Journal of Technology Management & Innovation | 2026. Volume 21, Issue 2

DOI: https://doi.org/10.4067/s0718-2724202600025068

The DSC-R Framework: Integrating Technology Transfer, Anthropotechnology, And Industry 4.0 For Digital Supply Chain Resilience

Danilo Inácio[1*], *João Luiz Kovaleski*[1], *Angelo Marcelo Tusset*[1], *Giane Gonçalves Lenzi*[1]

Abstract

Digital supply chains (DSCs) operate in increasingly volatile environments, demanding resilience capabilities that extend beyond technological integration. Although the literature extensively addresses Technology Transfer (TT), Anthropotechnology (AT), and Industry 4.0 (I4.0) as independent domains, a systematic search of the SCOPUS and Web of Science databases revealed no study simultaneously integrating these four constructs, namely TT, AT, I4.0, and DSC, within a single conceptual model, confirming a critical gap in the field. To address this gap, this study proposes the DSC-R Framework, an integrative model that extends the articulation of TT, AT, and I4.0 into the domain of digital supply chain resilience through a five-layer architecture that unifies human, technological, and organizational dimensions. A qualitative integrative literature review was conducted using Boolean operators across four thematic axes, followed by critical analysis, theoretical triangulation, and cross-validation of constructs. The resulting framework is organized into five interconnected layers, comprising strategic guidelines, an integrating triad (TT-AT-I4.0), resilience capabilities, vulnerability assessment, and consolidated results, supported by 14 operational resilience capabilities, key performance indicators, technology transfer pathways, and practical implementation tools. Four conceptual propositions demonstrate how dynamic learning, sociotechnical adaptation, and continuous innovation interact to sustain DSC resilience over time. The DSC-R Framework advances the state of the art by integrating traditionally isolated domains, providing theoretical foundations and managerial guidelines for building robust and adaptive digital supply chains. The model is particularly relevant for petrochemicals, Oil and Gas, fertilizers, and digital manufacturing, establishing a basis for future empirical validation through case studies, surveys, and quantitative modeling.

Keywords: Digital Supply Chain Resilience; Technology Transfer; Anthropotechnology; Industry 4.0; Sociotechnical Systems; Dynamic Capabilities.

Submitted: May 31, 2026 / Approved: July 28, 2026

1. Introduction

The intensification of global disruptions over the past decade, encompassing the COVID-19 pandemic, geopolitical conflicts, and critical raw material shortages, has exposed fundamental vulnerabilities in digital supply chains (DSCs) and elevated organizational resilience to the forefront of management research. Simulation-based analyses confirm that epidemic outbreaks alone affected over 94% of Fortune 1000 companies, generating cascading failures across interconnected supply networks worldwide (Dolgui et al., 2018; Ivanov, 2020). DSCs, defined as production and distribution networks underpinned by digital technologies such as the Internet of Things (IoT), Artificial Intelligence (AI), and cyber-physical systems, have become central to organizational competitiveness and long-term sustainability (Lasi et al., 2014; Waller & Fawcett, 2013). The accumulated evidence from these disruptions demonstrates that technological sophistication alone does not confer resilience. Building adaptive, robust, and recoverable digital supply chains requires the systematic integration of human, organizational, and technological dimensions within a coherent theoretical framework (Christopher & Peck, 2004; Hohenstein et al., 2015).

Research on supply chain resilience has advanced considerably, producing significant contributions on disruptions, recovery mechanisms, and adaptive capabilities (Castillo, 2023; Hohenstein et al., 2015). In parallel, Industry 4.0 (I4.0) has generated a robust body of knowledge on how digital technologies reshape production processes and organizational models, while imposing new demands on human capital and institutional processes (Geldes, 2023; Lasi et al., 2014; Peña & Caruajulca, 2022). Technology Transfer (TT) has equally attracted sustained academic attention as a critical process governing the diffusion and absorption of innovations, with absorptive capacity recognized as a determinant factor for successful assimilation (Alkhazaleh et al., 2022; Cohen & Levinthal, 1990; Corsi et al., 2021). More recently, Anthropotechnology (AT) has emerged as an essential theoretical lens for understanding sociotechnical adaptations when humans interact with complex technological systems, highlighting that cultural, cognitive, and contextual dimensions fundamentally mediate digital transformation (Peña & Caruajulca, 2022; Puzio, 2025).

However, these research streams have evolved largely in isolation. Despite the recognized interdependence between human factors, knowledge transfer processes, digital technologies, and organizatio-

[1]Departamento de Pós-Graduação, Universidade Tecnológica Federal do Paraná, Ponta Grossa, PR, Brazil.
*Corresponding author: daniloinacio@alunos.utfpr.edu.br

nal resilience Mick et al., (2024); Teece et al., (1997), no published framework integrates TT, AT, I4.0, and DSC resilience within a unified conceptual model. A systematic search of the SCOPUS and Web of Science databases, covering over 288,000 individual-axis records across the four thematic axes, returned zero studies simultaneously addressing all four constructs. This disciplinary fragmentation prevents organizations from developing the dynamic capabilities necessary to sustain flexibility, robustness, and adaptive learning in the face of contemporary disruptions (Dolgui et al., 2018; Teece et al., 1997). The absence is particularly consequential for capital-intensive sectors such as petrochemicals, Oil and Gas, and fertilizers, where supply chain disruptions carry severe operational and financial implications (Geldes, 2023; Valič & Uršič, 2024). Such fragmentation represents both a theoretical gap and a practical barrier to DSC resilience in complex digital environments (Corsi et al., 2021; Ivanov & Dolgui, 2020)

This study addresses the following research question: How can the integration of Technology Transfer, Anthropotechnology, and Industry 4.0 be structured into a coherent framework that strengthens resilience in digital supply chains? To answer this question, the study proposes the DSC-R Framework, an integrative conceptual model that systematically extends the articulation of TT, AT, and I4.0 into digital supply chain resilience, structuring their convergence into a five-layer architecture applicable to complex industrial environments. The framework is organized into five interconnected layers, comprising strategic guidelines, an integrating triad (TT-AT-I4.0), operational resilience capabilities, vulnerability assessment, and consolidated performance results, supported by 14 resilience capabilities, governance mechanisms, technology transfer pathways, and practical implementation tools.

This study advances the literature through three distinct theoretical contributions. First, it addresses the persistent fragmentation among TT, AT, and I4.0 research streams by proposing a systemic perspective on their interdependencies, demonstrating how their structured convergence enables organizations to sense, seize, and reconfigure capabilities in response to digital disruptions, consistent with the dynamic capabilities framework (Teece et al., 1997). Second, it positions Anthropotechnology as a central mediating axis in digital transformation processes within supply chain contexts, an element largely overlooked in existing DSC frameworks despite its demonstrated role in bridging technology adoption barriers and fostering human-organizational alignment (Corsi et al., 2021; Peña & Caruajulca, 2022). Third, it operationalizes theoretical constructs into practical management tools, including resilience indicators, organizational roles, technology transfer pathways, and implementation checklists, thereby addressing a recognized gap between conceptual frameworks and actionable managerial guidance in complex industrial environments (Hohenstein et al., 2015; Mick et al., 2024). The remainder of this paper is organized as follows: Section 2 reviews the theoretical foundations; Section 3 describes the methodological approach; Section 4 presents the conceptual model, framework architecture, and operationalization guidance; Section 5 discusses the findings in relation to the literature; and Section 6 presents conclusions, limitations, and directions for future research.

2. Literature Review

This chapter reviews the theoretical foundations underpinning resilience in digital supply chains (DSCs), critically examining four interrelated domains: Anthropotechnology (AT), Technology Transfer (TT), Industry 4.0 (I4.0), and Organizational Resilience. Rather than treating these domains in isolation, the review identifies convergences, tensions, and theoretical gaps that collectively motivate the integrative framework proposed in this study.

2.1. Anthropotechnology (AT): Human Mediation in Technological Systems

Anthropotechnology (AT) emerged from the ergonomic tradition of Wisner, (1995, 2004), who argued that effective technology transfer depends not only on technical compatibility but on the alignment of technological solutions with the cultural, historical, and cognitive context of the receiving organization. This origin positions AT as theoretically related to, but analytically distinct from, the broader sociotechnical systems (STS) tradition.

STS, originating with Trist & Bamforth, (1951) and developed through the Tavistock Institute tradition, is principally a theory of organizational design, establishing that optimal performance requires the joint optimization of social and technical subsystems within a given organizational unit. Its prescriptive orientation is toward restructuring organizations to align human and technical elements and does not, by design, address the conditions under which knowledge and technological artifacts are transferred, received, and assimilated by organizations that differ in culture, cognitive repertoire, and institutional context from those in which the technology was originally developed.

AT addresses precisely this boundary-crossing problem. Where STS asks how to optimize the relationship between people and technology within an existing organizational system, AT asks how technologies can be made transferable across cultural and contextual boundaries without losing effectiveness or generating resistance (Daniellou, 2006; Wisner, 1995). This distinction is consequential for DSC resilience: the challenge is not only the internal optimization of human-technology interaction within a single firm but the effective diffusion of digital technologies across organizational partners, national contexts, and sectoral specificities, where cultural and cognitive barriers are as determinant as technical compatibility (Corsi et al., 2021; Kovaleski et al., 2022).

This boundary-crossing function distinguishes AT not only from STS but also from boundary-spanning and boundary objects frameworks (Star & Griesemer, 1989), which address the coordination of heterogeneous actors across institutional domains but do not prescribe the human-adaptive and ergonomic conditions under which technology itself becomes transferable. AT's advantage derives from its specific theoretical origin in diagnosing failures of technology transfer from industrialized to developing economies (Wisner, 1995, 2004), precisely the challenge faced by capital-intensive sectors such as petrochemicals, Oil and Gas, and fertilizers, where digital technologies must be assimilated under high-regulation, high-complexity, and culturally heterogeneous conditions that more general boundary-spanning frameworks are not designed to address.

