

INTEGRATING HETEROGENEOUS DIGITAL TECHNOLOGIES IN HEAVY EQUIPMENT SUPPLY CHAINS: A SYSTEMATIC LITERATURE REVIEW

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Abstract

Heavy equipment supply chains face increasing pressure to adopt digital technologies such as Digital Twins, Machine Learning, the Internet of Things (IoT), Blockchain, and Artificial Intelligence (AI). These technologies offer tangible benefits, including predictive maintenance, real-time visibility, and end-to-end traceability. However, integrating heterogeneous technologies creates technical and organizational challenges that remain insufficiently understood, particularly in the context of complex, long-lived, and capital-intensive equipment. This study conducts a systematic literature review of studies published from 2016 to 2026 to address three research questions: (RQ1) Which digital technologies are currently used in heavy equipment supply chains? (RQ2) What barriers hinder seamless integration among these systems? (RQ3) What middleware solutions or architectural approaches have been proposed to overcome these challenges? Following the PRISMA 2020 guidelines, literature searches were conducted across SciSpace, Google Scholar, ScienceDirect, and ResearchGate using terms related to digital technologies in the sector. From 679 initial records, 66 studies met the inclusion criteria and were analyzed. The findings indicate that Digital Twin is the most extensively studied technology, appearing in 34 studies (59.6%), followed by IoT in 25 studies (43.9%), Blockchain in 18 studies (31.6%), and AI/ML in 15 studies (26.3%). The central finding is that improving heavy equipment supply chain performance requires not merely technology adoption, but the integration of heterogeneous digital technologies through interoperable middleware and enabling architectures capable of overcoming data, connectivity, interoperability, governance, and organizational barriers.

Keywords: *Artificial Intelligence; Blockchain; Digital Twins; Internet of Things; Middleware Architectures*

INTRODUCTION

Background and Motivation

Heavy equipment supply chains, encompassing agricultural machinery, industrial vehicles, construction machinery, and mining equipment, remain under-researched in the digital transformation literature. Compared with consumer goods or electronics manufacturing, heavy equipment is distinguished by asset lifecycles that typically span 20 to 30 years, capital-intensive procurement cycles, geographically dispersed multi-tier supplier networks, and complex aftermarket service ecosystems. These characteristics create distinctive obstacles to digital integration that remain insufficiently represented in broad Industry 4.0 approaches, which have largely been formulated for discrete or process manufacturing environments.

The need for digital transformation in heavy equipment supply chains arises from converging pressures: rising customer expectations for real-time asset visibility, regulatory requirements for emissions monitoring and safety compliance, competitive demands to reduce total cost of ownership through predictive maintenance, and supply chain disruptions exposed by recent global crises. In this context, conventional supply chain management practices based on fragmented information systems, manual data handling, and predominantly reactive maintenance are increasingly inadequate.

Nevertheless, combining these technologies introduces major interoperability challenges. Each technology is typically built on a different architectural model, relies on distinct communication protocols, and operates with different data structures. IoT generates large volumes of sensor data; AI/ML relies on curated and often labeled datasets; Blockchain requires consensus mechanisms and synchronization across distributed ledgers; and Digital Twins depend on continuous state synchronization between physical assets and their digital counterparts.

For heavy equipment, the act of integrating becomes tougher because the domain imposes its own limits. Legacy systems installed decades ago often lack modern connectivity interfaces, producing “brownfield” integration difficulties. Equipment is used in harsh, remote environments with intermittent network connectivity, which makes edge computing and offline-capable architectures necessary. In addition, the long asset lifecycle requires digital solutions to sustain data continuity over decades, manage versions, and maintain backward compatibility.

Although these issues are becoming increasingly important, the existing body of research remains

fragmented. Studies examining IoT in supply chains seldom address heavy-equipment-specific conditions. Research on AI/ML-based predictive maintenance typically targets generic industrial assets rather than mobile, long-lived machinery. Studies of Blockchain-based traceability focus mainly on fast-moving consumer goods or pharmaceuticals rather than capital equipment with complex service histories. Consequently, a comprehensive synthesis is still needed to explain how these technologies can work together, identify the barriers to integration, and outline architectural solutions capable of closing interoperability gaps in heavy equipment settings.

Problem Statement

This systematic literature review focuses on several core challenges affecting supply chain effectiveness. These include limited real-time supply chain visibility, which restricts the monitoring of equipment location, operating condition, and availability, particularly in large-scale projects. The industry also depends heavily on imported components, exposing companies to exchange-rate fluctuations, global supply chain disruptions, delivery delays, and counterfeit spare parts. In addition, the limited use of predictive maintenance means that many operators continue to rely on preventive or reactive maintenance, resulting in unplanned downtime and higher operating costs.

Other major challenges include limited transparency and spare-part traceability, which make it difficult to verify component authenticity and track transactions across the distribution network despite the potential of Blockchain technology. Fragmented information systems and poor interoperability among manufacturers, distributors, rental companies, contractors, and suppliers also create duplicated data, delayed information exchange, and inefficient coordination. Finally, gaps in digital skills and human capital, particularly in IoT, AI/ML, Blockchain, data analytics, and system integration, remain important barriers to successful digital transformation and the realization of its operational benefits.

Three specific gaps in knowledge drive this review. First, adoption patterns in heavy equipment supply chains are still unclear. Existing surveys combine data across multiple manufacturing sectors, which masks sector-specific adoption rates, implementation conditions, and performance outcomes.

Second, the characteristics and magnitude of interoperability barriers are not described with sufficient depth. Technical difficulties such as protocol heterogeneity, data format incompatibility, and scalability constraints are often mentioned in passing, yet they are rarely examined in a systematic manner. Organizational barriers including skills gaps, cost structures, regulatory compliance, and resistance from the workforce receive even less rigorous attention.

Third, middleware and architectural approaches proposed to address interoperability challenges have not been comparatively evaluated or validated in heavy equipment contexts. Standards such as OPC UA, frameworks such as Eclipse Arrowhead, and reference architectures including RAMI 4.0 and Asset Administration Shell (AAS) are discussed in the broader Industry 4.0 literature, but their relevance, performance characteristics, and limitations in heavy equipment supply chains remain unexamined.

Research Questions and Objectives

To fill the identified knowledge gaps, this systematic literature review is structured around three research questions:

RQ1: Which digital technologies are currently being used in heavy equipment supply chains?

RQ2: What barriers prevent these systems from working together seamlessly?

RQ3: What middleware solutions or architectural approaches have been proposed to overcome these challenges?

This review primarily aims to consolidate varied evidence streams into a coherent, usable resource that serves both researchers and practitioners. Above all, it benefits researchers by zeroing in on substantial gaps in understanding, revealing where existing methods may be made more robust or more precise, and specifying the priority themes that should direct later research.

Contribution and Scope

This systematic literature review makes several distinctive contributions to the supply chain management and digital transformation literature. First, it provides the most comprehensive synthesis to date of digital technology integration in heavy equipment supply chains, a sector that has received disproportionately little attention relative to its economic significance and unique technical challenges. By focusing specifically on heavy equipment rather than aggregating across diverse manufacturing sectors the review surfaces sector-specific insights that are obscured in broader Industry 4.0 surveys.

