategic level only	No explicit causal structure; roadmap lacks hierarchical system logic	Partially dynamic	Limited; workforce adaptation mentioned but not structurally integrated	Lacks evaluation framework and operational metrics	Provides evaluation logic with thresholds and constraints
Industry 5.0 maturity review [7]	Review of maturity models across Industry 5.0 domains	Mostly compensatory; identifies widespread use of additive scoring approaches	Rarely included; highlights absence of functional capabilities in existing models	Fragmented; sustainability treated inconsistently across reviewed models	No unified causal structure across models	Static	Partial; recognizes human-centricity as a principle but not operationalized	Fragmentation and lack of integration across dimensions	Integrates dimensions into unified system model
Green Logistics 5.0 [11]	Sustainability-oriented logistics models	Not formalized; conceptual approach without aggregation structure	Not included; system capabilities not considered	Strong environmental focus	No causal structure linking sustainability to system capabilities	Static	Limited; minimal integration of workforce or human factors	Lack of system integration and capability perspective	Embeds sustainability as system-level outcome
Smart logistics & sustainability [3]	Integration of smart technologies and sustainability in logistics systems	Not formalized; descriptive/conceptual evaluation	Limited; some references to adaptability, but not structured as capabilities	Included; sustainability addressed, but without clear metrics or system linkage	No causal structure	Static	Limited; partial consideration of workforce adaptation	Weak operationalization of sustainability and capabilities	Introduces measurable and non-compensatory sustainability
Green Warehouse 5.0 [68]	Warehouse-level sustainability and digital transformation	Not formalized	Not included	Strong environmental focus (energy, emissions, efficiency), limited systemic integration	No	Static	Limited; focus on efficiency rather than human-centric design	Narrow scope (subsystem-level only)	Extends sustainability to system-level performance

Table 6. *Cont.*

Model/Approach	Scope	Aggregation Logic	Functional Capabilities (Resilience, Adaptability, etc.)	Sustainability Treatment	Causal Structure (Readiness–Capabilities–Performance)	System Perspective (Static vs. Dynamic)	Human-Centricity	Key Limitation	Gap Addressed by Proposed Framework
Industry 5.0/Supply Chain 5.0 review [41]	Conceptual evolution of Supply Chain 4.0–5.0, research agenda	Not applicable (review-based synthesis; no formal aggregation method)	Conceptual references to resilience and agility, but not operationalized or measured	Sustainability discussed at strategic level (triple bottom line)	No explicit causal structure; relationships discussed narratively	Static (conceptual synthesis)	Partial (recognition of human-centricity, not formalized)	Lack of operationalization and measurable framework	Provides structured operationalization and explicit evaluation logic
AI-enabled Supply Chain 5.0 [70]	AI-driven, digitalized, and decarbonized supply chains in Industry 5.0 context	Not formalized (technology-driven narrative approach)	Implicit (AI enabling adaptability and responsiveness, not formalized)	Strong emphasis on decarbonization and sustainability; limited integration with system behavior	No explicit causal linkage between readiness, capabilities, and performance	Semi-dynamic (scenario-oriented discussion)	Moderate (human-AI collaboration conceptualized)	Technology-centric bias; lack of systemic evaluation framework	Embeds AI within broader system capabilities and non-compensatory logic
Digital readiness and value creation [71]	Empirical analysis of digital readiness, operations, and firm performance	Compensatory (regression-based statistical modeling)	Not explicitly modeled (capabilities inferred indirectly)	Sustainability not central; focus on economic/value outcomes	Partial causal analysis (readiness–value)	Dynamic (empirical relationships)	Limited (organizational aspects included, not human-centric design)	Missing system-level integration and sustainability dimension	Introduces missing capability layer and sustainability as system outcome
Digital readiness maturity model [72]	Assessment of digital readiness in manufacturing systems	Compensatory (scoring and aggregation of readiness dimensions)	Not included	Not considered	No causal linkage	Static	No	Structural bias toward technology adoption	Extends toward capabilities and sustainability performance
Resilience assessment framework [69]	Quantitative resilience assessment in engineering systems	Not fully integrated (multi-dimensional without system-wide aggregation logic)	Yes (resilience explicitly modeled and quantified)	Not central (engineering focus)	Partial (resilience–performance linkage)	Dynamic (scenario/failure-based)	Limited (technical focus)	Narrow applicability; lacks integration with digitalization and sustainability	Embeds resilience within integrated Logistics 5.0 architecture
Maintenance maturity model [73]	Maintenance system maturity assessment in industrial context	Compensatory (multi-criteria scoring framework)	Partially included (reliability-related aspects)	Not explicitly addressed	No explicit causal structure	Static	No	Narrow functional scope; lacks broader system integration	Integrates maintenance capabilities into system-wide framework
Proposed framework (this study)	**Integrated, system-level evaluation of Logistics 5.0 combining structural, functional, and sustainability dimensions**	**Non-compensatory (threshold-based conjunctive logic with balance condition)**	**Explicit and operationalized (resilience, robustness, adaptability, reliability as system properties)**	**Non-substitutable (strong sustainability across environmental, economic, and social dimensions)**	**Yes (hierarchical and causal: readiness–capabilities–performance)**	**Dynamic system-oriented**	**Fully integrated across layers (human–machine interaction, workforce, socio-technical system)**	—	**Bridges all identified gaps within unified framework**

Unlike prior reviews, this comparison is conducted using a consistent set of evaluation criteria, enabling direct identification of methodological gaps across models.

The comparative analysis in Table 6 confirms that existing maturity models address selected aspects of Logistics 5.0, such as digitalization, sustainability, or resilience, in a fragmented and often compensatory manner. However, none of the reviewed approaches integrates structural readiness, functional capabilities, and sustainability performance within a unified, causally structured framework.

These limitations indicate a structural gap in current maturity models, which remain inconsistent with the systemic nature of Logistics 5.0. This necessitates a shift toward non-compensatory, multi-layer evaluation approaches.

Importantly, the comparative evidence presented in Table 6 demonstrates that even advanced Industry 4.0/5.0 and Logistics 5.0 maturity models continue to rely, either explicitly or implicitly, on compensatory logic. Moreover, the analysis reveals that existing approaches typically capture only partial system perspectives (e.g., structural readiness, sustainability, or resilience), without integrating them into a unified, causally structured evaluation model. This reinforces the need for a fundamentally different evaluative paradigm that moves beyond additive aggregation toward a structured, threshold-based system perspective.

This critique provides the conceptual foundation for the framework proposed in this study, which explicitly separates structural readiness, functional capabilities, and sustainability performance. It integrates them through a non-compensatory logic aligned with system-level behavior.

In contrast to prior models, the proposed framework introduces a multi-layer, non-compensatory architecture that captures both the structural and behavioral dimensions of Logistics 5.0 systems, thereby addressing the key methodological gaps identified in Table 6.

4. Review Methodology

4.1. Review Design and Systematic Review Protocol (PRISMA)

This study adopts a systematic literature review (SLR) approach conducted in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA 2020) guidelines [74,75]. The PRISMA framework ensures transparency, reproducibility, and methodological rigor throughout the identification, screening, and selection of relevant studies, thereby minimizing selection bias and enhancing the validity of the results.

The main objective of this review is to investigate the conceptual evolution and current state of Logistics 5.0, with particular emphasis on maturity, capability development, resilience, sustainability, and digital transformation in logistics and supply chain systems. The study focuses on identifying how emerging paradigms such as smart logistics, digital logistics, and intelligent supply chains integrate human-centric principles, environmental sustainability, and advanced technologies within operational and strategic logistics frameworks.

Unlike domain-specific reviews, this study adopts a cross-sectoral perspective, including research from logistics, supply chain management, manufacturing systems, and industrial engineering, provided that it contributes to the conceptual understanding of Logistics 5.0 and its associated dimensions.

A structured review protocol was developed to guide the process in five main stages and was designed according to the principles given in [76–79]. These stages are illustrated in Figure 2, which presents the overall methodological framework used in this review:

- Definition of research objectives and scope—establishing the conceptual boundaries of Logistics 5.0 and defining the key analytical dimensions (maturity, resilience, sustainability, digitalization).

- Search strategy development—constructing a multi-term query reflecting the interdisciplinary nature of Logistics 5.0 and selecting the advanced academic discovery search engine Primo VE [80].
- Screening and eligibility assessment—applying inclusion and exclusion criteria at multiple levels (e.g., duplicate removal, full text availability) and performing title/abstract and full-text screenings.
- Snowballing procedure—expanding the dataset through backward and forward citation tracking.
- Data analysis and synthesis—integrating bibliometric mapping, network analysis, and content-based thematic classification.

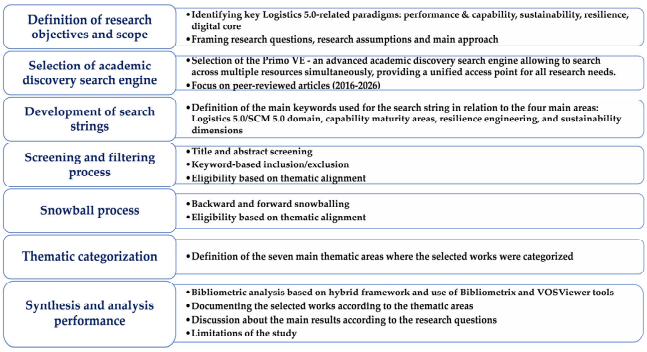

Figure 2. Research framework and methods/tools used for the systematic literature review conducted in this study, presenting the sequential stages of the review process and the associated tasks performed at each stage. Source: own contribution.

The overall methodological workflow is illustrated in Figure 2, while the PRISMA flow diagram summarizing the selection process is presented in Figure 3. The PRISMA checklist is given in Table S1 in the Supplementary Materials.

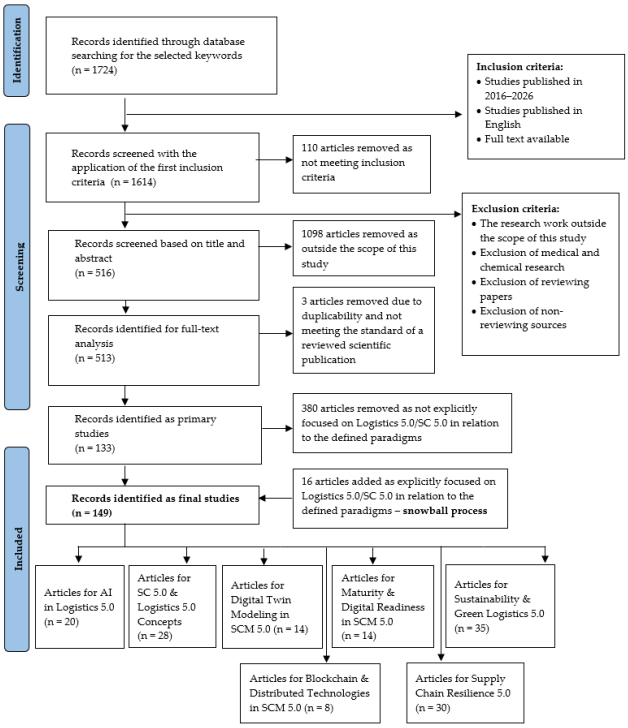

Figure 3. PRISMA-based flowchart of systematically selecting relevant studies in the analyzed research area, illustrating the full screening process across all review stages and the final allocation of selected publications into seven thematic categories. Source: own contribution based on [74].

Additionally, to ensure full transparency and reproducibility of the search process, a detailed description of the literature search strategy, including the complete Boolean query, stepwise query combination, filtering procedures, and corresponding numbers of retrieved records at each stage, is provided in Appendix A. These Supplementary Materials complement the PRISMA flow diagram by explicitly documenting the operational structure of the search process, which cannot be fully captured within the graphical PRISMA representation. In particular, Appendix A provides the exact search strings applied in the Primo Discovery System, together with a stepwise breakdown of query expansion and data reduction, thereby enhancing methodological rigor and enabling replication of the review process.

4.2. Identification—Data Sources and Search Strategy

The identification phase aimed to retrieve a comprehensive dataset of publications related to Logistics 5.0 and its associated conceptual dimensions, including supply chain digitalization, sustainability, resilience, and operational maturity.

The literature search was conducted using the ProQuest Primo Discovery System (Ex Libris), which functions as an integrated discovery platform aggregating records from multiple academic databases and publishers, rather than a single bibliographic database. The choice of the ProQuest Primo Discovery System was motivated by its ability to provide unified access to a broad range of multi-disciplinary databases (including, but not limited to, Scopus-indexed and Web of Science-indexed sources) through a single interface. This approach ensured a high level of coverage while enabling consistent query execution and result management across sources. Compared to conducting separate searches in multiple databases, the use of an integrated discovery system reduced the risk of inconsistencies in query syntax and filtering procedures. To further enhance robustness, a validation check was performed by manually verifying whether key seminal articles identified in prior reviews were retrieved through the applied search strategy. The searches were conducted during the period from 23 March 2026 to 6 April 2026.

The search process was carried out using a structured keyword strategy based on four thematic blocks:

- **Logistics 5.0 and system context**: “Logistics 5.0”, “supply chain 5.0”, “smart logistics”, “digital logistics”, “intelligent logistics”,
- **Capability and maturity dimension**: “maturity”, “capability”, “capabilities”, “performance”, “preparedness”,
- **Resilience and system robustness**: “readiness”, “resilience”, “robustness”, “adaptability”, “reliability”,
- **Sustainability dimension**: “sustainability”, “ESG”, “green”, “sustainable”, “circular economy”, “eco-friendly”.

The structured keyword strategy was developed through an iterative, literature-driven process. Initially, a scoping review of highly cited and seminal publications in Logistics 5.0, supply chain digitalization, resilience, and sustainability was conducted to identify recurring terminology and conceptual clusters (e.g., [3,4,8,11]). Based on this analysis, keywords were grouped into four thematic blocks reflecting the dominant analytical dimensions in the literature: technological system context, capability and maturity, resilience, and sustainability. The keyword structure was further refined through iterative pilot searches, where search results were evaluated for relevance and coverage of key seminal works. This process allowed for the adjustment of synonymous terms and the expansion of conceptually equivalent expressions to reduce terminology bias. The final keyword set was validated by ensuring that all previously identified seminal articles in the field were successfully retrieved through the applied search strategy. This procedure minimized subjectivity by

grounding keyword selection in established literature patterns and the recurrence frequency of key concepts.

The keyword groups were combined using Boolean AND and OR operators to ensure conceptual coherence across technological, operational, and sustainability perspectives. This initial phase ensured that the final query captured the diversity of terminologies used across academic communities.

To mitigate potential terminology bias associated with the explicit use of the term "Logistics 5.0", the search strategy was deliberately designed as concept-driven rather than label-driven. Therefore, the query structure included broader conceptual equivalents such as smart logistics, digital logistics, and intelligent logistics, as well as capability-, resilience-, and sustainability-related terms. In addition, backward and forward snowballing were applied to capture relevant studies that do not explicitly use the "5.0" terminology but address the same underlying system concepts.

The initial search returned 1724 records. Subsequent filtering and refinement steps were applied:

- Publication date restriction (2016–2026): 1656 records retained,
- English-language filter: 1614 records retained,
- Exclusion of medical and unrelated domains: 1397 records retained,
- Limitation to peer-reviewed journal publications: 516 records retained.

Following metadata screening and relevance assessment, 133 studies were selected for full-text review. Additional studies identified through backward and forward snowballing contributed 16 further publications, resulting in a final dataset of 149 articles included in the analysis.

4.3. Screening—Eligibility Criteria

The screening process was conducted in two stages: (i) preliminary filtering based on bibliographic metadata and (ii) thematic relevance assessment based on content analysis.

In the first stage, studies were excluded if they did not meet the following criteria: non-English language publications, non-peer-reviewed sources, conference proceedings, book chapters, and editorial materials. The exclusion of conference proceedings reflects a deliberate methodological choice aimed at ensuring consistency, comparability, and methodological rigor of the reviewed corpus. Conference papers in rapidly evolving domains such as Logistics 5.0 often represent preliminary findings, typically characterized by limited methodological detail, shorter formats, and reduced peer-review depth compared to journal publications. As a result, their inclusion may introduce heterogeneity and reduce the reliability of cross-study comparisons within a systematic review framework.

At the same time, it is acknowledged that in emerging research areas, including Industry 5.0 and smart logistics, conference venues frequently serve as early dissemination channels for novel concepts and technological developments. To mitigate the potential exclusion of relevant emerging contributions, a structured snowballing procedure was applied (Section 4.5), enabling the identification and inclusion of influential studies indirectly referenced in high-quality journal publications.

