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TRANSFORMATION OF SUPPLY CHAINS INTO DIGITAL VALUE NETWORKS IN THE CONTEXT OF INDUSTRY 5.0: A COMPETENCE-DRIVEN GOVERNANCE PERSPECTIVE

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Abstract: The transition from Industry 4.0 toward Industry 5.0 reflects a fundamental shift from technology-centered digitalization toward human-centric, sustainable, and resilient industrial systems. However, contemporary industrial transformation reveals an emerging paradox: while Industry 5.0 emphasizes the central role of humans, increasing autonomy of artificial intelligence and automated decision-making systems simultaneously reduces human involvement in operational processes, potentially leading to gradual competence erosion and weakened oversight capabilities. Existing research largely treats human-centricity as a normative objective, providing limited explanation of how meaningful human authority can be maintained in highly automated environments. This study addresses this gap by analyzing the transformation of supply chains into digital value networks through a competence-driven governance perspective. Building upon empirical findings from Supply Chain 4.0 environments, the paper integrates Industry 5.0, digital supply network, and human-in-the-loop research streams to develop a conceptual framework in which human competence functions as a governance mechanism rather than a complementary organizational attribute. The proposed model conceptualizes Industry 5.0 transformation as a layered process consisting of technological capability, process integration, organizational potentials, and human competence governance. Within this framework, competence governance determines the allocation of decision authority between human and algorithmic actors, enabling competent human supervision, interpretation, and critical evaluation of AI-supported processes. The study contributes by reframing human-centricity from a normative principle into an operational governance mechanism and by providing a structured conceptual bridge between digital integration, organizational adaptation, and governance of AI-supported decision-making. The findings suggest that successful Industry 5.0 implementation depends not only on technological advancement but on the development and distribution of competencies capable of governing increasingly autonomous digital systems across interconnected industrial networks.

Keywords: Industry 5.0, Supply Chain 4.0, Competence-based governance, Human-in-the-loop systems, Digital value networks.

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1. INTRODUCTION

The rapid digital transformation of industrial systems has fundamentally reshaped supply chain structures, enabling unprecedented levels of connectivity, automation, and data-driven decision-making. Technologies associated with Industry 4.0, including artificial intelligence, cyber-physical systems, Internet of Things, and advanced analytics, have transformed traditionally linear supply chains into digitally interconnected systems characterized by real-time visibility and algorithm-supported optimization. These developments have significantly improved operational efficiency, responsiveness, and transparency across industrial networks (Breque et al., 2021; Ivanov, 2021; Milosavljevic, 2025).

However, empirical research conducted within Supply Chain 4.0 environments demonstrates that technological integration alone does not guarantee improved adaptability or long-term performance. Previous studies have shown that organizational potentials—particularly flexibility, agility, and resilience—play a mediating role between digital technology adoption and performance outcomes, enabling organizations to translate digital connectivity into adaptive behavior under uncertainty (Li et al., 2023; Plekhanov et al., 2023). These findings indicate that digital transformation is inherently socio-technical, requiring alignment between technological capabilities, organizational structures, and human decision-making processes.

In parallel with the increasing maturity of Industry 4.0 technologies, the concept of Industry 5.0 has emerged as a new paradigm emphasizing human-centricity, sustainability, and resilience as fundamental objectives of industrial development. Industry 5.0 shifts the focus from efficiency-driven automation toward socio-technical systems in which technological progress supports human well-being, environmental sustainability, and long-term system robustness (Colon & Hochrainer-Stigler, 2022; Lu et al., 2022). Within this perspective, humans are repositioned as active decision-makers and system supervisors rather than passive operators within automated environments.

Despite this conceptual shift, a significant paradox has emerged in contemporary industrial practice. While Industry 5.0 promotes human-centric systems, ongoing technological development increasingly favors autonomous decision-making and algorithmic optimization. Artificial intelligence systems progressively assume analytical and operational roles traditionally performed by humans, reducing direct human involvement in decision processes (Carminati et al., 2025; Papacharalampopoulos et al., 2025). This development introduces a critical but insufficiently addressed risk: the gradual erosion of human capability to understand, evaluate, and govern increasingly complex digital systems. As decision-making becomes increasingly automated, human actors may lose process understanding and critical judgment skills, limiting their ability to identify incorrect or contextually inappropriate AI-generated outcomes (Jaakkola, 2020).

This contradiction reveals an important research gap within current Industry 5.0 discussions. Existing literature predominantly treats human-centricity as a normative objective or ethical principle, while limited attention has been given to the operational conditions required for maintaining meaningful human involvement in highly automated environments (MacInnis, 2011; Colon & Hochrainer-Stigler, 2022). In particular, the role of human competence as a prerequisite for effective human–AI collaboration remains insufficiently explored. Human-in-the-loop decision-making is frequently proposed as a solution; however, the mere presence of human supervision does not ensure effective governance of digital systems if individuals lack

the competencies required to interpret and critically assess algorithmic decisions (MacInnis, 2011; Shneiderman, 2022).