The scope of this review is deliberately bounded to ensure depth and rigor. Temporally, we focus on literature published between 2016 and 2026, to capture the period marked by rapid Industry 4.0 adoption and the rise of integrated digital supply chain concepts. (Ashfaq et al. 2025; dos Santos Souza et al. 2025). Technologically, we concentrate on four core technologies IoT, AI/ML, Blockchain, and Digital Twins while excluding other technologies (cloud computing, big data analytics, additive manufacturing) that serve primarily as enabling

infrastructure, Cloud migration involves several risks, including information security, loss of data access, virtual-machine risks, financial risks, and compliance risks (Maniah Soewito, Gaol, and Abdurachman 2021)

LITERATURE REVIEW

Industry 4.0 and Supply Chain Digitalization

Industry 4.0, also known as the Fourth Industrial Revolution, marks a paradigm shift in supply chain management and manufacturing. It is characterized by the integration of cyber-physical systems, the Internet of Things, cloud computing, and cognitive computing (Omoegun et al. 2024). Originating from Germany's 2011 high-technology strategy, the Industry 4.0 concept has evolved into a global framework for digital transformation, emphasizing real-time data exchange, autonomous decision-making, and flexible, reconfigurable production systems (Men et al. 2022; Ouedraogo et al. 2025). In heavy equipment supply chains, however, Industry 4.0 and digitalization concepts must be adapted to sector-specific realities. These supply chains are characterized by long asset lifecycles (20–30 years), high capital intensity, geographically dispersed operations, and complex multi-tier supplier networks (Kotte and Panyaram 2025; Nagy and Szentesi 2025). Equipment is often operated in harsh and remote environments, including construction sites, mines, and farms, where connectivity can be intermittent and environmental conditions are extreme.

Internet of Things in Heavy Equipment

The Internet of Things (IoT) refers to networks of physical devices equipped with sensors, actuators, and communication capabilities that enable data collection, remote monitoring, and autonomous control (Chowdury 2024; Luo and Ball 2024). In heavy equipment contexts, IoT technologies support real-time tracking of equipment location and utilization, continuous monitoring of operational parameters such as engine temperature, hydraulic pressure, and fuel consumption, anomaly and fault detection, and automated reporting to centralized management systems (S. Q. Liu et al. 2022; Xiros et al. 2025). Telematics further enables the collection and use of operational data from heavy-duty vehicles to support more accurate analysis and decision-making (Nariendra, PW and Lestiani 2025).

Artificial Intelligence and Machine Learning in Supply Chain Optimization

Artificial Intelligence (AI) and Machine Learning (ML) encompass a broad class of computational techniques enabling systems to learn from data, identify patterns, and generate predictions or make decisions without explicit programming (Shang et al. 2025). In supply chain contexts, AI/ML applications span demand forecasting, inventory optimization, predictive maintenance, quality control, route planning, and supplier risk assessment (Kanyepe n.d.; Smerichevska, Prodanova, and Yakushev 2024). The value proposition is to transform extensive volumes of operational data generated by IoT sensors, enterprise systems, and external sources into actionable insights that improve efficiency, reduce costs, and enhance resilience (Sah et al. 2024)

Blockchain for Traceability

Blockchain technology offers a distributed, immutable ledger for documenting transactions and tracking assets across multi-party networks without centralized intermediaries (Patel 2025; Saiful, Naseri, and Rasid 2024). In supply chain contexts, blockchain enables end-to-end traceability, provenance verification, and tamper-proof record-keeping, addressing longstanding challenges of information asymmetry, trust deficits, and fraud (Lau et al. 2025; Owusu-Berko 2025; Zhang et al. 2020). The core value proposition is to create a single source of truth shared among supply chain participants manufacturers, suppliers, logistics providers, customers, regulators where each transaction is cryptographically secured and permanently recorded (Kinzel and McLeod 2025).

Digital Twins in Supply Chain Management

Digital Twins (DTs) are virtual representations of physical assets, processes, or systems that correspond to their real-world counterparts through continuous, real-time data synchronization (Martinelli et al. 2025; Mumin, Mohammed, and Amedofu 2025). In supply chain management, DTs enable simulation, optimization, and predictive analytics by creating dynamic models that reflect the current state, historical behavior, and future trajectories of supply chain entities such as equipment, facilities, products, and networks (Roumeliotis et al. 2024; Siddiqi et al. 2025). Their value lies in supporting “what-if” scenario analysis, proactive risk mitigation, and continuous improvement through virtual experimentation without disrupting physical operations (Bitam et al. 2025).

METHOD

Research Design

This systematic literature review follows the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) 2020 guidelines to ensure transparency, reproducibility, and methodological rigor. The review adopts a comprehensive, structured approach to identify, screen, extract, and synthesize evidence from peer-reviewed literature addressing digital technology integration in heavy equipment supply chains. The research design encompasses five sequential phases: (1) protocol development and registration, (2) systematic search and study identification; screening and eligibility assessment; data extraction and quality appraisal; and synthesis and reporting.

The temporal scope spans January 2016 to January 2026, capturing the period of rapid Industry 4.0 adoption. The starting year 2016 marks the beginning of widespread Industry 4.0 discourse following the acceleration of IoT and cloud computing adoption in industrial contexts. The geographic scope is global, with no restrictions on publication origin or study location, though the review is limited to English-language publications due to resource constraints and the dominance of English in scientific and technical literature.

Database and Search Strategy

Systematic searches were conducted across four major academic sources selected for their broad coverage of engineering, computer science, and management literature: ScienceDirect, IEEE Xplore, ResearchGate, and Google Scholar.

The search strategy employed nine Boolean query strings designed to capture the intersection of digital technologies and heavy equipment supply chains. Query strings combined technology terms (IoT, AI, ML, Blockchain, Digital Twin), supply chain terms (supply chain, logistics, traceability, maintenance), and heavy equipment terms (heavy equipment, construction machinery, mining equipment, industrial equipment). The complete search strings are presented in Image 1 below.

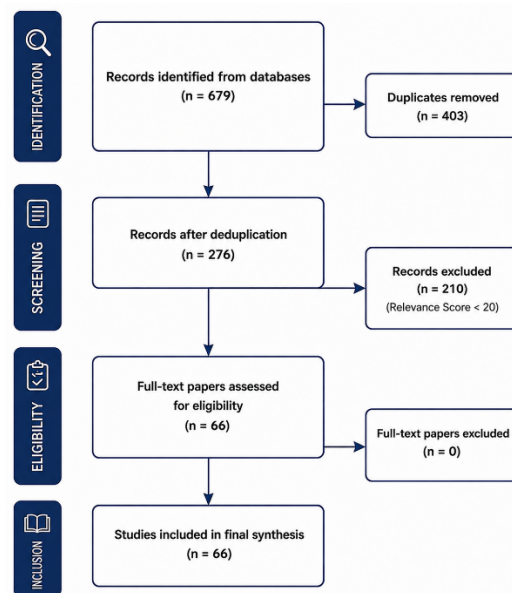


Image 1. Search Strings and Database Coverage

RESULTS AND DISCUSSION

Publication Trends and Geographic Distribution

The 66 studies included in the review exhibit pronounced temporal clustering, with 62% (n=171) published during the three-year period from 2023 to 2025, indicating accelerating research interest alongside the maturation of Industry 4.0 technologies.

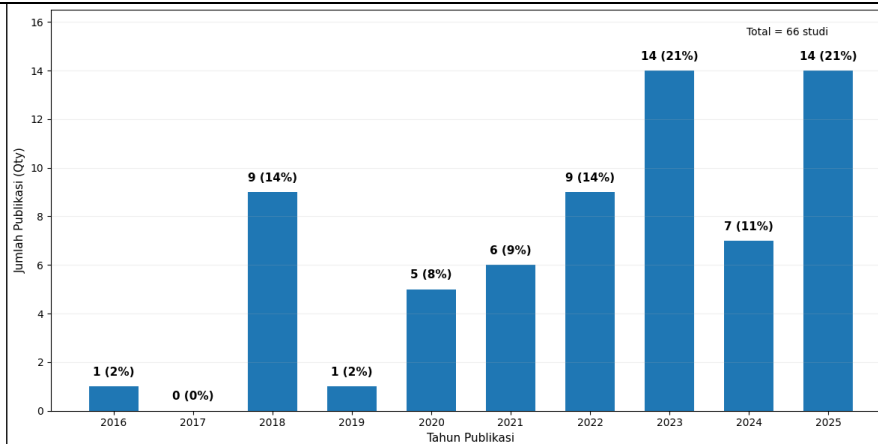


Image 2. Yearly Based Publication Study

A key finding is that 63% of the reviewed articles are concentrated in the 2023–2025 period, suggesting increased integration activity and technology readiness after the COVID-19 pandemic and the expansion of investment in Industry 4.0.