Consequently, this approach represents a trade-off between temporal coverage and analytical robustness, prioritizing conceptual maturity and methodological transparency while maintaining awareness of potential bias toward more consolidated research streams. Additionally, publications outside the scope of logistics, supply chain management, and industrial engineering were removed. Subject area filters were also employed to discard articles focused on medical, biological, or chemical applications. To increase transparency and facilitate replicability, the inclusion and exclusion criteria applied during the screening process are summarized in Table 7.

Table 7. Inclusion and exclusion criteria used in the screening process.

Criterion Type	Inclusion Criteria	Exclusion Criteria
Language	Articles published in English	Non-English publications
Publication type	Peer-reviewed journal articles	Review papers, book chapters, editorials, conference papers, theses
Subject area	Logistics systems, supply chains, manufacturing, and industrial systems	Medicine, biology, chemistry
Time period	Published between 2016 and 2026	Outside of this range
Topical relevance	Addresses Logistics 5.0/SCM 5.0 topics, sustainable/circular supply chains, maturity and capability modeling in logistics, resilient and robust supply chains, or smart technologies in logistics and supply chains	Articles that do not address any of the core concepts of resilience, predictive, or sustainable maintenance
Methodological quality	Presents original research with clear objectives, rigorous methodology, and contributions to theory or practice	Lacks methodological rigor or conceptual relevance
Full-text availability	Full-text available and accessible	Abstract-only or inaccessible full texts

In the second stage, a detailed content-based screening was performed. Articles were included only if they addressed at least one of the following thematic areas:

- Logistics 5.0, smart logistics, or digital supply chain systems,
- Maturity models, capability frameworks, or performance assessment in logistics systems,
- Resilience, robustness, adaptability, or operational reliability in logistics networks,
- Sustainability, circular economy, ESG integration, or green logistics approaches,
- Application of advanced technologies such as artificial intelligence, digital twins, IoT, or cyber-physical systems in logistics contexts.

This structured filtering ensured that the final dataset maintained both conceptual relevance and methodological consistency. The process was guided by a protocol aimed at maximizing both precision (removal of non-relevant articles) and recall (preservation of diverse but related studies).

4.4. Inclusion—Full-Text Review and Selection

A full-text review was conducted for the 133 initially selected studies. Each publication was evaluated in terms of methodological quality, conceptual contribution, and relevance to the research objectives.

Studies were included if they provided one or more of the following contributions:

- Development of conceptual frameworks for Logistics 5.0,
- Empirical analysis of digital, sustainable, or resilient logistics systems,
- Maturity or capability modeling approaches,
- Integration of human-centric or sustainability-oriented principles in logistics systems.

The evaluation was performed by two independent reviewers with expertise in the fields of Logistics 5.0/SCM 5.0 domain and resilience/sustainability areas. A collaborative spreadsheet was used to track decisions and notes, and any discrepancies were resolved through dialogue and reference to the study's relevance criteria.

This multi-stage inclusion process ensured a rigorous and transparent selection of high-quality sources that formed the foundation for the subsequent synthesis and discussion. Additionally, inter-rater reliability was assessed using Cohen's kappa coefficient [81] based on the independent screening decisions of two reviewers. The analysis indicated a moderate level of agreement between reviewers ($\kappa \approx 0.43$), despite a high observed agreement of 93.96%. This discrepancy reflects the known sensitivity of Cohen's kappa to highly imbalanced inclusion–exclusion distributions, where a predominance of exclusion decisions may substantially reduce κ values despite high observed agreement.

Beyond statistical effects related to prevalence imbalance, the observed disagreements primarily originated from differences in the interpretation of borderline studies, particularly those combining conceptual and empirical elements. In several cases, discrepancies arose from differing assessments of whether studies sufficiently addressed Logistics 5.0-specific constructs (e.g., functional capabilities or system-level sustainability outcomes) versus broader Industry 4.0/5.0 discussions. This indicates that inter-reviewer variability was mainly conceptual rather than procedural, reflecting the inherent ambiguity of inclusion criteria in emerging research domains rather than inconsistencies in the review protocol itself. All disagreements identified during the screening process were jointly discussed by both reviewers and re-evaluated against the predefined inclusion and exclusion criteria until consensus was achieved. Cohen's kappa coefficient was calculated prior to the consensus procedure and was not recomputed afterward, as the post-discussion phase reflects reconciled rather than independent reviewer judgments.

This approach enhanced transparency and methodological rigor, although a certain degree of subjectivity in eligibility assessment cannot be entirely excluded.

4.5. Snowballing Procedure

To ensure completeness of the dataset, a snowballing strategy was applied following the methodology proposed in the systematic review guidelines [82]. Backward snowballing involved screening reference lists of all included publications to identify additional relevant studies. Forward snowballing was conducted using citation tracking tools to identify newer studies citing the selected core articles (based on the Web of Science database).

This iterative process enabled the inclusion of additional high-relevance publications that were not captured in the initial database query, particularly emerging studies addressing Logistics 5.0, resilience-driven logistics systems, and sustainability-oriented supply chain transformation.

As a result, 16 additional studies were incorporated into the final dataset.

4.6. Bibliometric and Content Analysis

This stage corresponds to the last steps of the systematic literature review (SLR) process and focuses on the documentation, analysis, and synthesis of the selected literature.

Following PRISMA-based selection, a hybrid analytical approach was adopted, combining bibliometric analysis, network mapping, and qualitative synthesis.

The main bibliometric analysis was performed using the Bibliometrix tool [83], enabling statistical evaluation of publication trends, authors' productivity, and thematic structures. In particular, Bibliometrix was used to generate:

- Descriptive indicators (annual scientific production, sources, authorship patterns),
- Thematic maps based on keyword co-occurrence (Keywords Plus),
- Author and source collaboration networks,
- Preliminary clustering structures used for further validation.

Due to the heterogeneous origin of the dataset (Primo Discovery System and Mendeley exports), certain bibliographic fields (e.g., citation counts, author keywords) were incomplete. Consequently, citation-based indicators were excluded from the analysis, and the focus was placed on co-occurrence structures derived from Keywords Plus and abstract-level data. This limitation was explicitly addressed by complementing the analysis with external network visualization tools.

To enhance the robustness of thematic structure identification, network visualization and clustering were further conducted using VOSviewer (v. 1.6.18) [84], which enables the construction and visualization of bibliometric networks, particularly focusing on co-

authorship, keyword co-occurrence, citation relationships, and country-level collaboration [85]. This tool was used to perform:

- Co-word analysis based on term co-occurrence,
- Density visualization of research themes,
- Identification of dominant research clusters,
- Manual cluster labeling based on the semantic interpretation of the most frequent and central terms within each cluster.

To assess the quality and internal consistency of the identified clusters, validation metrics were applied. Specifically, modularity (Q) was used to evaluate the strength of division of the network into clusters, while the silhouette coefficient was calculated to assess the cohesion and separation of clusters. These metrics were derived from the clustering output obtained via Bibliometrix and interpreted in line with standard thresholds used in bibliometric network analysis. In general, modularity values above 0.3 were interpreted as indicating a significant clustering structure, while silhouette values closer to 1 suggest well-separated and internally coherent clusters, whereas values close to 0 indicate weak cluster separation.

The integrated analytical framework included the following components:

- Descriptive bibliometric indicators (publication trends, authorship patterns),
- Network-based analysis (keyword co-occurrence and clustering structures),
- Cluster validation metrics (modularity and silhouette coefficient),
- Visual mapping and density analysis (VOSviewer),
- Qualitative thematic synthesis based on cluster interpretation.

The selected corpus was systematically organized and coded to support content-based analysis, focusing on the evolution of Logistics 5.0 across dimensions of maturity, resilience, sustainability, and technological integration. The coding process enabled the identification of dominant research streams and conceptual relationships through iterative categorization and comparison of thematic patterns across the dataset. The management process was performed with the use of Mendeley reference management software [86], which facilitated both qualitative review and traceability.

In addition, the exclusion of conference proceedings may limit the representation of the most recent developments in this rapidly evolving field, although this effect was partially mitigated through the applied snowballing strategy.

Finally, the study acknowledges limitations, including data incompleteness in bibliometric fields and the reliance on hybrid analytical tools, which were mitigated through methodological triangulation (Bibliometrix–VOSviewer–content analysis), enhancing the robustness and reliability of the findings.

5. Results of the Conducted Literature Review Studies

This section presents the results of the systematic literature review conducted according to the defined research methodology (Figure 2). The findings are structured into two main components: (i) bibliometric analysis and (ii) content-based analysis. The bibliographic dataset and classification of the analyzed publications are provided in Supplementary Table S2.

5.1. Bibliometric Analysis Results

This section presents the quantitative and network-based characteristics of the selected literature, providing an overview of the scientific landscape in the field of Logistics 5.0 and its associated dimensions, including digital transformation, resilience, and sustainability.

The bibliometric analysis was performed on a consolidated dataset of 149 unique publications, including studies identified through the snowballing procedure, covering the period 2016–2026. A hybrid analytical approach was applied, combining Bibliometrix and VOSviewer tools. In particular:

- Bibliometrix was used for descriptive statistics, thematic mapping, and collaboration analysis,
- VOSviewer supported co-word clustering, density visualization, and cluster identification.

5.1.1. General Bibliometric Characteristics Based on Bibliometrix Tool Use

The dataset includes 149 publications from 93 sources, reflecting the interdisciplinary nature of Logistics 5.0 research. The field demonstrates a high annual growth rate of 63.32%, indicating rapid development and increasing academic interest. This growth rate was calculated as a compound annual growth rate (CAGR) over the period 2019–2025. However, it should be interpreted with caution, as the initial years of the analyzed period are characterized by very low publication counts (1–2 publications per year), which may artificially inflate the growth rate and reflect the emerging nature of the field rather than a stable long-term trend.

Based on keyword analysis and content screening, the identified publications were grouped into the following major thematic areas (in descending order):

- Sustainability and green Logistics 5.0—35 papers,
- Supply chain resilience 5.0—30 papers,
- Supply Chain 5.0 and Logistics 5.0 concepts—28 papers,
- AI in Logistics 5.0—20 papers,
- Digital twin modeling in SCM 5.0—14 papers,
- Maturity and digital readiness in SCM 5.0—14 papers,
- Blockchain and distributed technologies in SCM 5.0—8 papers.

Each publication was assigned to one dominant thematic category to ensure a mutually exclusive classification. The assignment was based on the primary research focus of the study, as identified through the title, abstract, and keyword analysis.

This classification highlights that sustainability and resilience constitute the dominant research streams, followed by conceptual and technological developments (AI, digital twins, blockchain). This approach ensures consistency and interpretability of the thematic distribution while maintaining methodological transparency.

In cases where publications addressed multiple thematic areas (e.g., sustainability and resilience, or digitalization and AI), a dominant theme was determined based on the central contribution of the paper. Borderline cases were discussed between two reviewers and resolved through consensus, in line with the inclusion procedure described in Section 4.4.

The temporal distribution of publications reveals a strong upward trend, particularly after 2023. While only single publications were recorded in 2019 and 2020, the number increased significantly to 71 publications in 2025, followed by 31 publications in early 2026. This confirms that Logistics 5.0 is an emerging and rapidly expanding research domain, still in an early stage of scientific consolidation. Figure 4 illustrates the distribution of publications according to their publication year.

The average document age (1.36 years) further supports this observation, indicating that the majority of studies are recent and reflect current research trends.

Due to limitations in the dataset (absence of citation metadata), citation-based indicators could not be evaluated. However, this does not affect the identification of thematic structures and research trends, which are primarily based on keyword co-occurrence and content analysis.

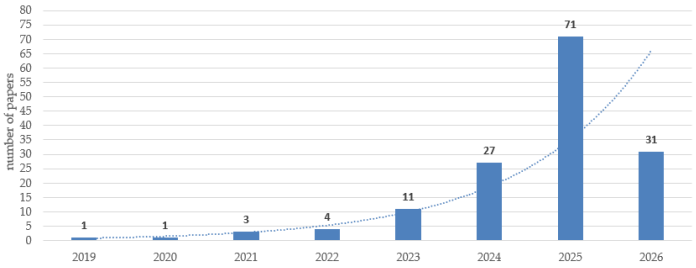

Figure 4. Distribution of publications by year.

The analyzed dataset includes 459 authors, with a total of 523 author appearances, indicating a relatively dispersed authorship structure. The average number of documents per author (0.325) suggests that the field is still fragmented, with limited concentration of contributions among leading researchers.

The collaboration structure shows that:

- The average number of co-authors per document is 3.51,
- Only 12 publications are single-authored.

This indicates that Logistics 5.0 research is predominantly collaborative, reflecting its interdisciplinary nature. However, international collaboration was not observed in the dataset, which may result from incomplete metadata or limitations of the data source.

The most productive authors include Hamani N., Nayeri S., Sazvar Z., and Appolloni A., each contributing between 3 and 4 publications. However, no dominant leading author or research group can be identified, which is typical for emerging research domains.

The analysis of author productivity over time indicates that research activity is concentrated in recent years, particularly between 2023 and 2026. Authors such as Ivanov D., Hamani N., and Nayeri S. demonstrate continuous contributions, suggesting emerging research leadership in specific thematic areas (e.g., resilience and supply chain transformation). However, the absence of long-term publication trajectories confirms that the field is still in an early development phase, without fully established research schools.

To confirm the above-presented analysis results, Figure 5 presents the evolution of author productivity over time, while Figure 6 illustrates the author collaboration network.

The publications are distributed across a wide range of journals and conference proceedings, confirming the multi-disciplinary character of the field. The most relevant sources include: IFAC-PapersOnLine (8 publications), Procedia Computer Science (4 publications), as well as Advanced Engineering Informatics (3 publications), or Computers and Industrial Engineering (3 publications). The most relevant sources are presented in Figure 7 (for sources that occur at least two times in the analyzed dataset).

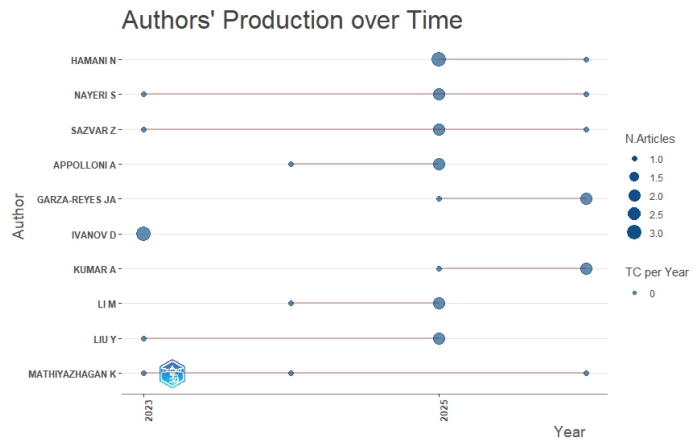

Figure 5. Authors' production over time. Source: Own contribution based on Bibliometrix tool use.

Figure 6. The authors' collaboration network for the analyzed dataset (for the top 100/70 authors). Source: Own contribution based on Bibliometrix tool use.