Contemporary AT scholarship extends this boundary-crossing perspective into the challenges of digital transformation. Corsi et al., (2021) demonstrate that AT, TT, and sustainable development are mutually reinforcing when managed strategically across organizational boundaries, while Peña & Caruajulca, (2022) show that the human factor is as determinant as technological selection in I4.0 adoption processes precisely because cultural and cognitive barriers mediate the reception of digital innovations. Puzio, (2025) advances this line of argument by proposing a new materialist account of human-technology entanglement, establishing that cognitive, cultural, and organizational adaptations are not peripheral conditions but structural prerequisites for sustainable digital innovation. A persistent gap in the AT literature concerns its limited application to supply chain contexts: while the field is well developed in ergonomics and organizational behavior, its integration with DSC resilience remains underexplored Corsi et al., (2021); Kovaleski et al., (2022), a gap that the DSC-R Framework is designed to address by embedding AT as a central mediating axis rather than a peripheral moderator.

2.2. Technology Transfer (TT): Knowledge Diffusion and Absorptive Capacity

Technology Transfer encompasses the multidimensional process of diffusing and assimilating knowledge, competences, and technological artifacts across organizational and sectoral boundaries (Alkhazaleh et al., 2022; Mick et al., 2024). The absorptive capacity framework of Cohen & Levinthal, (1990) remains the dominant theoretical lens, establishing that prior knowledge and the ability to recognize, assimilate, and apply new information are determinants of successful technology adoption (Alkhazaleh et al., 2022). Organizational culture and barriers including cultural incompatibilities, competence gaps, and resistance to change are well-documented moderators of TT effectiveness(Alkhazaleh et al., 2022; Corsi et al., 2021; Wisner, 1995, 2004). Digitalization is reshaping TT dynamics through interorganizational collaboration Adomako & Nguyen, (2024) and virtualization in strategic partnerships (Sarala et al., 2025), yet existing frameworks rarely address the human sociotechnical dimension, a gap AT is well positioned to fill (Kovaleski et al., 2022; Mick et al., 2024). University-industry collaboration through Technology Transfer Offices represents an emerging institutional mechanism for structuring this process (Valič & Uršič, 2024).

2.3. Industry 4.0 (I4.0): Digital Integration and Organizational Transformation

Industry 4.0 is characterized by the convergence of cyber-physical systems, IoT, AI, Big Data analytics, and intelligent automation, reshaping production processes and supply chain management (Lasi et al., 2014; Mick et al., 2024). I4.0 introduces organizational challenges requiring digital competencies and human capital investment (Alfaqiyah et al., 2025; Peña & Caruajulca, 2022), amplified in emerging economies by institutional barriers and resource constraints (Geldes, 2023). A central debate concerns the balance between technological capability and human readiness: while Lasi et al., (2014) and Sharma et al., (2024) emphasize operational efficiency, Peña & Caruajulca, (2022) and Mick et al., (2024) argue sociotechnical adaptation is equally essential, the gap AT and TT address within a unified framework.

2.4. Digital Supply Chain Resilience: Concepts, Capabilities, and Gaps

Organizational resilience in supply chains is broadly defined as the ability to anticipate, absorb, adapt to, and recover from disruptions, restoring operational functionality in a timely and cost-effective manner (Christopher & Peck, 2004; Hohenstein et al., 2015). Sheffi & Rice, (2005) distinguish between resilience as a structural property of supply chain design and as an organizational capability developed through culture and process, a distinction critical for the DSC-R Framework, which requires robust organizational and human foundations alongside technological investment. Digitalization enhances visibility and response speed through IoT, AI, blockchain, and advanced analytics (Waller & Fawcett, 2013; Winkelmann et al., 2024; Zhao et al., 2023), but also creates systemic risks as disruptions propagate across intertwined networks, the ripple effect (Dolgui et al., 2018; Ivanov & Dolgui, 2020). Li et al., (2023) show that effectiveness depends on governance and inter-organizational collaboration. The resilience literature consistently highlights that human and organizational dimensions are as determinant as technological capabilities Castillo, (2023); Hohenstein et al., (2015); Tortorella et al., (2022), yet existing frameworks rarely operationalize this interdependence.

2.5. Review Synthesis: Identifying the Integrative Gap

The four domains reviewed above, AT, TT, I4.0, and DSC resilience, share a fundamental theoretical concern: how do organizations build the dynamic capabilities necessary to sense environmental changes, seize adaptation opportunities, and reconfigure resources and competences in response to disruptions (Teece, 2007; Teece et al., 1997)? The dynamic capabilities perspective provides the overarching theoretical mechanism that connects the four domains, yet no published framework operationalizes this connection within a unified model applicable to digital supply chains.

The review reveals three specific gaps. First, AT and TT are rarely integrated with DSC resilience models, despite strong theoretical complementarity: AT addresses the human and cultural dimensions that TT models tend to overlook, and both are essential for the effective absorption of I4.0 technologies (Corsi et al., 2021; Kovaleski et al., 2022; Mick et al., 2024). Second, existing DSC resilience frameworks tend toward either purely technological approaches, neglecting human mediation, or purely organizational approaches, neglecting the enabling role of digital infrastructure, confirming the fragmentation identified in the SCOPUS and Web of Science search results. Third, the operationalization of resilience concepts into actionable management tools remains limited, with most frameworks offering theoretical taxonomies rather than implementable guidance for managers (Castillo, 2023; Hohenstein et al., 2015).

These three gaps collectively justify the development of the DSC-R Framework as a systemic, integrated, and operationally oriented response to the demands of digital supply chain resilience in the contemporary industrial environment.

ISSN: 0718-2724 - **Journal of Technology Management & Innovation** - **www.jotmi.org**

3. Methodology

To address the research question, how can the integration of Technology Transfer, Anthropotechnology, and Industry 4.0 be structured into a coherent framework that strengthens resilience in digital supply chains, this study adopts a qualitative, theoretical-integrative design. This chapter describes the research design, epistemological positioning, search strategy, selection procedures, and conceptual development process. All methodological choices are explicitly justified with respect to their suitability for the research objective and the integrative nature of the investigation.

3.1. Research Design and Epistemological Positioning

Qualitative and integrative approaches are particularly appropriate when the research objective involves synthesizing dispersed theoretical bodies, identifying convergences and gaps, and constructing new explanatory models from existing knowledge (Torraco, 2005; Whittemore & Knafl, 2005). The sociotechnical and organizational interrelations inherent to DSCs involve complex interdependencies among human, cultural, and technological dimensions that are not reducible to quantitative measurement alone, further justifying the adoption of an integrative review as the primary method (Mick et al., 2024; Peña & Caruajulca, 2022).

The epistemological positioning of this study is constructivist-interpretive, grounded in the assumption that theoretical constructs are socially situated and that knowledge advances through critical integration and reinterpretation of existing frameworks. This positioning is consistent with established practice in developing conceptual frameworks in management research, where the goal is to generate theoretical coherence, explanatory depth, and practical applicability rather than causal-predictive conclusions (Gioia et al., 2013). Regarding ethical considerations, this study relies exclusively on publicly indexed literature, with no human participant data. Accordingly, no ethical approval was required, and all sources are fully cited.

3.2. Search Strategy and Selection Criteria

The literature search was conducted in 2026, with no lower time limit, to maximize coverage of foundational and recent contributions across the four thematic axes. SCOPUS and Web of Science (WoS) were selected for their multidisciplinary coverage, international scope, and rigorous indexing standards, appropriate for systematic and integrative reviews in technology management and innovation research (Corsi et al., 2021; Tranfield et al., 2003). Using both databases reduces single-source dependency and enhances corpus representativeness and robustness. Advanced Boolean search strings were applied to titles, abstracts, and keywords across four thematic axes: Technology Transfer (TT), Anthropotechnology (AT), Industry 4.0 (I4.0), and Digital Supply Chain (DSC). Table 1 presents the keyword combinations employed.

Table 1. Combination of Keywords (Summary of Search Strings)

Axis 1 – Technology Transfer Keywords	Boolean Operator	Axis 2 – Anthropotechnology Keywords	Boolean Operator	Axis 3 – Industry 4.0 Keywords	Boolean Operator	Axis 4 – Digital Supply Chain Keywords
“technology transfer”	AND	“anthropotechnology”	AND	“industry 4.0”	AND	“digital supply chain”
OR		OR		OR		OR
“knowledge transfer”		“human-technology interaction”		“Industrie 4.0”		“supply chain 4.0”
OR		OR		OR		OR
“technology diffusion”		“human factors”		“fourth industrial revolution”		“intelligent supply chain”
OR		OR		OR		OR
“innovation adoption”		“socio-technical”		“smart manufacturing”		“smart supply chain”
OR		OR		OR		OR
“adoption of technology”		“sociotechnical systems”		“cyber-physical systems”		“supply chain automation”
OR		OR		OR		OR
“technological adoption”		“technology acceptance”		“digital transformation”		“supply chain digitalization”
OR		OR		OR		OR
“innovation diffusion”		“workforce adaptation”		“industrial IoT”		“connected supply chain”

Inclusion criteria: peer-reviewed articles or review papers published in English; fully available in SCOPUS or WoS; addressing one or more of the four thematic axes with theoretical or empirical relevance for innovation management, supply chain management, or technology adoption.

Exclusion criteria: conference proceedings without subsequent journal publication; grey literature and technical reports; articles with no direct conceptual connection to at least one of the four thematic axes; duplicate records identified across both databases.

ISSN: 0718-2724 - **Journal of Technology Management & Innovation** - **www.jotmi.org**

The search strategy served two complementary and methodologically distinct functions, each addressed through a dedicated procedure, consistent with integrative review practice (Torraco, 2005; Whittemore & Knafl, 2005): bibliometric gap identification, conducted through combined-axis searches; and theoretical corpus construction, conducted through targeted selection from individual-axis results. These two functions are reported separately in the following subsection. The complete search results for the gap identification function are presented in Table 2 and Table 3.

3.3. Search Outcomes and Gap Identification

The individual-axis searches returned a substantial corpus of indexed publications, confirming the academic maturity of each standalone theme. As shown in Table 2, the combined searches identified over 84,000 records for TT, 94,000 for AT, and 107,000 for I4.0 across SCOPUS and WoS, while DSC returned a more focused corpus of 1,831 records, totalling over 288,000 records across all four axes.

Table 2. Number of Studies Found in Each Independent Axis

DATABASE	AXIS 1 Technology Transfer	AXIS 2 Anthropotechnology	AXIS 3 Industry 4.0	AXIS 4 Digital Supply Chain
SCOPUS	50,328	53,268	59,046	1,063
WoS	34,227	41,570	48,265	768
TOTAL	**84,555**	**94,838**	**107,311**	**1,831**

When the axes were combined using AND operators, the volume of intersecting results decreased sharply, confirming the fragmented state of the literature across these domains. Table 3 presents the combined search results.