Addressing this gap, the present study builds upon prior empirical findings from Supply Chain 4.0 research and integrates recent Industry 5.0 literature to propose a competence-driven perspective on digital transformation. The central argument of the paper is that the transformation of supply chains into Industry 5.0 value networks requires the introduction of human competence as a governance layer connecting technological capabilities with organizational adaptability and Industry 5.0 objectives. Competent human actors are essential not only for supervising automated systems but also for designing, interpreting, and continuously improving AI-supported processes within complex digital networks.

The paper therefore develops a conceptual framework describing how technological capabilities, process integration, organizational potentials, and human competence governance jointly enable the emergence of Industry 5.0 value networks. By positioning human competence as a necessary condition for responsible and adaptive digital transformation, the study contributes to the ongoing debate on Industry 5.0 implementation and provides a structured foundation for integrating human-centric principles into digitally interconnected supply networks.

The remainder of the paper is structured as follows. Section 2 discusses the transition from Supply Chain 4.0 toward Industry 5.0 value networks and reviews recent literature on digital transformation and human-centric industrial systems. Section 3 introduces the competence-driven conceptual framework, followed by the research approach and analytical logic presented in Section 4. Section 5 discusses theoretical and managerial implications, while Section 6 concludes the paper and outlines directions for future research.

2. FROM SUPPLY CHAIN 4.0 TO INDUSTRY 5.0 VALUE NETWORKS

2.1. Digital Transformation in Supply Chain 4.0 Environments

The Industry 4.0 paradigm introduced a structural transformation of supply chains through digital connectivity, real-time data exchange, and algorithm-supported decision-making. Digital technologies such as artificial intelligence, cyber–physical systems, and advanced analytics have enabled supply chains to evolve from sequential and firm-centered structures toward interconnected systems characterized by distributed information flows and automated coordination. These developments have significantly improved operational efficiency, transparency, and responsiveness across industrial networks (Ivanov, 2021; Plekhanov et al., 2023).

However, accumulated empirical evidence indicates that technological integration alone does not ensure adaptive or resilient performance. Studies in Supply Chain 4.0 environments demonstrate that the effects of digitalization on performance outcomes are mediated by organizational capabilities rather than determined by technology itself. In particular, flexibility, agility, and resilience enable organizations to interpret digital information and translate connectivity into adaptive responses under uncertainty (Milosavljevic, 2025). These organizational potentials function as adaptive mechanisms that allow firms to manage volatility, disruptions, and environmental complexity within digitally integrated environments.

At the same time, efficiency-oriented optimization remains dominant in many Industry 4.0 implementations. Algorithmic decision systems primarily optimize measurable operational parameters such as cost, utilization, and delivery performance. While effective under stable conditions, such optimization logic may neglect contextual and systemic effects, especially in highly interconnected supply networks. As decision processes become increasingly automated,

local optimization may unintentionally amplify systemic vulnerabilities, allowing disturbances or suboptimal decisions to propagate across network actors (Ivanov, 2021; Colon & Hochrainer-Stigler, 2022).

These observations suggest that Supply Chain 4.0 transformation is inherently socio-technical: technological capability provides infrastructure for connectivity, while organizational interpretation determines adaptive outcomes. Nevertheless, existing research largely focuses on organizational adaptation without explicitly addressing how decision authority evolves in environments characterized by increasing algorithmic autonomy.

2.2. Emergence of Industry 5.0 and the Human-Centric Paradigm

The Industry 5.0 concept emerged as a response to the limitations of technology-centered industrial development. Policy and academic discussions increasingly emphasize human-centricity, sustainability, and resilience as guiding principles for future industrial systems. In contrast to Industry 4.0's focus on automation and efficiency, Industry 5.0 proposes a rebalancing between technological performance and human well-being, positioning humans as active contributors to value creation rather than passive operators within automated systems (Breque et al., 2021; Li et al., 2023).

Recent literature conceptualizes Industry 5.0 systems as socio-technical environments in which technological intelligence and human capabilities must operate in a complementary manner. Human roles are increasingly associated with interpretation, supervision, and strategic decision-making, while computational systems perform analytical and operational tasks. This redistribution of roles requires new competencies related to systems thinking, data interpretation, and interaction with AI-supported decision environments (Lu et al., 2022; Li et al., 2023).

Despite this conceptual advancement, the operationalization of human-centricity remains insufficiently specified. Much of the existing literature describes desired outcomes—such as improved wellbeing, sustainability, or collaboration—without clearly defining mechanisms through which meaningful human involvement is maintained as automation increases. Consequently, Industry 5.0 risks remaining a normative framework unless governance mechanisms linking human capability with digital decision-making are explicitly articulated (Li et al., 2023).

2.3. From Digital Supply Chains to Value Networks

The increasing complexity and interdependence of global industrial systems have contributed to a conceptual transition from traditional supply chains toward digital value networks. Unlike linear supply chains, value networks are characterized by multidirectional interactions, collaborative value creation, and distributed decision-making among multiple actors. Digital technologies enable real-time coordination and information sharing, transforming isolated optimization problems into network-level decision environments (Ivanov, 2021; Colon & Hochrainer-Stigler, 2022).