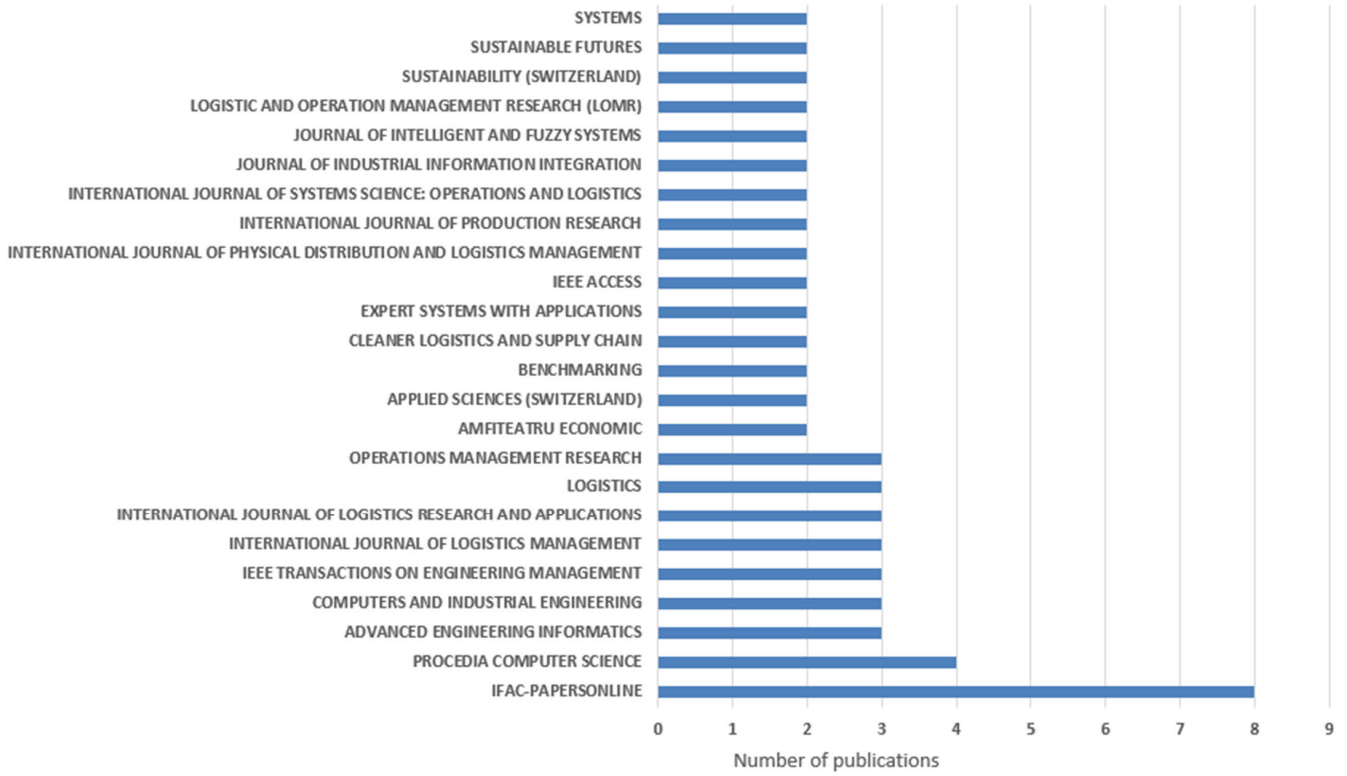

Figure 7. Most relevant sources in Logistics 5.0 research based on the number of publications. Source: Own contribution based on Bibliometrix tool use.

This distribution indicates that Logistics 5.0 research is positioned at the intersection of: engineering systems, operations management, digital technologies, and supply chain management.

Keyword analysis was conducted using Keywords Plus (ID) due to the absence of author keywords in the dataset. A total of 543 keywords were identified, forming the basis

for thematic mapping. The most frequently occurring keywords are presented in Table 8. To overcome the limitations of the prepared dataset, the extended analysis of keyword co-occurrence is presented in Section 5.2.2. with the use of the VOSViewer tool.

Table 8. Most relevant keywords based on the dataset analysis. Source: Own contribution based on Bibliometrix tool use.

No.	(Keywords-Plus ID)	Number of Publications
1	INDUSTRY 5.0	38
2	SUSTAINABILITY	26
3	INDUSTRY 4.0	21
4	SUPPLY CHAIN RESILIENCE	17
5	ARTIFICIAL INTELLIGENCE	15
6	RESILIENCE	13
7	CIRCULAR ECONOMY	12
8	DIGITAL TRANSFORMATION	11
9	SUPPLY CHAIN MANAGEMENT	11
10	DIGITALIZATION	10

The obtained results indicate that Logistics 5.0 research is strongly anchored in:

- The transition from Industry 4.0 to Industry 5.0,
- Sustainability and circular economy paradigms,
- Resilience and robustness of supply chains,
- The integration of artificial intelligence and digital technologies.

The thematic structure suggests that Logistics 5.0 research is evolving along three main trajectories:

1. Technological trajectory—focused on AI, digital twins, and blockchain,
2. System capability trajectory—addressing resilience, robustness, and adaptability,
3. Sustainability trajectory—emphasizing environmental and circular economy aspects.

These trajectories are increasingly converging, reflecting the shift toward integrated, human-centric, and sustainable logistics systems. Figure 8 presents the thematic map derived from keyword co-occurrence analysis.

To further assess the internal structure of the identified themes, clustering validation metrics were applied. The network analysis revealed a modularity value of Q = 0.75, indicating a well-defined clustering structure with a strong division between thematic groups. This suggests that the research field is composed of relatively distinct but internally coherent thematic areas.

At the same time, the average silhouette coefficient was 0.068, indicating low separation between clusters. This result reflects a high degree of thematic overlap, suggesting that research topics such as sustainability, resilience, and digital transformation are strongly interconnected rather than forming isolated domains.

This combination of high modularity and low silhouette value is characteristic of emerging interdisciplinary fields, where distinct research streams exist but remain conceptually interdependent and not yet fully consolidated.

Overall, the bibliometric results confirm that Logistics 5.0 is a rapidly evolving and structurally complex research domain, characterized by dynamic growth, high interdisciplinarity, and strong conceptual overlap between key themes.

The extended analysis of thematic structures and cluster relationships using VOSviewer is presented in the following subsection.

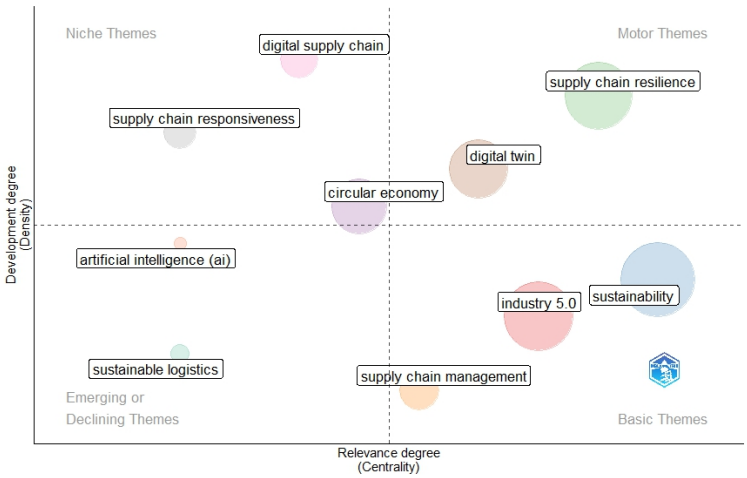

Figure 8. Thematic map based on keyword co-occurrence analysis. Source: Own contribution based on Bibliometrix tool use.

5.1.2. Clustering Analysis Based on VOSViewer Tool Use

The final stage of the bibliometric analysis focused on keyword co-occurrence mapping using VOSviewer, enabling the identification of the conceptual structure and thematic interdependencies within the Logistics 5.0 research domain.

In total, 442 unique keywords were identified across the analyzed publications, forming 42 initial clusters. These clusters were connected through 1640 co-occurrence links with a total link strength of 1763, indicating a dense and highly interconnected research landscape. However, to improve interpretability and focus on the most relevant themes, a threshold was applied to include only keywords occurring at least twice. As a result, 64 keywords were retained, forming 9 distinct clusters with 252 co-occurrence links and a total link strength of 375. Figure 9 presents the resulting co-occurrence network, illustrating the main thematic clusters and their interrelationships.

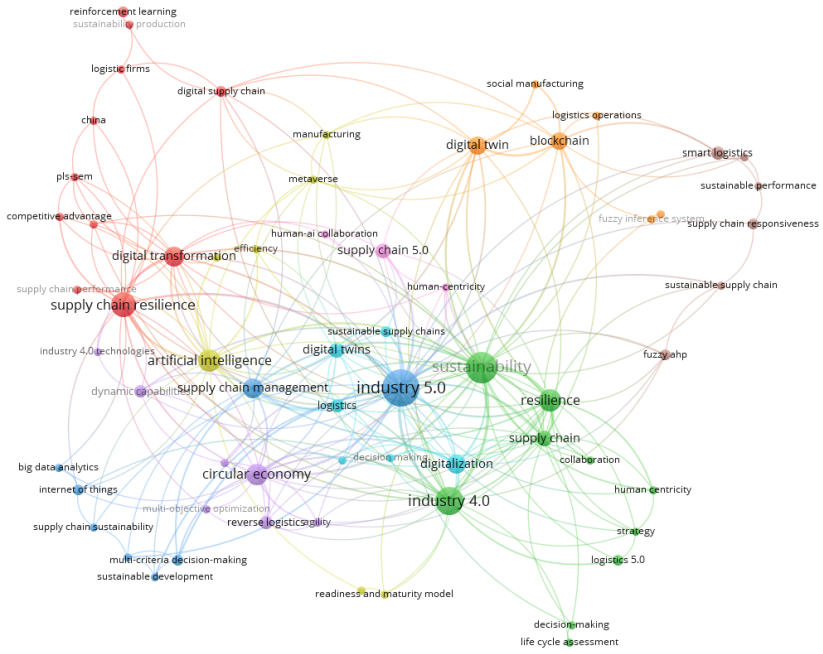

Figure 9. Mapping of the keywords that have occurred in the selected publications at least twice. Source: own development using VOSviewer software [84].

Cluster 1—Digital transformation and resilience (red, 11 items).

The largest cluster is centered around supply chain resilience, digital transformation, and digital supply chain, supported by related concepts such as digital maturity, competitive advantage, and logistics firms. The presence of methodological terms such as PLS-SEM and reinforcement learning further indicates the increasing use of advanced analytical approaches in this domain.

This cluster reflects a dominant research stream focused on the integration of digital transformation with resilience-oriented supply chain design, where digital capabilities are treated as enablers of adaptive and robust logistics systems. It also highlights the growing importance of linking technological advancement with performance outcomes such as competitiveness and operational stability.

Cluster 2—Sustainability and strategic supply chain management (green, 10 items).

The second-largest cluster is organized around sustainability, Industry 4.0, and supply chain, complemented by terms such as collaboration, decision-making, human-centricity, and life cycle assessment.

This cluster represents the strategic and sustainability-oriented perspective of Logistics 5.0, emphasizing environmental performance, decision-making processes, and the integration of human-centric principles. The co-occurrence of resilience within this cluster suggests a strong conceptual overlap between sustainability and robustness in supply chain systems.

Cluster 3—Industry 5.0 and system integration (blue, 8 items).

This cluster is anchored in Industry 5.0, supply chain management, and IoT, with additional elements such as big data analytics, multi-criteria decision making, renewable energy, and sustainable development.

It reflects the emerging paradigm shift from Industry 4.0 to Industry 5.0, where technological integration is extended toward sustainability, human-centricity, and system-level optimization. The inclusion of decision-support methods highlights the role of data-driven approaches in managing complex logistics systems.

Cluster 4—Artificial intelligence and operational efficiency (yellow, 7 items).

This cluster is centered around artificial intelligence and efficiency, with related concepts such as smart manufacturing, metaverse, and readiness and maturity modeling.

It represents a technology-driven research stream focused on AI-enabled optimization and system performance improvement, highlighting the role of intelligent systems in enhancing operational efficiency and supporting digital readiness assessment.

Cluster 5—Circular economy and dynamic capabilities (violet, 7 items).

Key terms in this cluster include circular economy, reverse logistics, agility, and dynamic capabilities, along with multi-objective optimization and Industry 4.0 technologies.

This cluster reflects the integration of circular economy principles with adaptive and capability-based approaches, emphasizing the need for flexible and responsive logistics systems capable of supporting sustainable resource flows.

Cluster 6—Digital twins and system modeling (light blue, 6 items).

This cluster includes digital twins, digitalization, logistics, and supply chain 4.0, supported by decision-making and sustainable supply chain.

It represents a modeling-oriented research stream, where digital twins are used as tools for simulation, monitoring, and decision support in complex logistics systems.

Cluster 7—Blockchain and emerging digital technologies (orange, 6 items).

The main keywords include blockchain, digital twin, logistics operations, and resource efficiency, complemented by fuzzy inference systems and social manufacturing.

This cluster highlights the role of distributed and emerging digital technologies in enhancing transparency, traceability, and efficiency within supply chains.

Cluster 8—Smart logistics and decision-support methods (brown, 6 items).

This cluster includes smart logistics, fuzzy AHP, supply chain responsiveness, and sustainable performance. It reflects a decision-support and optimization perspective, where multi-criteria methods and smart system concepts are applied to improve logistics performance under complex conditions.

Cluster 9—Human-centric Logistics 5.0 (magenta, 3 items).

The smallest cluster includes human–AI collaboration, human-centricity, and supply chain 5.0. Despite its limited size, this cluster is particularly significant as it captures the core conceptual shift toward human-centric Logistics 5.0, emphasizing the integration of human factors with advanced technologies.

The cluster structure reveals that Logistics 5.0 research is organized around several strongly interconnected thematic domains. Three overarching research directions can be identified (following the conclusions from Section 5.1.1):

- Technological domain—including AI, digital twins, blockchain, and IoT,
- System capability domain—focusing on resilience, agility, and dynamic capabilities,
- Sustainability domain—encompassing circular economy, environmental performance, and strategic supply chain management.

Importantly, the analysis demonstrates that these domains are not isolated, but rather form a highly interconnected conceptual network. The frequent co-occurrence of keywords such as sustainability, resilience, and digital transformation confirms that Logistics 5.0 is evolving toward an integrated, multi-dimensional paradigm.

At the same time, the relatively small size of the human-centric cluster suggests that, despite its conceptual importance, the human-centered perspective remains underdeveloped in current research. This observation highlights a critical research gap and justifies the need for more holistic frameworks that explicitly integrate technological, organizational, and human dimensions.

The results of the cluster analysis provide a structured foundation for the subsequent content-based analysis, where these thematic areas are examined in greater depth and linked to the development of the proposed conceptual framework.

5.2. Content-Based Analysis

This section presents a qualitative, content-based analysis of the 149 publications selected through the systematic literature review process. While the bibliometric analysis (Section 5.1) provided a quantitative and structural overview of the research field, this stage aims to deepen the understanding of the conceptual developments, research directions, and methodological approaches within Logistics 5.0.

Figure 10 presents the research landscape of Logistics 5.0 and the seven major thematic areas identified through keyword co-occurrence analysis, cluster identification, and full-text screening. The classification reflects the multi-dimensional nature of Logistics 5.0, encompassing technological, organizational, resilience-oriented, and sustainability-related perspectives. The following subsections synthesize the key research directions, methodological approaches, and emerging trends within each thematic domain.

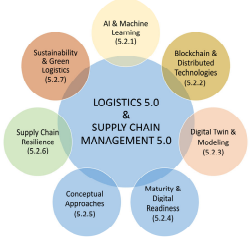

Figure 10. Mapping of Logistics 5.0 research domains across key system dimensions. Source: own contribution.

5.2.1. AI and Machine Learning in Logistics 5.0

The integration of Artificial Intelligence (AI) and Machine Learning (ML) constitutes one of the most dynamic and transformative research streams within Logistics 5.0. The analyzed body of 20 publications demonstrates that AI is not only a technological enabler but also a key driver of resilience, sustainability, and adaptive decision-making in logistics and supply chain systems.

A significant portion of the literature focuses on AI-driven optimization and decision support under uncertainty, particularly using advanced techniques such as reinforcement learning and multi-objective optimization. For instance, Almuwallad [87] proposes a deep reinforcement learning framework for resilient reverse logistics networks in electric vehicle battery supply chains, addressing disruption uncertainty and circular economy requirements. Similarly, Sethanan et al. [88] apply reinforcement learning to multi-period scheduling and fleet management, demonstrating improvements in operational efficiency and adaptability. Cai et al. [89] extend this approach to transportation systems, optimizing eco-driving strategies in smart logistics networks.

AI is also increasingly linked with digital supply chain transformation and performance enhancement. Empirical evidence provided by Dalain et al. [90] confirms the mediating role of AI in improving digital supply chain management performance. Wu et al. [53] further highlight that AI-driven transformation enhances both resilience and sustainability, positioning AI as a central component of Industry 5.0 supply chains. In a broader conceptual perspective, Azmat et al. [70] discuss AI-enabled, decarbonized supply chains as a foundation for future Logistics 5.0 systems.

The emergence of generative AI and foundation models introduces a new paradigm in logistics decision-making and system design. Hong et al. [91] identify a "new triad" of supply chain transformation, i.e., productivity, perspective, and power, driven by large-scale AI models such as generative AI systems. Similarly, Lin [92] proposes the UNISONE framework, integrating generative AI with predictive analytics for sustainable supply chain management.

Another major application area involves the integration of AI with digital twin technology and cyber-physical systems. Santos et al. [93] demonstrate how machine learning-enhanced digital twins can optimize industrial processes in Industry 5.0 environments. In a similar vein, İnanlar and Altay [94] explore AI-operated digital twins within metaverse environments, emphasizing their potential for improving sustainability, efficiency, and innovation in logistics-related processes.