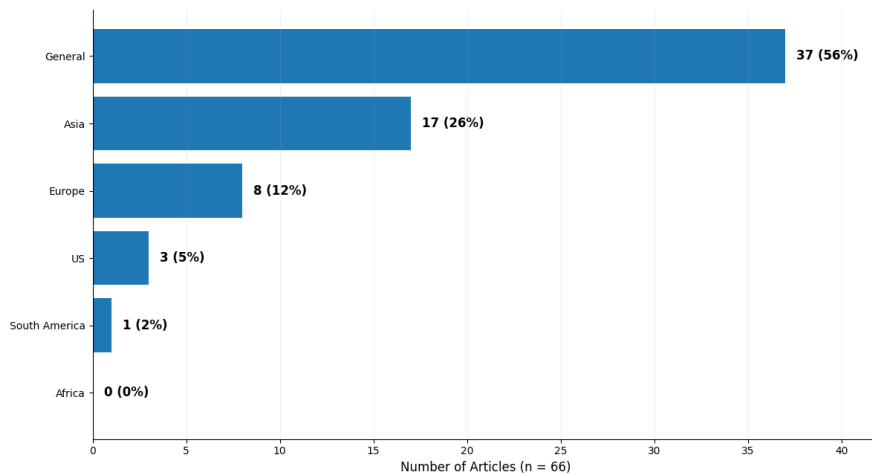


Image 3. Geographic Distribution of Included Studies

The geographic distribution indicates that the research is dominated by Asian countries, reflecting growing research activity and capability development in this area.

RQ1: Core Technologies

Analysis of technology coverage across the 66 included studies reveals distinct adoption patterns.

Table 1. Analysis of technology

Technology	Studies	%	Citation
Digital Twin	34	59,6	(Bandara, Thakur, and Breslin 2021; Baumgärtel and Verbeet 2020; Bhuvaneswari and Anitha 2022; Chaudhari et al. 2025; Chubin 2024; Ferko et al. n.d.; Ferko E. and Behnam 2024; Fett et al. 2024; N. Gupta et al. 2020; Jesus 2023; Khan and A 2024; Kozhakhmetova and Akhmetkaliyeva 2023; Kunwar et al. 2024; Kuruppuarachchi, Rea, and McGibney 2022; Lehmann et al. 2023; Martinelli et al. 2025; Miao et al. 2025; Minerva, Lee, and Crespi 2020; Moreira 2024; Newrzella S. R. and Haider 2022; Owusu-Berko 2025; Paul 2024; Pernici et al. 2020; Ramón, Ojeda, and Valera 2021; Schnicke F. and Antonino 2022; Serdyukova, k. Bashirzade, and Pakhomova 2020; Simatupang and Sridharan 2016; Simões et al. 2023; Wasi et al. 2025; Xiros et al. 2025; Ye X. and Hong 2023)(Wasi et al., 2025; Liu et al., 2025); (Martinelli et al., 2025; Xiros et al., 2025); (Owusu-Berko, 2025; Miao et al., 2025); (Fett et al., 2024; Moreira, 2024); (Gupta, 2023; Kozhakhmetova & Akhmetkaliyeva, 2023); (Jesus et al., 2023; Lehmann et al., 2023); (Simões et al., 2023; Liu et al., 2022); (Bhuvaneswari & Anitha, 2022; Khan et al., 2024); (Schnicke et al., 2022; Aziz et al., 2022); (Kuruppuarachchi et al., 2022; Newrzella et al., 2022); (Bandara et al., 2021; Pernici et al., 2020); (Baumgärtel & Verbeet, 2020; Minerva et al., 2020); (Khan et al., 2024; Paul, 2024); (Ferkko et al., 2024; Ramón et al., 2021);

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Technology	Studies	%	Citation
			(Serdyukova et al., 2020); (Khan et al., 2024; Paul, 2024); (Ferko et al., 2024; Chaudhari et al., 2025);(Kunwar et al., 2024; Chubin, 2024);(Simatupang & Sridharan, 2016)
IoT	25	43,9	(Abdelhamid, Sliman, and Djemaa 2024; Agarwal V. and Jawade 2021; Bandara, Thakur, and Breslin 2021; Bhuvaneswari and Anitha 2022; Chaudhari R. S. and Mogal 2025; Gnoni et al. 2020; V. K. Gupta 2023; Holloway and Holloway 2024; Kayembe and Obadire 2025; Khan 2025; Kozhakhmetova and Akhmetkaliyeva 2023; Kunwar et al. 2024; J. Liu et al. 2022; Minerva, Lee, and Crespi 2020; Mironescu and Verdeş 2023; Moreira 2024; Owusu-Berko 2025; Rane S. B. and Narvel 2021; Sah et al. 2024; Saidu et al. 2025; dos Santos Souza et al. 2025; Schnicke F. and Antonino 2022; Yang 2022)
Blockchain	18	31,6	(Abdelhamid, Sliman, and Djemaa 2024; Bandara, Thakur, and Breslin 2021; Bhuvaneswari and Anitha 2022; Charles, Emrouznejad, and Gherman 2023; Chaudhari et al. 2025; Holloway and Holloway 2024; Kozhakhmetova and Akhmetkaliyeva 2023; Kumar, Rabbani, and Khan 2024; Kunwar et al. 2024; Miao R. and Bao 2025; Mironescu and Verdeş 2023; Owusu-Berko 2025; Ramón, Ojeda, and Valera 2021; Sah et al. 2024; Saidu et al. 2025; dos Santos Souza et al. 2025; W. Wu et al. 2022)
AI/ML	15	26,3	(Abdelhamid, Sliman, and Djemaa 2024; Bhuvaneswari and Anitha 2022; Charles, Emrouznejad, and Gherman 2023; Gourisetti et al. 2023; Holloway and Holloway 2024; Kayembe and Obadire 2025; Khan 2025; Kozhakhmetova and Akhmetkaliyeva 2023; Kunwar et al. 2024; S. Q. Liu et al. 2022; Sah et al. 2024; Saidu et al. 2025; dos Santos Souza et al. 2025; Xiros et al. 2025; Yang J. and Qu 2022)

The SLR findings indicate that Digital Twin is the most extensively studied technology, appearing in 34 studies (59.6%), followed by IoT with 25 studies (43.9%), Blockchain with 18 studies (31.6%), and AI/ML with 15 studies (26.3%). This distribution suggests that current research is increasingly focused on integrating heterogeneous digital technologies to enhance supply chain visibility, traceability, predictive analytics, and intelligent decision-making. Digital Twin emerges as a central technology that can integrate real-time data from IoT with analytical capabilities from AI/ML, while Blockchain supports secure and transparent information exchange.

Table 2. Applications and Operational Benefits of Digital Technologies in Heavy Equipment Supply Chain Management

Technology	Citation	Implication for Heavy Equipment SCM	Description of Benefits
AI/ML	(Ramón, Ojeda, and Valera 2021; Saidu et al. 2025)	Demand forecasting and spare-parts inventory optimization	Improves forecasting accuracy while reducing overstock, stockouts, and inventory-related costs.
	(Yang et al. 2022)	Automation of operational decision-making	Enables real-time process monitoring and supports data-driven decision-making.
	(Kunwar et al. 2024; Saidu et al. 2025)	Anomaly detection and component traceability	Enhances data integrity and responsiveness to abnormal operating conditions.
	(Kayembe and Obadire 2025; Moghaddam and Karimzadeh 2025)	Logistics and delivery optimization	Supports route optimization, logistics automation, and improved distribution efficiency.
	(Sah et al. 2024; Serdyukova, k. Bashirzade, and Pakhomova 2020)	Transportation and logistics integration	Enables real-time tracking and facilitates data-driven logistics decision-making.
IoT	(Ali et al. 2024; Soe et al. 2022)	Heavy equipment condition and location monitoring	Provides real-time operational data, improving supply chain visibility and asset monitoring.