Within such environments, performance depends less on individual firm efficiency and more on collective adaptability. Organizational potentials identified in Supply Chain 4.0 research become particularly relevant, as flexibility, agility, and resilience enable coordinated responses to disruptions across network participants (Milosavljevic, 2025). However, increased connectivity simultaneously increases systemic exposure, as decisions taken at one node may produce unintended consequences elsewhere in the network (Colon & Hochrainer-Stigler, 2022).

Existing research on digital supply networks therefore increasingly emphasizes systemic risk propagation and the need for coordination mechanisms capable of stabilizing network behavior. Yet, while coordination and adaptation mechanisms are widely discussed, the question of who ultimately retains decision authority in highly automated environments remains insufficiently explored.

2.4. Human-in-the-Loop Decision-Making in Digital Value Networks

Human-in-the-loop (HITL) decision architectures have emerged as a prominent approach for balancing automation efficiency with human judgment. HITL systems introduce human intervention at selected decision points, particularly in contexts characterized by uncertainty, ethical implications, or limited explainability of algorithmic outputs. In principle, this approach aims to combine computational speed with contextual human reasoning (Lu et al., 2022).

However, existing HITL literature frequently assumes that human involvement itself guarantees effective oversight. This assumption neglects an important limitation: human participation does not necessarily imply effective governance. When human actors lack sufficient process understanding, analytical capability, or system awareness, supervision may become symbolic rather than functional. Under such conditions, automation bias and overreliance on algorithmic outputs may persist despite nominal human involvement (Lu et al., 2022; Li et al., 2023).

This limitation reveals a conceptual gap between human participation and human authority within digital decision environments. The effectiveness of HITL architectures therefore depends not only on system design but on the competence of human actors responsible for interpreting and governing AI-supported processes. Addressing this gap requires moving beyond participation-oriented interpretations of human-centricity toward competence-driven governance mechanisms capable of maintaining meaningful human decision authority in digitally integrated value networks.

This observation provides the conceptual foundation for the competence-driven framework introduced in the following section.

3. CONCEPTUAL FRAMEWORK: COMPETENCE-DRIVEN TRANSFORMATION TOWARD INDUSTRY 5.0 VALUE NETWORKS

3.1. From Human Participation to Competence-Driven Governance

The literature reviewed in the previous sections demonstrates that digital transformation research has evolved along three largely independent streams. Industry 4.0 and digital supply chain literature primarily explains technological integration and connectivity (Ivanov, 2021; Plekhanov et al., 2023), while Supply Chain 4.0 research emphasizes organizational potentials—flexibility, agility, and resilience—as mechanisms enabling adaptive performance under uncertainty (Milosavljevic, 2025). In parallel, Industry 5.0 research introduces human-centricity as a normative objective and promotes human-in-the-loop (HITL) approaches as mechanisms for balancing automation and human judgment (Breque et al., 2021; Lu et al., 2022; Li et al., 2023).

Despite these advances, an important conceptual gap remains. Existing research explains technological capability, organizational adaptation, and human participation largely as separate dimensions, while providing limited explanation of how decision authority should be allocated in environments characterized by increasing algorithmic autonomy. HITL approaches

assume effective human oversight but do not explicitly address the competence conditions required for meaningful governance of AI-supported decision processes. Consequently, the transition toward Industry 5.0 remains operationally ambiguous, particularly in digitally integrated value networks where decision consequences propagate across multiple actors.

Addressing this gap requires shifting the analytical focus from human participation toward competence-driven governance. Rather than asking whether humans remain involved in decision processes, the central question becomes how competence determines the allocation of decision authority between human and algorithmic actors within digitally integrated systems.

3.2. Empirical Foundation: Organizational Potentials as Adaptive Mechanisms

The proposed framework builds upon empirical findings from Supply Chain 4.0 environments demonstrating that organizational potentials mediate the relationship between technological integration and performance outcomes (Milosavljevic, 2025). Flexibility enables rapid process reconfiguration, agility supports timely response to environmental changes, and resilience allows systems to absorb disruptions and recover functionality.

These organizational capabilities explain why technologically similar firms exhibit different adaptive outcomes despite comparable levels of digitalization. Organizational interpretation and coordination transform technological capability into adaptive behavior, particularly in environments characterized by uncertainty and systemic interdependencies (Ivanov, 2021; Colon & Hochrainer-Stigler, 2022).

However, while organizational potentials explain adaptation, they do not fully address governance challenges introduced by AI-supported decision-making. Organizational adaptability describes *how systems respond*, but does not explain *who retains decision authority* when analytical and operational decisions become increasingly automated. As algorithmic systems assume a growing share of decision tasks, governance challenges shift from coordination and adaptation toward supervision, interpretation, and critical evaluation of automated outcomes.

This limitation motivates the introduction of an additional analytical layer addressing competence-based decision governance.

3.3. Defining Human Competence Governance

To avoid conceptual ambiguity, this study distinguishes between **human competence** and **competence governance**.