AI is also widely applied in sustainable and circular logistics systems, particularly in reverse logistics and resource optimization. Mukherjee et al. [95] show how AI-based reverse logistics systems can enhance circular economy performance, especially in developing countries. Mohsen and Mohsen [96] investigate AI-driven energy optimization in urban logistics, while Kumar and Khedlekar [97] propose a hybrid AI–blockchain framework for sustainable supply chain optimization, integrating demand forecasting and supplier selection.

AI is further applied to resilience-oriented and adaptive supply chain design. Rezaei et al. [98] develop an AI-enabled operations research model for adaptive and resilient supply chains, while Suleiman Shlash Mohammad et al. [99] propose a predictive maintenance and cost-risk framework for improving logistics reliability in maritime systems. These studies highlight the role of AI in enhancing system robustness and recovery capabilities.

The literature also emphasizes human-centric AI and Industry 5.0 principles, reflecting the shift from purely automated systems toward human–AI collaboration. Yan et al. [100] provide a comprehensive perspective on human-centric AI, while Williamson and Prybutok [101] introduce a neuromorphic computing-based framework (NAToRM) that integrates sustainability and human-centric automation. Sevastyanov [102] further highlights the importance of adaptive AI models supporting economically sound decision-making.

Several studies address the strategic and systemic implications of AI adoption in logistics. Nicoletti and Appolloni [103] analyze the impact of AI foundation models on digital engineering in supply chains, while Kolos et al. [104] demonstrate how AI-driven automation improves both efficiency and resilience in production-logistics systems.

Overall, the literature indicates that AI and ML are evolving toward integrated, adaptive, and human-centric decision-support systems within Logistics 5.0 environments. The reviewed studies consistently position AI as a key enabler of resilience, sustainability, intelligent automation, and data-driven supply chain management.

5.2.2. Blockchain and Distributed Technologies in Logistics 5.0

Blockchain and distributed technologies represent an important technological pillar of Logistics 5.0, particularly in the context of transparency, trust, traceability, and decentralized coordination of supply chain processes. The analyzed set of eight publications demonstrates that blockchain is increasingly integrated with other Industry 5.0 technologies, contributing to enhanced sustainability, resilience, and operational efficiency.

The literature primarily associates blockchain technologies with transparency, traceability, and circular economy integration in supply chains [105–108]. Existing studies emphasize their role in improving data integrity, lifecycle tracking, stakeholder trust, and resource efficiency, particularly in complex multi-tier logistics networks. Blockchain is also increasingly linked with circular supply chain management through applications supporting resource tracking, waste reduction, and stakeholder coordination [107,108].

Another major research stream links blockchain adoption with resilience and sustainability performance. Wang et al. [109] provide empirical evidence from Chinese logistics firms, indicating that blockchain-enabled supply chains positively influence both resilience capabilities and sustainability outcomes. This finding confirms that blockchain is not only a data management tool but also a strategic enabler of adaptive and robust supply chain systems.

Blockchain is also applied in performance optimization and advanced analytics within Industry 5.0 environments. Tsang et al. [110] introduce the concept of blockchain sharding for e-commerce supply chains, demonstrating its potential to enhance scalability and performance analytics. In parallel, Wang et al. [111] discuss the integration of blockchain with IoT technologies, emphasizing its contribution to intelligent logistics systems through real-time data exchange and dynamic demand management.

Blockchain technologies are further explored in smart logistics and autonomous delivery systems integrated with drones and cyber-physical systems. Xiao and Gao [112] propose a resilient last-mile logistics framework based on drone–truck collaboration in smart cities, where distributed coordination mechanisms, conceptually aligned with blockchain principles, support time-dependent and multi-visit delivery optimization.

Across the reviewed studies, blockchain is rarely treated as a standalone solution and is typically integrated with AI, IoT, and digital platforms to support intelligent and decentralized logistics systems. Overall, the literature positions blockchain as an enabling infrastructure for transparent, resilient, and sustainability-oriented Logistics 5.0 ecosystems.

5.2.3. Digital Twin and Digital Modeling in SCM 5.0

Digital twin (DT) technology and advanced digital modeling approaches constitute a key enabler of Logistics 5.0 and Supply Chain Management (SCM) 5.0, supporting real-time monitoring, predictive analytics, and intelligent decision-making. The analyzed set of 14 publications demonstrates that digital twins are increasingly used to bridge the gap between physical logistics systems and their digital representations, enabling more resilient, sustainable, and human-centric supply chain operations.

A dominant research stream focuses on the role of digital twins in enhancing the resilience and sustainability of supply chains. Cimino et al. [113] propose a cyclic and holistic methodology for supply chain digital twins, emphasizing their capability to support adaptive and resilient decision-making. Similarly, Straube et al. [114] highlight that digital logistics twins enable the integration of sustainability and resilience objectives within manufacturing networks. Nie et al. [115] further demonstrate how digital twin-based models can optimize food supply chains by incorporating sustainability criteria into design and operational decisions. Elghomri and Messaoudi [116] underline that digital twins play a critical role in developing low-carbon supply chains, although they also identify a gap between academic research and industrial adoption.

Digital twins are also increasingly linked with Industry 5.0 principles, particularly human-centricity and circularity. Li et al. [117] introduce an operation twin-driven approach for human-centric replenishment and kitting synchronization, highlighting the role of digital twins in supporting customized and flexible production logistics. Tyagi and Tyagi [58] identify key readiness factors for implementing digital twins in sustainable supply chains, emphasizing their contribution to circular economy transitions. Alguirat et al. [118] further extend this perspective by integrating digital twins with lean management, proposing a conceptual framework for sustainable and efficient supply chains in Industry 5.0.

Several studies examine the integration of digital twins with IoT, blockchain, and cloud systems. Felice et al. [119] present an integrated IoT–digital twin framework for sustainable textile manufacturing, demonstrating how real-time data acquisition enhances system performance and sustainability outcomes. Latha and Mokkhamakkul [120] propose a cloud–twin synchronization model for Supply Chain 5.0, enabling continuous data exchange and system synchronization. Pu et al. [121] develop a cyber-physical integrated digital twin network model, supporting high-performance logistics operations in enterprise systems.

Another emerging direction concerns the combination of blockchain and digital twins for secure and synchronized logistics operations. Cuñat Negueroles et al. [122], Zhang et al. [123] and Zhang et al. [124] combine blockchain and digital twins to support secure, synchronized, and decentralized decision-making in logistics and manufacturing systems.

The literature also points toward the evolution of digital twins into immersive and next-generation digital environments, such as the metaverse. Dolgui and Ivanov [125] introduce the concept of metaverse supply chains, where digital twins act as core components enabling virtual representation, simulation, and coordination of logistics operations. This extends digital twins beyond monitoring functions toward integrated digital ecosystems.

Overall, the reviewed studies position digital twins as a foundational technology for Logistics 5.0, supporting predictive decision-making, system synchronization, and sustainability-oriented supply chain management. The literature particularly emphasizes their integration with IoT, blockchain, and cyber-physical systems, as well as their role in enabling adaptive and human-centric logistics operations.

5.2.4. Maturity and Digital Readiness Models in Logistics 5.0/SCM 5.0

Maturity and digital readiness models constitute a critical research stream within Logistics 5.0, providing structured approaches for assessing the preparedness of organizations to adopt advanced technologies, implement sustainable practices, and enhance system resilience. The analyzed set of 14 publications demonstrates that this research area is evolving from Industry 4.0-based assessment frameworks toward more integrated, human-centric, and sustainability-oriented models aligned with Industry 5.0 principles.

A significant portion of the literature focuses on readiness assessment frameworks for digital transformation in supply chains and logistics systems. Tripathi and Gupta [126]

evaluate the readiness of supply chain ecosystems for Industry 4.0 adoption, identifying key technological and organizational barriers. Similarly, Ebrahimi and Szmerekovsky [127] assess Industry 4.0 readiness in biomass supply chains, emphasizing the role of digital technologies in enabling sustainable energy systems. Beducci et al. [128] provide a sector-specific perspective by evaluating digital maturity in the dairy industry, demonstrating how readiness assessment can support targeted transformation strategies.

Another important research direction concerns the development of comprehensive maturity models integrating sustainability and smart supply chain capabilities. Demir et al. [129] propose a model for assessing the readiness and maturity of smart and sustainable supply chains, incorporating both technological and environmental dimensions. This approach is further extended by Gündüz et al. [130], who develop a roadmap integrating lean and smart tools with sustainability objectives, highlighting the need for structured transformation pathways.

The literature also emphasizes the role of organizational and human factors in digital readiness, particularly in the context of Logistics 5.0. Gupta et al. [131] introduce a readiness index framework focused on human resource development for logistics digitalization, underlining the importance of skills, competencies, and organizational culture. Mohammadian et al. [132] further explore readiness in SMEs, proposing a framework that integrates educational and capability-building components necessary for Industry 4.0 and 5.0 adoption. Marjerison et al. [71] complement this perspective by analyzing the relationship between digital readiness, operational factors, and value creation, showing that readiness directly influences firm performance and satisfaction.

Recent studies increasingly extend maturity models toward Industry 5.0 dimensions, including human-centricity, resilience, and sustainability. Himmiche et al. [133] propose a process-based Industry 5.0 maturity model for supply chains, emphasizing the integration of technological and human dimensions. Machado et al. [59] develop a Logistics 5.0 maturity measurement model based on an integrative literature review, highlighting the multi-dimensional nature of maturity, including digital, organizational, and sustainability aspects.

In addition, several studies focus on methodological advancements in maturity modeling, including the use of advanced analytical techniques. Bukowski and Werbinska-Wojciechowska [134] propose a multi-dimensional maintenance maturity model based on fuzzy logic, demonstrating how predictive modeling can support decision-making under uncertainty and ensure operational continuity. Jamwal et al. [135] develop a maturity model for Industry 4.0 practices in SMEs, emphasizing scalability and adaptability of assessment frameworks across different organizational contexts.

Several studies integrate maturity assessment with advanced digital infrastructures. Shang et al. [136] introduce the DigiPyramid framework, combining digital twin concepts with multi-resolution maturity assessment for logistics systems. Earlier work by Zoubek and Simon [137] provides a Logistics 4.0 maturity framework for internal logistics that forms a basis for further Logistics 5.0 developments.

Overall, the literature shows a transition from static Industry 4.0 assessment tools toward multi-dimensional maturity frameworks integrating technological, organizational, sustainability, and resilience-related dimensions. Increasing attention is also given to advanced evaluation approaches based on fuzzy logic, digital twins, and decision-support methods, reflecting the growing complexity of Logistics 5.0 systems.

5.2.5. SCM 5.0 and Logistics 5.0 Conceptual Approaches

The analysis of the selected publications (28 items) shows that Supply Chain 5.0 and Logistics 5.0 are conceptualized as integrated, human-centric, and sustainability-

oriented systems evolving beyond the Industry 4.0 paradigm. Existing studies present complementary perspectives that collectively define the emerging Logistics 5.0 framework.

A fundamental aspect of this body of research is the attempt to define the core principles and conceptual foundations of Logistics 5.0. In this context, the study by Ivanov [138] plays a pivotal role, proposing a viability-based framework that integrates resilience, sustainability, and human-centricity as the three pillars of Industry 5.0 systems. This triadic perspective is consistently reinforced across the literature. Ghobakhloo et al. [139] further extend this view by outlining a transition toward a human-centric digital society, where technological advancement is aligned with social and environmental objectives. Similarly, Difrancesco and Klumpp [140] emphasize the importance of network cascading effects and human-centric operations, while Fares et al. [141] discuss the strategic implications of Industry 5.0 for supply chain management, particularly in terms of adaptability and long-term value creation.

Human-centricity constitutes one of the defining characteristics of Logistics 5.0. Existing studies emphasize human–machine collaboration, operator-centered system design, workforce adaptation, and the integration of Lean and Industry 5.0 principles [142–147]. Another major research stream focuses on intelligent and data-driven logistics systems integrating AI, IoT [148], automation [149], semantic technologies, and smart infrastructure solutions. The development of autonomous and intelligent logistics systems is also explored by Ma et al. [150], who introduced parallel system-based distribution models, and by Burmambet [151], who examines the transformation of maritime ports into smart logistics hubs. Additionally, Saidi et al. [152,153] highlight the importance of semantic technologies and knowledge graphs in enabling reconfigurable and intelligent supply chains, while Hmamed et al. [154] address the need for secure digital infrastructures through zero-trust architectures. These studies highlight the increasing role of digital technologies in enabling adaptive, interconnected, and secure Logistics 5.0 environments.

Resilience, adaptability, and responsiveness are increasingly recognized as core Logistics 5.0 capabilities [153]. Existing studies emphasize adaptive decision-making, flexible system architectures, and resilience-oriented performance assessment frameworks in digitally enabled logistics environments [155–158].

Sustainability and circular economy principles also constitute a central theme in Logistics 5.0 research [52]. Existing studies link Industry 5.0 implementation with sustainable supply chain management [159], operational excellence [156], human capital development [160,161], and sustainability-oriented digitalization [162]. These works emphasize that environmental and social objectives are increasingly integrated with resilience and digital transformation strategies.

Several studies also propose multi-dimensional performance and evaluation frameworks tailored to Logistics 5.0 systems, including Warehouse 5.0 [163], SCOR 5.0 [148], and decentralized smart supply chain assessment models [164].

Overall, the reviewed studies show that Logistics 5.0 is evolving toward an integrated paradigm combining digitalization, resilience, sustainability, and human-centric system design. The literature also demonstrates that Logistics 5.0 represents a multi-dimensional and interdisciplinary research domain integrating perspectives from operations management, engineering, information systems, and sustainability science.

5.2.6. Supply Chain Resilience 5.0

The concept of supply chain resilience within the Logistics 5.0 and SCM 5.0 paradigm represents one of the most extensively developed and multi-dimensional research areas identified in the analyzed literature. To synthesize the evolution of resilience concepts identified in the literature, Figure 11 presents a transition from static robustness-oriented

approaches toward dynamic and adaptive system perspectives characteristic of Logistics 5.0. As shown, resilience has evolved from a focus on resistance and redundancy to a broader conceptualization that includes adaptability, recovery, and system transformation.

Figure 11 illustrates the transition from robustness-oriented approaches toward adaptive and capability-driven resilience models characteristic of Logistics 5.0 systems. Recent studies increasingly conceptualize resilience as a systemic capability embedded within digitalized, sustainable, and human-centric supply chains. A major research stream focuses on digital technologies as enablers of supply chain resilience. Studies demonstrate that AI, digital transformation, and big data analytics improve the ability of supply chains to anticipate, absorb, and adapt to disruptions [165–169]. In particular, Belhadi et al. [165] highlight the role of AI-driven innovation in improving resilience and supply chain performance, while Khan et al. [168] and Gao and Zhao [169] emphasize the importance of digital resource orchestration and data-driven risk prediction.

Additional studies link resilience with digital innovation ecosystems, smart technologies, and low-carbon transformation strategies [170–174]. These works further reinforce the interdependence between resilience, sustainability, and digitalization in Logistics 5.0 systems.

Another important research direction concerns the integration of sustainability and resilience in supply chains. Existing studies address green [175] and humanitarian logistics [176], resilient network design [177], sustainability-oriented risk management [178], and environmental investments [179] emphasizing the growing importance of environmentally and socially responsible resilience strategies.

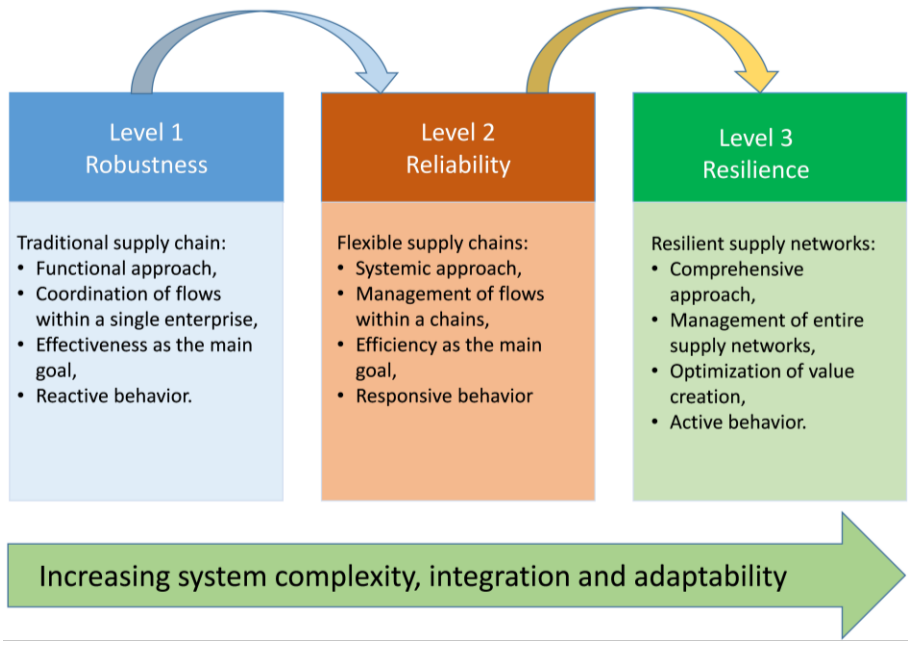

Figure 11. Evolution of supply chain resilience concepts in the transition toward Logistics 5.0 systems, showing the progression from robustness (Level 1) through reliability (Level 2) to resilience (Level 3) in the context of increasing system complexity, integration, and adaptability. Source: own contribution.

