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SMART MANUFACTURING ON THE HORIZON: A Conceptual Shift from Industry 4.0 to Industry 5.0: Industrija

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A Human-Centric Digital Twin Framework for Industry 5.0 in Transport and Logistics

Osman Lindov*¹

Abstract: *The transition from Industry 4.0 to Industry 5.0 represents a fundamental shift in the design and operation of transport and logistics systems. While Industry 4.0 emphasizes automation, connectivity, and data-driven optimization, Industry 5.0 introduces a human-centric, sustainable, and resilient approach to system development. This paper examines this transition through a conceptual and analytical framework, focusing on the integration of digital twins, artificial intelligence (AI), and human-in-the-loop (HITL) decision-making. A reference architecture is proposed to illustrate a closed-loop cyber-physical system that connects physical logistics operations with sensing technologies, edge/cloud computing, and digital twin-based simulation. The framework incorporates multi-objective optimization, integrating operational efficiency with sustainability metrics and resilience indicators. Furthermore, the study evaluates the role of standardized emissions accounting and circular logistics principles in enabling environmentally responsible transport systems. Selected case studies, including port digital twins, warehouse robotics, and AI-driven route optimization, are analyzed to demonstrate real-world applicability. The results indicate that Industry 5.0 enables more adaptive, transparent, and sustainable logistics systems by aligning technological innovation with human and environmental priorities.*

Keywords: *Industry 5.0, Industry 4.0, smart logistics, digital twin, artificial intelligence sustainable transport, circular logistics, resilience, cyber-physical systems.*

1. Introduction

Industry 4.0 and Industry 5.0 represent complementary paradigms for digital transformation in modern industrial and logistics systems. Industry 4.0 focuses on automation, connectivity, and data-driven optimization enabled by cyber-physical systems, the Internet of Things (IoT), and advanced analytics. In contrast, Industry 5.0 extends this paradigm by emphasizing human-centricity, sustainability, and resilience as core design principles [1], [24].

The transition toward Industry 5.0 introduces a fundamental shift from efficiency-driven optimization to multi-objective system design, where technological performance is balanced with environmental and social considerations. In the context of transport and logistics, this transformation enables the development of

¹University of Sarajevo, Faculty of Traffic and Communications, Sarajevo, Bosnia and Herzegovina
E-mail: olindov@gmail.com

adaptive, intelligent, and sustainable systems supported by advanced digital technologies such as artificial intelligence (AI), digital twins, and edge/cloud computing.

This paper aims to analyze the transition from Industry 4.0 to Industry 5.0 in transport and logistics and to propose a conceptual reference architecture that integrates technological, human, and sustainability dimensions.

The novelty of this study lies in the integration of Industry 4.0 technologies with Industry 5.0 principles through a unified architecture that incorporates human-in-the-loop governance, sustainability metrics, and resilience-oriented design.

2. Theoretical Background and Literature Review

Industry 4.0 is characterized by the integration of cyber-physical systems, the Internet of Things (IoT), and data-driven optimization to enhance automation and operational efficiency. In transport and logistics, this paradigm enables real-time visibility, automated operations, and optimized decision-making across complex supply chain networks. However, its primary focus on efficiency has revealed limitations related to sustainability, system resilience, and human wellbeing.

In contrast, Industry 5.0 represents a conceptual shift toward human-centric, sustainable, and resilient systems. Rather than focusing solely on efficiency, Industry 5.0 integrates human oversight, environmental responsibility, and long-term system adaptability as fundamental design principles. This transition reflects a broader evolution from purely technological optimization toward a socio-technical approach that balances economic performance with societal and environmental outcomes [1], [24]. Consequently, the transition from Industry 4.0 to Industry 5.0 can be understood not as a technological replacement, but as a strategic reorientation of existing technologies toward human-centered and sustainable objectives.