Human competence refers to the individual and collective capability to understand processes, interpret data, and interact effectively with AI-supported systems. In Industry 5.0 environments, relevant competence dimensions include:

- process literacy, enabling understanding of operational constraints and causal relationships;
- data and AI literacy, enabling interpretation and questioning of algorithmic outputs;
- systems thinking, enabling recognition of interdependencies across network actors;
- critical evaluation capability, enabling detection of biased or contextually inappropriate recommendations.

Competence governance, in contrast, is defined as:

the organizational and network-level mechanism through which decision authority is allocated and maintained based on competence within AI-supported decision environments.

This distinction is critical. Competence governance does not merely describe skills or learning processes but represents a structural governance mechanism determining when automated decisions are accepted, supervised, or overridden by human actors.

This perspective addresses a limitation of both organizational capability theory and HITL approaches. Organizational capabilities explain adaptation but do not specify decision authority under algorithmic autonomy, while HITL architectures assume human effectiveness without explicitly addressing competence distribution (Lu et al., 2022; Li et al., 2023). Competence governance therefore functions as an integrative layer linking technological capability, organizational adaptation, and human-centric Industry 5.0 objectives.

3.4. Operational Mechanisms of Competence-Driven Transformation

To operationalize competence governance within digital value networks, the framework specifies three mechanisms through which competence stabilizes decision processes in highly automated environments.

M1 — Risk-Based Allocation of Human Decision Authority

Human involvement is concentrated at decision points characterized by high uncertainty, high systemic impact, or limited explainability of algorithmic outcomes. Rather than opposing automation, this mechanism allocates human authority where contextual interpretation is required, reducing automation bias and preventing unintended systemic consequences (Ivanov, 2021; Lu et al., 2022).

M2 — Competence Reinforcement Through Continuous Learning

Automation reduces experiential learning when human actors are removed from operational processes. Continuous competence development therefore becomes a structural requirement for governance rather than a purely human resource activity. Reskilling and upskilling ensure that human actors retain the ability to interpret and supervise automated systems over time (Li et al., 2023; Carminati et al., 2025; Papacharalampopoulos et al., 2025).

M3 — Transparency and Explainability as Enablers of Oversight

Explainable AI and transparent decision processes enable effective human oversight by making algorithmic reasoning interpretable. Transparency acts as an enabling condition for competence governance, allowing human actors to challenge automated decisions and maintain meaningful authority within socio-technical systems (Papacharalampopoulos et al., 2025).

3.5 The Competence-Driven Industry 5.0 Value Network Model

Integrating empirical Supply Chain 4.0 findings with Industry 5.0 literature, the proposed model conceptualizes transformation as a layered process consisting of:

1. **Technological capability**, enabling connectivity and data-driven decision-making;
2. **Process integration**, enabling coordinated operation across network actors;
3. **Organizational potentials**, enabling adaptive system responses;
4. **Competence governance**, enabling responsible allocation of decision authority.

Each layer fulfills a distinct analytical function. Technological capability generates information and optimization potential; process integration enables coordination; organizational potentials enable adaptation; competence governance stabilizes decision authority in environments characterized by increasing autonomy.

Industry 5.0 value networks emerge when these layers co-evolve. Importantly, competence governance introduces feedback effects: competent human actors reshape technological deployment and organizational processes, preventing rigid automation trajectories and enabling long-term adaptability. By explicitly defining governance mechanisms and competence-based decision authority, the framework reduces the operational ambiguity frequently associated with Industry 5.0 and provides a structured explanation of how human-centric principles can be implemented in digitally integrated value networks. The **Figure 1** presents a layered transformation model in which technological capability and process integration enable digital connectivity, while organizational potentials mediate adaptive system behavior.