Recent studies increasingly focus on capability-based and adaptive resilience frameworks. Mohammed et al. [180] introduce the concept of dynamic capabilities 5.0, highlighting the role of internal organizational capabilities in achieving business resilience. Similarly, Patrucco et al. [181] extend the classical Triple-A framework (agility, adaptability, alignment) into the AAA+ model, incorporating digitalization, sustainability, and ecosystem resilience. Sunmola and Baryannis [182] contribute to this perspective by proposing the 4-C resilience model (context, capabilities, choices, and contingencies), emphasizing the role of AI in supporting decision-making under uncertainty.

The literature also increasingly applies quantitative and hybrid decision-support approaches for resilience enhancement, including fuzzy-TOPSIS models [183], digital analytics [184], network design [177] and AI-based evaluation frameworks [185].

Several studies also examine operational and structural resilience strategies in response to disruptions such as pandemics, conflicts, and global supply chain shocks [186–188]. These works emphasize agility, flexibility, and technology-supported coordination mechanisms across supply chains. Several studies also emphasize the role of human-centric design and human–technology interaction in building resilient supply chains [189,190].

The emergence of intelligent and autonomous supply chain systems further extends resilience capabilities through digital integration [191], collaboration mechanisms [192], and metaverse-based environments [193]. Resilience maturity and assessment frameworks are also gaining increasing attention within Logistics 5.0 research [194].

Overall, resilience in Logistics 5.0 is increasingly treated as a dynamic and system-embedded capability closely linked with digitalization, sustainability, and adaptive decision-making.

5.2.7. Sustainability and Green Logistics 5.0

Sustainability and Green Logistics 5.0 represent the most extensive and dynamically evolving research stream identified in this review, encompassing 35 publications. Again, to synthesize the evolution of sustainability concepts identified in the literature, Figure 12 illustrates the transition from efficiency-driven and compliance-based approaches toward integrated and system-embedded sustainability perspectives characteristic of Logistics 5.0.

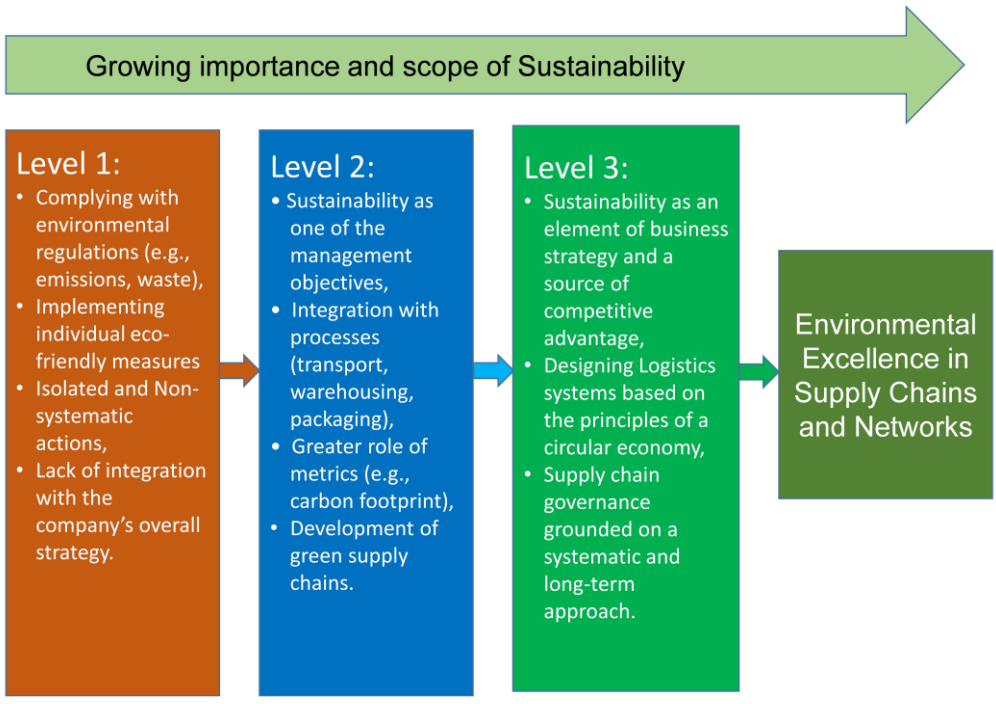

Figure 12. Evolution of sustainability concepts in Logistics 5.0: from efficiency-driven to system-embedded sustainability across three levels, reflecting the growing importance and expanding scope of sustainability in increasingly complex logistics systems. Source: own contribution.

Figure 12 illustrates the transition from efficiency-oriented sustainability approaches toward integrated and system-embedded sustainability perspectives characteristic of Logistics 5.0. The reviewed studies collectively emphasize the convergence of circular economy principles, digital technologies, sustainability assessment frameworks, and adaptive supply chain design within increasingly complex logistics ecosystems.

A major research direction concerns the integration of circular economy principles within Logistics 5.0 systems. The literature emphasizes closed-loop supply chains [195–197], reverse logistics, circular resource flows [198–201], and sustainability-oriented suppliers [202–204] and network design supported by fuzzy, hybrid, and multi-criteria decision-making methods. The business process management integration in Life Cycle Assessment and Reliability-Centered Maintenance is presented in [205].

Another important stream focuses on digital technologies as enablers of sustainable logistics transformation. Existing studies highlight the role of AI, IoT, blockchain, digital platforms [206–209], and smart monitoring systems in improving transparency, traceability, operational visibility, and environmental performance within supply chains [210,211].

The literature also proposes various sustainability assessment and performance measurement frameworks based on fuzzy logic, AHP, DEMATEL, and hybrid analytical methods [212,213]. These approaches typically integrate environmental, social, and economic dimensions aligned with ESG and SDG principles, while emphasizing logistics capabilities such as flexibility, visibility, and responsiveness as important drivers of sustainable performance [214,215].

Another research direction concerns the integration of sustainability with operational optimization and low-carbon system design [216,217]. The analyzed studies propose energy-efficient logistics models, sustainable scheduling approaches, robust and fuzzy optimization methods, and lifecycle-oriented frameworks supporting environmentally responsible supply chain operations under uncertainty [218,219].

Several studies additionally emphasize the growing importance of human-centric and organizational dimensions of sustainability in Logistics 5.0. The literature highlights the role of human capital, workforce capabilities, social responsibility, and operational excellence in supporting circular economy implementation and long-term sustainable value creation [220–222].

The reviewed studies also demonstrate broad sector-specific applications of sustainable Logistics 5.0 solutions across renewable energy [223,224], food supply chains [225], manufacturing systems, and urban logistics environments [226,227]. These applications mainly focus on sustainability-oriented decision-making, smart logistics systems, environmental performance improvement, and Industry 5.0 readiness.

Several studies underline the strong interdependencies between sustainability, resilience, and digital transformation within Logistics 5.0 systems [228,229]. The literature indicates that digital technologies simultaneously support environmental objectives, adaptive capabilities, and supply chain responsiveness.

Overall, the literature positions sustainability as a core and non-separable component of Logistics 5.0 systems, closely interconnected with resilience, digitalization, and adaptive system design.

6. Discussion: Logistics 5.0 in the 5.0 Ecosystem: A Systemic Interpretation

Table 9 synthesizes the functional roles of the key research domains identified in the Logistics 5.0 literature. The analysis indicates that while AI, digital twins, and blockchain strongly support digital readiness and operational integration, resilience and sustainability are still insufficiently embedded within unified system-level frameworks.

The literature review demonstrates that Logistics 5.0 is evolving as a multi-dimensional ecosystem integrating technological, organizational, resilience, and sustainability dimensions. However, these dimensions are still frequently analyzed in isolation, resulting in fragmented conceptualizations and limited system-level integration. The following discus-

sion synthesizes the findings in relation to RQ1–RQ4 and identifies the key research gaps motivating the framework proposed in Section 7.

According to RQ1, which investigates *how Logistics 5.0 readiness is conceptualized and measured*, the conducted review demonstrates that readiness is predominantly approached through maturity and readiness models rooted in Industry 4.0 paradigms. Existing approaches primarily emerge from the maturity and readiness literature (Section 5.2.4), where readiness is defined as the degree to which organizations are capable of adopting Industry 4.0/5.0 technologies and practices. Thus, readiness is largely interpreted as an input-oriented construct describing the structural preparedness of organizations rather than their actual system performance.

Table 9. Functional roles of key research domains in Logistics 5.0 literature (content-based analysis).

Research Domain	Role in Logistics 5.0 System	Contribution to Readiness	Contribution to System Capabilities	Contribution to Sustainability
AI and data analytics	Core decision-support and predictive engine enabling real-time optimization	Enables advanced digital readiness through data-driven integration and intelligent automation	Supports adaptability, responsiveness, and predictive resilience through forecasting and anomaly detection	Indirect contribution via efficiency improvements and resource optimization
Blockchain and distributed technologies	Trust and transparency infrastructure for decentralized supply chain coordination	Enhances data reliability, traceability, and interoperability readiness	Strengthens robustness and system integrity through secure and immutable transactions	Supports circular economy, traceability, and responsible sourcing
Digital twins and modeling	Virtual representation and simulation layer of logistics systems	Enables advanced system visibility and integration readiness	Supports dynamic adaptation, scenario analysis, and recovery planning	Enables optimization of resource flows and environmental impact reduction
Maturity and readiness models	Assessment and benchmarking tools for digital and organizational transformation	Core framework for evaluating readiness levels across dimensions	Limited direct contribution; rarely incorporates dynamic capabilities explicitly	Often weakly integrated; sustainability treated as an additional dimension
SCM 5.0 conceptual approaches	Integrative theoretical frameworks linking human-centricity, resilience, and digitalization	Provides conceptual structure for defining readiness dimensions	Highlights importance of systemic capabilities but rarely operationalizes them	Emphasizes sustainability as a core pillar, but often at conceptual level
Supply chain resilience	System response and adaptation mechanisms under disruption	Rarely integrated into readiness models explicitly	Core domain defining adaptability, robustness, and recovery capabilities	Increasingly linked with sustainability, especially in risk-aware systems
Sustainability and green logistics	Performance-oriented domain focusing on environmental and social outcomes	Often treated as a separate or secondary readiness dimension	Limited integration with system capabilities and dynamics	Core domain defining environmental, economic, and social performance

Following the analyzed literature, three dominant measurement perspectives can be identified:

- Technology-oriented readiness, focusing on the adoption of digital tools such as AI, IoT, digital twins, and blockchain [126,128],
- Process and capability maturity, assessing organizational processes, integration levels, and operational performance [129,133],
- Human and organizational readiness, incorporating workforce skills, human-centricity, and collaboration [131,146].

A major limitation is the widespread use of compensatory logic, where weaknesses in one dimension (e.g., sustainability or human factors) may be offset by strengths in another (e.g., technological advancement). This may lead to overestimated readiness levels and highlights the need for non-compensatory assessment structures.

Building upon this, RQ2 addresses *how resilience and system-level capabilities are integrated into these models*. The findings indicate that resilience is widely recognized in the literature (Sections 5.2.1 and 5.2.6), particularly in the context of AI-driven systems, digital twins, and supply chain risk management. In this area, the literature identifies several approaches to resilience integration:

- Technology-driven resilience, where AI, big data, and digital twins are used for prediction, adaptation, and recovery [113,165],
- Capability-based resilience, focusing on agility, adaptability, and robustness [181,185],
- System-level resilience, incorporating network structures, collaboration, and ecosystem dynamics [168,177].

However, resilience is typically treated as an outcome rather than an embedded system property within readiness frameworks. Although agility, adaptability, and dynamic capabilities are widely discussed, they are rarely formalized as measurable and integrable system components.

In line with this, RQ3 explores *how sustainability performance is assessed in Logistics 5.0 research*. As identified in Section 5.2.7, sustainability constitutes a dominant research stream, with numerous studies proposing evaluation frameworks based on circular economy principles, ESG metrics, and multi-criteria decision-making methods. Indeed, three main approaches to sustainability evaluation can be identified:

- Multi-criteria decision-making (MCDM) frameworks, including fuzzy AHP, TOPSIS, and DEMATEL methods, used to assess sustainability performance and technology adoption [212,213],
- Circular economy and lifecycle-based metrics, focusing on resource efficiency, waste reduction, and closed-loop systems [198,204],
- Performance-based indicators, integrating environmental, economic, and social dimensions, often aligned with ESG or SDG frameworks [215,221].

Despite the large number of sustainability-oriented studies, sustainability is frequently treated as a secondary or compensable dimension subordinated to technological or efficiency objectives. Moreover, sustainability assessment is often weakly integrated with resilience and dynamic system behavior, limiting the evaluation of Logistics 5.0 systems under uncertainty and disruption.

The literature, therefore, indicates the need for more holistic sustainability assessment approaches capable of integrating environmental, operational, and social dimensions within dynamic Logistics 5.0 systems. This gap supports the introduction of a dedicated sustainability layer based on strong sustainability principles.

Finally, RQ4 examines *the conceptual gaps between structural readiness and sustainable system outcomes*. The conducted analysis clearly shows that existing research suffers from a fundamental disconnect between input-oriented models (readiness, maturity) and output-oriented objectives (resilience, sustainability performance).

This gap can be synthesized into several key structural and conceptual deficiencies in the current body of research:

1. Lack of causal linkage—existing models rarely establish explicit relationships between readiness dimensions (e.g., digital maturity) and system outcomes such as resilience or sustainability performance. As a result, it remains unclear how readiness translates into measurable system benefits.
2. Fragmentation of research streams—the literature is divided into separate domains (AI, blockchain, digital twins, sustainability, resilience), with limited integration across them. This fragmentation prevents the development of coherent, system-level models.

3. Static vs. dynamic perspective—most readiness and maturity models are static, while Logistics 5.0 systems operate in dynamic, uncertain environments. This creates a mismatch between assessment approaches and real system behavior.
4. Limited human-centric integration—although human-centricity is a key pillar of Industry 5.0, it is often underrepresented in operational models and performance assessments. The interaction between human, technological, and organizational dimensions remains insufficiently explored.
5. Insufficient system-level modeling—few studies adopt a holistic systems perspective that integrates structure, behavior, and performance. Consequently, Logistics 5.0 is often analyzed at the component level rather than as an interconnected ecosystem.

To sum up, the combined interpretation of RQ1–RQ4 leads to a key conclusion: Logistics 5.0 research lacks an integrated, system-level conceptualization that connects readiness, capabilities, and performance outcomes within a coherent structure. More specifically, the literature remains predominantly input-oriented (readiness-focused) or output-oriented (performance-focused), while failing to explicitly model the mechanisms that link these two perspectives.

Based on the findings, Logistics 5.0 may be conceptualized as a complex adaptive system in which readiness provides the structural foundation, digital technologies act as enabling mechanisms, resilience reflects adaptive system behavior, and sustainability represents the overarching performance objective. However, the literature still suffers from three major limitations: (i) reliance on compensatory and static readiness models, (ii) insufficient integration of functional system capabilities such as resilience and adaptability, and (iii) weak integration of sustainability within system-level assessment structures. These limitations indicate the need for integrated, dynamic, and human-centric Logistics 5.0 assessment frameworks.

The identified limitations directly motivate the framework proposed in Section 7, particularly the introduction of: (i) a non-compensatory assessment structure, (ii) a functional capability layer capturing resilience and adaptability, and (iii) a dedicated sustainability layer based on strong sustainability principles. Consequently, Logistics 5.0 should be interpreted as an interconnected system linking readiness, capabilities, and performance outcomes.