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Technology	Citation	Implication for Heavy Equipment SCM	Description of Benefits
	(Gnoni M. G. and Monica 2020)	Maintenance digitalization	Improves maintenance traceability, certification, and regulatory compliance.
	(Yang J. and Qu 2022)	Component production process monitoring	Enhances process control and quality traceability.
	(Chaudhari et al. 2025; Kunwar et al. 2024)	IoT–Blockchain integration	Improves supply chain transparency, boosts logistics efficiency, and supports sustainability
	(Agarwal et al. 2021; Kunwar et al. 2024)	Full end-to-end supply chain visibility.	Enables monitoring of spare-parts location, quantity, and condition while reducing inventory-related costs.
Digital Twin	(Khan A. U. and Liu 2024)	Heavy equipment performance and maintenance prediction	Supports predictive maintenance and enhances machine performance.
	(Zhidchenko, Startcev, and Handroos n.d.)	Machine condition simulation	Enables performance simulation and data-driven operational decision-making.
	(Pernici et al. 2020)	Agile supply chain management	Enhances the supply chain's ability to adapt to operational changes and disruptions
	(Y. Liu, Nifa, and Teong 2025)(W. Wu et al. 2022)	Digital Twin–Blockchain integration	Improves transparency, data security, and supply chain efficiency in large-scale projects.
	(Bhuvaneswari & Anitha, 2022; Joshi et al., 2025)	Warehouse and distribution simulation	Facilitates bottleneck identification and supports logistics planning and optimization.
Blockchain	(Y. Wu, Zhang, and He 2025)	Remanufacturing traceability for mining equipment	Ensures component authenticity and maintains the integrity of asset lifecycle records.
	(Ramón, Ojeda, and Valera 2021; Saidu et al. 2025)	Procurement transparency	Enhances transaction security, auditability, and procurement transparency.
	(Yang et al. 2022)	IIoT data security	Supports data authentication, integrity, and security within supply chain operations.
	(Kunwar et al. 2024; Saidu et al. 2025)	EPC resource management	Supports coordination and data-driven decision-making in asset-intensive projects.
	(Kayembe and Obadire 2025; Moghaddam and Karimzadeh 2025)	Green supply chain management	Enhances transparency, procurement efficiency, and environmental sustainability.

The main finding is that digital technologies can shift heavy equipment supply chain management from reactive and fragmented practices toward a more predictive, visible, secure, and data-driven model. However, the greatest potential lies in multi-technology integration rather than the isolated adoption of individual technologies.

RQ2: Technical Barriers

Technical barrier analysis identified five primary categories with distinct prevalence and severity profiles. The barrier taxonomy is grounded in 66 studies, with frequency calculated as the proportion of studies explicitly identifying each barrier type.

Table 3. Technical Barrier Taxonomy and Prevalence

Technical Barrier	Citation	Relevance to Heavy Equipment Supply Chain	Impact on Heavy Equipment Supply Chain Operations
Scalability and Latency	(Abdelhamid, Sliman, and Djemaa 2024; Bandara, Thakur, and Breslin 2021)	The large volume of machine, IoT, GPS, and ERP data can be difficult to process in real time, particularly in large-scale projects.	Delays in inventory updates, shipment tracking, and multi-vendor coordination.
System and Protocol Heterogeneity	(Soe et al., 2022; Kharlamova et al., 2021)	Legacy ERP/CMMS platforms and heterogeneous vendor systems are hard to integrate with the Internet of Things, Digital Twin, and Blockchain technologies.	Data remain isolated in silos, limiting full end-to-end visibility across the supply chain
Data Security and Cybersecurity Vulnerabilities	(Bandara, Thakur, and Breslin 2021; J. Liu et al. 2022)	Procurement, asset, and contractual data are sensitive and vulnerable to cyberattacks, manipulation, and unauthorized access.	Increased risks of data breaches, inspection-data manipulation, and supplier certificate forgery.
Data Inconsistency and Quality Issues	(Gourisetti et al. 2023; Yang J. and Qu 2022)	Sensor, manual, supplier, and field data are often incomplete, non-standardized, or inconsistent.	Reduced spare-parts forecasting accuracy, disrupted equipment monitoring, and decreased traceability.
Digital Twin Complexity	(J. Liu et al. 2022; W. Wu et al. 2022; Y. Wu, Zhang, and He 2025)	Turning physical assets into digital models is a complex process. Because heavy equipment and its components are highly heterogeneous.	Limited supply disruption simulation and suboptimal predictive maintenance performance.
Lack of Standards and Interoperability	(J. Liu et al. 2022; Soe et al. 2022)	Widely accepted standards for integrating IoT, Blockchain, and Digital Twin technologies across different vendors remain limited.	Complicates supplier onboarding, tracking-system integration, and comprehensive supply chain auditing.

The findings indicate that the principal technical barriers are not limited to the individual technologies themselves but arise primarily from the complexity of integrating heterogeneous digital systems at scale. The most critical issues include scalability, interoperability, cybersecurity, data quality, and Digital Twin complexity.

For heavy equipment supply chains, these barriers can directly affect inventory visibility, equipment monitoring, shipment tracking, predictive maintenance, supplier coordination, and end-to-end traceability. Consequently, successful digital transformation requires an architecture capable of handling high-volume real-time data, integrating legacy and heterogeneous systems, maintaining data security and quality, and establishing common interoperability standards.

RQ2: Organizational Barriers

Organizational barriers prove equally prevalent and often more intractable than technical barriers, reflecting the human and institutional dimensions of digital transformation.

Table 4. Organizational Barrier Taxonomy and Prevalence

Operational Barrier	Citation	Relevance to Heavy Equipment Supply Chain	Impact on Heavy Equipment Supply Chain Operations
Human Resource Competency Gaps	(Gourisetti et al. 2023; Soe P. K. and Chakravarthy 2022)	Supply chain personnel may lack sufficient competencies to operate and manage AI, IoT, and Blockchain technologies.	Low technology adoption, resistance to organizational change, and increased risk of human error.
Budget Constraints and Implementation	(Gourisetti et al. 2023; Parmar,	Implementing IoT, Digital Twin, Blockchain, and	Delayed digital modernization and a tendency to adopt fragmented or partial

Operational Barrier	Citation	Relevance to Heavy Equipment Supply Chain	Impact on Heavy Equipment Supply Chain Operations
Costs	James, and Asjad (2023)	system-integration technologies requires substantial investment.	solutions.
Cross-Chain Communication and Collaboration	(Simatupang and Sridharan 2016; W. Wu et al. 2022)	Coordination among principals, dealers, suppliers, and contractors remains limited across the heavy equipment supply chain.	Increased bullwhip effects, delivery mismatches, and inefficient claims-management processes.
External Instability and Regulatory Uncertainty	(Bandara, Thakur, and Breslin 2021; Kharlamova, Kharlamov, and Lemeshchenko 2021)	Differences in regulations, economic conditions, and trade-related risks affect global supply chain operations.	Supply disruptions, lead-time uncertainty, and increased regulatory compliance risks.

The organizational barriers indicate that digital transformation in heavy equipment supply chains is shaped not only by technological limitations but also by organizational capabilities, financial resources, inter-organizational coordination, and the external regulatory environment.