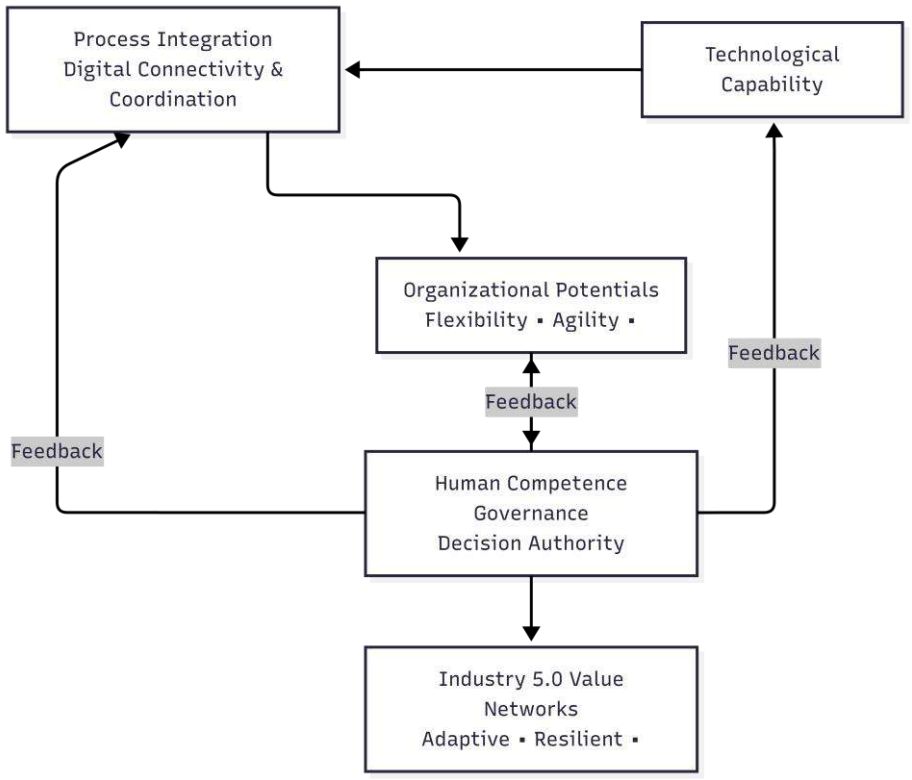


Figure 1. Competence-Driven Industry 5.0 Value Network Transformation Model

As illustrated in Figure 1, the transformation toward Industry 5.0 value networks is conceptualized as a layered process in which each level fulfills a distinct but interdependent function. Technological capability and process integration establish the digital infrastructure, while organizational potentials enable adaptive responses under uncertainty. However, these layers remain insufficient in environments characterized by increasing algorithmic autonomy.

The model therefore introduces human competence governance as a higher-order stabilizing mechanism that determines the allocation of decision authority between human and AI actors. In this way, competence governance resolves the identified gap between technological capability, organizational adaptation, and effective decision control in digitally integrated value networks.

Beyond its structural representation, Figure 1 also captures the interdependencies and feedback relationships between layers. Technological capability not only enables process integration, but is continuously reshaped by organizational responses and competence-based interventions. Similarly, organizational potentials do not operate independently; their effectiveness depends on the ability of human actors to interpret system behavior and adjust

decision-making processes accordingly. Competence governance therefore functions not as a static layer, but as an active regulatory mechanism that dynamically influences both technological deployment and organizational adaptation. Through these feedback loops, the model reflects the inherently co-evolutionary nature of Industry 5.0 transformation, where human competence does not merely respond to digital systems but actively shapes their development and operational boundaries.

While Figure 1 defines the structural logic of competence-driven transformation, Figure 2 extends this logic by illustrating its dynamic implications under increasing levels of automation. Specifically, Figure 2 contrasts two alternative transformation paths emerging from digitally integrated value networks.

In the absence of competence governance, increasing reliance on algorithmic decision-making leads toward autonomous optimization, where locally efficient decisions may propagate unintended consequences across interconnected actors. This trajectory reflects the failure mechanism identified in highly automated environments, where reduced human involvement and competence erosion limit the ability to critically evaluate AI-supported decisions.

In contrast, competence governance introduces a stabilizing feedback loop by linking decision authority to competence and risk exposure. Through mechanisms such as risk-based human intervention, continuous competence development, and explainability of decision processes, human actors retain meaningful oversight over automated systems. This enables the emergence of adaptive and resilient Industry 5.0 value networks, rather than purely efficiency-driven but potentially unstable systems.

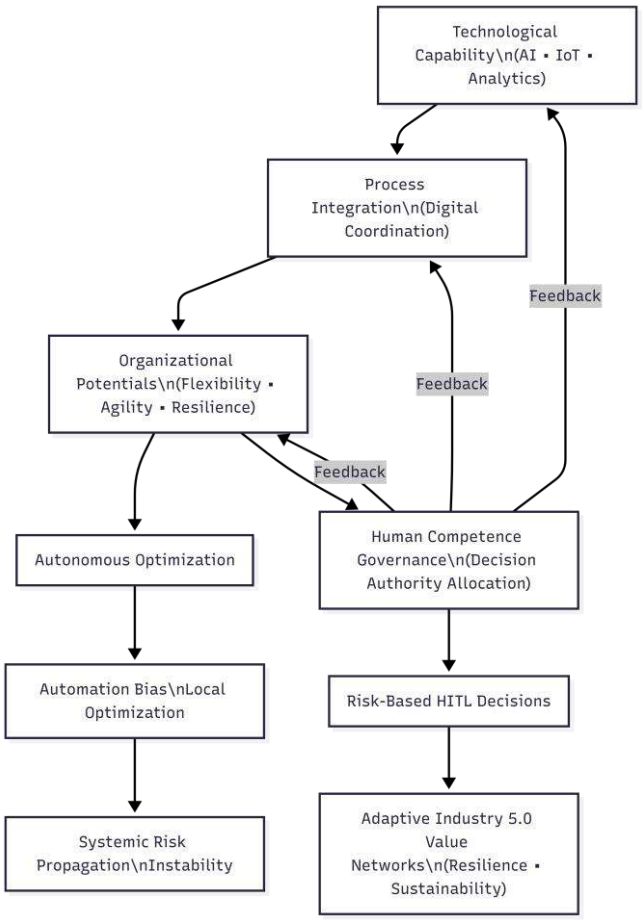


Figure 2. Competence Governance as a Stabilizing Mechanism in Digital Value Networks