Table 10 summarizes the identified research gaps and their corresponding conceptual responses incorporated into the proposed Logistics 5.0 framework.

Table 10. Mapping of identified research gaps and corresponding conceptual responses in the proposed Logistics 5.0 framework.

Identified Gap	Description (Literature Insight)	Framework Response (Section 7)
Compensatory logic in readiness models	Existing maturity and readiness models allow trade-offs between dimensions (e.g., high digitalization compensating for low sustainability), leading to overestimated system readiness.	Non-compensatory model structure, ensuring minimum threshold conditions across critical dimensions (e.g., resilience, sustainability).
Weak sustainability perspective	Sustainability is often treated as a subordinate or compensable dimension, with environmental and social impacts offset by economic or technological gains.	Dedicated sustainability layer, based on strong sustainability principles and non-substitutability of environmental and social criteria.
Lack of functional system capabilities	Resilience, adaptability, and recovery are treated as outcomes rather than embedded system properties, and are not formally integrated into maturity models.	Functional capability layer, explicitly modeling dynamic system properties such as resilience, adaptability, and robustness.
Lack of causal linkage	Limited understanding of how readiness (input) translates into system performance (output), particularly in terms of resilience and sustainability.	Hierarchical and causal structure, linking readiness–capabilities–performance outcomes.

Table 10. *Cont.*

Identified Gap	Description (Literature Insight)	Framework Response (Section 7)
Fragmentation of research streams	Separate development of AI, blockchain, digital twins, sustainability, and resilience research streams without systemic integration.	Integrated multi-layer framework, combining technological, organizational, and sustainability dimensions within a unified architecture.
Static assessment approaches	Most models are static and do not reflect dynamic system behavior under uncertainty and disruption.	Dynamic system perspective, enabling analysis of system evolution, adaptation, and response to disruptions.
Limited human-centric integration	Human factors are underrepresented or weakly operationalized in Logistics 5.0 models.	Human-centric integration across layers, embedding human capabilities and interactions within readiness and capability structures.

As shown in Table 10, the identified gaps are structurally interconnected and jointly justify the need for an integrated and non-compensatory Logistics 5.0 framework linking structural readiness, functional capabilities, and sustainability-oriented performance outcomes.

7. Proposed Non-Compensatory Conceptual Framework

Building on the findings of the systematic literature review and the identified limitations discussed in Section 6, this study proposes a non-compensatory, multi-layer conceptual framework for Logistics 5.0 systems. The framework addresses the critical gaps related to compensatory logic, fragmented modeling approaches, lack of functional system capabilities, and weak integration of sustainability.

In contrast to existing models, which often rely on additive or compensatory aggregation mechanisms, the proposed framework adopts a non-compensatory logic, ensuring that deficiencies in critical dimensions (e.g., sustainability or resilience) cannot be offset by strengths in others (e.g., digitalization level). This reflects the systemic nature of Logistics 5.0, where minimum conditions must be satisfied across all key dimensions to ensure reliable and sustainable system performance.

The framework conceptualizes Logistics 5.0 as a hierarchically structured and causally linked system, composed of three interrelated layers:

- Layer 1—Structural Readiness, representing the foundational conditions enabling system operation,
- Layer 2—Functional Capabilities, capturing dynamic system properties such as resilience and adaptability,
- Layer 3—Sustainability Performance, reflecting system-level outcomes aligned with strong sustainability principles.

These layers are interconnected through causal relationships, where structural readiness enables the development of system capabilities, which in turn determine performance outcomes. This structure directly responds to the lack of causal linkage identified in the literature.

Furthermore, the framework integrates human-centricity and system dynamics across all layers, ensuring that Logistics 5.0 is not reduced to a purely technological paradigm but is instead treated as a socio-technical system.

The following subsections present a detailed description of each layer, starting with the structural readiness dimension.

7.1. Layer 1—Structural Readiness

Layer 1 represents the structural foundation of Logistics 5.0 systems, defining the extent to which an organization is prepared to support advanced, adaptive, and sustainable operations. In contrast to traditional readiness models, this layer is not limited to technology

adoption but reflects a multi-dimensional configuration of digital, organizational, and data-related enablers.

Importantly, in line with the non-compensatory logic of the framework, all components of structural readiness must reach a minimum acceptable level, as deficiencies in one dimension cannot be offset by strengths in others.

Based on the findings from Sections 5.2.1–5.2.4, structural readiness is decomposed into three key dimensions: digitalization, automation, and data integration.

Digitalization refers to the extent to which logistics processes, resources, and decision-making mechanisms are supported by advanced digital technologies, including artificial intelligence, digital twins, IoT, and blockchain. The literature review (Sections 5.2.1 and 5.2.3) indicates that digitalization is a primary driver of Logistics 5.0 transformation, enabling predictive analytics, real-time monitoring, and intelligent decision-making. However, existing studies tend to evaluate digitalization primarily in terms of technology adoption levels, without considering its integration into system behavior and outcomes.

In the proposed framework, digitalization is understood not merely as the presence of technologies, but as their functional embeddedness within logistics processes, including:

- Real-time visibility and monitoring,
- Predictive and prescriptive analytics,
- Digital representation of physical systems (e.g., digital twins),
- Integration with decision-support systems.

Thus, digitalization constitutes a necessary but not sufficient condition for Logistics 5.0 readiness, requiring alignment with other structural dimensions.

Automation represents the degree to which logistics operations are executed through autonomous or semi-autonomous systems, including robotics, autonomous vehicles, and intelligent control systems. The literature (Sections 5.2.1 and 5.2.5) highlights the increasing role of automation in enhancing efficiency, responsiveness, and operational consistency. However, in the context of Industry 5.0, automation must be reinterpreted beyond full autonomy toward human-centric automation, where human–machine collaboration is emphasized.

Accordingly, in the proposed framework, automation is conceptualized as:

- The level of process automation and autonomy,
- The integration of collaborative systems (e.g., human–robot interaction),
- The flexibility and reconfigurability of automated systems,
- The alignment between automation and human decision-making.

This perspective ensures that automation contributes not only to efficiency but also to adaptability and system resilience, addressing the gap related to limited human-centric integration identified in the literature.

Data integration refers to the ability of the logistics system to collect, process, and synchronize data across organizational, functional, and network levels, enabling coherent and informed decision-making. The literature review (Sections 5.2.1–5.2.3) emphasizes the importance of data as a key enabler of AI, digital twins, and blockchain-based systems. However, many studies focus on data availability rather than data interoperability and systemic integration.

In the proposed framework, data integration encompasses:

- Interoperability between systems and platforms,
- Real-time data exchange across supply chain partners,
- Integration of structured and unstructured data sources,
- Data governance, quality, and reliability mechanisms.

A high level of data integration is essential for enabling system-wide coordination, transparency, and responsiveness, forming the backbone for higher-level capabilities such as resilience and sustainability.

The three dimensions, digitalization, automation, and data integration, jointly define the structural readiness of Logistics 5.0 systems. Their interaction determines the system's ability to support advanced capabilities and achieve desired performance outcomes.

Crucially, due to the non-compensatory nature of the framework:

- High digitalization without data integration leads to fragmented systems,
- Automation without human-centric alignment reduces adaptability,
- Data integration without digital tools limits analytical potential.

Therefore, structural readiness must be interpreted as a balanced and threshold-based configuration, rather than an aggregate score.

7.2. Layer 2—Functional Capabilities

Building upon the limitations identified in the literature (Section 6), the second layer of the proposed framework introduces functional system capabilities, which represent the dynamic and behavioral properties of Logistics 5.0 systems. This layer directly addresses the critical research gap related to the lack of explicit modeling of system-level capabilities, particularly resilience, adaptability, and robustness, within existing readiness and maturity frameworks.

In contrast to Layer 1, which focuses on structural readiness (i.e., what the system has), the functional capability layer captures what the system can do under varying operational conditions. This distinction is essential, as the literature consistently demonstrates that high levels of digitalization or technological advancement do not automatically translate into improved system performance, especially in dynamic and uncertain environments [4,138,165]. The functional capability layer is therefore conceptualized as a set of non-substitutable system properties, which emerge from the interaction between technological, organizational, and human factors. These capabilities are not treated as outcomes, but as intrinsic system attributes that determine how the system behaves under disruption, variability, and change.

Based on the synthesis of Sections 5.2.1, 5.2.3 and 5.2.6, four core functional capabilities are defined: resilience, robustness, adaptability, and reliability.

Resilience is conceptualized as the system's ability to anticipate, absorb, recover from, and adapt to disruptions while maintaining or restoring acceptable levels of performance. The literature highlights that resilience in Logistics 5.0 is increasingly enabled by digital technologies such as artificial intelligence, digital twins, and big data analytics, which support predictive and prescriptive decision-making [113,165,169]. However, as identified in Section 6, resilience is often treated as a performance outcome, rather than an embedded system property. In the proposed framework, resilience is reinterpreted as a core functional capability, which emerges from the integration of: real-time data visibility, decision-making agility, network collaboration, and human–machine interaction. This aligns with the shift toward Industry 5.0 principles, where resilience is co-created through the interaction of technological and human-centric elements [189,190].

Importantly, resilience is modeled as a non-compensatory capability, meaning that it cannot be substituted by high performance in other dimensions (e.g., digitalization or efficiency).

Robustness refers to the system's ability to maintain stable performance under disturbances without significant degradation. While resilience focuses on recovery and adaptation, robustness emphasizes resistance to disruption.

The literature on supply chain design and risk management highlights the importance of robustness in ensuring continuity under uncertain conditions, particularly through

redundancy, diversification, and network design strategies [175,177]. In Logistics 5.0 systems, robustness is increasingly supported by:

- Distributed and decentralized architectures,
- Redundancy in supply and logistics networks, and
- Predictive risk assessment models.

However, current maturity models rarely capture robustness explicitly, often conflating it with resilience or ignoring it altogether. The proposed framework distinguishes robustness as a separate capability, ensuring that systems are not only able to recover but also resist disruptions proactively.

Adaptability is defined as the system's ability to adjust its structure, processes, and decision rules in response to changing conditions. This capability reflects the dynamic and evolutionary nature of Logistics 5.0 systems operating in highly volatile environments.

The literature emphasizes adaptability as a key component of dynamic capabilities and supply chain agility, particularly in the context of digital transformation and AI-driven decision-making [168,180]. Digital twins and real-time analytics further enhance adaptability by enabling continuous system reconfiguration and scenario-based optimization [113,124]. Despite its importance, adaptability is rarely operationalized within readiness or maturity models. In the proposed framework, it is treated as a core functional capability, reflecting the system's ability to:

- Reconfigure logistics networks,
- Modify operational strategies, and
- Respond to demand and supply variability.

Adaptability is particularly critical in the context of Supply Chain 5.0, where responsiveness must be aligned with sustainability and human-centric objectives.

Reliability refers to the system's ability to consistently perform its intended functions over time under specified conditions. Unlike resilience or adaptability, which focus on response to change, reliability emphasizes the stability and predictability of operations.

The importance of reliability is well-established in logistics and maintenance literature, particularly in relation to operational continuity and risk mitigation [134]. In the context of Logistics 5.0, reliability is increasingly influenced by:

- Predictive maintenance,
- Data-driven monitoring systems, and
- Integrated digital infrastructures.

While reliability is often considered a traditional performance metric, its role within the proposed framework is elevated to a functional capability, as it directly affects the system's ability to sustain performance over time and under uncertainty.

The four defined capabilities, resilience, robustness, adaptability, and reliability, collectively define the behavioral profile of Logistics 5.0 systems. Importantly, these capabilities are:

- Interdependent, yet non-substitutable,
- Emergent, arising from interactions across system components, and
- Dynamic, evolving over time in response to internal and external conditions.

This layer establishes the critical causal bridge between structural readiness (Layer 1) and system performance outcomes (Layer 3), addressing one of the key gaps identified in the literature (RQ4).

By explicitly modeling functional capabilities, the proposed framework moves beyond static and compensatory maturity models toward a systemic, dynamic, and non-compensatory representation of Logistics 5.0, where system behavior becomes a central element of analysis.

To further enhance the practical interpretability and future operationalization of the proposed framework, Table 11 presents illustrative examples of measurable indicators that may be used to assess the key functional capabilities of Logistics 5.0 systems. The presented indicators are not intended to constitute a fixed or exhaustive measurement system, but rather to demonstrate possible assessment directions and operationalization pathways for future empirical applications.

Table 11. Illustrative indicators for assessing functional capabilities in Logistics 5.0 systems.

Functional Capability	Illustrative Measurable Indicators	Assessment Rationale and Interpretation
Resilience	• Recovery time after disruption • Disruption absorption capacity • Continuity of operations during disturbance events • Time to restore service levels	Reflects the system's ability to anticipate, absorb, recover from, and adapt to disruptions while maintaining acceptable operational performance
Robustness	• Service continuity under stress conditions • Redundancy ratio in logistics networks • Supplier diversification index • Performance degradation level under disruptions	Assesses the system's resistance to disturbances and its ability to maintain stable performance without significant functional deterioration
Adaptability	• Network reconfiguration time • Responsiveness to demand variability • Flexibility of routing and scheduling • Speed of operational adjustment	Captures the system's capability to modify structures, processes, and decision rules in response to changing operational and environmental conditions
Reliability	• Failure frequency • On-time delivery stability • Mean time between failures (MTBF) • Operational consistency indicators	Measures the stability, predictability, and continuity of logistics operations under specified operating conditions

The proposed indicators should be interpreted as illustrative operationalization examples rather than universal evaluation criteria. Depending on the application context, sector characteristics, and data availability, different quantitative, qualitative, or hybrid indicators may be employed. Importantly, the indicators may be integrated with expert-based assessment methods, simulation approaches, fuzzy logic systems, or data-driven analytics to support empirical implementation of the framework. This perspective reinforces the framework's applicability while maintaining its conceptual and system-oriented nature.

7.3. Layer 3—Sustainability Performance

The third layer of the proposed framework represents the sustainability and system performance dimension, which constitutes the ultimate objective of Logistics 5.0 systems. This layer directly responds to the limitations identified in Section 6, particularly the dominance of weak sustainability perspectives, the fragmentation of sustainability assessment approaches, and the lack of integration between sustainability and system dynamics.

In contrast to conventional maturity models, where sustainability is often treated as a complementary or compensatory dimension, the proposed framework conceptualizes sustainability as a non-substitutable and governing performance layer, aligned with the principles of strong sustainability. This implies that environmental and social criteria cannot be offset by improvements in economic or technological performance, thereby introducing strict boundary conditions for system evaluation.

Building upon the synthesis of Section 5.2.7, sustainability in Logistics 5.0 is operationalized through three interrelated dimensions: environmental, economic, and social performance, which are interpreted not as independent metrics, but as interdependent system outcomes emerging from the interaction between structural readiness (Layer 1) and functional capabilities (Layer 2).

Environmental performance reflects the system's ability to minimize ecological impact, reduce resource consumption, and support circular economy principles. The literature emphasizes that Industry 5.0 technologies, such as IoT, AI, and blockchain, play a crucial role in enabling environmental sustainability through improved visibility, optimization, and traceability [206,207,209]. Key aspects of environmental performance include:

- Reduction of carbon emissions and energy consumption,
- Efficient resource utilization and waste minimization,
- Implementation of circular supply chain practices, and
- Support for low-carbon and net-zero strategies.

However, as identified in the review, many existing models adopt a compensatory logic, where environmental degradation can be offset by economic gains. In the proposed framework, environmental performance is treated as a non-negotiable constraint, forming a critical boundary condition for system evaluation.

Economic performance captures the system's ability to generate value, ensure efficiency, and maintain competitiveness within the Logistics 5.0 ecosystem. The literature highlights the role of digital transformation, data-driven decision-making, and operational optimization in enhancing economic outcomes [211,214]. Key components include:

- Operational efficiency and cost optimization,
- Service quality and responsiveness,
- Value creation through innovation and digitalization, and
- Long-term economic viability.

Importantly, within the proposed framework, economic performance is not treated as the dominant dimension, but rather as conditionally dependent on environmental and social constraints. This reflects a shift from traditional efficiency-driven paradigms toward balanced and responsible value creation, consistent with Industry 5.0 principles.

Social performance reflects the human-centric dimension of Logistics 5.0, which has been identified in the literature as a critical yet underdeveloped component of supply chain models [220,225]. This dimension includes:

- workforce well-being, safety, and ergonomics,
- human–machine collaboration and augmentation,
- skills development and digital competencies, and
- ethical and inclusive system design.