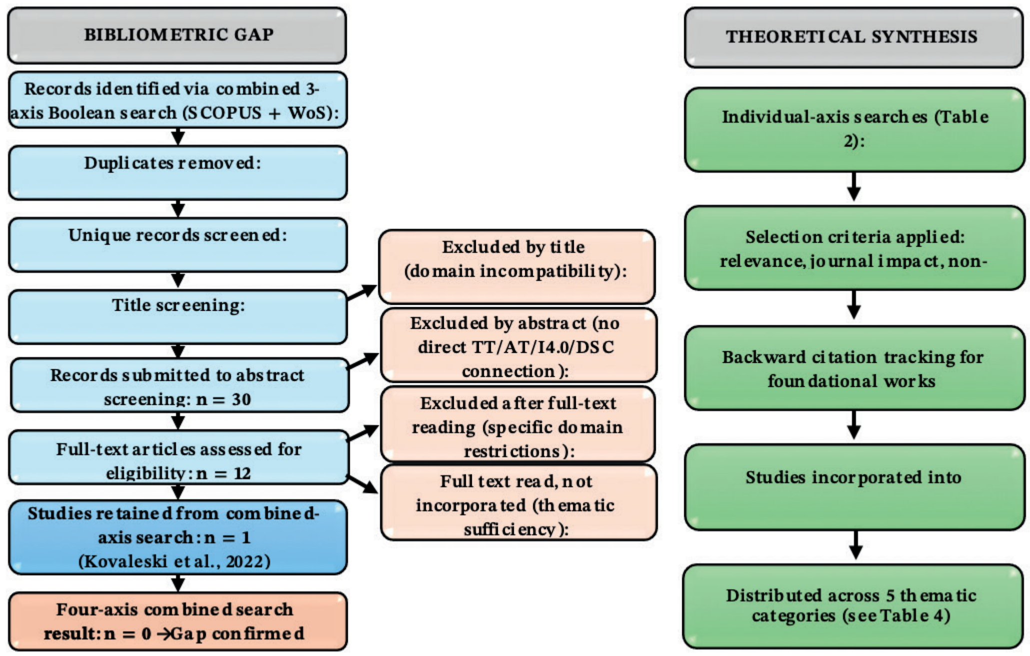
Table 3. Number of Studies Found in Combined Axes

DATABASE	(AXIS 1 + AXIS 2 + AXIS 3)	(AXIS 1 + AXIS 2 + AXIS 3 + AXIS 4)
SCOPUS	44	0
WoS	36	0
TOTAL	**80**	**0**

Search Outcomes: Bibliometric Evidence of the Research Gap: The absence of any study simultaneously integrating all four constructs, confirmed by zero results in both databases for the four-axis combination, constitutes the primary bibliometric evidence of the research gap addressed by this study. This absence is not attributable to limited scholarly attention, each individual axis attracts tens of thousands of indexed publications, but rather to disciplinary boundaries that have historically separated technology management, ergonomics, digital operations, and supply chain research.

The screening procedure applied to the combined-axis corpus produced the following outcomes (Figure 1). Of the 80 records retrieved from the three-axis search, 26 cross-database duplicates were removed, yielding 54 unique records for screening. Title screening excluded 24 records due to domain incompatibility, including studies on education, healthcare, agriculture, pure technology acceptance models (TAM/TOE), and industrial sectors unrelated to digital supply chain management. The remaining 30 records underwent abstract screening, excluding 18 records lacking direct conceptual connections to TT, AT, I4.0, or DSC resilience. Twelve records proceeded to full-text assessment. Of these, 3 were excluded due to domain restrictions incompatible with the study scope, while 8 were reviewed but not included, as their theoretical dimensions were already represented by higher-impact references in the individual-axis corpus. One study was retained from the combined-axis screening and incorporated into the synthesis: Kovaleski et al., (2022), representing the closest existing integration of TT, AT, and I4.0 in indexed literature. Figure 1 presents the complete selection flow.

Figure 1. Literature Search and Selection Flow



Individual-axis search results are detailed in Table 2. The synthesis corpus distribution by thematic category is presented in Table 4. Records in the right column were not screened through the five-step procedure, as they were selected through targeted quality-based criteria rather than exhaustive retrieval.

Theoretical Synthesis Corpus: Given that the combined-axis search confirmed the absence of prior integrative frameworks, the theoretical corpus was constructed through targeted selection from the individual-axis searches (Table 2,), supplemented by backward citation tracking from retained records. Articles were selected according to three hierarchical criteria applied sequentially: direct conceptual relevance to at least one thematic axis (TT, AT, I4.0, or DSC resilience); publication in a recognized high-impact journal or established seminal status within the relevant research domain; and non-redundant theoretical contribution to the synthesis. Foundational works that predate contemporary database indexing were incorporated through backward citation tracking from the retained records, consistent with integrative review methodology (Torraco, 2005).

The resulting synthesis corpus comprises 42 references distributed across five thematic categories: Anthropotechnology (n = 7), Technology Transfer (n = 9), Industry 4.0 (n = 5), Digital Supply Chain Resilience (n = 13), and cross-axis integrative contributions (n = 3), supplemented by four methodological references. Table 4 presents the distribution of the synthesis corpus by thematic category and source type.

Table 4. Distribution of the Theoretical Synthesis Corpus by Thematic Category

Thematic Category	Classical Foundational Works	Recent High-Impact Contributions	Total
Anthropotechnology (AT)	5	2	7
Technology Transfer (TT)	2	7	9
Industry 4.0 (I4.0)	1	4	5
Digital Supply Chain Resilience (DSC-R)	6	7	13
Cross-axis integrative (TT+AT+I4.0)	1	2	3
Organizational Theory	2	0	2
Methodological references	4	0	4
Total	**21**	**22**	**42**

Classical foundational works were incorporated through backward citation tracking from retained records. Cross-axis integrative references address two or more thematic axes simultaneously. Methodological references guided the integrative review design and are not counted in the thematic synthesis totals.

ISSN: 0718-2724 - **Journal of Technology Management & Innovation** - www.jotmi.org

3.4. Conceptual Framework Development Process

The development of the DSC-R Framework was structured in three sequential stages, aligned with established integrative review methodology Torraco, (2005), with the search and selection procedures informed by systematic review principles (Tranfield et al., 2003). In the first stage, the integrative review enabled the systematic identification of theoretical constructs, interdisciplinary relationships, and convergences across AT, TT, I4.0, and DSC resilience literature. In the second stage, critical and comparative analysis of the constructs was conducted to map synergies, tensions, and unexplored intersections, guided by the dynamic capabilities framework as an overarching theoretical lens (Teece et al., 1997). In the third stage, conceptual modeling integrated the theoretical elements into a cohesive, multi-layered structure organized according to strategic, tactical, and operational levels of analysis.

Theoretical validity was ensured through three mechanisms: source triangulation across both SCOPUS and WoS databases; cross-validation of constructs against recognized frameworks in supply chain resilience literature (Hohenstein et al., 2015; Ivanov & Dolgui, 2020); and systematic comparison of complementary theoretical perspectives to verify internal consistency. As a conceptual study, the framework lacks quantitative empirical validation, a recognized limitation explicitly addressed in the Discussion and Conclusions sections. Future studies employing case analyses, structured surveys, and advanced quantitative modeling are recommended to test and refine the model across diverse industrial contexts.

4. Results

The integrative review produced three interconnected results: first, the convergence of TT, AT, and I4.0 generates emergent integration mechanisms no single axis can produce independently; second, this convergence was formalized into four conceptual propositions; and third, the propositions were operationalized into the DSC-R Framework, a modular five-layer architecture. Each component is presented below.

4.1. Multidisciplinary Theoretical Integration

The synthesis of TT, AT, and I4.0 reveals that their convergence produces adaptive properties that cannot be attributed to any single axis operating independently. This claim requires explicit justification, as convergence between theoretical domains does not automatically produce emergence: it does so only when the interaction between domains generates mechanisms that are absent when each domain operates alone.

The argument for emergence proceeds in two steps. First, each axis contributes a distinct and non-substitutable capability to the integrative triad: TT supplies the organizational infrastructure for absorbing and routinizing new knowledge across boundaries (Cohen & Levinthal, 1990; Mick et al., 2024); AT supplies the human-adaptive mechanisms that determine whether knowledge transfer produces genuine behavioral and cultural change or remains a formal transaction (Corsi et al., 2021; Wisner, 1995); and I4.0 supplies the digital infrastructure that accelerates sensing, processing, and response across supply chain networks (Alfaqiyah et al., 2025; Lasi et al., 2014). Each of these contributions is present, to varying degrees, in existing frameworks. What is not present in any existing framework is their structured co-activation.

The term "emergent," as employed in this study, denotes organizational-level capabilities that arise from the structured co-activation of TT, AT, and I4.0 and that are not attributable to any single axis operating independently. This usage is consistent with the dynamic capabilities framework, in which higher-order capabilities emerge from the coordinated deployment of complementary organizational routines (Teece et al., 1997), and does not invoke the stronger epistemological claims associated with emergence in complex adaptive systems theory. The three mechanisms identified in the following subsection, Knowledge Flow, Sociotechnical Flow, and Technological Flow, constitute the specific interaction pathways through which this organizational-level emergence operates, and their empirical verification remains a priority for future research.

As shown in Table 5, the individual contributions of each axis to DSC resilience are substantial but partial: TT addresses knowledge diffusion, AT addresses human mediation, and I4.0 addresses digital integration, and none of these dimensions alone is sufficient to sustain resilience in the face of contemporary disruptions.