Importantly, the divergence between the two trajectories illustrated in Figure 2 is not driven by technological differences, but by the presence or absence of governance mechanisms linking decision authority to competence. This highlights a critical implication of the proposed framework: systemic instability in digital value networks does not arise from automation itself, but from ungoverned automation. As algorithmic decision-making expands across interconnected actors, local optimization logic may become misaligned with system-level objectives, leading to cascading effects and amplified vulnerabilities. Competence governance mitigates this risk by introducing context-sensitive decision control, ensuring that human intervention is activated where uncertainty, complexity, or systemic impact exceed the reliable scope of automated reasoning. In this sense, the model reframes Industry 5.0 transformation as a shift from efficiency-driven automation toward governance-driven adaptability, where long-term system performance depends on the continuous alignment between technological capability, organizational response, and human decision authority.

4. RESEARCH APPROACH AND ANALYTICAL FRAMEWOR

4.1. Research Design and Positioning

The objective of this study is to develop a competence-driven conceptual framework explaining the transformation of digitally integrated supply chains into Industry 5.0 value networks. Given the emerging nature of Industry 5.0 research and the absence of stable implementation models, the study adopts an integrative conceptual research design combining empirical grounding with structured literature synthesis and theory-building logic (MacInnis, 2011; Jaakkola, 2020).

Conceptual research plays an important role in emerging technological domains where empirical regularities are still evolving and theoretical constructs remain insufficiently defined. In such contexts, theory development proceeds through the integration and reinterpretation of existing empirical findings and literature streams rather than through immediate empirical testing (Jaakkola, 2020).The present study follows this logic by extending empirically validated Supply Chain 4.0 constructs with governance-oriented mechanisms derived from Industry 5.0 and human–AI interaction literature.

The framework therefore does not seek to generalize prior empirical findings directly. Instead, empirical results related to organizational potentials serve as analytical boundary conditions that define the limits of technology-centered explanations and motivate the introduction of competence governance as an additional explanatory layer.

4.2. Analytical Logic of Framework Development

The analytical development of the framework follows a layered transformation logic derived from the synthesis of insights established in the previous chapters.

Step 1 — Technological Capability and Digital Integration

The first analytical step considers Industry 4.0 technologies as enabling infrastructure for digitally integrated supply networks. Artificial intelligence, cyber–physical systems, and advanced analytics enable real-time coordination and automated decision-making across organizational boundaries (Ivanov, 2021; Plekhanov et al., 2023). Existing literature demonstrates that these technologies improve visibility and operational efficiency but do not inherently ensure adaptability or long-term resilience (Ivanov, 2021).

This observation establishes technological capability and process integration as necessary but insufficient conditions for Industry 5.0 transformation.

Step 2 — Organizational Potentials as Adaptive Mediators

The second analytical step incorporates empirical findings demonstrating that flexibility, agility, and resilience mediate the relationship between technological capability and performance outcomes (Milosavljevic, 2025). Organizational potentials explain how firms interpret digital information and respond to environmental uncertainty, enabling adaptive behavior within interconnected supply networks.

Digital supply network research further confirms that increased connectivity amplifies both positive and negative effects, allowing disturbances and suboptimal decisions to propagate across actors when coordination mechanisms are insufficient (Colon & Hochrainer-Stigler, 2022) However, while organizational potentials explain adaptive response, they do not address governance challenges introduced by autonomous or semi-autonomous decision systems.

This limitation indicates that adaptation alone is insufficient in environments characterized by increasing algorithmic autonomy.

Step 3 — Governance Gap Under Algorithmic Autonomy

The third analytical step introduces the governance gap identified in Sections 2 and 3. As AI-supported decision-making increases, decision authority gradually shifts from human actors toward algorithmic systems. Existing governance approaches, including human-in-the-loop architectures, assume that human involvement ensures effective oversight (Lu et al., 2022; Li et al., 2023). However, recent studies in AI governance and socio-technical systems demonstrate that human participation without sufficient competence may result in automation bias, reduced critical evaluation, and overreliance on algorithmic outputs (Rahwan et al., 2019; Shneiderman, 2022).

This creates a structural risk in digitally integrated value networks. Without competence-based governance mechanisms, autonomous optimization may improve local efficiency while increasing systemic vulnerability through unintended network-level consequences. The failure pathway illustrated in the conceptual construct therefore represents a plausible outcome of ungoverned automation rather than an exceptional case.

The introduction of competence governance addresses this gap by linking decision authority with competence distribution, thereby stabilizing decision processes in highly automated environments.

4.3. Mapping Literature Streams to Model Layers

To ensure analytical consistency, the framework maps existing literature streams onto the proposed model layers:

- Industry 4.0 and digital transformation literature explains technological capability and process integration (Ivanov et al., 2021; Plekhanov et al., 2023);
- Supply Chain 4.0 empirical research explains organizational adaptation through flexibility, agility, and resilience Milosavljevic, 2025);
- Industry 5.0 and human-centric manufacturing literature explains the normative objectives of future industrial systems (Breque et al., 2021; Li et al., 2023);
- Human-in-the-loop and AI governance literature explains the conditions for effective human oversight in automated environments (Rahwan et al., 2019; Lu et al., 2022; Shneiderman, 2022).