The literature emphasizes that human capital and organizational culture play a key role in enabling both resilience and sustainability outcomes. However, social aspects are often underrepresented or weakly operationalized in existing frameworks. The proposed model explicitly integrates social performance as a core and non-substitutable dimension, ensuring that technological advancement does not come at the expense of human well-being.

A key contribution of this layer lies in redefining sustainability as a dynamic system-level outcome, rather than a static performance metric. The literature indicates that sustainability performance is highly dependent on system behavior under changing conditions, including disruptions, demand variability, and environmental constraints [138,227]. In this context, sustainability emerges from:

- the structural readiness of the system (e.g., digital infrastructure, integration),
- the functional capabilities (e.g., resilience, adaptability), and
- the interaction between technological, organizational, and human factors.

This perspective directly addresses the gap identified in RQ4, namely the lack of causal linkage between readiness and performance outcomes.

The sustainability and system performance layer represents the final evaluative dimension of the proposed Logistics 5.0 framework. It integrates environmental, economic,

and social outcomes into a coherent structure, governed by non-compensatory logic and grounded in system behavior. Importantly, this layer:

- provides a normative benchmark for system evaluation,
- ensures alignment with Industry 5.0 principles,
- establishes a direct link between system capabilities and performance outcomes.

Together with the structural readiness and functional capability layers, it completes the hierarchical and causal architecture of the proposed framework, enabling a comprehensive and system-oriented assessment of Logistics 5.0.

7.4. Non-Compensatory Evaluation Logic

A central contribution of the proposed Logistics 5.0 framework is the introduction of a non-compensatory evaluation logic, which fundamentally departs from the dominant assessment approaches identified in the literature. As discussed in Section 6, most existing maturity and readiness models rely on compensatory mechanisms, allowing high performance in one dimension (e.g., digitalization) to offset deficiencies in others (e.g., sustainability or resilience). This often leads to overestimated system readiness and misleading performance interpretations. To address this limitation, the proposed framework adopts a threshold-based, non-compensatory logic, ensuring that critical system dimensions must be satisfied independently, without trade-offs.

The evaluation of Logistics 5.0 systems is based on the definition of minimum threshold levels for each key dimension across all layers of the framework:

- Structural readiness (Layer 1),
- Functional capabilities (Layer 2),
- Sustainability performance (Layer 3).

Each dimension is associated with a minimum acceptable level of performance, below which the system cannot be considered mature or viable, regardless of its performance in other areas. The threshold definition constitutes a critical element of the proposed non-compensatory evaluation logic. In practical applications, minimum acceptable levels may be established using multiple complementary approaches. These include:

(i) Expert-based methods, such as Delphi studies or structured expert judgment,
(ii) Regulatory or normative benchmarks, for instance, ESG standards or industry-specific sustainability requirements, and
(iii) Empirical calibration based on observed data distributions (e.g., percentile-based thresholds or performance benchmarks within a given sector).

In the context of this study, threshold values are introduced at a conceptual level to illustrate the evaluation logic rather than to provide a fixed parametrization. Their precise specification is therefore context-dependent and should be adapted to the characteristics of the analyzed logistics system and its operational environment.

This approach reflects the systemic nature of Logistics 5.0, where failure in one critical dimension (e.g., lack of resilience) may compromise the entire system.

The framework assumes that certain capabilities and performance outcomes are non-negotiable conditions for Logistics 5.0 systems. These include, in particular:

- Minimum levels of resilience (ability to respond to disruptions),
- Baseline environmental sustainability (e.g., compliance with low-carbon requirements),
- Acceptable social conditions (e.g., workforce safety and human-centric design).

These requirements act as hard constraints, rather than flexible evaluation criteria. Consequently, systems that fail to meet these minimum conditions are classified as non-compliant, even if they exhibit high levels of digitalization or efficiency.

From a methodological perspective, the proposed evaluation approach corresponds to a conjunctive decision rule, commonly recognized in the multi-criteria decision-making (MCDM) literature. According to this logic, a system is classified as viable only if all evaluated dimensions meet or exceed their respective threshold levels. This implies that the overall system assessment is not derived from aggregation, but from a logical condition of the form:

$$\text{System viability} = (C_1 \geq T_1) \wedge (C_2 \geq T_2) \wedge \ldots \wedge (C_n \geq T_n) \quad (1)$$

where C_i denotes the performance level of a given dimension and T_i its corresponding threshold.

This conjunctive structure ensures that no dimension can be substituted or compensated for by another, which directly addresses the limitations of additive and weighted aggregation models identified in the literature.

In addition, a key implication of the non-compensatory logic is the explicit rejection of trade-offs between critical dimensions. In contrast to traditional multi-criteria decision-making approaches (e.g., weighted aggregation), the proposed framework assumes that:

- Environmental degradation cannot be offset by economic gains,
- Low resilience cannot be compensated for by high automation or digital maturity,
- Poor social conditions cannot be justified by efficiency improvements.

This principle is directly aligned with the concept of strong sustainability and responds to one of the most significant gaps identified in the literature (Section 6).

Beyond minimum thresholds, the framework introduces the concept of a system balance condition, which complements the conjunctive evaluation logic. While threshold conditions ensure feasibility, the balance condition addresses the internal coherence of system development across dimensions.

Operationally, system balance can be interpreted as the absence of excessive disparities between dimensions. In practical terms, this may be assessed through:

(i) The range of performance values (difference between maximum and minimum scores),
(ii) The dispersion of scores across dimensions, or
(iii) The identification of critical outliers that significantly deviate from the overall system profile.

A system may formally satisfy minimum thresholds while still exhibiting structural imbalance, for example, when high technological advancement is not matched by corresponding levels of resilience or sustainability. Such an imbalance increases systemic vulnerability and reduces long-term viability. Therefore, the balance condition acts as a secondary evaluation layer, supporting the identification of structurally inconsistent configurations that require coordinated development across dimensions.

The system balance condition ensures that Logistics 5.0 systems evolve in a coordinated and harmonized manner, reflecting their nature as complex adaptive systems.

The adoption of a non-compensatory evaluation logic leads to a fundamental reinterpretation of system maturity and performance. In particular:

- High digital maturity cannot compensate for low resilience or poor sustainability performance,
- System evaluation shifts from optimization to feasibility and viability,
- The focus moves from isolated indicators to holistic system integrity.

This approach provides a more realistic and robust basis for assessing Logistics 5.0 systems, particularly in environments characterized by uncertainty, disruption, and increasing sustainability requirements.

The proposed non-compensatory logic is conceptually related to established approaches in the MCDM literature, including conjunctive screening rules and outranking methods (e.g., ELECTRE-type approaches), which also reject full compensability between criteria. However, the contribution of this study does not lie in the development of a new decision-making algorithm, but in the system-level integration and reinterpretation of non-compensatory logic within the context of Logistics 5.0 systems.

In particular, the novelty of the proposed framework lies in:

- Embedding non-compensatory evaluation within a multi-layer architecture linking structural readiness, functional capabilities, and performance outcomes,
- Explicitly treating sustainability dimensions as non-substitutable system constraints, rather than additional evaluation criteria, and
- Integrating dynamic system properties (e.g., resilience and adaptability) into the evaluation logic, thereby extending beyond static maturity assessment models.

This positioning allows the framework to bridge the gap between operations research-based decision logic and system-oriented modeling of complex socio-technical logistics systems.

Following the above considerations, the non-compensatory logic acts as a governing mechanism that integrates all layers of the proposed framework:

- It constrains structural readiness by enforcing meaningful adoption of technologies,
- It validates functional capabilities by requiring operational effectiveness under real conditions,
- It ensures that sustainability performance is achieved in a balanced and non-substitutable manner.

As such, this logic represents the core evaluative principle of the proposed model and directly operationalizes the systemic perspective developed throughout Sections 5 and 6. To provide a holistic representation of the proposed approach, Figure 13 illustrates the architecture of the non-compensatory Logistics 5.0 framework, integrating structural readiness, functional capabilities, sustainability performance, and the governing evaluation logic into a coherent system.

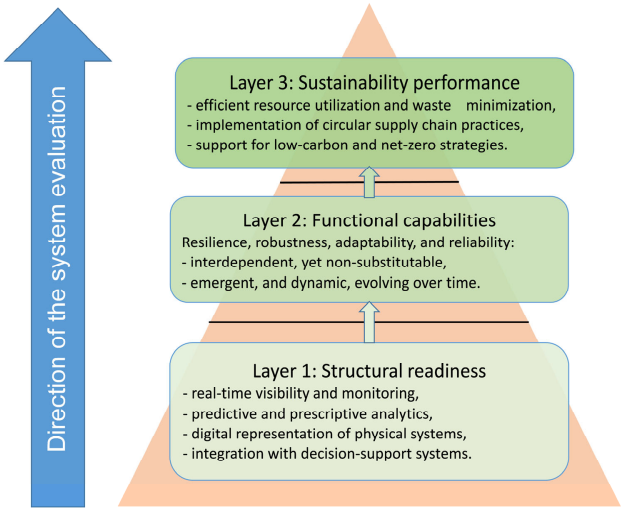

Figure 13. Architecture of the Non-Compensatory Logistics 5.0 Framework, illustrating a three-layer structure comprising structural readiness (Layer 1), functional capabilities (Layer 2), and sustainability performance (Layer 3) in line with the directional logic of system evaluation. Source: own contribution.

Figure 13 presents the architecture of the proposed non-compensatory Logistics 5.0 framework, structured as a hierarchical and causally linked system composed of three

primary layers: structural readiness, functional capabilities, and sustainability-oriented system performance.

The bottom layer represents structural readiness, encompassing key technological and organizational enablers, including digitalization, automation, and data integration. This layer defines the foundational conditions required for system operation.

The second layer captures functional system capabilities, including resilience, robustness, adaptability, and reliability. These capabilities represent dynamic and interdependent system properties that determine how the system responds to disruptions, uncertainty, and operational variability. Importantly, this layer acts as a bridge between structural conditions and performance outcomes.

The top layer reflects sustainability and system performance, structured along environmental, economic, and social dimensions. In contrast to traditional models, these dimensions are treated as non-substitutable and jointly determine the overall viability of the system.

A defining feature of the framework is the integration of a non-compensatory evaluation logic, represented as a governing mechanism spanning all layers. This mechanism enforces threshold conditions, eliminates trade-offs between critical dimensions, and ensures system balance. As a result, high performance in one dimension (e.g., digitalization) cannot compensate for deficiencies in others (e.g., resilience or sustainability).

The overall architecture reflects a bottom-up causal logic, where structural readiness enables functional capabilities, which in turn drive system-level performance outcomes. This hierarchical structure addresses the key gaps identified in the literature by explicitly linking system inputs, behaviors, and outputs within a coherent and non-compensatory framework.

The proposed architecture provides a coherent and system-oriented representation of Logistics 5.0, addressing the fragmentation and limitations identified in the literature. By integrating structural, functional, and performance dimensions under a non-compensatory logic, the framework offers a robust foundation for both theoretical development and practical application.

This conceptualization serves as a basis for future research on operationalization, measurement, and empirical validation of Logistics 5.0 systems.

From a practical implementation perspective, the proposed non-compensatory evaluation logic can be operationalized through a structured stepwise procedure. First, the boundaries of the logistics system under analysis should be defined, including the organizational level, supply chain segment, or functional unit of assessment. Second, relevant indicators for structural readiness, functional capabilities, and sustainability performance should be selected and quantified using available operational data, expert judgment, or hybrid assessment methods. Third, minimum threshold values for each dimension should be established based on regulatory requirements, industry standards, or empirical benchmarking. Fourth, each dimension should be evaluated independently against its respective threshold in a layer-specific manner. Finally, the conjunctive decision rule is applied to determine system viability, ensuring that all critical dimensions simultaneously satisfy minimum requirements. This stepwise procedure enables direct translation of the conceptual framework into decision-support applications for managers and policymakers, supporting structured evaluation and informed decision-making in Logistics 5.0 systems.

To further strengthen the decision-making applicability of the proposed framework, its non-compensatory logic can be explicitly aligned with structured multi-criteria decision-making (MCDM) screening procedures. In particular, the evaluation process can be interpreted as a sequential filtering model consisting of three operational stages: (i) dimensional screening, (ii) threshold validation, and (iii) conjunctive feasibility assessment. In the first stage, all relevant indicators are collected and normalized within each of the three

framework layers (structural readiness, functional capabilities, and sustainability performance). In the second stage, each dimension is independently compared against predefined minimum threshold values derived from expert judgment, regulatory standards, or empirical benchmarks. In the final stage, a conjunctive decision rule is applied to determine system feasibility, ensuring that only systems satisfying all minimum requirements across all dimensions are classified as viable. This procedure is conceptually consistent with screening-based decision models in the MCDM literature (e.g., conjunctive screening and outranking logic), while extending them through explicit integration into a multi-layer socio-technical architecture. As a result, the proposed framework can be operationalized not only as a conceptual model, but also as a structured decision-support methodology for evaluating Logistics 5.0 system viability under uncertainty.

7.5. Illustrative Application of the Non-Compensatory Evaluation Logic

To demonstrate the practical applicability, interpretability, and discriminative power of the proposed non-compensatory framework, this section presents a simplified comparative example of two hypothetical Logistics 5.0 systems. The objective is to illustrate how different evaluation logics, compensatory versus non-compensatory, lead to fundamentally different system classifications, despite similar or even superior aggregate performance levels.

Two stylized logistics systems are defined:

- System A—characterized by high structural readiness and strong economic performance, but weak resilience and sustainability,
- System B—representing a balanced system with moderate but consistent performance across all dimensions.

Step 1: Definition of system profiles

Each system is evaluated across the three layers of the proposed framework using a simplified ordinal scale from 1 (low) to 5 (high). The assigned values reflect typical configurations observed in the literature, where high digital maturity may coexist with low sustainability or resilience. The results are given in Table 12.

Table 12. Comparative evaluation of hypothetical Logistics 5.0 systems.

Dimension	Layer	System A	System B
Digitalization	L1	5	3
Automation	L1	5	3
Data integration	L1	4	3
Resilience	L2	2	3
Robustness	L2	2	3
Adaptability	L2	3	3
Reliability	L2	3	3
Environmental performance	L3	2	3
Economic performance	L3	5	3
Social performance	L3	2	3

System A reflects a technologically advanced but unbalanced configuration, while System B represents a structurally and functionally consistent system.

Step 2: Evaluation using compensatory logic

To reflect dominant approaches identified in the literature, a simple additive (compensatory) aggregation is applied, assuming equal weights across all dimensions.

The overall performance score is calculated as the arithmetic mean:

- System A: $(5 + 5 + 4 + 2 + 2 + 3 + 3 + 2 + 5 + 2)/10 = 33/10 = 3.3$

- System B: (3 + 3 + 3 + 3 + 3 + 3 + 3 + 3 + 3 + 3)/10 = 30/10 = 3.0

Under compensatory evaluation, System A is classified as superior, as high performance in digitalization and economic dimensions offsets deficiencies in resilience and sustainability.

Step 3: Evaluation using non-compensatory logic

In the proposed framework, system evaluation is based on minimum threshold conditions, reflecting the non-substitutability of critical dimensions.

Assuming a minimum acceptable threshold of 3 (moderate level) for each dimension:

- System A:
  - Resilience = 2—not satisfied
  - Robustness = 2—not satisfied
  - Environmental performance = 2—not satisfied
  - Social performance = 2—not satisfied

  Conclusion: Threshold condition not satisfied—System classified as non-viable
- System B:
  - All dimensions ≥ 3

  Conclusion: Threshold condition satisfied—System classified as viable.

Step 4: Interpretation and implications

The comparison clearly demonstrates the limitations of compensatory evaluation approaches. Despite achieving a higher aggregate score, System A fails to meet the minimum requirements in critical dimensions, particularly resilience and sustainability. As a result, it is classified as non-viable under the proposed framework.

In contrast, System B, although characterized by moderate performance across all dimensions, satisfies the threshold conditions and is therefore considered systemically viable.

This result highlights three key insights:

- High digitalization and economic performance do not guarantee system viability,
- Strengths in other areas cannot offset deficiencies in resilience and sustainability,
- Balanced system development is more critical than maximizing isolated performance indicators.

Step 5: Contribution to framework validation

This illustrative example confirms the core assumption of the proposed framework: *Logistics 5.0 system performance must be evaluated as a condition of feasibility rather than optimization*. The non-compensatory logic enables the identification of structurally unbalanced systems that would otherwise be misclassified as high-performing under traditional models. This directly addresses the key limitations identified in the literature, particularly the reliance on compensatory aggregation and the weak integration of sustainability constraints.