Table 5. Synthesis of the Foundations and Contributions of the TT, AT, and I4.0 Axes

Axis	Main Theoretical Foundations	Relevant Contributions to Resilience in DSCs	Key References
Technology Transfer (TT)	Multidimensional process of dissemination and absorption of knowledge and innovation.	Facilitates the integration of disruptive technologies into production chains.	(Alkhazaleh et al., 2022; Cohen & Levinthal, 1990; Mick et al., 2024).
	Organizational absorptive capacity as a critical factor.	Supports technological adaptation and continuous innovation.	
	Cultural, cognitive, and organizational barriers to technological diffusion.	Promotes alignment between technological demands and internal capabilities.	
Anthropotechnology (AT)	Human–technology interaction in sociotechnical contexts.	Favors the overcoming of cultural and cognitive resistance.	(Corsi et al., 2021; Peña & Caruajulca, 2022; Puzio, 2025).
	Learning, cultural adaptation, and digital competencies.	Enhances organizational learning and sociotechnical adaptation.	
	Focus on the centrality and active mediation role of the human agent.	Sustains human engagement for effective use of digital technologies.	
Industry 4.0 (I4.0)	Convergence of advanced digital technologies: IoT, AI, Big Data, cyber-physical systems.	Provides real-time visibility and control of the chain.	(Alfaqiyah et al., 2025; Lasi et al., 2014; Sharma et al., 2024).
	Intelligent automation and cyber integration.	Demands digital skills and collaborative models.	
	Digital transformation of production processes.	Imposes challenges for innovation and resilience.	

Second, and critically, the emergent properties arise from the recursive interdependencies among the three axes, not from their mere coexistence. Three specific mechanisms illustrate this argument. The Knowledge Flow mechanism represents the capacity to sense and absorb new knowledge continuously: TT provides the formal and informal pathways, but this absorption is enabled only when AT has reduced cultural and cognitive resistance sufficiently for new knowledge to be recognized as legitimate, and only when I4.0 provides the digital infrastructure through which knowledge circulates in real time (Cohen & Levinthal, 1990; Mick et al., 2024). Neither TT nor AT nor I4.0 alone produces this sensing-and-absorbing capacity at scale; it is a product of their interaction. The Sociotechnical Flow mechanism represents the capacity to seize adaptation opportunities and build social capital under conditions of digital disruption: this requires AT's sociotechnical protocols to transform digitally mediated disruptions into learning events, which in turn requires I4.0 visibility to detect disruptions rapidly and TT pathways to diffuse adaptive responses across organizational boundaries (Corsi et al., 2021; Puzio, 2025).

Again, no single axis produces this capacity independently. The Technological Flow mechanism represents the capacity to reconfigure operational processes in real time: I4.0 provides the predictive analytics and automation, but reconfiguration without AT-mediated human adaptation produces resistance and workarounds that neutralize the technological capability, while reconfiguration without TT-structured knowledge diffusion fails to propagate improvements across supply chain partners (Alfaqiyah et al., 2025; Ivanov & Dolgui, 2020).

These three mechanisms are absent from any single-axis or dual-axis framework because they depend on the simultaneous activation of all three axes. Organizations that invest in I4.0 without TT and AT systematically fail to internalize innovations, a pattern extensively documented in emerging economy contexts (Geldes, 2023). Organizations that invest in TT without I4.0 lack the real-time feedback infrastructure needed to accelerate diffusion. Organizations that invest in AT without TT and I4.0 develop adaptive cultures without the knowledge pathways or digital infrastructure to deploy them effectively. The DSC-R Framework is architecturally designed to address these partial-investment failures by embedding the simultaneous deployment of all three axes in Layer 2. The three flows operate recursively, reinforcing each other and producing the learning, adaptation, and innovation cycles that constitute dynamic resilience as a system-level property. Figure 2 illustrates this systemic interaction.

Figure 2. Multidisciplinary Theoretical Integration among TT, AT, and I4.0

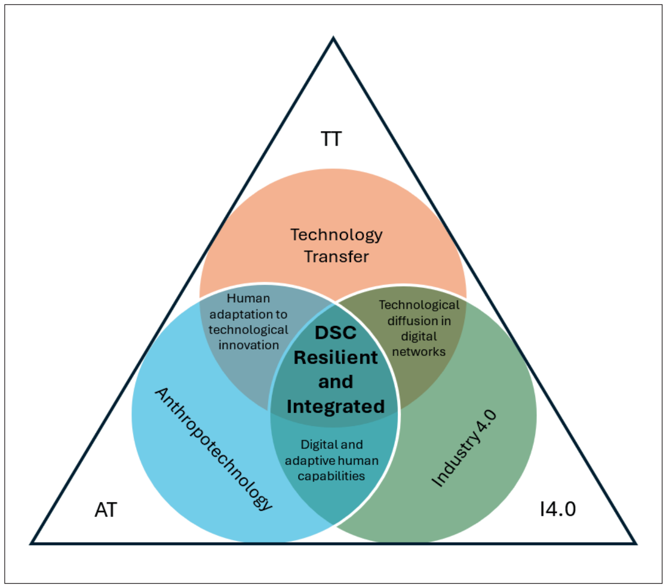


Figure 2 reveals that the three axes operate in a triangulated, recursive pattern where each domain reinforces the others. TT provides the knowledge base that AT mediates sociotechnically and I4.0 amplifies through digital infrastructure; AT provides human adaptation mechanisms enabling TT absorption and effective I4.0 utilization; and I4.0 provides real-time feedback and predictive intelligence accelerating TT diffusion and AT learning. This interdependence is the theoretical core of the DSC-R Framework and distinguishes it from additive multidomain models treating each axis as an independent resilience lever.

4.1. Conceptual Propositions

Four conceptual propositions formalize the theoretical integration above, each identifying a specific interaction mechanism among TT, AT, and I4.0; they are summarized in Table 6.

P1: The effectiveness of Technology Transfer in digital environments is conditioned by organizational absorptive capacity, which is enhanced by sociotechnical learning processes mediated by Anthropotechnology. Grounded in Cohen & Levinthal, (1990), absorptive capacity in DSC contexts is profoundly shaped by cultural, organizational, and contextual conditions that AT addresses, including identification of invisible barriers, development of adaptive competencies, and fostering of collaborative environments (Corsi et al., 2021; Peña & Caruajulca, 2022).

P2: Industry 4.0 technologies strengthen DSC resilience by increasing visibility, traceability, and control over production and logistics processes, provided strategic, cultural, and human capital alignment is maintained. While I4.0 technologies provide the digital infrastructure for monitoring, analytics, and rapid response Alfaqiyah et al., (2025); Lasi et al., (2014), high digital interconnectedness amplifies systemic vulnerability when human and organizational conditions are misaligned Dolgui et al., (2018); Ivanov & Dolgui, (2020), making strategic alignment and human capital as important as technology itself (Sharma et al., 2024).

ISSN: 0718-2724 - **Journal of Technology Management & Innovation** - **www.jotmi.org**

P3: Anthropotechnology strengthens DSC resilience by positioning human adaptation, collective learning, and sociotechnical engagement as determinants of prompt response and recovery from disruptions. Resilience in DSCs is fundamentally sociotechnical (Hohenstein et al., 2015; Peña & Caruajulca, 2022). AT's emphasis on the active role of human agents highlights that response speed and quality depend on sociotechnical learning depth, collaborative cultures, and adaptive engagement, dimensions that purely technological frameworks overlook (Puzio, 2025; Trist & Bamforth, 1951).

P4: The integrated convergence of TT, AT, and I4.0 drives dynamic capabilities that transcend reactive resilience, incorporating organizational learning and continuous innovation as structural properties of sustainable digital supply chains. Supply chains that learn from disruptions develop the strongest resilience (Castillo, 2023; Christopher & Peck, 2004). TT-AT-I4.0 convergence produces this generative capacity (Alfaqiyah et al., 2025; Teece et al., 1997)

Table 6. Conceptual Propositions and Hypotheses – Description and Theoretical Foundation

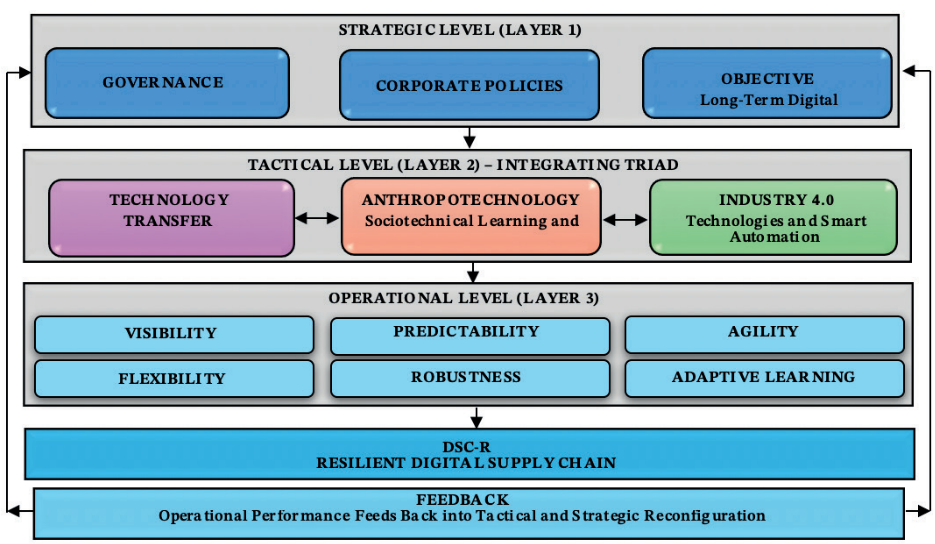
Proposition	Description	Theoretical Foundation
P1	The effectiveness of TT in digital environments is conditioned by organizational absorptive capacity, enhanced by sociotechnical learning processes mediated by AT.	Absorptive capacity is a central element for innovation (Cohen & Levinthal, 1990); AT emphasizes human and cultural mediation in technology adoption (Alkhazaleh et al., 2022; Peña & Caruajulca, 2022)
P2	Industry 4.0 technologies increase control over logistics and production processes, strengthening the resilience of DSCs, provided there is strategic and cultural alignment and ongoing human capital development.	I4.0 promotes automation and cyber integration (Lasi et al., 2014); human capacity building is vital for effective adoption (Sharma et al., 2024).
P3	AT contributes to organizational resilience by highlighting that human adaptation, collective learning, and sociotechnical engagement are determinants for prompt response and recovery of DSCs in the face of disruptions.	Sociocultural adaptation and collaborative environments foster social capital and continuous innovation (Peña & Caruajulca, 2022; Puzio, 2025).
P4	The integrated convergence of TT, AT, and I4.0 drives dynamic capabilities that go beyond resilience, incorporating organizational learning and innovation for the sustainability of DSCs.	Systemic resilience models emphasize continuous learning and innovation as structural pillars (Alfaqiyah et al., 2025; Castillo, 2023; Christopher & Peck, 2004).