The most fundamental organizational issue is the competency gap among human resources, which can reduce technology adoption and increase resistance to change. At the same time, high implementation costs may delay modernization and encourage organizations to implement isolated rather than integrated digital solutions.

RQ3: Middleware Solutions

Middleware and architectural solutions analysis identified five primary categories of integration approaches, ranging from mature production-ready standards to emerging conceptual frameworks. Coverage frequencies indicate the proportion of studies addressing each solution type.

Table 5. Five Primary Categories of integration approaches

Middleware Solution	Definition and Purpose	Citation	Key Benefits	Impact on Heavy Equipment Supply Chain
OPC UA	A communication standard that enables secure and interoperable connectivity among devices and systems from different vendors.	(Khan 2025; Pereira P. H. M. and de Freitas 2023)	• Cross-vendor interoperability • Data security • Communication standardization	Connects heavy equipment IoT sensors with SCM and cloud platforms without dependence on a single technology vendor.
Eclipse Arrowhead	A service-oriented architecture (SOA) framework developed to be service-focused to manage communication and IoT services within local networks.	(Ferko 2024; Joshi 2025)	• IoT service orchestration • Low latency • Support for heterogeneous systems	Suitable for coordinating heavy equipment operations at construction and mining sites where network connectivity may be limited.
AAS / RAMI 4.0	A consistent digital format for physical assets that supports data integration and asset lifecycle management.	(Joshi 2025; Ye X. and Hong 2023)	• Asset standardization • Data interoperability • Lifecycle tracking	Supports heavy equipment lifecycle management from procurement and operation through maintenance and end-of-life disposal.
Microservices Architecture	A software architecture that decomposes a	(Simões B. and Alcaín 2023; Ye X. and Hong	• Modularity and scalability • Flexible deployment • Fault	Facilitates the integration of sensors, ERP systems, suppliers, and Digital Twin platforms within

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Middleware Solution	Definition and Purpose	Citation	Key Benefits	Impact on Heavy Equipment Supply Chain
	system into small, independent services connected through APIs.	2023)	isolation	large-scale heavy equipment supply chains.
Composite Digital Twin (CDT)	A network of interconnected Digital Twins that links physical assets and organizations within a shared digital ecosystem.	(Ali et al. 2024; Galli et al. 2023; Kuruppuarachchi, Rea, and McGibney 2022; Mironescu and Verdeş 2023)	• Cross-organizational collaboration • End-to-end visibility • Secure data sharing	Highly relevant for integrating principals, dealers, contractors, suppliers, and heavy equipment operators within a collaborative supply chain ecosystem.

The middleware solutions identified in the literature address a fundamental challenge in heavy equipment supply chain digitalization: the integration of heterogeneous systems, devices, platforms, and organizational actors.

OPC UA primarily addresses communication interoperability and secure connectivity, whereas Eclipse Arrowhead supports decentralized IoT service orchestration with low-latency communication. AAS/ RAMI 4.0 delivers a standardized way to represent assets and manage their lifecycle information, while Microservices Architecture enhances system modularity, scalability, and flexibility. Composite Digital Twin (CDT) extends integration beyond individual assets by connecting multiple Digital Twins and organizations within a shared digital ecosystem.

Table 6. Digital Technology Integration Patterns in Heavy Equipment Supply Chains

Integration	APA Citation	Context and Benefits in Heavy Equipment SCM
IoT – AI/ML	(Chubin 2024; Kuruppuarachchi, Rea, and McGibney 2022; Liang C. and Zhang 2025; Pereira P. H. M. and de Freitas 2023; Serdyukova, k. Bashirzade, and Pakhomova 2020; Simatupang and Sridharan 2016; Tao F. and Jin 2024; Wasi A. T. and Ahsan 2025; Zhidchenko V. and Handroos 2022) (Mulyati and Pardede 2025)	IoT sensors provide real-time equipment data (temperature, vibration, fuel, and pressure) for AI/ML analysis. Benefits: predictive maintenance, spare-parts demand forecasting, fleet routing and dispatch optimization, and a continuous data-to-decision feedback loop.
Blockchain – IoT	(Chubin 2024; Liang C. and Zhang 2025; Mironescu and Verdeş 2023; Simatupang and Sridharan 2016; Soe et al. 2022; Wasi et al. 2025; W. Wu et al. 2022)	Blockchain securely records IoT data to provide immutable traceability and maintenance records. Benefits: end-to-end spare-parts traceability, verified maintenance history, smart-contract-enabled procurement, and improved transparency. Challenge: limited Blockchain throughput may constrain high-volume IoT data processing.
DT – IoT – AI/ML	(Serdyukova, k. Bashirzade, and Pakhomova 2020; Simatupang and Sridharan 2016)	IoT continuously updates the Digital Twin, while AI/ML enables simulation and prediction. Benefits: what-if analysis, proactive failure prediction, condition-based maintenance, and fleet allocation optimization. Requirement: reliable sensing and edge/cloud computing infrastructure.
Blockchain – DT	(Khan and A 2024; Mironescu 2023; Simatupang and Sridharan 2016)	Blockchain records Digital Twin state changes as an immutable lifecycle audit trail. Benefits: secure lifecycle documentation, forensic and warranty dispute resolution, multi-party accountability, and transparent end-of-life management, including remanufacturing and recycling.

The integration patterns demonstrate that digital technologies create greater value when combined rather than deployed independently. IoT provides the real-time data layer, AI/ML provides prediction and decision intelligence, Digital Twin provides simul

ation and optimization capabilities, and Blockchain provides traceability, integrity, and multi-party verification.

Table 7. RQ1-RQ2-RQ3 Interrelationship in Heavy Equipment Supply Chains

Heavy Equipment Supply Chain Problem	RQ1: Digital Technologies	RQ2: Key Barriers	RQ3: Middleware / Enabling Architecture	Integrated Solution
Limited real-time visibility of equipment condition	IoT + AI/ML sensors, telematics, anomaly detection	Sensor-protocol heterogeneity, IoT security, and remote-site connectivity limitations	OPC UA cross-vendor protocol standardization	IoT sensors → OPC UA gateway → AI analytics → predictive-maintenance alerts
Limited traceability of spare parts and difficulty distinguishing genuine from counterfeit components	Blockchain + IoT immutable records and RFID scanning	Blockchain scalability, lack of standards, and low supplier adoption	Composite Digital Twin + Hyperledger Fabric permissioned Blockchain	Blockchain-based identification of critical components from OEM → operator → disposal
Unexpected equipment failures due to insufficient component-condition prediction	Digital Twin + AI/ML wear simulation and physics-based equipment models	Asset-mapping complexity, real-time synchronization, and Digital Twin implementation costs	AAS/RAMI 4.0 + Microservices modular Digital Twin architecture	Unit-level Digital Twin → AI-based failure prediction → preventive-maintenance scheduling
Inefficient spare-parts procurement, including long lead times, stockouts, and overstock	AI/ML + Blockchain demand forecasting and smart contracts	Poor data quality, legacy ERP integration, and limited digital skills	Microservices + OPC UA API gateway for legacy ERP/WMS integration	AI-based spare-parts forecasting → smart contract → automated PO → scheduled delivery
Limited collaboration and transparency among contractors, suppliers, and principals/EPC stakeholders	Blockchain + Digital Twin shared ledger and Composite Digital Twin	Data-ownership uncertainty and complex governance	Composite Digital Twin + Federated Learning privacy-preserving collaboration	CDT connects partner-level Digital Twins; Blockchain records transactions; Federated Learning enables analytics without sharing raw data
SCM performance below industry benchmarks due to manual processes and limited digital knowledge	IoT + Digital SCM 4.0 progressive process digitalization	Limited SCM knowledge, organizational resistance, and budget constraints	Eclipse Arrowhead + SCOR 12.0 local SOA for constrained site environments	Progressive SCM 4.0 adoption using SCOR 12.0 as the standardized process framework

Together, the findings from RQ1–RQ3 show that the biggest issues in heavy equipment supply chains are tightly linked, so no single digital technology can solve them on its own. Key challenges include limited real-time visibility, weak traceability, unexpected equipment failures, inefficient spare-parts procurement, limited stakeholder collaboration, and low levels of digital maturity.