Although simplified, the example demonstrates the practical applicability of the framework and provides a foundation for future research focused on its quantitative operationalization and empirical validation.

From a practical perspective, the illustrative application presented in Section 7.5 demonstrates how the proposed framework may support managerial decision-making in Logistics 5.0 environments. In particular, the non-compensatory logic enables organizations to identify structurally imbalanced system configurations that may remain undetected under traditional additive maturity models. This may support practitioners in prioritizing investments not only toward digitalization but also toward resilience, sustainability, and human-centric capabilities. The framework may therefore serve as a strategic assessment and diagnostic tool for evaluating the viability of logistics systems under increasing operational uncertainty and sustainability constraints. Moreover, its layered architecture enables

adaptation to different organizational contexts, including warehousing, transportation systems, and supply chain networks.

The presented illustrative example may be further extended in future studies through the integration of quantitative indicators for resilience, robustness, adaptability, and reliability assessment, enabling empirical validation and sector-specific operationalization of the proposed framework.

8. Implications for Sustainable Economic Transformation

The proposed non-compensatory conceptual framework for Logistics 5.0 carries important implications that extend beyond the operational and organizational levels, contributing to a broader understanding of sustainable economic transformation. In contrast to traditional efficiency-oriented logistics paradigms, the findings of this study indicate a fundamental shift toward viability-oriented systems, in which resilience, sustainability, and human-centricity are not treated as auxiliary dimensions but as core and non-substitutable system properties. This transition reflects a deeper reconfiguration of how logistics systems are conceptualized, designed, and evaluated within the emerging Industry 5.0 ecosystem.

One of the key implications concerns the redefinition of performance logic in logistics and supply chain systems. The dominance of compensatory models in existing maturity and readiness frameworks has historically allowed trade-offs between critical dimensions, enabling high levels of digitalization or efficiency to offset deficiencies in sustainability or resilience. However, as demonstrated in this study, such an approach is increasingly insufficient in the context of complex and uncertain environments. The introduction of a non-compensatory logic implies that minimum threshold conditions must be satisfied across all critical dimensions, particularly in terms of environmental sustainability and system resilience. This represents a shift from optimization under constraints to system viability, where failure in one dimension cannot be neutralized by excellence in another. Consequently, the proposed framework supports the development of more balanced and robust logistics systems capable of sustaining long-term performance under disruption.

From a systemic perspective, the framework reinforces the view of Logistics 5.0 as a complex adaptive system characterized by the dynamic interaction of structural, functional, and performance layers. Digital technologies, including artificial intelligence, blockchain, and digital twins, act as enabling mechanisms that enhance system visibility, integration, and decision-making. However, their true value emerges only when they are embedded within a broader system architecture that explicitly incorporates functional capabilities such as adaptability, robustness, and recovery. This highlights a critical implication: technological advancement alone is insufficient to drive sustainable transformation unless it is aligned with system-level capabilities and performance objectives. As such, the integration of a dedicated functional capability layer within the framework provides a necessary bridge between technological readiness and actual system behavior.

The implications for sustainability are particularly significant. The findings of the literature review reveal that sustainability in Logistics 5.0 research is often treated as a secondary or compensable dimension, frequently subordinated to economic or technological objectives. In contrast, the proposed framework adopts a strong sustainability perspective, in which environmental and social dimensions are treated as non-substitutable and structurally embedded within the system. This has direct consequences for both research and practice, as it challenges prevailing approaches that rely on partial or indirect sustainability metrics. By introducing a dedicated sustainability layer, the framework enables a more comprehensive and integrated assessment of system performance, capturing not only efficiency gains but also long-term environmental and societal impacts.

At the organizational level, the framework provides guidance for decision-making and strategic planning in logistics and supply chain systems. It suggests that investments in digital technologies should be evaluated not only in terms of their immediate operational benefits but also in terms of their contribution to system resilience and sustainability. This implies a need for more holistic evaluation criteria, incorporating multi-dimensional performance indicators and non-compensatory assessment mechanisms. Furthermore, the explicit inclusion of human-centric aspects across system layers highlights the importance of workforce capabilities, collaboration, and human–technology interaction in achieving sustainable transformation. This aligns with the broader objectives of Industry 5.0, where human well-being and system performance are jointly optimized.

From a policy and economic perspective, the proposed framework supports the development of regulatory and strategic initiatives aimed at fostering resilient and sustainable supply chain ecosystems. The shift toward non-compensatory and system-based evaluation models implies that policy frameworks should move beyond incentivizing isolated technological adoption and instead promote integrated solutions that simultaneously address digitalization, resilience, and sustainability. This is particularly relevant in the context of global disruptions, climate change, and increasing regulatory pressure related to ESG and sustainability reporting. By providing a structured approach to linking readiness, capabilities, and performance outcomes, the framework can support policymakers in designing more effective instruments for guiding the transformation of logistics systems at regional and national levels.

Overall, the implications of this study suggest that sustainable economic transformation in the context of Logistics 5.0 requires a paradigm shift from fragmented and technology-centric approaches to integrated, system-level thinking. The proposed framework contributes to this transition by offering a coherent structure that aligns structural readiness, functional capabilities, and sustainability performance within a unified architecture. In doing so, it not only addresses the key gaps identified in the literature but also provides a foundation for future research and practical implementation aimed at developing resilient, sustainable, and human-centric logistics systems.

9. Conclusions

This study set out to systematize and critically assess the evolving body of knowledge on Logistics 5.0, with a particular focus on the relationships between readiness, system capabilities, and sustainability performance. By combining a structured literature review with a content-based analysis and a systemic interpretation, the paper identifies key conceptual inconsistencies and gaps that limit the current understanding and operationalization of Logistics 5.0. In response, a non-compensatory conceptual framework was proposed, aiming to integrate structural readiness, functional capabilities, and sustainability performance within a coherent, multi-layered architecture.

The findings of this study lead to several important conclusions. First, while Logistics 5.0 is widely recognized as a necessary evolution of logistics and supply chain systems in the context of Industry 5.0, it is not, in itself, sufficient to ensure sustainable and resilient outcomes. The literature demonstrates a strong focus on digitalization and technological advancement; however, these elements alone do not guarantee improvements in sustainability or system robustness. This highlights a fundamental misalignment between the means (digital transformation) and the desired ends (sustainable and resilient performance).

Second, the analysis clearly shows that readiness does not equate to sustainability. Existing maturity and readiness models predominantly assess the capability of organizations to adopt digital technologies and advanced practices, but they do not adequately capture whether such adoption leads to positive environmental or social outcomes. As

a result, systems characterized by high levels of digital maturity may still exhibit low sustainability performance, particularly when environmental and social dimensions are treated as secondary or compensable factors.

Third, sustainability in Logistics 5.0 should be understood as an emergent system property, rather than as an isolated or additive dimension. The results of the literature review indicate that sustainable performance arises from the interaction between structural readiness, functional system capabilities, and operational behavior under dynamic conditions. This reinforces the need for integrated and systemic modeling approaches that move beyond linear and static assessment frameworks.

Fourth, the study highlights the critical need for non-compensatory models in the evaluation and design of Logistics 5.0 systems. The dominance of compensatory logic in existing approaches leads to overestimation of system performance and obscures critical weaknesses, particularly in the areas of resilience and sustainability. By introducing a non-compensatory evaluation logic, the proposed framework ensures that minimum-threshold conditions must be satisfied across all key dimensions, preventing trade-offs that could undermine long-term system viability.

Despite these contributions, the study is subject to several limitations that should be acknowledged. First, the analysis is based on a structured literature review, which, although comprehensive, is inherently dependent on the selection criteria, databases, and keywords used. As a result, some relevant studies may not have been included, particularly those published in emerging or interdisciplinary outlets. Second, the proposed framework is conceptual in nature and has not yet been empirically validated. While it is grounded in an extensive synthesis of the literature, its practical applicability and effectiveness in real-world logistics systems require further testing. Third, the study adopts a qualitative and interpretative approach to content analysis, which, despite its depth, may introduce a degree of subjectivity in the classification and synthesis of research domains. Finally, the framework does not explicitly incorporate sector-specific or regional differences, which may influence the applicability of Logistics 5.0 concepts across different industries and economic contexts. Nevertheless, the use of a single discovery platform may introduce potential coverage bias, as not all records indexed in Scopus or Web of Science are necessarily fully represented or identically indexed within Primo. In particular, differences in metadata quality, indexing delays, and database-specific coverage may affect the completeness of retrieved results. This limitation is acknowledged and should be considered when interpreting the findings. However, the breadth of sources aggregated within Primo and the complementary use of additional search strategies (e.g., backward and forward snowballing) mitigate this risk and support the overall robustness of the review.

These limitations open several avenues for future research. A key direction involves the empirical validation and operationalization of the proposed non-compensatory framework, including the development of measurable indicators, thresholds, and decision-support tools. Future studies could also explore the integration of quantitative methods, such as fuzzy logic, multi-criteria decision-making, or system dynamics modeling, to enhance the robustness and applicability of the framework. Additionally, there is a need to investigate the dynamic behavior of Logistics 5.0 systems under disruption, particularly through simulation-based approaches and digital twin environments. Further research should also examine the role of human-centric factors, including skills, collaboration, and human–technology interaction, in shaping system performance. Finally, cross-sectoral and cross-regional studies would provide valuable insights into how the proposed framework can be adapted to different industrial contexts and policy environments.

In conclusion, this study contributes to the advancement of Logistics 5.0 research by shifting the focus from fragmented and technology-centric approaches toward an inte-

grated, system-level perspective. By emphasizing the interdependencies between readiness, capabilities, and sustainability performance, and by introducing a non-compensatory evaluation logic, the proposed framework provides a foundation for more robust, resilient, and sustainable logistics systems. This perspective is essential for bridging the gap between conceptual development and practical implementation, and for supporting the broader transition toward sustainable economic systems in the era of Industry 5.0.

Supplementary Materials: The following supporting information can be downloaded at https://www.mdpi.com/article/10.3390/su18115630/s1, Table S1: The PRISMA Checklist, Table S2: Bibliographic dataset and classification of analyzed publications. In addition, the systematic review protocol has been prospectively registered in the Open Science Framework (OSF) under the identifier: https://doi.org/10.17605/OSF.IO/HS32W.

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Abbreviations

The following abbreviations are used in this manuscript:

AHP	Analytical Hierarchy Process
AI	Artificial Intelligence
CO_2	Carbon dioxide
DEMATEL	Decision-Making Trial and Evaluation Laboratory
DT	Digital Twin
ESG	Environmental, Social, and Governance
IoT	Internet of Things
MCDM	Multi-Criteria Decision-Making
ML	Machine Learning
NAToRM	Neuromorphic Adaptive Topological Risk Management
PRISMA	Preferred Reporting Items for Systematic Reviews and Meta-Analyses
SCM	Supply Chain Management
SCOR	Supply Chain Operations Reference
SDGs	Sustainable Development Goals
SMEs	Small and Medium-Sized Enterprises
TOPSIS	Technique for Order of Preference by Similarity to Ideal Solution

Appendix A. Detailed Search Strategy and Review Protocol Transparency

Appendix A.1. Database and Search Platform

The literature search was conducted using the ProQuest Primo Discovery System (Ex Libris), available via the Wroclaw University of Science and Technology library portal (https://omnis-pwr.primo.exlibrisgroup.com/) (accessed on 1 May 2026). Primo functions as an integrated discovery platform aggregating records from multiple academic databases (e.g., Scopus, Web of Science collections, Springer, Elsevier, IEEE), enabling broad and interdisciplinary coverage. While Primo is not a single bibliographic database, it provides unified access to multiple sources through a centralized query interface. This approach was selected to ensure comprehensive retrieval of literature across logistics, engineering, and sustainability domains.

Appendix A.2. Search Query and Sequential Filtering

The search strategy was constructed using four thematic query blocks combined with the Boolean operator **AND**, while synonyms within each block were combined using **OR**. The search was performed in the **"any field"** category.

Full Boolean query:

(Logistics 5.0 OR supply chain 5.0 OR smart logistics OR digital logistics OR intelligent logistics)

AND

(maturity OR capability OR capabilities OR performance OR preparedness)

AND

(readiness OR resilience OR robustness OR adaptability OR reliability)

AND

(sustainability OR ESG OR green OR sustainable OR circular economy OR eco-friendly)

Appendix A.3. Stepwise Search Results (Query Combination Logic)

To ensure transparency and reproducibility, the search process was conducted sequentially, combining query blocks step by step. The results at each stage are summarized in Table A1.

Table A1. Stepwise query combination and number of retrieved records.

Step	Query Combination	Description	Number of Records
Q1	("Logistics 5.0" OR "supply chain 5.0" OR "smart logistics" OR "digital logistics" OR "intelligent logistics")	Domain-related keywords	884,803
Q1 + Q2	Q1 AND (maturity OR capability OR capabilities OR performance OR preparedness)	Addition of maturity/performance dimension	35,758
Q1 + Q2 + Q3	(Q1 + Q2) AND (readiness OR resilience OR robustness OR adaptability OR reliability)	Addition of system capability dimension	5531
Q1 + Q2 + Q3 + Q4	(Q1 + Q2 + Q3) AND (sustainability OR ESG OR green OR sustainable OR "circular economy" OR "eco-friendly")	Full query	1618
Q1–Q4 + expanded results	Full query with Primo "expand results" option enabled	Inclusion of additional relevant records	1724

Appendix A.4. Filtering and Refinement Process

Following the initial search, a series of filters was applied to refine the dataset. The filtering process and corresponding results are presented in Table A2.

Table A2. Filtering steps and reduction of records.

Step	Filter Applied	Description	Number of Records
F1	Time range (2016–2026)	Restriction to relevant publication period	1656
F2	Language (English only)	Exclusion of non-English publications	1614
F3	Exclusion of medical-related databases	Removal of irrelevant disciplinary domains	1397
F4	Peer-reviewed publications only	Inclusion of scientific journal articles	516
F5	Accessibility filter	Removal of inaccessible records	513

After applying all filters, 513 publications were retained for further screening and eligibility assessment.

Appendix A.5. Screening and Selection Procedure

The screening process followed PRISMA guidelines and included relevance-based filtering:

- Initial screening (title/abstract/full text): **133 publications selected** (non-relevant and purely review-type papers excluded)
- Snowballing procedure (backward and forward citation tracking): **+16 additional publications**
- Final dataset: **149 publications**

Appendix A.6. Inter-Reviewer Agreement

To ensure consistency and reduce selection bias, a dual-reviewer screening approach was applied during the eligibility assessment stage. The independent inclusion/exclusion decisions of both reviewers are summarized in Table A3.

Table A3. Results of the dual-reviewer approach.

	Reviewer B: Include	**Reviewer B: Exclude**
Reviewer A: Include	136	8
Reviewer A: Exclude	1	4

Based on these results, the observed agreement between reviewers reached 93.96%. Inter-rater reliability was additionally evaluated using Cohen's kappa coefficient ($\kappa \approx 0.43$), indicating a moderate level of agreement. The relatively moderate κ value, despite the high observed agreement, is associated with the imbalanced inclusion–exclusion distribution, where inclusion decisions substantially dominated the screening outcomes. This phenomenon is consistent with the known sensitivity of Cohen's kappa to prevalence imbalance in binary classification tasks.

All disagreements were subsequently discussed jointly by both reviewers and resolved through consensus based on the predefined eligibility criteria. The kappa coefficient was calculated before the consensus discussion stage and was not recomputed afterward, as the final decisions reflected reconciled rather than independent reviewer assessments.

Appendix A.7. Analytical Workflow

A hybrid analytical approach was adopted:

PRISMA → Bibliometrix → VOSviewer → validation metrics → content-based analysis

- Bibliometric analysis: Bibliometrix (R package), R 4.6.0 and RStudio 2026.05.0+218
- Network analysis: VOSviewer version 1.6.20
- Validation: clustering and consistency metrics
- Qualitative synthesis: aligned with research questions

Appendix A.8. Methodological Limitations

Despite the comprehensive approach, several limitations should be acknowledged:

- The use of a single discovery platform (Primo), although aggregating multiple sources, may introduce **coverage bias** compared to explicitly querying Scopus or Web of Science independently.
- The application of the **"expand results"** function may affect strict reproducibility across different institutional settings.
- Terminological variability across disciplines may result in partial omission of relevant studies.
- Restricting the search to English-language publications may limit the inclusion of regional research.

To mitigate these limitations, a **snowballing procedure** was applied, and the query was designed to ensure broad conceptual coverage.

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