This mapping demonstrates that competence governance does not replace existing research streams but functions as an integrative mechanism connecting technological capability, organizational adaptation, and human-centric objectives within a coherent governance structure.

4.4 Analytical Implications for Human–AI Decision Architectures

The analytical framework suggests that human involvement in digital value networks should follow a risk-based rather than uniform logic. Human intervention becomes particularly relevant in decision contexts characterized by high uncertainty, limited explainability, or significant systemic impact.

This interpretation aligns with contemporary research emphasizing explainability, transparency, and competence development as enabling conditions for effective human–AI collaboration (Papacharampopoulos et al., 2025; Shneiderman, 2022). Competence governance therefore operates as a stabilizing mechanism that reduces automation bias and enables adaptive decision-making across network actors.

Importantly, the framework also explains the failure mechanism observed in highly automated environments. When competence governance is absent, increasing automation may lead to reduced human engagement, gradual competence erosion, and increased dependence on algorithmic optimization. Over time, this dynamic may reduce the capacity of organizations to detect incorrect or contextually inappropriate decisions, increasing systemic risk within digitally interconnected networks.

By integrating both stabilization and failure pathways, the analytical framework provides a structured explanation of how competence-driven governance enables the transition from digitally integrated supply chains toward adaptive Industry 5.0 value networks.

5. DISCUSSION

5.1. Resolving the Industry 5.0 Paradox Through Competence Governance

The central paradox identified in this study concerns the discrepancy between the human-centric aspirations of Industry 5.0 and the increasing autonomy of AI-supported industrial systems. While digital transformation has significantly improved efficiency, responsiveness, and coordination across supply networks, the progressive delegation of decision-making to automated systems introduces the risk of reduced human engagement and gradual competence erosion. This development challenges the practical realization of Industry 5.0 principles, as human-centricity cannot be achieved solely through the presence of humans within automated decision architectures (Breque et al., 2021; Shneiderman, 2022; Li et al., 2023).

The competence-driven framework proposed in this study addresses this paradox by reframing human involvement as a governance mechanism rather than as a complementary social dimension. Within this perspective, Industry 5.0 transformation does not imply a reduction of automation but a redefinition of human roles toward competence-based decision authority. Human actors retain relevance not through operational participation but through their capacity to interpret, supervise, and critically evaluate AI-supported processes. This interpretation aligns with socio-technical perspectives emphasizing meaningful human oversight while extending existing literature by explicitly linking competence to decision governance under algorithmic autonomy (Shneiderman, 2022; Li et al., 2023).

5.2. Extension of Supply Chain 4.0 Empirical Findings

The proposed framework represents an analytical extension of previously established Supply Chain 4.0 findings. Prior empirical research demonstrated that organizational

potentials—flexibility, agility, and resilience—mediate the relationship between digital technologies and performance outcomes (Milosavljevic, 2025). These capabilities explain why digital connectivity alone does not ensure adaptive performance and why organizational interpretation remains essential in digitally integrated environments.

The present study extends this logic by demonstrating that, in highly autonomous decision environments, organizational adaptability alone becomes insufficient. As algorithmic systems increasingly perform analytical and operational tasks, governance challenges shift from adaptation toward supervision and decision authority allocation. Competence governance therefore complements organizational potentials by explaining how adaptive capabilities remain effective when decision processes are partially automated.

This extension provides a theoretical explanation for observed inconsistencies in digitally advanced supply networks, where high levels of technological integration coexist with systemic vulnerability and coordination failures (Ivanov, 2021; Colon & Hochrainer-Stigler, 2022). Without sufficient competence distribution across network actors, automated optimization may amplify local efficiency while increasing network-level risk.

5.3. Positioning Within Contemporary Industry 5.0 Research

Recent Industry 5.0 research emphasizes reskilling, upskilling, and human-centric system design as key enablers of future industrial transformation (Li et al., 2023; Carminati et al., 2025; Papacharalampopoulos et al., 2025). While these contributions highlight the importance of human capabilities, competence is frequently treated as a workforce development or organizational learning issue. The competence-driven framework proposed in this study advances this discussion by positioning competence as a structural governance requirement within digital value networks.

Similarly, human-in-the-loop approaches are increasingly proposed as mechanisms for balancing automation and human judgment (Lu et al., 2022). However, existing approaches often assume that human presence ensures effective oversight. The findings of this study suggest that effective human oversight depends on competence distribution rather than participation alone. When competence levels are insufficient, human involvement may become symbolic, increasing the risk of automation bias and uncritical acceptance of algorithmic decisions (Rahwan et al., 2019; Shneiderman, 2022; Milosavljevic et al., 2024).

By introducing competence governance as an integrative mechanism, the framework contributes to resolving ongoing critiques regarding the conceptual ambiguity of Industry 5.0. The model specifies operational mechanisms through which human-centric principles can be implemented in practice rather than remaining normative objectives.