The four propositions form a hierarchical structure: P1 and P3 establish human-organizational conditions, P2 establishes I4.0's conditionality, and P4 synthesizes the convergence into a dynamic capability greater than the sum of its parts - directly informing the framework's architecture.

4.1. The DSC-R Conceptual Model

The four propositions converge into a structured model organized across three levels. At the strategic level, the organization establishes digital resilience direction, governance policies, and long-term objectives. At the tactical level, the TT-AT-I4.0 triad translates strategic guidelines into knowledge transfer pathways, anthropotechnological adaptation protocols, and I4.0 technology deployment. At the operational level, these processes become resilience capabilities, including visibility, agility, flexibility, robustness, and adaptive learning. The model is recursive rather than linear: operational performance feeds back into tactical adjustments, informing strategic reconfiguration, consistent with the dynamic capabilities logic of sensing, seizing, and reconfiguring (Teece et al., 1997). Figure 3 illustrates this model.

Figure 3. Structured Conceptual Model



ISSN: 0718-2724 - **Journal of Technology Management & Innovation** - **www.jotmi.org**

The five-layer framework developed in the following subsection operationalizes this three-level model in full organizational detail.

4.4. The DSC-R Framework: Five-Layer Architecture and Success Factors

The DSC-R Framework translates the four propositions into a five-layer architecture: P1 and P3 inform Layers 2 and 3 (human-technological integration); P2 informs Layers 3 and 4 (conditionality of I4.0); P4 informs Layer 5 (continuous learning as a performance outcome).

Layer 1 - Strategic Level establishes long-term guidelines, corporate policies, and digital resilience objectives governing subsequent layers. It encompasses technology investment, governance architecture, and innovation culture, expressed through indicators such as the Digital Maturity Index, Innovation Rate, and CAPEX percentage dedicated to technology.

Layer 2 - Tactical Level (Integrating Triad) operationalizes TT, AT, and I4.0. Technology Transfer uses formal pathways (contracts, partnerships, university-industry collaboration) and informal channels (communities of practice, adaptive training). Anthropotechnology applies human-technological protocols and sociotechnical adaptation plans. Industry 4.0 deploys IoT, AI, Machine Learning, cyber-physical systems, and cloud-integrated traceability. Key indicators are Technology Absorption Rate, Human Readiness Index, and Organizational Learning Rate for continuous monitoring.

Layer 3 - Operational Level implements 14 resilience capabilities organized into macrocapacities and complementary attributes. The macrocapacities are: (1) Visibility, (2) Predictability, (3) Agility, (4) Flexibility, (5) Robustness, (6) Redundancy, and (7) Adaptability. The complementary attributes are: (8) Recoverability, (9) Reconfigurability, (10) Dynamism, (11) Responsiveness, (12) Innovation, (13) Adaptive Learning, and (14) Integration. Each capability is associated with operational indicators, including Mean Time to Recovery (TTR), Logistics Flexibility Index, and Continuous Improvement Rate.

Layer 4 - Vulnerability Assessment Level aanalyzes internal and external risks across demand, supply, operational processes, and control and governance, defining preventive, corrective, and adaptive mitigation strategies informed by Layers 2 and 3. This layer produces antifragile protocols strengthening the chain through managed disruptions (Dolgui et al., 2018; Ivanov & Dolgui, 2020).

Layer 5 - Results Level consolidates impacts from preceding layers into global performance indicators: Global Resilience Index (GRI), Responsiveness Index, Operational Reliability, Strategic Flexibility Index, and Innovation and Digitalization Index. This layer feeds back to Layers 1 and 2, ensuring continuous strategic and tactical recalibration.

Figure 4 presents the complete systemic view of the framework.

Figure 4. Integrative Framework for Resilient Digital Supply Chains (Systemic and Complete View)

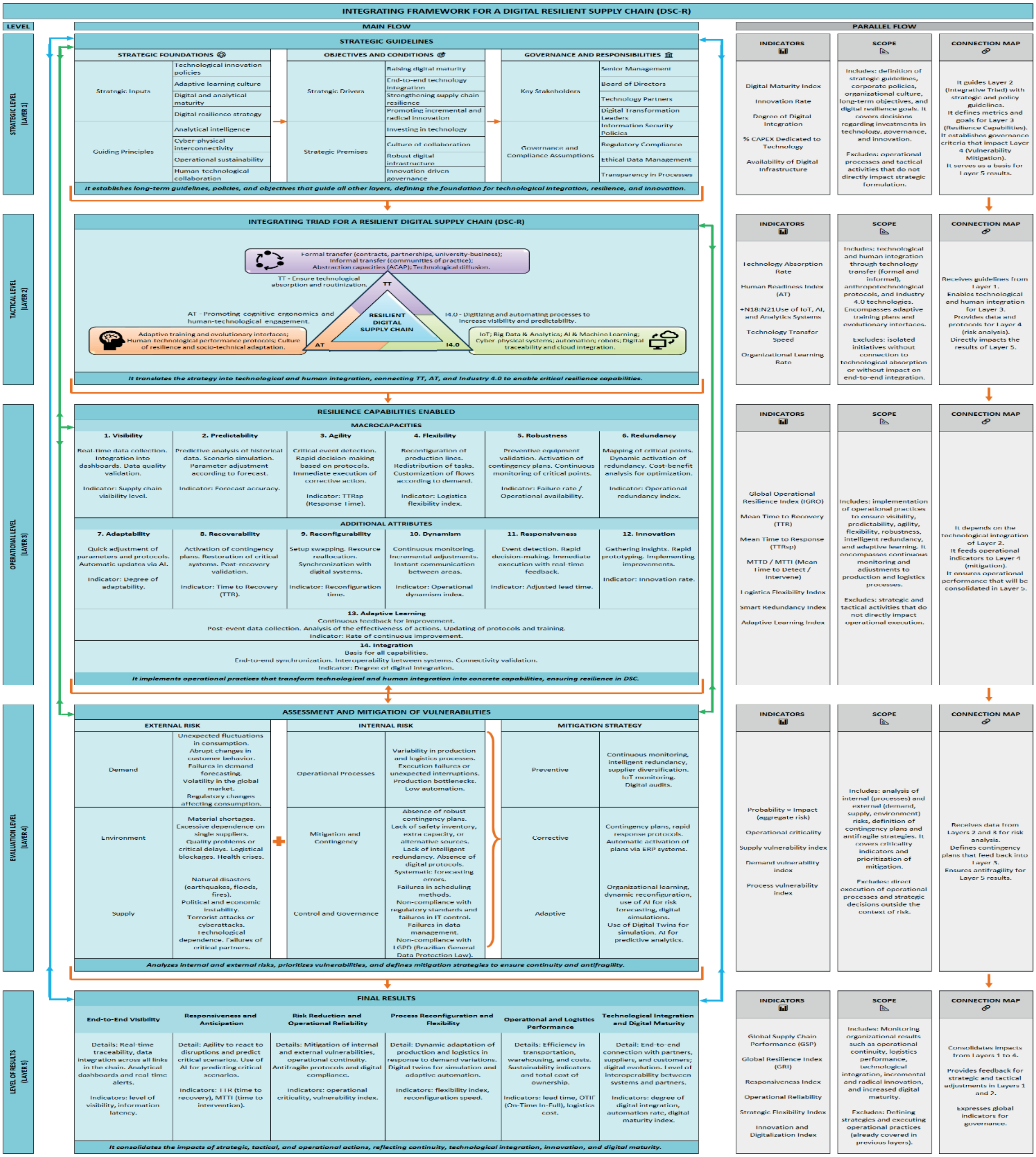


Figure 4 illustrates the framework's bidirectional architecture: a vertical flow from Layer 1 to Layer 5 and a feedback loop to strategic and tactical levels, sustaining dynamic capabilities over time. The DSC-R Framework's effectiveness depends on integrated management of critical success factors across technological, human, organizational, and transversal categories. The transversal category, collaborative governance and strategic alignment, reflects the core finding that DSC resilience requires coordinated management of all dimensions simultaneously rather than isolated interventions (Hohenstein et al., 2015; Ivanov & Dolgui, 2020). Table 7 presents these factors and associated impact mechanisms.

Table 7. Critical Success Factors and Impact Mechanisms on Resilience

Category	Critical Success Factors	Associated Impact Mechanisms
Technological	Integration of cyber-physical systems.	Improved real-time visibility and control.
	Intelligent automation and predictive analytics.	Rapid and precise responses to disruptions.
Human	Continuous training and competency development.	Engagement and sociotechnical adaptation.
	Organizational culture favorable to innovation.	Overcoming resistance and fostering learning.
Organizational	Structured technology transfer processes.	Efficiency in innovation assimilation and dissemination.
	Flexibility and reconfiguration capability.	Rapid adaptation and operational resilience.
Transversal	Collaborative governance and strategic alignment.	Effective coordination among chain actors and alignment of objectives.

The critical success factors in Table 7 constitute an integrated system of enablers; together with the propositions and five-layer architecture, they advance the state of the art in DSC resilience management.

4.5. Operationalization and Implementation Guidance

Addressing the gap between theoretical constructs and actionable guidance Castillo, (2023); Hohenstein et al., (2015), the DSC-R Framework operationalization follows a dynamic, iterative cycle of seven phases:

The seven phases are: (1) Diagnosis - assessing maturity and vulnerabilities (Layers 1 and 4); (2) Planning - consolidating objectives and governance (Layers 1–2); (3) Training - developing digital and sociotechnical competencies (Layer 2 AT protocols); (4) Technological Implementation - integrating I4.0, IoT, AI, and analytics; (5) Knowledge Transfer Management - activating TT pathways; (6) Collaborative Governance - defining policies and strategic alignment; and (7) Continuous Monitoring - tracking resilience indicators and feeding adjustments back into Layer 1 (Figure 5).