The evolution from Industry 4.0 to Industry 5.0 has been widely explored in recent academic and policy literature. Industry 4.0 technologies—such as IoT, cyber-physical systems, and data-driven automation—enable real-time monitoring and optimization of industrial and logistics processes, significantly improving operational efficiency, transparency, and responsiveness [7], [8]. However, emerging research highlights the need to complement these capabilities with sustainability-oriented and human-centric approaches.

A key enabling concept in both paradigms is the digital twin, which provides a virtual representation of physical systems for monitoring, simulation, and optimization. Recent studies demonstrate its potential in transport and logistics for improving system performance, predicting disruptions, and supporting real-time

decision-making [22], [25]. In addition, research on supply chain risk and resilience emphasizes the role of digital technologies in mitigating disruption propagation (the ripple effect) and enhancing adaptive system capabilities under uncertainty [23].

Artificial intelligence (AI) and machine learning further extend these capabilities by enabling predictive analytics, dynamic optimization, and autonomous decision-making. However, the increasing reliance on AI introduces challenges related to transparency, accountability, and governance, which are addressed through emerging regulatory frameworks such as the European Union Artificial Intelligence Act [13].

Sustainability has also become a central focus of recent research, particularly in the context of emissions reduction, energy efficiency, and circular logistics. Frameworks such as ISO 14083 and the Global Logistics Emissions Council (GLEC) methodology provide standardized approaches for measuring and managing transport-related emissions, thereby supporting the integration of sustainability into operational decision-making processes [2], [3].

Despite these advancements, existing studies often address technological, environmental, and human dimensions in isolation. This reveals a critical research gap: the lack of integrated frameworks that combine digital technologies with human-centric design, sustainability objectives, and resilience strategies. The present study addresses this gap by proposing a unified reference architecture for Industry 5.0-aligned transport and logistics systems.

3. Methodology

This study adopts a conceptual and analytical methodology to examine the transition from Industry 4.0 to Industry 5.0 within transport and logistics systems. The research approach is structured around three main components: (i) a systematic literature review, (ii) comparative analysis, and (iii) the development of a reference system architecture.

First, a comprehensive review of academic literature, international standards, and policy frameworks was conducted to identify the defining characteristics of Industry 4.0 and Industry 5.0 paradigms. Particular emphasis was placed on sources related to digital transformation, smart logistics, sustainability, and human-centric system design principles [4], ensuring both theoretical and practical relevance.

Second, a comparative analysis was performed to evaluate the differences between Industry 4.0 and Industry 5.0 in terms of technological focus, system objectives, and operational implications for transport and logistics. This analysis enabled the identification of key conceptual shifts, including the transition toward

multi-objective optimization, human–machine collaboration, and resilience-oriented system design.

Third, a reference architecture was developed to illustrate the integration of key enabling technologies, including IoT, edge and cloud computing, digital twins, and artificial intelligence (AI)-driven decision-making within a cyber-physical framework [7]. The proposed architecture incorporates human-in-the-loop (HITL) mechanisms and sustainability considerations, providing a conceptual model for Industry 5.0-aligned transport and logistics systems [23].

Although the study is conceptual in nature, the proposed framework is supported by real-world case studies and established standards, enhancing its applicability to practical transport and logistics systems.

This methodological approach ensures both conceptual rigor and practical relevance for real-world transport and logistics systems.

3.1. System Architecture

The proposed architecture is based on a closed-loop cyber-physical system in which real-world operations continuously inform digital models, while optimized decisions are fed back into the physical system. This bidirectional interaction enables real-time monitoring, adaptive control, and continuous system improvement across transport and logistics processes.

Unlike traditional Industry 4.0 architectures, which primarily focus on efficiency and automation, the proposed model integrates human-in-the-loop (HITL) governance and multi-objective optimization. This ensures that operational performance is balanced with sustainability, resilience, and social impact. The architecture is aligned with Industry 5.0 principles, emphasizing human-centric and environmentally responsible system design. The proposed reference architecture is illustrated in Fig.1.