The SLR points to the need for an integrated digital architecture. IoT and telematics supply real-time equipment data, AI/ML turns that data into predictive and optimization capabilities, a Digital Twin supports asset-level simulation and condition representation, and Blockchain improves traceability, transparency, and trusted transactions. Even so, adoption is hindered by protocol differences, cybersecurity risks, poor data quality, difficulty

integrating legacy systems, scalability concerns, governance gaps, limited digital skills, and organizational resistance.

Accordingly, the proposed approach is a layered, interoperable architecture built from OPC UA, AAS/RAMI 4.0, Microservices, Composite Digital Twin, Blockchain/Hyperledger Fabric, and Eclipse Arrowhead, with SCOR 12.0 used as the process framework. This architecture links physical equipment to IoT/telematics, then to middleware, Digital Twin, AI/ML analytics, Blockchain, and finally supply-chain management processes supporting predictive maintenance, spare-parts forecasting, automated procurement, traceability, and collaborative decision-making.

CONCLUSION

This systematic review of the literature synthesized evidence from 66 peer-reviewed studies published from 2016 to 2026 to examine the integration of heterogeneous digital technologies, Digital Twins, IoT, Blockchain, and AI/ML in heavy equipment supply chains. The review addressed three research questions concerning technology adoption patterns (RQ1), interoperability barriers (RQ2), and middleware solutions (RQ3).

Regarding RQ1 (technology adoption), Digital Twins dominate the digital technology landscape with a prevalence of 59.6%, followed by IoT (43.9%), AI/ML (34%), and Blockchain (31.6%). Publication trends show accelerating research interest, with 63% of studies concentrated in 2023-2025 and a peak of 14 papers in 2024.

Regarding RQ2 (barriers), the review developed a structured taxonomy encompassing technical and organisational dimensions. Technical barriers include protocol heterogeneity, data heterogeneity, scalability constraints, security vulnerabilities, and legacy system integration challenges. Organisational barriers include skills gaps, implementation costs, workforce resistance, and legal/regulatory complexity. These barriers are interconnected and mutually reinforcing: skills gaps drive costs, costs trigger resistance, and regulatory uncertainty amplifies all three.

Regarding RQ3 (middleware solutions), five primary categories were identified: OPC UA for field-level interoperability, microservices architectures for distributed digital twin management, Eclipse Arrowhead for service-oriented local clouds, Asset Administration Shell and RAMI 4.0 for standardised digital representations, and composite digital twin frameworks for cross-organisational collaboration. Maturity ranges from production-ready (OPC UA, microservices) to conceptual (composite DTs), with adoption rates reflecting these differences.

The RQ framework demonstrates a sequential relationship between supply chain problems, digital technologies, implementation barriers, and enabling middleware architectures. RQ1 identifies the technologies capable of addressing operational problems; RQ2 reveals the technical and organizational barriers that constrain their implementation; and RQ3 identifies middleware and architectural solutions that enable interoperability, scalability, security, and integration.

The central finding is that improving heavy equipment supply chain performance requires not merely technology adoption, but the integration of heterogeneous digital technologies through interoperable middleware and enabling architectures that can overcome data, connectivity, interoperability, governance, and organizational barriers.

REFERENCES

- Abdelhamid, M. M., Sliman, L., & Djemaa, R. B. (2024). AI-Enhanced Blockchain for Scalable IoT-Based Supply Chain. *Logistics*. <https://doi.org/10.3390/logistics8040109>
- Agarwal, V., Shiralkar, S., Aaher, S., & Jawade, S. (2021). The Supply Chain Management Revolution. *International Journal of Engineering Research & Technology*. <https://doi.org/10.5281/zenodo.18515095>
- Aziz, A., Schelen, O., Bodin, U., Romer, L., Jeroschewski, S. E., & Kristan, J. (2022). Empowering The Eclipse Arrowhead Framework with a Digital Twin as a Proxy Service. *IEEE ICCAS*. <https://doi.org/10.23919/ICCAS55662.2022.10003919>
- Bandara, K. Y., Thakur, S., & Breslin, J. G. (2021). End-to-End Tracing and Congestion in a Blockchain: A Supply Chain Use Case in Hyperledger Fabric. <https://doi.org/10.4018/978-1-7998-6650-3.CH004>
- Baumgärtel, H., & Verbeet, R. (2020). Service and Agent based System Architectures for Industrie 4.0 Systems. *IEEE NOMS*. <https://doi.org/10.1109/NOMS47738.2020.9110406>
- Bhuvaneswari, K., & Anitha, R. (2022). Building Digital Twins to Produce Virtual Counterparts in Logistics. <https://doi.org/10.54368/qijmsrd.1.3.0004>
- Taimia Bitam, Aya Yahiaoui, Djallel Eddine Boubiche, Rafael Martínez-Peláez, & Homero Toral-Cruz, Artificial intelligence of things for next-generation predictive maintenance, <https://doi.org/10.3390/s25247636>, 2025.
- Charles, V. S., Emrouznejad, A., & Gherman, T. (2023). A critical analysis of the integration of blockchain and artificial intelligence for supply chain. *Annals of Operations Research*. <https://doi.org/10.1007/s10479-023-05169-w>