Figure 5. DSC-R Framework Operational Cycle

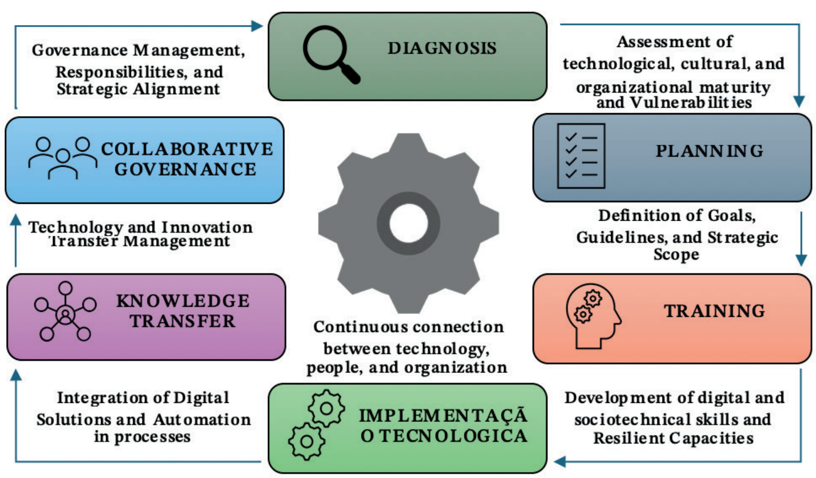


Table 8 synthesizes the mechanisms, facilitating factors, and metrics supporting each phase.

Table 8. Synthesis of Mechanisms, Facilitating Factors, and Metrics for Continuous Monitoring.

Framework Mechanism	Facilitating Factors	Indicators/Examples
Vulnerability Assessment	Diagnosis, risk analysis, engagement	Probability and impact of events, risk map
Resilience Capabilities	Digital competencies, flexibility, agility	Response time, flexibility index, robustness
Digital Integration and Automation	Interoperability, automation, analytics	Degree of IoT integration, use of AI, automation
Technology Transfer	Formal processes, innovation culture	Adoption rate, frequency of training sessions
Collaborative Governance	Clear policies, role alignment	Existence of committees, periodic reviews, compliance
Continuous Monitoring and Improvement	Feedback, audits, learning loop	Performance indicators, number of improvements

ISSN: 0718-2724 - **Journal of Technology Management & Innovation - www.jotmi.org**

Table 9 maps the principal application sectors. Implementation emphasis varies: capital-intensive sectors (petrochemicals, Oil and Gas, fertilizers) prioritize predictive maintenance and operational safety (Geldes, 2023; Ivanov & Dolgui, 2020), while digital manufacturing environments prioritize system integration and cybersecurity. All applications must account for local sociotechnical specificities, consistent with the anthropotechnological principle of context-aligned technology transfer (Corsi et al., 2021; Wisner, 1995).

Table 9. Application Contexts - Sectoral Characteristics and Challenges

Sector	Main Characteristics	Relevant Challenges for Digital Resilience	Application Opportunities
Fertilizer Industry	Complex chemical processes; high dependency on inputs; strong environmental regulation	Environmental risk management; price volatility; limited technological integration	The integration of digital technologies for monitoring and human capacity building is essential to mitigate risks and ensure compliance.
Petrochemical and Oil & Gas Industry	Critical and large-scale operations; distributed infrastructure; stringent regulatory environments	Predictive maintenance; operational safety; adaptation to regulatory changes	The integration of digital technologies for monitoring and human capacity building is essential to mitigate risks and ensure compliance.
Digital Manufacturing / Industry 4.0	High degree of automation; intensive use of digital technologies; customized production	System integration; human capacity building; cybersecurity	The model supports collaborative environments, interoperability, and cybersecurity.
Other Relevant Sectors	Varies by sector (e.g., pharmaceutical, automotive, food)	Technological diversity; supply chain complexity; regulatory requirements	The framework's application must account for technological and cultural specificities.

The framework requires observable indicators across five domains: TT - know-how internalization, collaborative projects, diffusion time (Adomako & Nguyen, 2024; Cohen & Levinthal, 1990); AT - training participation, user satisfaction, safety climate (Corsi et al., 2021; Puzio, 2025); I4.0 - automation degree, IoT coverage, analytics utilization (Alfaqiyah et al., 2025; Benitez et al., 2020; Lasi et al., 2014); DSC - response time, flexibility index, predictive analytics (Bahrami & Shokouhyar, 2022; Fornasiero & Tolio, 2025; Li et al., 2023); and Governance - risk coverage, compliance rates, responsibilities (Castillo, 2023; Cugno et al., 2022; Grimaldi et al., 2025; Valič & Uršič, 2024). Table 10 specifies component variables, scale, and data sources.

Table 10. Specification of Key Performance Indicators: Variables, Scale, and Data Sources

Indicator	Layer	Type	Component Variables	Scale	Data Sources
Mean Time to Recovery (TTR)	3	Observable	Time elapsed from disruption detection to full operational restoration	Hours; days; lower values indicate higher recoverability	ERP incident logs; operational control systems; maintenance records
Mean Time to Response (TTRsp)	3	Observable	Time elapsed from disruption detection to first corrective action	Hours; lower values indicate higher agility	IoT event logs; control room timestamps; SCADA systems
Logistics Flexibility Index (LFI)	3	Composite	Weighted average of: route reconfiguration speed (days); supplier substitution rate (%); demand absorption capacity (% variance handled without SLA breach)	0 to 1 normalized scale; higher values indicate greater flexibility	ERP transportation modules; supplier performance records; demand planning systems
Technology Absorption Rate (TAR)	2	Observable	Number of new technologies effectively internalized per period / total technologies introduced; operationalized via post-training performance assessments	Ratio (0 to 1); higher values indicate higher absorptive capacity	HR training records; technology deployment logs; performance audit reports
Human Readiness Index (HRI)	2	Composite	Composite of: digital competency assessment score (0-100); participation rate in sociotechnical training (%); safety climate survey score (validated scale)	0 to 100 composite score; multi-item instrument required for latent dimension	HR systems; validated digital competency surveys (e.g., adapted from Peña & Caruajulca, 2022); safety climate instruments
Global Resilience Index (GRI)	5	Composite	Weighted composite of Layer 3 and Layer 4 indicators: GRI = w1(TTR) + w2(LFI) + w3(Operational Reliability) + w4(Adaptive Learning Index); weights defined by organizational priority and sectoral context	0 to 100 normalized composite; requires empirical calibration of weights	Aggregated from Layers 2, 3, and 4 operational dashboards; validated through expert panels in future empirical studies
Operational Reliability	5	Observable	Percentage of operational processes completed without unplanned interruption within a defined period	Percentage (0-100%); higher values indicate higher reliability	CMMS (Computerized Maintenance Management Systems); ERP production modules; operational audit records
Digital Maturity Index (DMI)	1	Composite	Multi-dimensional assessment of: IoT integration coverage (%); AI utilization rate (%); systems interoperability score; digital skills index	Composite scale (e.g., adapted from IMDS or equivalent validated instrument); 1-5 Likert aggregation	Organizational technology audits; IoT platform dashboards; validated digital maturity assessment instruments
Adaptive Learning Index (ALI)	3	Composite	Weighted composite of: rate of post-disruption protocol updates (number per period); participation rate in post-event learning sessions (%); implementation rate of corrective actions identified in audits (%)	0 to 100 normalized composite; higher values indicate stronger organizational learning capacity	Operational audit records; training management systems; corrective action tracking logs (CAPA systems); post-event review documentation

Observable indicators can be computed directly from organizational records and operational systems. Composite indicators require multi-item measurement instruments and are proposed here as constructs for empirical validation in future studies, consistent with the conceptual nature of this framework. TTR and TTRsp are well-established operations management metrics (Hohenstein et al., 2015; Ivanov & Dolgui, 2020). GRI weights should be calibrated through expert panel consultation or Delphi methods in future empirical applications.

The framework distinguishes between two categories of indicators with different operationalization requirements. Observable indicators, including TTR, TTRsp, Operational Reliability, and Technology Absorption Rate, can be computed directly from organizational records, ERP systems, IoT platforms, and operational dashboards, and are specified with their component variables, scales, and data sources in Table 10. Composite indicators, including the Global Resilience Index, Human Readiness Index, and Digital Maturity Index, require multi-item measurement instruments and cross-source data aggregation; their component variables and proposed scales are detailed in Table 10, and their empirical validation through expert panels, Delphi methods, or structural equation modeling constitutes a priority for future research. The Adaptive Learning Index (ALI), a component variable of the Global Resilience Index, is similarly classified as a composite indicator requiring multi-item instrumentation; its proposed operationalization through audit records, training systems, and corrective action logs provides an initial measurement structure subject to empirical refinement in future studies. This distinction is methodologically consequential: the framework's operational applicability is immediate for observable indicators and conditional on instrument development and validation for composite indicators. Both categories are necessary for a complete picture of DSC resilience, and their joint deployment is what distinguishes the DSC-R Framework from approaches that rely exclusively on either qualitative assessments or single-source quantitative metrics (Castillo, 2023; Hohenstein et al., 2015; Mick et al., 2024).

5. Discussion

The DSC-R Framework shows that integrating Technology Transfer, Anthropotechnology, and Industry 4.0 creates a multi-layered model strengthening digital supply chain resilience through three reinforcing mechanisms: structured knowledge diffusion, sociotechnical adaptation, and real-time digital responsiveness. This discussion positions these findings within the literature, identifies theoretical advances, draws managerial implications, and establishes an agenda for future empirical research.

5.1. Alignment of the Framework with the Conceptual Propositions

The DSC-R Framework substantiates the four conceptual propositions. P1 is reflected in the tactical layer, where TT pathways operate through anthropotechnological protocols, extending Cohen & Levinthal, (1990) insight by showing AT builds absorptive capacity in digital environments (Corsi et al., 2021; Mick et al., 2024). P2 is validated by Layer 2's simultaneous deployment of TT, AT, and I4.0, responding to Ivanov & Dolgui, (2020) finding that digital interconnectedness amplifies vulnerability without organizational preparedness, consistent with Dolgui et al., (2018) ripple effect thesis. P3 is reflected in Layer 3, where adaptive learning and integration reinforce Hohenstein et al., (2015) conclusion that human dimensions are as important as technological capabilities for resilience. P4 is manifested in Layer 5, where innovation and digitalization are outcomes, consistent with Teece et al., (1997) argument that competitive advantage derives from continuously sensing, seizing, and reconfiguring capabilities.

5.2. Theoretical Contributions

The DSC-R Framework advances the state of the art in three specific ways.

Prior research has addressed TT, AT, and I4.0 as separate theoretical domains, producing rich individual-axis literatures but failing to formalize their interdependencies within a unified model (Castillo, 2023; Mick et al., 2024). The DSC-R Framework resolves this fragmentation by demonstrating that TT, AT, and I4.0 are not merely complementary but structurally interdependent: the effectiveness of each axis is conditioned by the presence and quality of the other two. This interdependence had been theorized in parts by Corsi et al., (2021) and Mick et al., (2024), but was never operationalized into a model applicable to DSCs, a gap that the SCOPUS and WoS search confirmed with zero results across all four combined axes.