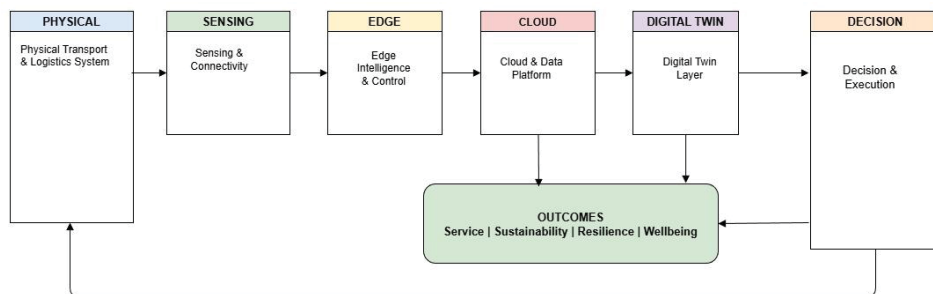


Figure 1. Industry 5.0-oriented digital twin architecture for smart transport and logistics systems integrating physical infrastructure, sensing, edge/cloud computing, AI-based decision-making, and human-in-the-loop governance

The architecture presented in Fig. 1 represents a closed-loop cyber-physical system for transport and logistics aligned with the Industry 5.0 paradigm. It integrates physical assets and infrastructure with sensing technologies, including IoT devices and communication networks, enabling real-time data acquisition and system visibility. Edge intelligence and cloud-based data platforms support distributed processing, data storage, and advanced analytics.

A multi-scale digital twin layer enables real-time synchronization between physical and virtual systems, as well as scenario-based simulation for disruptions, emissions, and policy interventions. Decision-making processes are supported by AI-driven optimization combined with human-in-the-loop oversight, ensuring transparency, safety, and accountability in operational environments [22], [25].

Furthermore, the architecture explicitly links operational layers to outcome-oriented performance indicators, including service efficiency, sustainability (e.g., ISO 14083 and GLEC-based emissions metrics), resilience, and worker wellbeing [2], [3]. This reflects the transition from efficiency-driven Industry 4.0 systems toward human-centric, sustainable, and resilient Industry 5.0 logistics.

The proposed architecture provides a scalable and interoperable framework for implementing Industry 5.0 principles in real-world transport and logistics systems.

4. Results and Discussion

The maturity assessment below is evidence-led (standards maturity + deployment signal from case studies + literature caution where relevant).

Table 1. Technology maturity and adoption signals for transport and logistics

<i>Technology</i>	<i>Typical logistics use cases</i>	<i>Maturity signal</i>	<i>Practical implication</i>
IoT (sensing, telemetry, tracking)	Asset tracking, ETA prediction inputs, cold-chain monitoring	High: strong vocabulary and reference models; widely deployed in ports/vehicles	Focus shifts to data quality, interoperability, and governance rather than “adding sensors”
AI/ML (optimization + prediction)	Dynamic routing, demand forecasting, yard/workforce planning	High in narrow tasks; governance expanding	Requires robust monitoring and human oversight; regulatory expectations growing (EU AI Act [13])

Digital twins (asset + network)	Port/terminal twins, network disruption simulation, urban mobility twins	Medium: standards exist, but SCM deployments often rarer than claimed	Strong value when synchronization, decision integration, and operational ownership exist; otherwise becomes “digital shadow”
Robotics (AMRs/AGVs, cobots)	Goods-to-person picking, pallet moves, yard automation	High in intralogistics; safety standards mature	Best results when designed for augmentation, safety, and job quality; strong change management needed
Edge computing	Low-latency perception, local safety interlocks, V2X-like control	Medium–high: strong standardization; deployment growing	Enables real-time operations and privacy-preserving designs (process data locally)
5G/advanced wireless	Dense sensing, low-latency control, connected mobility	Medium: capability well- defined; rollout uneven by geography	Treat as an enabler (not a prerequisite): architecture should degrade gracefully to LTE/Wi-Fi
Blockchain/DLT	Traceability, document authenticity, multiparty workflows	Mixed: standards vocab exists; network effect risk proven	Consider “minimum blockchain”: align first on standards- based data exchange; use DLT selectively where governance justifies it