- Chaudhari, R. S., Rane, S. B., Mahajan, S. K., Phanden, R. K., & Mogal, Y. K. (2025). Integrated IoT-Blockchain architecture for sustainable green supply chains in agriculture equipment manufacturing industries: A TOPSIS approach. <https://doi.org/10.1080/0951192x.2025.2467085>
- Adam Faturahman, Nugroho Prihantoni Wibowo, Fitra Putri Oganda, Jihan Zanubiya, & Todd Green, Digital Transformation in Supply Chain for Business Operational Efficiency, <https://doi.org/10.34306/abdi.v6i1.1239>, 2025.
- E. Mulyati, Maniah, Noviana, and N. Pardede, "Performance Analysis of the IndoBERT-Prophet Hybrid Model for Logistics Applications," *Spektrum Industri*, vol. 23, no. 2, pp. 293–305, 2025, doi: 10.12928/si.v23i2.480.
- Ferko, E., Bucaioni, A., Pelliccione, P., & Behnam, M. (2024). *Analysing Interoperability in Digital Twin Software Architectures for Manufacturing*. Springer. https://doi.org/10.1007/978-3-031-42592-9_12
- Fett, M., Kraft, M., Wilking, F., Goetz, S., Wartzack, S., & Kirchner, E. (2024). Medium-Level Architectures for Digital Twins: Bridging Conceptual Reference Architectures to Practical Implementation in Cloud, Edge and Cloud-Edge Deployments. *Electronics*. <https://doi.org/10.3390/electronics13071373>
- Galli, E., Lacroix, S., Fani, V., Le Duigou, J., Bandinelli, R., Eynard, B., & Godart, X. (2023). Literature review and comparison of digital twin frameworks in manufacturing. *Proceedings of the 37th ECMS International Conference on Modelling and Simulation*, 428–434. <https://doi.org/10.7148/2023-0428>
- Gnoni, M. G., Elia, V., Anastasi, S., & Monica, L. (2020). Supporting maintenance and mandatory inspections through digital technologies on lifting equipment. <https://doi.org/10.4018/978-1-7998-3904-0.CH015>
- Gupta, V. K. (2023). Changing Facet of Supply Chain Management – Is Human Factor No More Relevant? – A Study on Developing Countries. *International Journal of Supply Chain Management*. <https://doi.org/10.59160/ijscm.v12i3.6181>
- Holloway, S. (2024). Digital Transformation in Supply Chain Management: A Systematic Literature Review of Trends and Applications. <https://doi.org/10.20944/preprints202411.2423.v1>
- Jesus, V., Kalaitzi, D., Batista, L., & Lopez, N. L. (2023). Digital Twins of Supply Chains: A Systems Approach. *IEEE Transactions on Engineering Management*. <https://doi.org/10.1109/TEM.2024.3468177>
- Joshi, R., Ruikar, S., & Sapte, S. (2025). AI-driven digital twins: A theoretical framework for predictive decision-making in manufacturing and supply chains. *Journal of Computer Science and Technology Studies*, 7(11), 421–427. <https://doi.org/10.32996/jcsts.2025.7.11.39>
- Kayembe, M. T., & Obadire, A. M. (2025). Navigating the transformation: a systematic analysis of Building Information Modelling, Artificial Intelligence and Internet of Things in smart construction logistics. *Modern supply chain research and applications*. <https://doi.org/10.1108/mscra-07-2024-0027>
- Khan, S. A., Rao, P. V., Ghosh, A., Banerjee, R., Jeniffer, J. T., & Mukherjee, D. (2025). Integrating Blockchain with IoT and AI: Toward a Secure and Intelligent Future. *Dandao Xuebao / Journal of Ballistics*. <https://doi.org/10.52783/dxjb.v37.176>
- Khan, A. U., Huang, L., Onstein, E., & Liu, Y. (2024). Overview of Emerging Technologies for Improving the Performance of Heavy-Duty Construction Machines. *IEEE Access*. <https://doi.org/10.1109/ACCESS.2022.3209818>
- Kharlamova, T., Kharlamov, A., & Lemeshchenko, P. (2021). Innovative solutions for forming supply chains in the conditions of economic instability. <https://doi.org/10.1051/E3SCONF/202125806046>
- Michael Kinzel, & Alister McLeod, *Integrated Frameworks Enable Specific Use-Case Implementations Over the Digital Twin Life Cycle*, 2025.
- Kulasekhara Reddy Kotte, & Sudheer Panyaram, *Supply Chain 4*, 0. <https://doi.org/10.4018/979-8-3693-9750-3.ch016>, 2025.
- Kozhakhmetova, A., & Akhmetkaliyeva, S. (2023). Digital transformation of logistics centres: bibliometric analysis. "Türan" universitetinin habarsysy. <https://doi.org/10.46914/1562-2959-2023-1-1-267-278>
- Kunwar, F. B., Singh, H., Malviya, L., Yadav, R. K., Misra, V. K., & Narooka, P. (2024). Establishing a Secure and Reliable AI-Driven Framework for Operations in the Industrial Internet of Things (SCM) Using Blockchain and DL Technology. <https://doi.org/10.1109/cisct62494.2024.11134253>
- Kuruppuarachchi, P., Rea, S., & McGibney, A. (2022). An Architecture for Composite Digital Twin Enabling Collaborative Digital Ecosystems. *IEEE CSCWD*. <https://doi.org/10.1109/CSCWD54268.2022.9776073>
- Lehmann, J., Lober, A., Häußermann, T., & Rache, A. (2023). The Anatomy of the Internet of Digital Twins: A Symbiosis of Agent and Digital Twin Paradigms Enhancing Resilience (Not Only) in Manufacturing Environments. *Machines*. <https://doi.org/10.3390/machines11050504>
- Zhimei Lei, Bingbing Liu, Ming K. Lim, & Yui-yip Lau, A textual powered by data method to measure the capabilities and core paths of different digital technologies to improve supply chain resilience, <https://doi.org/10.1080/13675567.2024.2446247>, 2025.
- Liang, C., Li, X., Niu, W., & Zhang, Y. (2025). Internet of things driven digital twin for intelligent manufacturing in shipbuilding workshops. *Future Internet*, 17(8), 368. <https://doi.org/10.3390/fi17080368>

- Liu, Y., Nifa, F. A. A., & Teong, L. K. (2025). Blockchain-enabled digital twin integration for supply chain transparency enhancement in large-scale engineering project optimization. *Edelweiss applied science and technology*. <https://doi.org/10.55214/25768484.v9i7.8863>
- Liu, J., Yeoh, W., Qu, Y., & Gao, L. (2022). Blockchain-based Digital Twin for Supply Chain Management: State-of-the-Art Review and Future Research Directions. <https://doi.org/10.48550/arxiv.2202.03966>
- Yin Luo, Tengda Li, Guojin Li, Svetlana Besklubova, & Ray Y. Zhong, Cyber-physical internet based intelligent operation platform for off-site construction supply chain management, <https://doi.org/10.1080/17517575.2024.2346743>, 2024.
- Maniah, M., Soewito, B., Gaol, F. L., & Abdurachman, E., A systematic literature review: Risk analysis in cloud migration, *Journal of King Saud University - Computer and Information Sciences*. <https://doi.org/10.1016/j.jksuci.2021.01.008>, 2021.
- Martinelli, M., Barbone, A., Morandi, R., Picone, M., Burattini, S., & Ricci, A. (2025). Modular Engineering of Industrial Digital Twins: The WLDT Approach. Institute of Electrical and Electronics Engineers Inc. <https://doi.org/10.1109/DCOSS-IoT65416.2025.00077>
- Chubin (2024). Use of digital technologies to optimise the supply of construction materials and equipment. *Шляхи підвищення ефективності будівництва в умовах формування ринкових відносин*. [https://doi.org/10.32347/2707-501x.2024.53\(2\).351-367](https://doi.org/10.32347/2707-501x.2024.53(2).351-367)
- Miao, R., Liu, S., Sun, Y., Du, M., & Bao, J. (2025). Streamlining digital twin development and operation with DTOps. *Journal of Intelligent Manufacturing*. <https://doi.org/10.1007/s10845-025-02608-2>
- Minerva, R., Lee, G. M., & Crespi, N. (2020). Digital Twin in the IoT Context: A Survey on Technical Features, Scenarios, and Architectural Models. *Proceedings of the IEEE*. <https://doi.org/10.1109/JPROC.2020.2998530>
- Mironescu, A., & Verdeş, C. (2023). The post-pandemic challenges of digitization ascendancy within reverse logistics. *Proceedings of the.. International Management Conference*. <https://doi.org/10.24818/imc/2022/03.11>
- Moghaddam, G. K., & Karimzadeh, M. (2025). AI-Driven Digital Transformation and Sustainable Logistics: Innovations in Global Supply Chain Management. <https://doi.org/10.21203/rs.3.rs-6086101/v1>
- Moreira, J. (2024). The role of interoperability for digital twins. *Lecture Notes in Business Information Processing*. https://doi.org/10.1007/978-3-031-54712-6_9
- Mubarik Abdul Mumin, Abdul-Latif Mohammed, & Mawuli Kobla Amedofu, Leveraging IoT and Blockchain for Smarter Supply Chains and Logistics, <https://doi.org/10.4018/979-8-3373-2120-2.ch008>, 2025.
- Gábor Nagy, & Szabolcs Szentesi, Enhancing supply chain agility and quality through digitalization, <https://doi.org/10.32971/als.2025.002>, 2025.
- P. W. Nariendra and M. E. Lestiani, Calibration of HDM-4 model for fuel consumption in heavy-duty trucks: Integration of telematics, engine speed, and aerodynamics, *Automotive Experiences*, vol. 8, no. 1, pp. 109–121, 2025, doi: 10.31603/ae.12862
- Newrzella, S. R., Franklin, D. W., & Haider, S. (2022). Three-Dimension Digital Twin Reference Architecture Model for Functionality, Dependability, and Life Cycle Development Across Industries. *IEEE Access*. <https://doi.org/10.1109/ACCESS.2022.3202941>
- Owusu-Berko, L. (2025). Advanced supply chain analytics: Leveraging digital twins, IoT and blockchain for resilient, powered by data business operations. *World Journal of Advanced Research and Reviews*. <https://doi.org/10.30574/wjarr.2025.25.2.0572>
- Parmar, N. J., James, A. T., & Asjad, M. (2023). Analysis of maintenance outsourcing challenges for belt conveyors in the Industry 4.0 era. *Journal of global operations and strategic sourcing*. <https://doi.org/10.1108/jgoss-06-2022-0050>
- Kevin Patel, AI+IoT+Blockchain Triad for Smart Traceability in The Automotive Industry, <https://doi.org/10.51244/ijrsi.2025.120700023>, 2025.
- Paul, S. (2024). Integration of Digital Twin and AI-enabled ERP Systems: A Conceptual Framework for Intelligent Electronics Manufacturing Services. *IEEE CIEES*. <https://doi.org/10.1109/CIEES66347.2025.11300246>
- Pereira, P. H. M., Cainelli, G. P., Pereira, C. E., & Pignaton de Freitas, E. (2023). Interoperability middleware for IIoT gateways based on standard ontologies and AAS. *IFAC-PapersOnLine*, 56(2), 9831–9836. <https://doi.org/10.1016/j.ifacol.2023.10.403>
- Pernici, B., Plebani, P., Mecella, M., Leotta, F., Mandreoli, F., Martoglia, R., & Cabri, G. (2020). AgileChains: Agile Supply Chains through Smart Digital Twins. *ESREL 2020*. https://doi.org/10.3850/978-981-14-8593-0_3697-CD
- Ramón, C., Ojeda, A., & Valera, J. (2021). Best Practices Of Artificial Intelligence In Supply Chain Management. *International Journal of Scientific & Technology Research*.
- Rane, S. B., & Narvel, Y. A. M. (2021). Powered by data decision making with Blockchain-IoT integrated architecture: a project resource management agility perspective of industry 4.0. *International Journal of Systems Assurance Engineering and Management*. <https://doi.org/10.1007/S13198-021-01377-4>