5.4. Implications for Digital Value Networks

The competence-driven perspective also redefines the transformation of supply chains into digital value networks. In highly interconnected environments, performance increasingly depends on collective adaptability rather than individual firm efficiency. Competence distribution across network actors becomes a critical determinant of resilience, sustainability, and long-term stability.

This implies that Industry 5.0 implementation cannot be achieved solely through technological investments at the firm level. Instead, governance mechanisms, transparency of decision processes, and competence development must extend across organizational boundaries. Asymmetric competence levels within supply networks may introduce structural

vulnerabilities, particularly in multi-tier supply chains where decision consequences propagate rapidly across actors (Colon & Hochrainer-Stigler, 2022; Milosavljevic et al., 2024).

From a network perspective, competence governance therefore functions as a stabilizing mechanism that reduces systemic risk by ensuring that automated optimization remains aligned with contextual and system-level objectives.

5.5. Theoretical Contributions

The study contributes to the literature in three primary ways.

First, it extends Supply Chain 4.0 research by integrating empirically validated organizational potentials with emerging Industry 5.0 principles, demonstrating that adaptive capabilities alone do not resolve governance challenges introduced by algorithmic autonomy.

Second, it reframes human-centricity from a normative objective into an operational governance mechanism. This shift enables a more precise theoretical understanding of how human roles evolve within digitally integrated industrial systems.

Third, the study introduces competence-driven transformation as a conceptual bridge linking technological integration, organizational adaptation, and governance of AI-supported decision processes. By explicitly addressing decision authority allocation, the framework contributes to ongoing discussions on AI governance and socio-technical system design within industrial contexts (Rahwan et al., 2019; Shneiderman, 2022).

6. CONCLUSION

The transition from Industry 4.0 toward Industry 5.0 represents a fundamental shift from technology-centered digitalization toward governance-centered transformation of industrial systems. While Industry 4.0 enabled unprecedented levels of connectivity, automation, and data-driven decision-making, the findings of this study indicate that technological advancement alone does not ensure adaptive, resilient, or human-centric outcomes in digitally integrated supply networks (Breque et al., 2021; Ivanov, 2021).

This study addressed a central paradox emerging in contemporary industrial transformation. Although Industry 5.0 emphasizes human-centricity, the increasing autonomy of AI-supported systems may simultaneously reduce human engagement in operational decision-making and weaken competence required for effective oversight. Existing research largely defines the objectives of Industry 5.0—human-centricity, sustainability, and resilience—while providing limited explanation of the mechanisms through which these objectives can be operationalized in highly automated environments (Breque et al., 2021; Li et al., 2023).

Building upon empirically grounded Supply Chain 4.0 findings, where organizational potentials were identified as mediating mechanisms between technological integration and performance outcomes, this study introduced **human competence governance** as an additional analytical layer required for Industry 5.0 transformation (Milosavljevic, 2025). The proposed framework demonstrates that technological capability enables digital integration, organizational potentials enable adaptive responses, and competence governance stabilizes decision authority within AI-supported environments. In this perspective, Industry 5.0 transformation is understood not as a reduction of automation but as a reconfiguration of governance structures ensuring meaningful human authority within socio-technical systems.

From a theoretical perspective, the study contributes by linking three previously fragmented research streams: digital supply chain transformation, organizational adaptation, and human-centric Industry 5.0 research. By reframing human-centricity as an operational

governance mechanism rather than a normative objective, the framework clarifies how human roles evolve in environments characterized by increasing algorithmic autonomy. The study further contributes to emerging discussions on AI governance and socio-technical system design by introducing competence-driven decision authority as a stabilizing mechanism in digitally interconnected value networks (Rahwan et al., 2019; Shneiderman, 2022; Milosavljevic et al., 2024).

From a managerial perspective, the findings suggest that Industry 5.0 implementation cannot be achieved solely through technological investments or process digitalization. Organizations must actively manage competence development, transparency of decision processes, and governance mechanisms that enable effective human oversight over automated decisions. In highly interconnected supply networks, competence distribution across actors becomes a critical determinant of systemic resilience and long-term sustainability.

Despite these contributions, the study has inherent limitations. As a conceptual framework, the model does not provide empirical validation of competence governance mechanisms or quantitative measurement of competence distribution within value networks. Furthermore, the framework assumes environments characterized by advanced digital integration and AI-supported decision-making, and its applicability may be limited in low-digitalization contexts or industries with predominantly manual processes.

Future research should therefore focus on empirical validation of competence governance across different industrial contexts, development of measurable indicators linking competence levels with resilience and sustainability outcomes, and investigation of governance mechanisms at the inter-organizational network level. In particular, longitudinal studies examining competence dynamics under increasing automation may provide valuable insight into how Industry 5.0 systems evolve over time.

Overall, the study suggests that the successful realization of Industry 5.0 depends not only on technological advancement but on the ability of organizations and networks to govern increasingly autonomous digital systems through competence-based decision authority. In this sense, Industry 5.0 represents less a technological revolution and more a transformation in how digital intelligence and human competence are jointly governed within adaptive industrial ecosystems.

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