(based on [7], [10], [11], [13], [26])

4.1. Human-Centric Design and Human-in-the-Loop Systems

Human-centric design and human-in-the-loop (HITL) systems play a critical role in ensuring transparency, safety, and accountability in AI-driven logistics [4]. By integrating human oversight into automated decision-making processes, these systems enable more reliable, explainable, and ethically aligned operations, particularly in safety-critical and high-impact transport environments [13].

From an Industry 5.0 perspective, human-centricity extends beyond usability toward the design of socio-technical systems that prioritize human wellbeing, trust, and collaboration. In this context, HITL mechanisms support decision validation, system supervision, and intervention in cases of uncertainty or system failure, thereby enhancing operational robustness and governance.

Furthermore, the integration of human expertise with AI-driven systems improves decision quality by combining data-driven insights with contextual knowledge and experience. This collaborative approach enables adaptive and resilient logistics operations while addressing emerging challenges related to ethics, accountability, and workforce transformation.

This approach reflects a shift from automation-centric systems toward collaborative human–AI ecosystems, which are fundamental to the Industry 5.0 paradigm.

4.2. Sustainability and Circular Logistics

Sustainability is integrated as a core operational constraint using standardized emissions metrics and environmental performance indicators. In Industry 5.0-oriented logistics systems, sustainability is not treated as a secondary outcome but as a fundamental design objective, supported by frameworks such as ISO 14083 and the Global Logistics Emissions Council (GLEC) methodology [2], [3].

From a systems perspective, sustainability is operationalized through the incorporation of emissions-aware decision-making, where routing, modal selection, and resource allocation are evaluated based on both efficiency and environmental impact. This enables a shift toward multi-objective optimization, where economic performance is balanced with carbon reduction targets and energy efficiency.

Furthermore, circular logistics principles—such as resource reuse, reverse logistics, and waste reduction—are integrated into supply chain design to enhance environmental efficiency and long-term system viability. These principles extend traditional linear logistics models by incorporating closed-loop flows, thereby supporting sustainable resource management and reducing environmental externalities.

This integration positions sustainability as an active control parameter within logistics systems rather than a passive reporting outcome.

4.3. Resilience and Risk Management

Resilience in transport and logistics systems is addressed through the integration of structured risk management frameworks and digital twin-based simulation approaches. Established standards, such as ISO 31000 and ISO 22301, provide systematic methodologies for identifying, assessing, and mitigating risks across complex supply chain networks [5], [6].

In parallel, digital twin technologies enable scenario-based analysis and real-time evaluation of disruptions, including infrastructure failures, demand fluctuations, and external shocks. By simulating alternative operational strategies and system

responses, digital twins support proactive and data-driven decision-making under uncertainty [23], [25].

The integration of risk management principles with simulation capabilities enhances the system's ability to anticipate disruptions, adapt to dynamic conditions, and recover efficiently from adverse events. As a result, resilience becomes an embedded system property rather than a reactive response, contributing to the stability and long-term reliability of transport and logistics operations.

This approach aligns with the Industry 5.0 paradigm, where resilience is treated as a fundamental design objective alongside efficiency and sustainability.

5. Case Studies and Applications

Case studies and real-world applications demonstrate the practical implementation of Industry 4.0 and Industry 5.0 concepts in transport and logistics. Notable examples include the use of digital twins in port operations, large-scale deployment of warehouse robotics, and AI-driven route optimization systems.

Digital twin implementations in port environments enable real-time monitoring, predictive analytics, and improved coordination of complex operations, contributing to both efficiency and resilience. Similarly, the adoption of warehouse robotics enhances operational productivity while supporting human-machine collaboration, reflecting the human-centric principles of Industry 5.0. In addition, AI-driven route optimization systems improve transport efficiency and reduce environmental impact by minimizing fuel consumption and emissions.