While AT has been extensively applied in ergonomics since Wisner, (1995) and Daniellou, (2006), its integration into supply chain frameworks has been systematically absent (Kovaleski et al., 2022; Puzio, 2025). Existing DSC resilience frameworks, including those reviewed by Hohenstein et al., (2015) and Castillo, (2023), address human dimensions peripherally, treating them as contextual moderators rather than structural determinants of resilience. The DSC-R Framework overcomes this limitation by embedding AT at the tactical level of the architecture as a central mediating axis, making human-technological adaptation a structural property of resilience rather than an afterthought.

This architectural choice is grounded in a theoretically consequential distinction between AT and the broader STS tradition from which it derives. STS frameworks prescribe internal organizational alignment, while AT addresses the conditions under which technologies successfully cross organizational and cultural boundaries in the first place. In DSC contexts, where resilience depends on the coordinated response of multiple supply chain partners across diverse institutional and cultural environments, AT's cross-boundary mediation function is theoretically well-positioned to address the inter-organizational and cross-cultural dimensions of digital resilience that STS frameworks, by their organizational-design orientation, are not configured to perform (Corsi et al., 2021; Wisner, 1995).

Existing frameworks typically operate at single or dual levels of analysis (Castillo, 2023; Hohenstein et al., 2015). The DSC-R Framework introduces a five-layer, recursive architecture capturing the strategic-to-operational spectrum within a coherent model. The recursive logic, where Layer 5 outcomes feed back into Layer 1 strategy, formalizes continuous organizational learning as a structural property of the architecture (Alfaqiyah et al., 2025; Teece et al., 1997).

ISSN: 0718-2724 - **Journal of Technology Management & Innovation** - **www.jotmi.org**

5.3. Managerial Implications

The DSC-R Framework offers four actionable implications for managers in complex digital industrial environments.

First, managers should reframe resilience investment as a portfolio decision rather than a technology budget. Organizations investing exclusively in I4.0 technologies without parallel TT processes and AT protocols will underperform in absorptive capacity, as documented in emerging economy contexts Geldes, (2023) and addressed by Proposition P2. Each I4.0 investment should include resources for training, sociotechnical protocols, and knowledge transfer pathway design.

Second, managers should adopt the seven-phase operational cycle as a diagnostic and planning instrument rather than a rigid sequence. Its iterative design enables organizations to enter at any phase based on maturity level and Section 4.5 indicators, progressing non-linearly as conditions evolve. This approach is especially relevant for capital-intensive sectors such as petrochemicals, Oil and Gas, and fertilizers, where sequencing must consider regulatory and safety constraints.

Third, managers should treat collaborative governance as a strategic resilience mechanism, not an administrative function. Resilience in digital supply chains is fundamentally an inter-organizational property, requiring coordination among technology partners, suppliers, clients, and regulatory bodies (Li et al., 2023; Valič & Uršič, 2024). Investment in governance infrastructure, joint committees, shared data protocols, and inter-organizational platforms builds coordination capabilities that buffer disruption propagation.

Fourth, managers should avoid implementing the framework uniformly across contexts. Capital-intensive, highly regulated sectors should prioritize vulnerability assessment, resilience planning, and antifragile governance protocols in Layers 4 and 1 before accelerating I4.0 adoption in Layer 2, while digital manufacturing environments can advance faster, provided cybersecurity and interoperability investments occur concurrently.

5.4. Limitations

Four limitations constrain this study's findings.

The primary limitation is the framework's conceptual nature. While source triangulation across SCOPUS and WoS and validation against established resilience frameworks Hohenstein et al., (2015); Ivanov & Dolgui, (2020) ensure theoretical validity, the framework remains empirically untested. The proposed relationships among TT, AT, I4.0, and DSC resilience remain theoretical propositions rather than confirmed associations, and causal claims require validation through primary data.

The second limitation concerns the scope of the theoretical synthesis. The review focused on SCOPUS and Web of Science publications in English, which may not capture regional contributions from emerging economies or practitioner literature, particularly relevant because I4.0 adoption in petrochemicals and fertilizers is influenced by local institutional, regulatory, and cultural specificities underrepresented in global databases (Geldes, 2023).

The third limitation concerns the proposed indicators. The domain-specific indicators in Section 4.5 were derived from theoretical literature rather than validated through expert consultation or empirical testing. Their applicability and measurement precision may vary across organizational and sectoral contexts, requiring adaptation in future studies.

The fourth limitation concerns the static nature of the framework's technological layer. The I4.0 technologies in Layer 2 reflect the 2026 state of the art. Emerging technologies, including generative AI, digital twins, and advanced blockchain applications, are evolving rapidly and may alter the knowledge and technological flow mechanisms identified in Section 4.1, requiring future revisions to the framework's tactical architecture.

5.5. Agenda for Future Empirical Research

The limitations described above define a structured and prioritized agenda for future empirical research. Table 11 summarizes the recommended methods, sectoral contexts, and partnership configurations for this agenda.

Table 11. Suggestions for Empirical Validation (Methods, Contexts, and Partnerships)

Aspect	Suggestions
Methods	Case studies, surveys, Structural Equation Modeling, Decision Making Trial and Evaluation Laboratory, fuzzy logic, Social Network Analysis.
Sectoral Contexts	Petrochemicals, fertilizers, digital manufacturing and oil & gas
Partnerships	Industrial companies, technology clusters, universities, research centers
Limitations and Considerations	Sector diversity, organizational complexity, data availability and quality

The priority is empirical testing of the four conceptual propositions through structured surveys using SEM or PLS, quantifying relationships among absorptive capacity, sociotechnical adaptation, I4.0 integration, and resilience outcomes. Validated scales from organizational learning and digital transformation literatures should measure latent variables, while observable variables should use organizational records as described in Section 4.5. Following validation, case studies in petrochemical, Oil and Gas, and fertilizer industries would refine framework indicators, with mixed-methods validation assessing generalizability and contextual applicability (Gioia et al., 2013; Tranfield et al., 2003). Longitudinal studies would assess whether recursive learning logic produces the dynamic capability building proposed by

ISSN: 0718-2724 - **Journal of Technology Management & Innovation** - **www.jotmi.org**

P4. Finally, investigating emerging technologies, including generative AI, digital twins, and advanced predictive analytics, would determine whether these innovations alter Knowledge Flow and Technological Flow mechanisms identified in Section 4.1.

6. Conclusions

This study responds to the research question, how can the integration of Technology Transfer, Anthropotechnology, and Industry 4.0 be structured into a coherent framework that strengthens resilience in digital supply chains, by proposing the DSC-R Framework, a conceptual model that formalizes the structured convergence of these four constructs into a unified, operationally applicable architecture, advancing beyond prior partial integrations by embedding their interdependencies within a five-layer recursive design. The answer is that this integration is not only possible but theoretically compelling: TT, AT, and I4.0 are mutually conditioning rather than merely complementary, and their convergence is theorized to generate emergent resilience capabilities through three reinforcing mechanisms, namely knowledge diffusion, sociotechnical adaptation, and digital responsiveness, that no single axis can produce independently; the empirical verification of these mechanisms across diverse organizational contexts constitutes a primary priority for the future research agenda.

The framework's operational applicability is graduated: observable indicators are immediately deployable through existing organizational information systems, while composite indicators require instrument development and empirical validation before full deployment, a progression that the future research agenda addresses explicitly.

The principal theoretical contribution of this study is the demonstration that disciplinary fragmentation across TT, AT, and I4.0 research is not merely a bibliometric observation but a consequential barrier to organizational resilience, one that the DSC-R Framework addresses by formalizing the structural interdependencies among these domains within a unified architecture. By integrating these domains within a five-layer recursive architecture informed by the dynamic capabilities framework Teece et al., (1997), the DSC-R model advances beyond existing approaches in three ways: it formalizes the structural interdependence of the three axes, it introduces Anthropotechnology as a central mediating axis rather than a peripheral moderator in DSC resilience, and it provides a multi-level model that captures the strategic-to-operational spectrum of resilience management within a single coherent structure. These contributions respond to theoretical gaps identified by Mick et al., (2024), Castillo, (2023) and Hohenstein et al., (2015), and are grounded in a systematic source triangulation that confirmed the absence of any prior framework integrating all four constructs simultaneously, establishing the theoretical originality of the proposed model.

The practical contribution is equally significant. The DSC-R Framework offers managers a structured, sector-adaptable instrument comprising a seven-phase operational cycle, five indicator domains, and sector-specific guidance for capital-intensive sectors such as petrochemicals, Oil and Gas, and fertilizers, where a governance-first implementation logic prioritizes vulnerability assessment before accelerating digital adoption.

Future research should prioritize SEM or PLS-based testing of the four propositions, followed by case studies in capital-intensive sectors and longitudinal analyses of resilience evolution. The investigation of generative AI and digital twins on the framework's tactical architecture constitutes an increasingly urgent priority.

In summary, the DSC-R Framework establishes that resilience in digital supply chains is not a technological property but a fundamentally systemic one, produced by the structured convergence of knowledge transfer, human adaptation, and digital integration. By providing the theoretical foundations and operational tools necessary to build this convergence, the study contributes to the advancement of innovation management and sociotechnical systems research, and offers a theoretically grounded and operationally structured reference model for organizations navigating the compounding challenges of digital transformation and supply chain disruption in contemporary industrial environments.