- Christos Roumeliotis, Minas Dasygenis, Vasilis Lazaridis, & Michael Dossis, Blockchain and Digital Twins in Smart Industry 4, 0: The Use Case of Supply Chain-A Review of Integration Techniques and Applications. <https://doi.org/10.3390/designs8060105>, 2024.
- Sah, B. P., Hasan, M. A., Shofiullah, S., & Faysal, S. A. (2024). AI-Driven IoT And Blockchain Integration In Industry 5.0 A Systematic Review Of Supply Chain Transformation. <https://doi.org/10.70937/itej.v1i01.12>
- Saidu, Y., Shuhidan, S. M., Aliyu, D. A., Aziz, I. A., & Adamu, S. (2025). Convergence of Blockchain, IoT, and AI for Enhanced Traceability Systems: A Comprehensive Review. IEEE Access. <https://doi.org/10.1109/ACCESS.2025.3528035>
- Schnicke, F., Haque, A., Kuhn, T., Espen, D., & Antonino, P. O. (2022). Architecture Blueprints to Enable Scalable Vertical Integration of Assets with Digital Twins. IEEE ETFA. <https://doi.org/10.1109/ETFA52439.2022.9921728>
- Serdjukova, L. O., Bashirzade, R. R. K., & Pakhomova, A. V. (2020). Digital platforms for development of innovative transport logistic systems. *π-Economy*. <https://doi.org/10.18721/JE.13206>
- Wei Shang, Yijun Wang, Anding Zhu, Yan Chen, & Peihua Fu, DigiPyramid: A Multiresolution Digital Twin Framework for Reliable Logistics Management Conceptualization, Implementation, and Intelligentization, <https://doi.org/10.1109/access.2025.3606168>, 2025.
- Simatupang, T. M., & Sridharan, R. (2016). A critical analysis of supply chain issues in construction heavy equipment. The international journal of construction management. <https://doi.org/10.1080/15623599.2016.1142250>
- Simões, B., Carretero, M. D. P., Santiago, J. M., Segovia, S. M., & Alcain, N. (2023). TwinArk: A Unified Framework for Digital Twins based on Micro-frontends, Micro-Services, and Web 3D. ACM Web3D. <https://doi.org/10.1145/3611314.3615915>
- Svitlana Smerichevska, Larysa Prodanova, & Oleksandr Yakushev, Digitization of logistics and supply chain management, <https://doi.org/10.46783/smart-scm/2024-26-9>, 2024.
- Soe, P. K., Ghosh, A., Bhaumik, A., & Chakravarthy, M. (2022). Review of Current Supply Chain Management Practices in Myanmar Heavy Equipment Machinery Industry. International Journal on Recent Trends in Business and Tourism. <https://doi.org/10.31674/ijrtbt.2022.v06i01.004>
- Souza, H. J. D. S., Rosa, J. L., Cardozo, N. L., de Souza, N. B. P., & Junior, M. W. J. S. (2025). Logística 4.0 e cadeia de suprimentos na engenharia de produção: avanços tecnológicos e desafios na era digital. Brazilian Journal of Production Engineering. <https://doi.org/10.47456/bjpe.v11i3.48533>
- Tao, F., Sun, X., Cheng, J., Zhu, Y., Liu, W., Wang, Y., Xu, H., Hu, T., Liu, X., Liu, T., Sun, Z., Xu, J., Bao, J., Xiang, F., & Jin, X. (2024). makeTwin: A reference architecture for digital twin software platform. Chinese Journal of Aeronautics, 37(1), 1–18. <https://doi.org/10.1016/j.cja.2023.05.002>
- Wasi, A. T., Anik, M. A., Rahman, A., Hoque, M. I., Islam, M. S., & Ahsan, M. M. (2025). A Theoretical Framework for Graph-based Digital Twins for Supply Chain Management and Optimization. arXiv. <https://doi.org/10.48550/arXiv.2504.03692>
- Wu, Y., Zhang, Y., & He, L. (2025). Blockchain-Based remanufacturing traceability system design for coal mining equipment with improved consensus. Engineering Design. <https://doi.org/10.1080/09544828.2025.2558335>
- Xiros, V., Castro, J. M. G., Fernandez-Pelaez, F., Magoutas, B., & Christidis, K. (2025). Supply Chain Data Analytics for Digital Twins: A Comprehensive Framework. Applied Sciences. <https://doi.org/10.3390/app15126939>
- Yang, J., Lan, X., Cao, Z., Liu, W., Deng, W., & Qu, W. (2022). Research on Production Process Control Method of Discrete Manufacturing Digital Workshop. <https://doi.org/10.1109/ICCNEA57056.2022.00091>
- Ye, X., Xu, W., Liu, J., Zhong, Y., Liu, Q., Zhou, Z., Song, W. S., & Hong, S. H. (2023). Implementing digital twin and asset administration shell models for a simulated sorting production system. IFAC-PapersOnLine, 56(2), 11880–11887. <https://doi.org/10.1016/j.ifacol.2023.10.600>
- Zhang, J., Ellwein, C., Heithoff, M., Michael, J., & Wortmann, A. (2025). Digital twin and the asset administration shell: An analysis of the three types of AASs and their feasibility for digital twin engineering. Software and Systems Modeling, 24, 771–793. <https://doi.org/10.1007/s10270-024-01255-0>
- Zhidchenko, V., Startcev, E., & Handroos, H. (2022). Reference architecture for running computationally intensive physics-based digital twins of heavy equipment in a heterogeneous execution environment. IEEE Access, 10, 54164–54184. <https://doi.org/10.1109/ACCESS.2022.3176645>