These applications illustrate how advanced technologies can be effectively integrated to enhance operational efficiency, improve sustainability outcomes, and support the development of human-centric and resilient logistics systems. They also demonstrate the transition from isolated technological solutions toward integrated, system-level approaches aligned with Industry 5.0 principles.

Furthermore, these case studies highlight the importance of aligning technological innovation with governance, workforce adaptation, and sustainability objectives to ensure successful implementation.

6. Implementation Roadmap and Governance

A phased implementation approach is essential to ensure scalability, interoperability, and compliance with relevant standards and regulatory requirements in transport and logistics systems. This approach supports the gradual transition from Industry 4.0 capabilities toward Industry 5.0-aligned operations.

The implementation process typically begins with the establishment of a data and interoperability foundation, including standardized data models, integration platforms, and secure data exchange mechanisms. This is followed by pilot deployment of digital twin systems in selected operational contexts, enabling validation of system performance and decision-making processes.

Subsequently, human-in-the-loop (HITL) decision mechanisms are integrated to ensure transparency, accountability, and effective human oversight in AI-driven operations. The final phase involves system scaling, supported by robust cybersecurity frameworks and risk management practices, ensuring system reliability and resilience at scale.

Effective governance frameworks, aligned with standards such as ISO/IEC 42001 [9] and emerging regulatory requirements, play a critical role in managing system complexity, ensuring ethical AI deployment, and maintaining compliance. These frameworks provide the foundation for transparent, accountable, and sustainable system operation in accordance with Industry 5.0 principles.

This phased approach reduces implementation risk and facilitates the alignment of technological deployment with organizational and regulatory readiness.

Industry 5.0 requires KPIs that are **balanced** and **auditable**—not only operational efficiency metrics.

Table 2. KPI framework for Industry 5.0-aligned transport and logistics

<i>KPI category</i>	<i>Example metrics</i>	<i>Why it matters</i>	<i>Notes on measurement sources</i>
Efficiency & service	OTIF, lead time, dwell time at hubs, vehicle utilization, empty-mile ratio	Maintains core logistics performance	Standard ops metrics; link to digital twin interventions
Sustainability & emissions	gCO ₂ e/ton-km, CO ₂ e per shipment/parcel, energy per km, % low/zero-emission miles; circular return rate	Converts sustainability into operational control	ISO 14083 provides common methodology; GLEC offers implementable guidance aligned with ISO 14083

Resilience	Time-to-detect, time-to-recover, service level under disruption, supplier/route concentration indices	Captures network robustness under shocks	Risk and continuity frameworks (ISO 31000/22301) provide process foundations; viability research provides conceptual targets
Human wellbeing	Recordable incident rate, near-miss frequency, ergonomic risk indicators, workload (shift overruns), retention/absenteeism	Aligns with “worker at the center”	ISO 45001 supports OH&S management; ILO highlights OSH policy challenges in digitalized workplaces
Trust & compliance	AI decision audit rate, override rate, model drift incidents, cybersecurity incidents; compliance evidence “completeness”	Prevents unmanaged automation risk	EU AI Act emphasizes oversight, logging, post-market monitoring; NIST AI RMF supports risk framing

(based on [2], [3], [5], [6], [13], [21])

7. Economic Impact and Business Models

Digital transformation fundamentally reshapes cost structures and value creation mechanisms in transport and logistics systems. The integration of advanced technologies, such as artificial intelligence (AI), digital twins, and automation, enables the emergence of new business models based on data-driven services, platform ecosystems, and performance-based logistics.

From an economic perspective, these transformations shift value creation from traditional asset utilization toward data-centric and service-oriented models. Logistics providers increasingly leverage real-time data, predictive analytics, and digital platforms to optimize operations, enhance customer experience, and create differentiated service offerings. This evolution supports the transition from transactional business models to integrated, value-added logistics solutions.