References

Adomako, S., & Nguyen, N. P. (2024). Digitalization, inter-organizational collaboration, and technology transfer. *Journal of Technology Transfer*, *49*(4), 1176–1202. https://doi.org/10.1007/s10961-023-10031-z

Alfaqiyah, E., Alzubi, A., Aljuhmani, H. Y., & Öz, T. (2025). How Industry 4.0 Technologies Enhance Supply Chain Resilience: The Interplay of Agility, Adaptability, and Customer Integration in Manufacturing Firms. *Sustainability (Switzerland)*, *17*(17). https://doi.org/10.3390/su17177922

Alkhazaleh, R., Mykoniatis, K., & Alahmer, A. (2022). The Success of Technology Transfer in the Industry 4.0 Era: A Systematic Literature Review. *Journal of Open Innovation: Technology, Market, and Complexity*, *8*(4), 196. https://doi.org/10.3390/joitmc8040202

Bahrami, M., & Shokouhyar, S. (2022). The role of big data analytics capabilities in bolstering supply chain resilience and firm performance: a dynamic capability view. *Information Technology and People*, *35*(5), 1621–1651. https://doi.org/10.1108/ITP-01-2021-0048

Benitez, G. B., Ayala, N. F., & Frank, A. G. (2020). Industry 4.0 innovation ecosystems: An evolutionary perspective on value cocreation. *International Journal of Production Economics*, *228*, 107735. https://doi.org/10.1016/j.ijpe.2020.107735

Castillo, C. (2023). Is there a theory of supply chain resilience? A bibliometric analysis of the literature. *International Journal of Operations and Production Management*, *43*(1), 22–47. https://doi.org/10.1108/IJOPM-02-2022-0136

ISSN: 0718-2724 - **Journal of Technology Management & Innovation** - **www.jotmi.org**

Christopher, M., & Peck, H. (2004). Building the resilient supply chain. *International Journal of Logistics Management*, *15*(2), 1–13. https://doi.org/10.1108/09574090410700275

Cohen, W. M., & Levinthal, D. A. (1990). Absorptive Capacity: A New Perspective on Learning and Innovation. *Administrative Science Quarterly*, *35*(1), 128–152. https://doi.org/10.2307/2393553

Corsi, A., Kovaleski, J. L., & Pagani, R. N. (2021). Technology Transfer, Anthropotechnology and Sustainable Development: How Do the Themes Relate? *J. Technol. Manag. Innov.*, *16*(4), 96–108. https://doi.org/10.4067/S0718-27242021000400061

Cugno, M., Castagnoli, R., Büchi, G., & Pini, M. (2022). Industry 4.0 and production recovery in the covid era. *Technovation*, *114*, 102443. https://doi.org/10.1016/j.technovation.2021.102443

Daniellou, F. (2006). "«Je me demanderais ce que la société attend de nous…» À propos des positions épistémologiques d'Alain Wisner." *Travailler*, *15*(1), 23–38. https://doi.org/10.3917/trav.015.0023

Dolgui, A., Ivanov, D., & Sokolov, B. (2018). Ripple effect in the supply chain: an analysis and recent literature. *International Journal of Production Research*, *56*(1–2), 414–430. https://doi.org/10.1080/00207543.2017.1387680

Fornasiero, R., & Tolio, T. A. M. (2025). Digital supply chains for ecosystem resilience: a framework for the Italian case. *Operations Management Research*, *18*(1), 210–225. https://doi.org/10.1007/s12063-024-00511-2

Geldes, C. (2023). Challenges of industry 4.0 for companies in emerging economies: Some inputs for the research. *J. Technol. Manag. Innov.*, *18*(3), 3–4. https://doi.org/10.4067/S0718-27242023000300001

Gioia, D. A., Corley, K. G., & Hamilton, A. L. (2013). Seeking Qualitative Rigor in Inductive Research: Notes on the Gioia Methodology. *Organizational Research Methods*, *16*(1), 15–31. https://doi.org/10.1177/1094428112452151

Grimaldi, M., Troisi, O., Papa, A., & de Nuccio, E. (2025). Conceptualizing data-driven entrepreneurship: from knowledge creation to entrepreneurial opportunities and innovation. *Journal of Technology Transfer*, 1–52. https://doi.org/10.1007/s10961-024-10176-5

Hohenstein, N. O., Feisel, E., Hartmann, E., & Giunipero, L. (2015). Research on the phenomenon of supply chain resilience: A systematic review and paths for further investigation. *International Journal of Physical Distribution and Logistics Management*, *45*(1–2), 90–117. https://doi.org/10.1108/IJPDLM-05-2013-0128

Ivanov, D. (2020). Predicting the impacts of epidemic outbreaks on global supply chains: A simulation-based analysis on the coronavirus outbreak (COVID-19/SARS-CoV-2) case. *Transportation Research Part E: Logistics and Transportation Review*, *136*, 101922. https://doi.org/10.1016/j.tre.2020.101922

Ivanov, D., & Dolgui, A. (2020). Viability of intertwined supply networks: extending the supply chain resilience angles towards survivability. A position paper motivated by COVID-19 outbreak. *International Journal of Production Research*, *58*(10), 2904–2915. https://doi.org/10.1080/00207543.2020.1750727

Kovaleski, F., Picinin, C. T., & Kovaleski, J. L. (2022). The Challenges of Technology Transfer in the Industry 4.0 Era Regarding Anthropotechnological Aspects: A Systematic Review. *SAGE Open*, *12*(3), 1–13. https://doi.org/10.1177/21582440221111104

Lasi, H., Fettke, P., Kemper, H. G., Feld, T., & Hoffmann, M. (2014). Industry 4.0. *Business and Information Systems Engineering*, *6*(4), 239–242. https://doi.org/10.1007/s12599-014-0334-4

Li, Y., Li, D., Liu, Y., & Shou, Y. (2023). Digitalization for supply chain resilience and robustness: The roles of collaboration and formal contracts. *Frontiers of Engineering Management*, *10*(1), 5–19. https://doi.org/10.1007/s42524-022-0229-x

Mick, M. M. A. P., Kovaleski, J. L., Yoshino, R. T., & Chiroli, D. M. de G. (2024). The Influence Between Industry 4.0 and Technology Transfer: A Framework Based on Systematic Literature Review. *SAGE Open*, *14*(4), 1–15. https://doi.org/10.1177/21582440241295580

Peña, J., & Caruajulca, P. (2022). Industry 4.0 Evolutionary Framework: The Increasing Need to Include the Human Factor. *J. Technol. Manag. Innov.*, *17*(3), 70–83. https://doi.org/10.4067/S0718-27242022000300070

Puzio, A. (2025). The entangled human being – a new materialist approach to anthropology of technology. *AI and Ethics*, *5*(3), 2339–2356. https://doi.org/10.1007/s43681-024-00537-z

Sharma, M., Antony, R., Vadalkar, S., & Ishizaka, A. (2024). Role of industry 4.0 technologies and human-machine interaction for decarbonization of food supply chains. *Journal of Cleaner Production*, *468*, 142922. https://doi.org/10.1016/j.jclepro.2024.142922

Sheffi, Y., & Rice, J. B. (2005). A Supply Chain View of the Resilient Enterprise. *MIT Sloan Management Review*, *47*(1), 41–48. https://doi.org/https://sloanreview.mit.edu/article/a-supply-chain-view-of-the-resilient-enterprise/

Star, S. L., & Griesemer, J. R. (1989). Institutional ecology,'translations,'and boundary objects: Amateurs and professionals in Berkeley's Museum of Vertebrate Zoology, 1907–1939. *Social Studies of Science*, *19*(3), 387–420. https://doi.org/10.1177/030631289019003001

Teece, D. J. (2007). Explicating dynamic capabilities: The nature and microfoundations of (sustainable) enterprise performance. *Strategic Management Journal*, *28*(13), 1319–1350. https://doi.org/10.1002/smj.640

Teece, D. J., Pisano, G., & Shuen, A. (1997). Dynamic capabilities and strategic management. *Strategic Management Journal*, *18*(7), 509–533. https://doi.org/10.1002/smj.4250180703

Torraco, R. J. (2005). Writing Integrative Literature Reviews: Guidelines and Examples. *Human Resource Development Review*, *4*(3), 356–367. https://doi.org/10.1177/1534484305278283

Tortorella, G. L., Fogliatto, F. S., Saurin, T. A., Tonetto, L. M., & McFarlane, D. (2022). Contributions of Healthcare 4.0 digital applications to the resilience of healthcare organizations during the COVID-19 outbreak. *Technovation*, *111*, 102379. https://doi.org/10.1016/j.technovation.2021.102379

Tranfield, D., Denyer, D., & Smart, P. (2003). Towards a Methodology for Developing Evidence-Informed Management Knowledge by Means of Systematic Review. *British Journal of Management*, *14*(3), 207–222. https://doi.org/10.1111/1467-8551.00375

Trist, E. L., & Bamforth, K. W. (1951). Some social and psychological consequences of the longwall method of coal-getting: An examination of the psychological situation and defences of a work group in relation to the social structure and technological content of the work system. *Human Relations*, *4*(1), 3–38. https://doi.org/10.1177/001872675100400101

Valič, T. B., & Uršič, E. D. (2024). Technology Transfer Offices for Better Management of The University-Industry Collaboration: Comparison of Slovenia, Italy, And Malta. *J. Technol. Manag. Innov.*, *19*(2), 43–53. https://doi.org/10.4067/S0718-27242024000200001

Waller, M. A., & Fawcett, S. E. (2013). Data science, predictive analytics, and big data: A revolution that will transform supply chain design and management. *Journal of Business Logistics*, *34*(2), 77–84. https://doi.org/10.1111/jbl.12010

Whittemore, R., & Knafl, K. (2005). The integrative review: updated methodology. *Journal of Advanced Nursing*, *52*(5), 546–553. https://doi.org/10.1111/j.1365-2648.2005.03621.x

Winkelmann, S., Guennoun, R., Möller, F., Schoormann, T., & van der Valk, H. (2024). Back to a resilient future: Digital technologies for a sustainable supply chain. *Information Systems and E-Business Management*, *22*(2), 315–350. https://doi.org/10.1007/s10257-024-00677-z

Wisner, A. (1995). The etienne grandjean memorial lecture situated cognition and action: Implications for ergonomic work analysis and anthropotechnology. *Ergonomics*, *38*(8), 1542–1557. https://doi.org/10.1080/00140139508925209

Wisner, A. (2004). 7. Towards an anthropotechnology. X. A new activity for the united nations in the service of economic development: specifying requirements for technology transfers in given geographical and anthropological locations. In *Advances in Human Performance and Cognitive Engineering Research* (Vol. 4, pp. 215–221). Emerald. https://doi.org/10.1016/S1479-3601(03)04007-4

Zhao, N., Hong, J., & Lau, K. H. (2023). Impact of supply chain digitalization on supply chain resilience and performance: A multimediation model. *International Journal of Production Economics*, *259*, 108817. https://doi.org/10.1016/j.ijpe.2023.108817

ISSN: 0718-2724 - **Journal of Technology Management & Innovation** - **www.jotmi.org**