Furthermore, the adoption of Industry 5.0 principles introduces additional economic dimensions, including sustainability-driven value creation and resilience-oriented investments. Improvements in energy efficiency, emissions reduction, and operational robustness contribute not only to cost savings but also to long-term competitiveness and regulatory compliance.

Overall, these transformations lead to increased operational efficiency, reduced costs, and the generation of additional value through enhanced service quality,

sustainability performance, and system resilience, thereby redefining the economic landscape of modern transport and logistics systems. This transformation highlights the growing importance of intangible assets, such as data, algorithms, and digital capabilities, as primary drivers of competitive advantage in logistics systems.

Table 3. Illustrative cost–benefit scenarios

<i>Scenario</i>	<i>Typical capability scope</i>	<i>Cost drivers</i>	<i>Benefit drivers</i>	<i>Major risks</i>
Incremental Industry 4.0 upgrade	IoT tracking, basic analytics, WMS/TMS integration	Sensors, integration work, data platform	Visibility, fewer delays, incremental efficiency	Data quality failure; “dashboard without decisions”
Integrated Industry 4.0 + Industry 5.0	Add emissions accounting, HITL workflows, safety governance, resilience planning	Governance overhead, training, measurement systems	Measurable emissions cuts, safer operations, improved reliability under shocks	KPI conflicts; change fatigue; misaligned incentives
Transformational Industry 5.0 operating model	Digital twins with closed-loop optimization, robotics at scale, advanced edge/5G segments	Capex for automation, advanced modeling, cyber hardening	Step-changes in throughput + sustainability + resilience; new service revenue	Over-automation, workforce pushback, regulatory noncompliance, cyber risk

(author’s conceptual synthesis)

8. Barriers, Ethics, and Workforce Transformation

The adoption of Industry 5.0 concepts in transport and logistics is accompanied by several challenges, including skills gaps, governance complexities, and ethical considerations. The increasing reliance on artificial intelligence (AI)-driven systems raises critical concerns related to transparency, fairness, accountability, and data privacy, particularly in safety-critical and high-impact operational environments.

From an organizational perspective, the transition toward Industry 5.0 requires significant workforce transformation, including the development of new

competencies in digital technologies, data analytics, and human-machine collaboration. This shift also necessitates changes in organizational culture, training strategies, and job design to support effective interaction between human operators and intelligent systems.

Ethical considerations further extend to issues of algorithmic bias, decision accountability, and the potential impact of automation on employment and working conditions. Addressing these challenges requires a multidisciplinary approach that combines technological innovation with robust governance frameworks, regulatory compliance, and continuous workforce development.

Ensuring a balanced integration of technology and human factors is therefore essential for the responsible and sustainable implementation of Industry 5.0 systems.

9. Conclusion

Industry 5.0 represents a significant evolution in the development of transport and logistics systems, enabling a transition toward human-centric, sustainable, and resilient operations. By integrating advanced digital technologies with human oversight and environmental considerations, Industry 5.0 frameworks support more balanced and adaptive decision-making processes across complex logistics networks. This study has demonstrated that the shift from Industry 4.0 to Industry 5.0 is not merely technological but fundamentally conceptual, redefining system objectives from efficiency-driven optimization toward multi-objective performance that includes sustainability, resilience, and human wellbeing. The proposed reference architecture highlights how digital twins, AI-driven decision-making, and human-in-the-loop mechanisms can be integrated within a closed-loop cyber-physical system to support this transformation. Overall, Industry 5.0 enables the development of intelligent and adaptive logistics systems that align technological innovation with societal and environmental objectives, thereby ensuring long-term system viability and sustainable growth in the transport and logistics sector.

Future research should focus on the empirical validation of Industry 5.0 frameworks through real-world implementations and quantitative performance evaluation. These findings contribute to the growing body of research on Industry 5.0 by providing a structured framework for its implementation in complex logistics environments.

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